Appendix 24-A

Ammonia Fate and Effects Study

PROJECT NUJIO'QONIK
Fate and Transport of Ammonia in Marine Water

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PROJECT NUJIO'QONIK
Fate and Transport of Ammonia in Marine Water

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Abbreviations

(NH_4^+)	ammonium
(OH^-)	hydroxide (OH^-)
2D	Two-dimensional
BC	British Columbia
BCMOE	British Columbia Ministry of Environment
CCME	Canadian Council of Ministers of the Environment
CD	Chart Datum
CHS	The Canadian Hydrographic Service
DFO	Fisheries and Oceans Canada
EA	Environmental assessment
EA Regulations	Environmental Protection Act and associated Environmental Assessment Regulations
ECCC	Environment and Climate Change Canada
EIS	Environmental Impact Statement
ESDV	Emergency Shutdown Valves
gr/cm^3	grams per cubic centimetre
GTM	Global Tide Model
GW	gigawatt
HD	Hydrodynamic
HHWLT	Higher High Water Large Tide
HHWMT	Higher High Water Mean Tide
hr	hour
H_s	Significant Wave Height

Kg/s	kilograms per second
km	kilometre
K_n	Nikuradse roughness
LLWLT	Lower Low Water Large Tide
LLWMT	Lower Low Water mean Tide
LPG	Liquified Petroleum Gas
m	metre
m/s	metres per second
m^3	cubic metre
m^3/hr	cubic metres per hour
mg/L	milligrams per litre
MSC	Meteorological Service of Canada
Mt	megatons
MW	megawatt
MWL	mean water level
n	Manning roughness coefficient
NH_3	Un-ionized ammonia
NH_4OH	ammonium hydroxide
NL	Newfoundland and Labrador
NOAA	National Oceanic and Atmospheric Administration
º	degrees
ºC	degrees Celsius
PSU	practical salinity unit
R^2	coefficient of determination
SCADA	Supervisory Control and Data Acquisition

SW	Spectral Wave
t	tonne
the Project	Project Nujio'qonik GH2
Town of Stephenville, NL	Port of Stephenville
Tp	Peak Wave Period
TR	Transport
UTC	Universal Time Coordinated

1.0 Introduction

Project Nujio'qonik GH2 (the Project) involves the development, construction, operation, maintenance, and eventual decommissioning and rehabilitation of one of the first Canadian, commercial-scale, "green hydrogen"[1] and ammonia production plants powered by renewable wind energy. Located on the western coast of the island of Newfoundland, Newfoundland and Labrador (NL) (Figure 1.1), the Project will have a maximum production of up to approximately 206,000 tonnes (t) of green hydrogen (equivalent to approximately 1.17 megatons (Mt) of ammonia per year. The hydrogen produced by the Project will be converted into ammonia and exported to international markets by ship. The hydrogen / ammonia plant and associated storage and export facilities will be located at the Port of Stephenville (in the Town of Stephenville, NL) on a privately-owned brownfield site and at an adjacent existing marine terminal, both of which are zoned for industrial purposes.

Renewable energy from two approximately 1,000 megawatt (MW) / 1 gigawatt (GW) onshore wind farms on the western coast of Newfoundland will be used to power the hydrogen and ammonia production processes. These wind farms (referred to herein as the "Port au Port area wind farm" and the "Codroy area wind farm") will include up to 328 turbines and collectively produce approximately 2,000 MW / 2 GW of renewable electricity. The Port au Port area wind farm will include up to 164 wind turbines on the Port au Port Peninsula, NL and adjacently on the Newfoundland "mainland" (i.e., northeast of the isthmus at Port au Port). The Codroy area wind farm will consist of up to 164 wind turbines located on Crown land in the Anguille Mountains of the Codroy Valley, NL.

The Project is subject to provincial environmental assessment (EA) requirements under the NL *Environmental Protection Act* and associated *Environmental Assessment Regulations* (EA Regulations). This document is the fate and transport of ammonia in marine water, prepared in support of an Environmental Impact Statement (EIS) and specifically for Chapter 24 of the EIS (Accidents and Malfunctions). It was prepared in consideration of the EIS guidelines which require an assessment of accidental spill and/or releases of hydrogen, ammonia, chemicals, pesticides or other potentially hazardous substances.

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[1] "Green hydrogen" is produced via electrolysis using renewable electricity to split the hydrogen bond with oxygen, liberating both elements at the atomic level. This type of hydrogen, which is referred to by the European Commission (n.d.) as "renewable fuel of non-biological origin", is often called "green hydrogen" in industry.

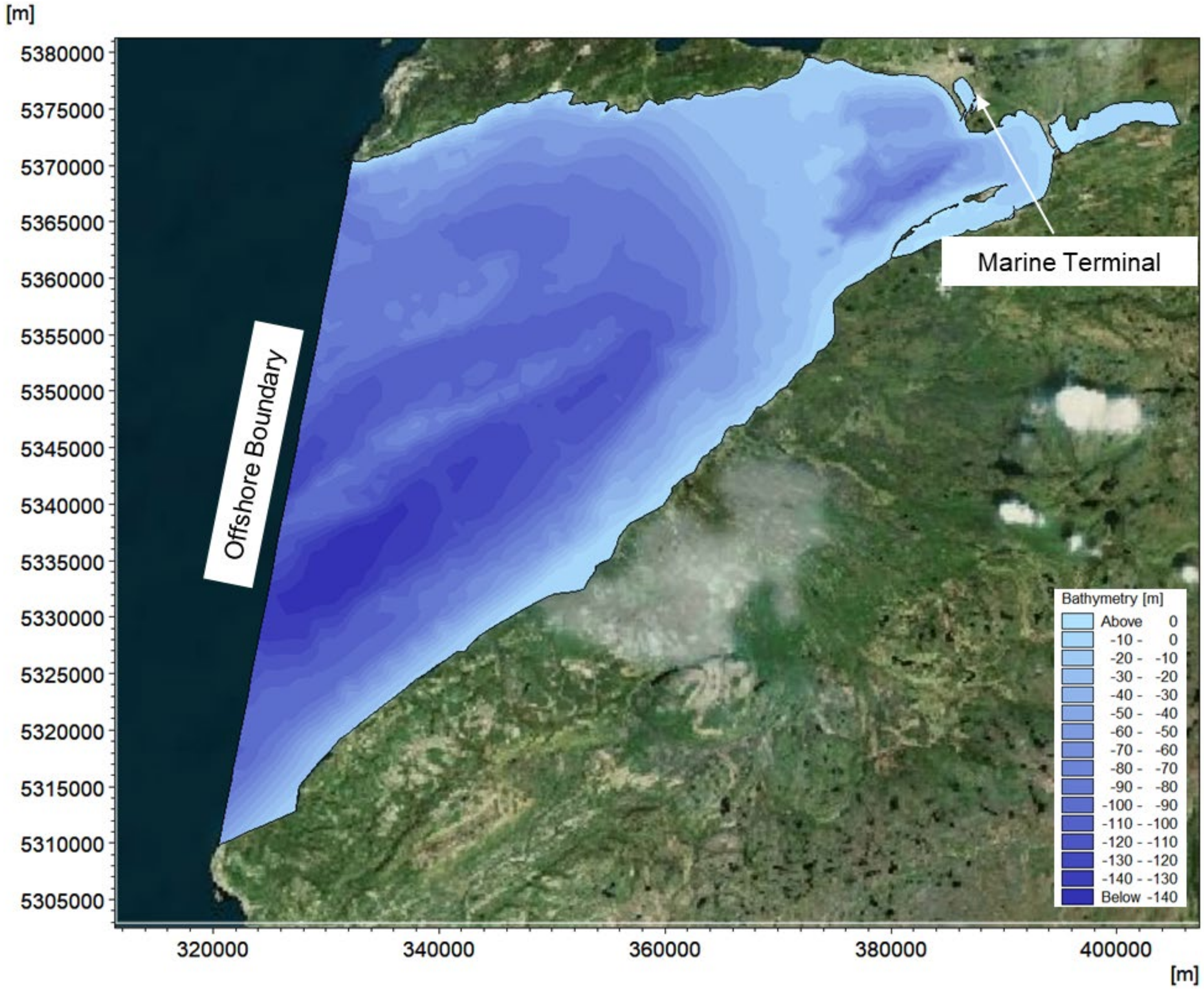


Figure 1.1 Study Area and Model Domain

1.1 Project Background

In support of the EIS, a study is required to evaluate the fate and transport of ammonia due to an accidental spill into the marine environment and its potential impact on the marine environment.

A numerical modelling approach using a coupled two-dimensional (2D) hydrodynamic, wave, and dispersion model was conducted to simulate liquified anhydrous ammonia (NH_3, otherwise referred to as un-ionized ammonia) dispersion during and after a spill event. This report summarizes the approach and results of the numerical modelling study.

1.2 Objectives

The primary objective of the ammonia transport and fate modelling study is to understand ammonia transport and dispersion in the marine environment due to an accidental spill, to identify the potential impacts of the spill on the marine environment, and to provide the following information required for the impact assessment:

- Short- and long-term transport and fate modelling based on the instantaneous ammonia spill under the action of tidal currents and wave climate for typical summer and winter conditions
- Variation of current speed, significant wave height, and ammonia dispersion for each modelling scenario during a tidal cycle including flood and ebb tides
- The maximum extent of an ammonia plume based on long-term model scenarios

A 2D model was utilized to evaluate the hydrodynamics of tidal circulations, waves, currents, and ammonia transport and fate within the study area. The ammonia transport modelling was used to simulate the ammonia plume within the study area under different seasonal conditions (i.e., summer and winter).

1.3 Methods

A hydrodynamic and ammonia transport model was built in the MIKE 21 Coupled Model, which is a 2D hydrodynamic model with an integrated wave and sediment transport modelling approach. MIKE 21 integrates Hydrodynamic (HD), Spectral Wave (SW), and Transport (TR) modules to simulate various aspects of the integrated hydrodynamic process of tidal and wind induced currents, waves, and ammonia fate and transport. The model was implemented using a flexible mesh (an unstructured triangular mesh) technique that allows for different spatial resolution as needed, in particular near and along the shorelines. A finer mesh size was applied near the potential spill areas.

1.4 Study Area

A large study area was selected to eliminate model boundary effects on currents and ammonia fate and transport processes for the purpose of the hydrodynamic and ammonia fate and transport modelling and based on available oceanographic data. Figure 1.1 provides the extent of the model domain and study area, extending approximately 60.5 kilometres (km) north to south by 85.1 km east to west. For consistency, the vertical datum and horizontal coordinate system are with respect to chart datum (CD) and World Mercator, respectively.

2.0 Available Data

This section summarizes available physical oceanographic and water quality data within the study area that were used to set up the coupled hydrodynamic and ammonia transport model. The datasets consisted of bathymetric data, tides, waves, and water quality data. Sources used include publicly available information, field surveys, data collection, and relevant environmental studies. Table 2.1 provides a summary of the available data and collected information, with its spatial correlation shown in Figure 2.1. The physical oceanographic and hydrometric data were obtained and compiled to develop the required parameters for defining the computational model domain and boundary conditions.

Table 2.1 Available Data and Sources Within the Study Area

Data Type	Data Source and Description
Bathymetry	• Canadian Hydrographic Services (CHS) NONNA10 and NONNA 100 data
Tides	• Predicted tide at Fisheries and Oceans Canada (DFO) station 2710 at Port Harmon • Predicted tide at DFO station 2720 at St. George’s Bay
Waves	• Hourly wave data at Meteorological Service of Canada (MSC) 50 North Atlantic Wave Hindcast grid M6013677 • Hourly wave data at MSC50 North Atlantic Wave Hindcast grid M6014156
Wind	• Hourly wind data at MSC50 North Atlantic Wave Hindcast grid M6013677 • Hourly wind data at Environment and Climate Change Canada (ECCC) climate station 8403800 and 8403801 at Stephenville A
Ammonia	• Project specific requirement and shipping method

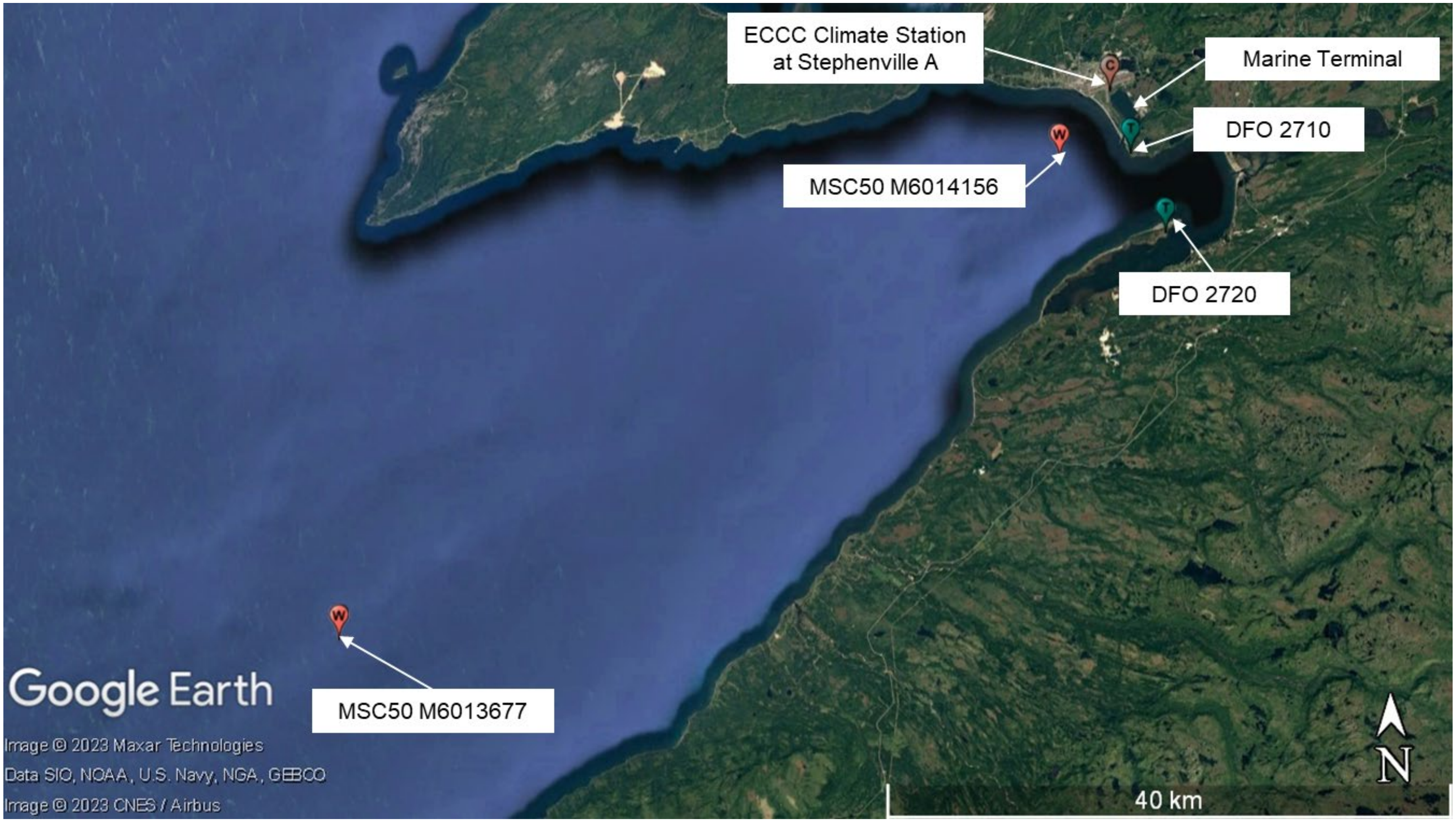


Figure 2.1 **Location Map of Data Sources Within the Study Area**

2.1 Bathymetry and Topography

Bathymetry is required to represent seabed elevations in the model domain. Table 2.1 summarizes available sources of bathymetric data within the study area, including CHS data. The CHS data was used to define seabed elevation within the model domain.

2.2 Tide and Water Levels

The tides along the southern coast of St. George Bay are classified as mixed, mainly semi-diurnal with successive highs and lows of unequal heights. The tides in the area also have a spring-neap cycle where tidal ranges that occur during the spring tides are approximately double those that occur during the neap tides. CHS tide tables provide tide levels due to astronomical tides. Table 2.2 summarizes tidal levels at DFO stations #2710 and #2720 in Port Harmon and St. George's Bay, respectively referenced to the chart datum (CD).

Table 2.2 DFO Tide Levels in St. Georges

Tides	DFO station #2710 Elevation (m, CD)	DFO station #2720 Elevation (m, CD)
Highest Astronomical Tide	1.58	1.60
Higher High Water Large Tide (HHWLT)	1.57	1.58
Higher High Water Mean Tide (HHWMT)	1.36	1.32
Mean Water Level (MWL)	0.84	0.82
Lower Low Water mean Tide (LLWMT)	0.32	0.34
Lower Low Water Large Tide (LLWLT)	0.02	0.03
Lowest Astronomical Tide	-0.01	0.00
Source 2023 DFO Tide Station #2710: Port Harmon and #2720: St. Georges		

2.3 Wind

Hourly wind data available within the study area are available at ECCC climate stations 8403800 and 8403801 at Stephenville A and MSC50 grid M6013677 located 66 km southwest of Stephenville. Table 2.3 summarizes available records of wind data at these two stations.

A wind rose of hourly wind speed and wind direction at ECCC climate station at Stephenville A for the period of 1941 through 2022 is presented in Figure 2.2. Wind speed for this period varied between 0 and 35.5 metres per second (m/s) with an average wind speed of 5.3 m/s. A review of the rose plot indicates that the dominant wind directions are from the west and southwest.

A wind rose of hourly wind speed and wind direction at MSC50 grid M6013677 for the period of 1954 through 2018 is presented in Figure 2.2. Wind speed for this period varied between 0 and 28.4 m/s with an average wind speed of 7.9 m/s. A review of the rose plot indicates that the dominant wind directions are from the west, northwest, and southwest.

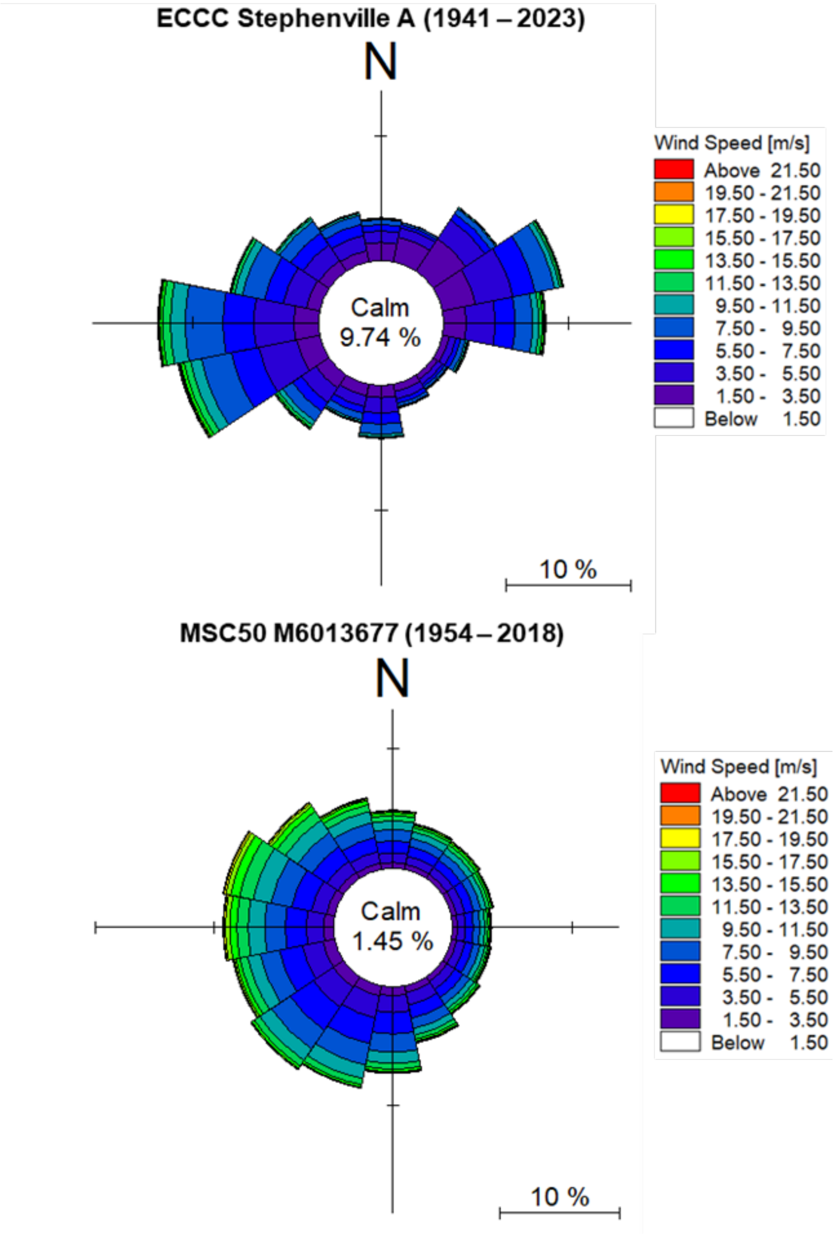


Figure 2.2 **Rose Plot of Hourly Wind Speed and Wind Direction (from) at ECCC Climate Station Stephenville A for the Period of 1941 – 2023 and MSC 50 M6013677 for the Period of 1954 – 2018**

Table 2.3 Wind Records in the Study Area

Station Name	Station ID	Coordinates		Available Data Records
		Easting (m)	Northing (m)	
Stephenville A	8403800 & 8403801	385593.6	5377635.0	Hourly wind speed and direction from 10/1941 to 02/2023
MSC50	M6013677	329099.6	5341087.6	Hourly wind speed and direction from 1/1954 to 12/2018

2.4 Offshore Waves

Offshore wave data is required to define offshore wave boundary conditions at the western offshore boundary of the model. In addition, wave data was used to analyze seasonal variations for waves within the study area and to select a typical seasonal wave scenario for simulations. Wave data at MSC50 grid point M6013677 was used to define wave conditions at the western offshore boundary conditions of the model and wave data at MSC50 grid point M6014156 was used to define wave conditions near the shoreline of the ammonia shipping facility.

Hourly records of wave data including significant wave height (Hs), peak wave period (Tp), and mean wave direction were available at MSC50 grid points M6013677 and M6014156 located approximately 5 km and 65 km southwest of Stephensville, respectively. Table 2.4 summarizes available records of wave data at these two grid point locations.

A wave rose of hourly significant wave height and wave direction at MSC50 grid M6013677 for the period 1954 to 2018 is presented in Figure 2.3. Significant wave height for this period ranged from 0.10 m to 9.63 m with an average significant wave height of 1.42 metres (m). A review of the rose plot indicates that the dominant wave direction is from the west and southwest.

A wave rose of hourly significant wave height and wave direction at MSC50 grid M6014156 for the period 1954 to 2018 is presented in Figure 2.3. Significant wave height for this period ranged from 0.10 m to 4.8 m with an average significant wave height of 0.74 m. A review of the rose plot indicates that the dominant wave direction is from the west and southwest.

Table 2.4 Offshore MSC50 Wave Records in the Study Area

MSC50 Grid Point	Coordinates		Available Data Records
	Easting (m)	Northing (m)	
M6013677	329099.6	5341087.6	Hourly significant wave height, peak wave period, and wave direction from 1/1954 to 12/2018
M6014156	381806.9	5373111.7	Hourly significant wave height, peak wave period, and wave direction from 1/1954 to 12/2018

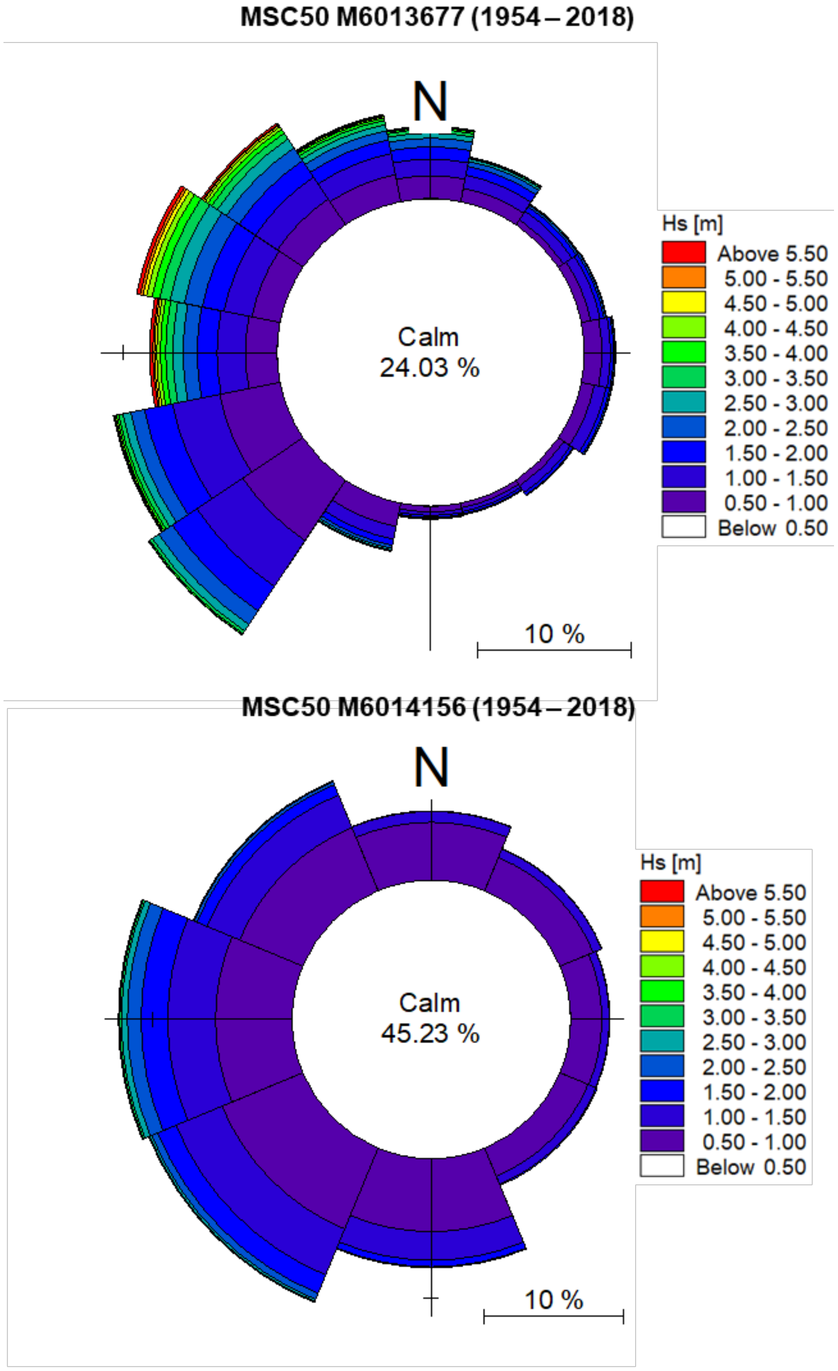


Figure 2.3 Rose Plot of Hourly Significant Wave Height and Wave Direction (from) at MSC50 M6013677 and M6014156 for the Period 1954 – 2018

2.5 Temperature and Salinity

Recorded sea surface water temperature data at Stephenville crossing by the National Oceanic and Atmospheric Administration (NOAA) summarized in Figure 2.4 (seatemperature.org) which indicates a range from -1.8 ºC (degrees Celsius) to 17.4 ºC for near surface temperature. A review of literature indicates that depth-averaged salinity approximately varied between 30 PSU (practical salinity unit) and 33.7 PSU with an average 31.8 PSU from 0 to 50 m depth near the study area (Cyr et al. 2021).

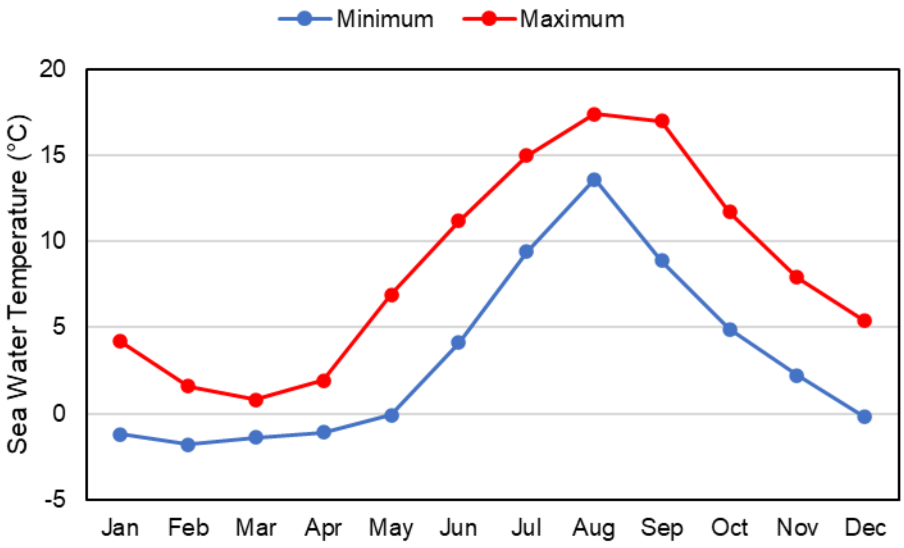


Figure 2.4 Seawater Surface Temperature at Stephenville Crossing

2.6 Ammonia Transport and Spill

2.6.1 Ammonia Reaction in Water

Ammonia is a colorless gas with a pungent odor at ambient conditions. Its odor threshold is very low compared to levels at which acute harmful effects occur; therefore, its smell provides warning and allows quick response. Ammonia is very soluble in water and produces ammonium hydroxide (NH_4OH) solution. During transportation on cargo ships, unionized ammonia is stored as a refrigerated liquid at atmospheric pressure. If a vessel was involved in an accident that ruptured the storage tanks/containers, except for a small fraction that will flash, most of the vessel's content will spill into the water (Dharmavaram et al. 1994). Liquid anhydrous ammonia, with a density of 0.683 grams per cubic centimetre (gr/cm^3), is buoyant and soluble in water. Research has shown that if a spill occurs underwater approximately between 80% and 95% of the anhydrous ammonia mixes with the water and if a spill occurs at the surface between 70% and 75% mixes with water and the rest will vaporize (Raj et al. 1974). Therefore, an underwater spill scenario is the worst-case condition for the purpose of ammonia fate and transport modelling in water. Ammonia in marine waters will also undergo a chemical reaction with water that will release heat and form NH_4OH. The portion of ammonia that remains reactive reaches equilibrium as un-ionized ammonia which is the primary contributor to ammonia's toxicity to plant and animal life in the marine environment. As the anhydrous ammonia mixes and disperses in water, a chemical reaction occurs that creates NH_4OH as described by the following equation:

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$$

The equilibrium for this reaction depends on parameters including the temperature, pH and salinity of the seawater (CCME, 2010). However, anhydrous ammonia is a weak base and only a small portion of it changes to ammonium ($\mathrm{NH_4^+}$) and hydroxide ($\mathrm{OH^-}$) and mainly NH_3 remains dissolved in water. Ammonia (NH_3, un-ionized) is highly soluble and toxic in water and is transported in liquid form in this case. Ammonia is non-persistent, not recalcitrant and is not bio-concentrating or bio-accumulative.

2.6.2 Ammonia Transportation and Potential Spill

The anhydrous ammonia will be transported to market by ships designed and certified for carriage of its product. Many Liquified Petroleum Gas (LPG) carrier ships are designed for carrying gases in liquid form including ammonia. As described in Chapter 2 of the EIS (Project Description), ammonia carriers are typically in the range 15,000 to 85,000 cubic metres (m^3); the three common vessel sizes are 30,000 m^3, 52,000 m^3, and 80,000 m^3. The existing quay will be inspected and load rated as part of detailed engineering for the Project to verify that it can accommodate the berthing and mooring loads from the maximum anticipated size ship.

Ships will use the marine terminal in Port Harmon to load anhydrous ammonia from the facility via a 24" diameter pipe. The base vessel loading with a capacity of 35,000 m^3 takes approximately 25 hours (hr). Therefore, the ammonia transport rate via the 24" diameter pipe to the base ship is 1,400 cubic metres per hour (m^3/hr) with an average velocity of 1.33 m/s in the pipe. The berthing location is shown on Figure 2.5. The offloading system design remains under consideration. While options are being considered, the base case is the jettyless floating offloading system. With hoses connected, these systems are floated to the vessels side by tugs and secured to the vessels hull with a specialized mooring system. Specifically, the Jettyless Econnect system is one option that could provide greater versatility to the port. Following a cargo transfer, the system would be purged with nitrogen and moored to the extreme end of a dock in such a way to allow access for other vessels or continued development of the Project.

Figure 2.5 Potential Location of Anhydrous Ammonia Spill in Port Harmon

According to Chapter 24 (Accidents and Malfunctions), the potential accidental spill releases of ammonia into marine waters can occur during the following scenario:

- During the loading process to the vessel via the 24" diameter pipe: based on the Project's specific information, ammonia transportation rate is approximately 1,400 m^3/hr in the pipe. It is the intent of the project that the Emergency Shutdown System be designed as per the requirements of Title 33 of the United States (US) Code of Federal Regulations (https://www.ecfr.gov/current/title-33/chapter-I/subchapter-O/part-154/subpart-C/section-154.550) and other applicable international and Canadian codes and standards. This code also applies to some Canadian ships, and states that there must be a means to stop the flow within 30 seconds in the event of an accidental spill. It has been assumed that a total release time of 2 minutes is a conservative assumption for this scenario. The project will be designed and operated such that if a release of this magnitude occurred, multiple alarms would be activated and at least one operator would monitor the transfer and would observe the release as it happened. Additionally, there would be a strong smell of ammonia, which would indicate to anyone in the area that a large spill had occurred. The means to stop the flow would occur almost immediately, thus using a 2 minute release time is a conservative estimate since it allows for 90 seconds to initiate the means to stop the flow.

  As a conservative assumption it was assumed that the spill occurred under the water and 100% of the anhydrous ammonia mixes and dissolves in the water (Raj et al. 1974). Therefore, a total spill rate of 46.7 m^3 (i.e., 31.87 t) over a period of 2 minutes near the marine terminal berth was modelled for this scenario.

3.0 Hydrodynamic Model Setup

The MIKE 21 Coupled Model was used to simulate hydrodynamic conditions and ammonia fate and transport within the study area. The HD, SW and TR modules in the MIKE 21 Coupled Model were used to simulate various aspects of the integrated hydrodynamic process of water levels, wind and wave climates, and ammonia transport and fate including dispersion and processes. The following are a brief description of each module used in this study:

- HD Module – simulates unsteady flow taking into account density variations, bathymetry and external forcings in rivers, lakes, estuaries and coastal areas. The modelling system is based on a numerical solution of the 2D incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and hydrostatic pressure. Thus, the model consists of continuity and momentum equations, and it is closed by a turbulent closure scheme (DHI, 2019a). The HD Module is the basic computational component of the modelling system and can be extended to simulate reciprocal interactions among currents, waves, water quality, and sediment dispersion by coupling with the other modules.
- SW Module—a third generation spectral wind-wave model that simulates the growth, decay, and transformation of wind-generated waves and swells in offshore and coastal areas. The model includes the following physical phenomena: wave growth by action of wind, non-linear wave-wave interaction, dissipation due to white-capping, dissipation due to bottom friction, dissipation due to breaking, refraction, and shoaling due to depth variation; and wave-current interaction (DHI, 2019b).
- TR Module – simulates the spreading and fate of dissolved or suspended substances by solving the 2D advection-dispersion equations in lakes, estuaries, coastal areas, and oceans. The substance may be of any kind, conservative or non-conservative, organic or inorganic. Coupled with the HD module, the TR module is typically applied in tracer simulation, flushing, and water quality studies. (DHI, 2019c).

Available bathymetric data was used to create a model domain using a flexible mesh technique. The model was calibrated to measured water levels near the study area. The following two sections describe computational model domain creation and model inputs and boundary conditions.

3.1 Computational Domain and Mesh

A well-structured computational mesh based on sufficient bathymetric data is essential for obtaining reliable results, especially in the vicinity of the potential spill locations. Available bathymetric data were used to develop the seabed bathymetry. The CHS bathymetric data were used to define the seabed elevations in the computational model domain.

Figure 3.1 presents the model domain and generated mesh near the Base. The generated mesh contains 21,130 nodes and 40,483 elements. The resolution of the mesh and time-steps govern the Courant number developed in the model setup. The Courant number affects the numerical stability of the model. The mesh was optimized based on the level of detail required in the vicinity of the potential spill locations and the amount of computational time necessary to run the model.

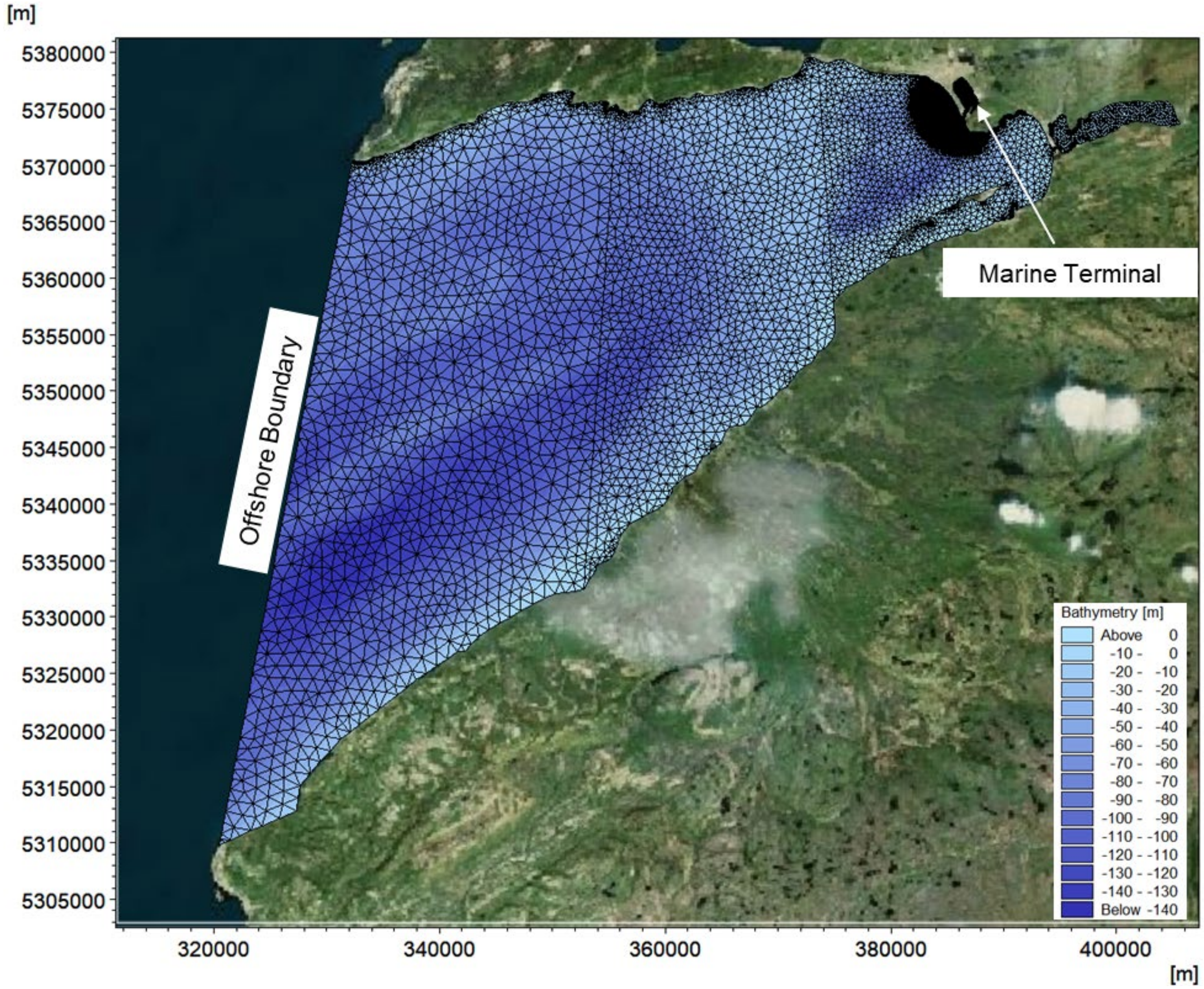


Figure 3.1 Computational Model Domain and Mesh

3.2 Domain and Boundary Settings

Key parameters for the domain and boundaries of the hydrodynamic model were set up as follows:

- Model domain – The MIKE 21 model is based on a flexible mesh approach in this study; in the horizontal domain an unstructured triangular mesh was used.
- Coastal boundary – The coastal boundary was defined by the shoreline. The model treated this boundary as solid, with no wave or current transmission.
- Offshore boundary – The offshore boundary conditions of the model were for tides and waves.
- Domain wind forcing – Hourly wind records collected from MSC50 grid M6013677 were used to simulate wind-driven waves and currents. Wind speed and direction were applied as constant values in the domain and varied in time.
- Anhydrous/un-ionized ammonia spill rate: a spill rate of 265.8 kilograms per second (kg/s) for a period of 2 minutes in the port near the berth
- Coriolis forcing – Coriolis forcing is included in the modelling and varied in the domain.

3.3 Model Setup

3.3.1 Global Tide Model

MIKE 21 Global Tide Model (GTM) can generate data to predict tidal level (DHI, 2018). The GTM is available on a 0.125 degrees (º) x 0.125º resolution grid for the ten major constituents in the tidal spectrum. The model uses the latest 17 years of multi-mission measurements from TOPEX/Poseidon, Jason-1, and Jason-2 satellite altimetry for sea level residuals analysis. Using these measurements, harmonic coefficients were calculated. The constituents consider the semidiurnal M2, S2, K2, N2, the diurnal S1, K1, O1, P1, Q1, and the shallow water constituent M4. A global set of tide gauge readings has been defined by the TOPEX/Poseidon ocean tide subcommittee for the investigation of ocean tide models on a common basis (Le Provost et al. 1994). The GTM was validated by a set of tide gauges constructed from 102 tide gauges (42 in the Atlantic Ocean, 18 in the Indian Ocean, and 42 in the Pacific Ocean). Based on the GTM, a time series of water levels for any period and any position on the globe can be extracted to create boundary conditions for local or regional models. The time zone for the extracted time series is given in Universal Time Coordinates (UTC).

In order to calibrate the GTM for the Project's study area, the predicted time series of tides using the GTM was compared with the predicted tide levels by DFO at DFO station 2710 in Port Harmon for the period January 2022 to December 2022. The tide levels predicted by the GTM had the same phases of tide constituents, but the amplitudes were adjusted by applying a scaling factor of 0.75. Table 3.1 presents statistics of the predicted tides using the GTM and DFO station 2710. A review of the table indicates that there was good agreement between the predicted tides using the GTM and predicted tide at DFO station 2710 with a coefficient of determination (R^2) of 0.99. The predicted tidal levels using the GTM during this period can cover the site-specific range of tidal cycles including the spring and neap tides. Figure 3.2 provides predicted tide levels using the GTM versus tide levels at DFO station 2710 for January, April, July, and October 2022.

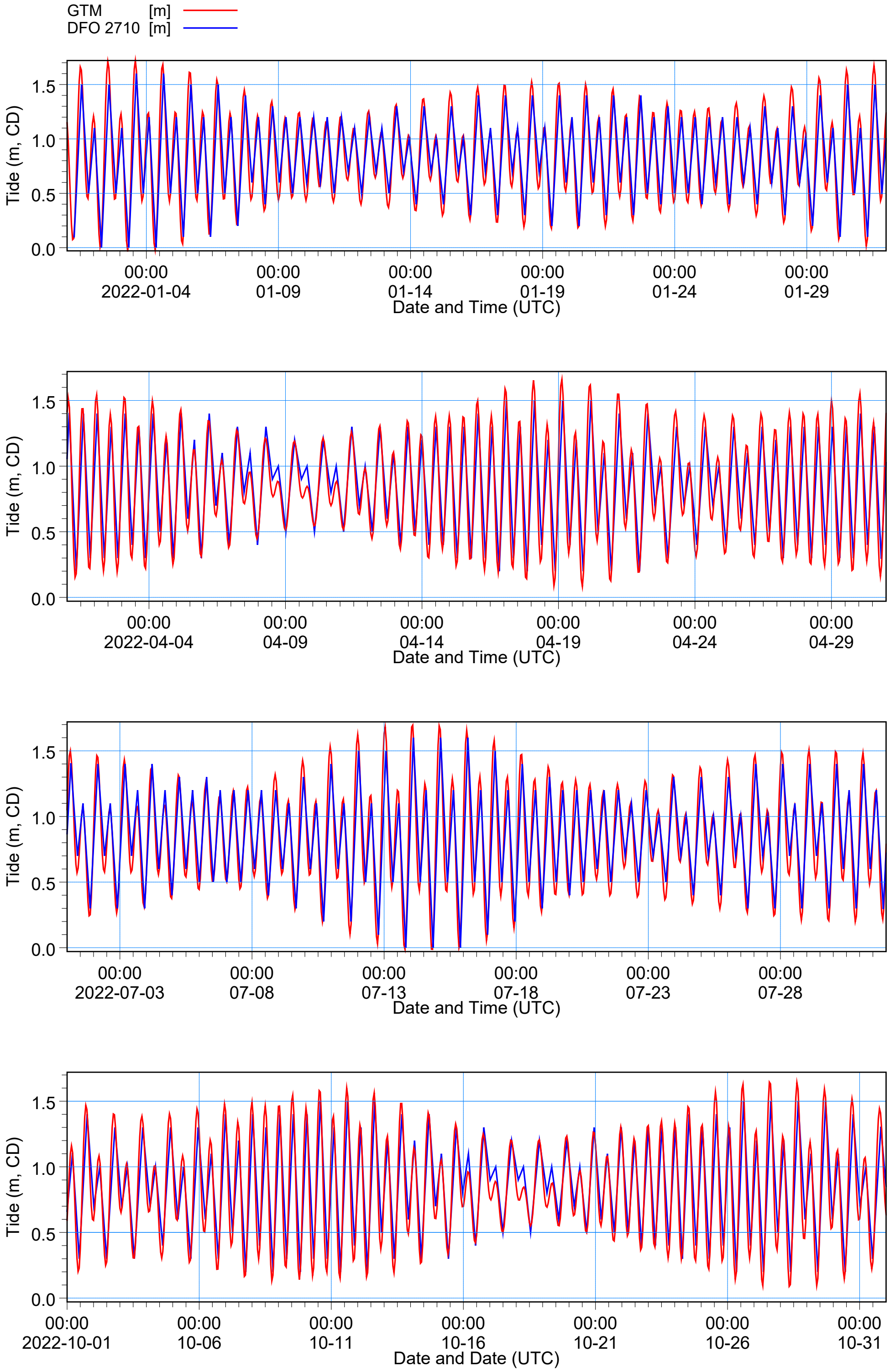


Figure 3.2 **Predicted Tide Levels by the GTM and by DFO at DFO station 2710 for January, April, July, and October 2022**

Table 3.1 Statistics of Predicted Hourly Tides for January to December 2022

Predicted Tide	Minimum (m CD)	Maximum (m CD)	Mean (m CD)	R^2	RMSE (m)
DFO station 2710	0.00	1.60	0.85	0.99	0.06
GTM	0.06	1.64	0.84		

3.3.2 Spectral Wave Model

The MIKE 21 SW module simulates wind-driven waves and the process of wave generation, growth, propagation, and transformation. The wave model was built using available bathymetry, hourly wind speed and direction and hourly wave parameters at the offshore boundary conditions. Hourly wave parameters at the offshore boundary (i.e., significant wave height, peak wave period, and wave direction) were obtained from MSC50 data at gride point M6013677. The wave model was calibrated to hourly wave data at MSC50 grid point M6014156 near the shoreline of the study area for the period of January 1 to January 15, 2018 when significant wave height increased to 5.60 m at the offshore boundary of the model. During this period significant wave height varied between 0.86 m and 5.60 m with an average of 2.89 m at the offshore boundary of the model and wind speed varied between 6 m/s and 22.2 m/s with an average of 12.4 m/s. Table 3.2 presents statistics of simulated and recorded significant wave height at MSC50 grid point M6014156 and indicated a good agreement between simulated and recorded wave heights with an R^2 of 0.87. The following parameters were used in the SW module:

- Time step: a time step of 900 seconds was used in this study.
- Bottom friction: the bottom friction in the wave model was defined using a Nikuradse roughness (K_n). A Kn value of 0.04 m was used in the model.
- Wave Breaking: depth-induced wave breaking was included in the simulation. Battjes and Janssen (1978) formulation is used in the SW module (DHI, 2019b).
- Water level: variable water level generated by the calibrated GTM was used in the model run

Table 3.2 Statistics of MSC50 and Simulated Significant Wave Height at MSC50 Grid Point M6014156 for the Period of January 1 to 15, 2018

Wave Height	Minimum (m)	Maximum (m)	Mean (m)	R^2	RMSE (m)
MSC50 M6014156	0.43	3.13	1.58	0.87	0.26
Simulated	0.31	3.03	1.55		

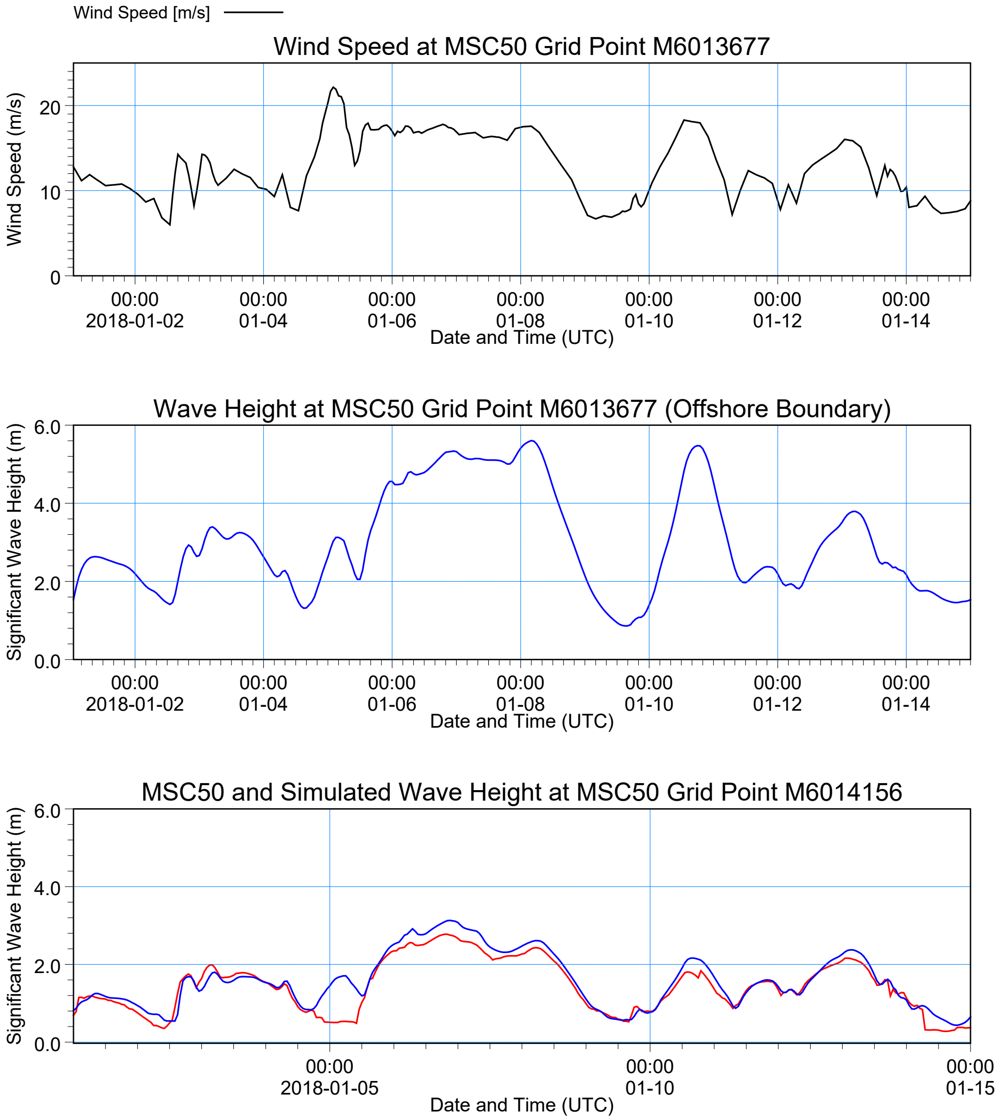


Figure 3.3 **MSC50 and Simulated Significant Wave Height at MSC50 Grid Point M6014156**

3.3.3 Hydrodynamic Module

The MIKE 21 HD module simulates water levels and wind- and wave-induced currents within the model domain. The following parameters were used in the HD module:

- Time step: a time step of 60 seconds was used in this study.
- Courant number: the numerical stability and computing time depends not only on the number of nodes in the mesh and the simulation time step, but also the resulting Courant numbers (which needs to be less than 1). A critical Courant number of 0.8 was used in this study.
- Bed roughness: the bed resistance in the HD module was defined using a Manning's number of 40, which is a reciprocal form of the Manning roughness coefficient (n) of 0.025 was adopted in this study.
- Eddy viscosity: The eddy viscosity in the MIKE 21 is based on a Smagorinsky formulation (DHI, 2019a). The default value of 0.28 was used in the calibrated model.

4.0 Ammonia Fate and Transport Modelling

4.1 Approach and Scenarios

The objective of the ammonia fate and transport modelling was to identify the potential impacts of an accidental spill on the marine environment and to provide the following information required for the impact assessment:

- Short- and long-term transport and fate modelling based on an instantaneous anhydrous ammonia release during the loading process of a vessel at the marine terminal under the action of tidal currents and wave climate for two seasons.
- Variation of current speed, significant wave height, un-ionized ammonia concentration, and un-ionized ammonia plume for each modelling scenario under different tidal conditions including flood and ebb tide.
- The maximum extent of un-ionized ammonia plume.

The TR module was integrated into the calibrated hydrodynamic model to carry out the fully coupled hydrodynamic, wave, and dispersion modelling for a simulation period of one month to characterize the circulation patterns and indications of un-ionized ammonia in the study area. The TR module simulates fate and transport of hazardous material due to an accidental spill under combined currents and waves conditions. The following steps were undertaken to achieve this objective:

- Defining modelling scenarios and conditions;
- Developing a fully coupled hydrodynamic and dispersion model using HD, SW, and TR modules; and
- Applying the model defined scenarios to evaluate ammonia fate and transport in the study area.

In total, two seasonal modelling scenarios were defined to take into account the following un-ionized ammonia spill scenario under typical winter and summer conditions within the study area:

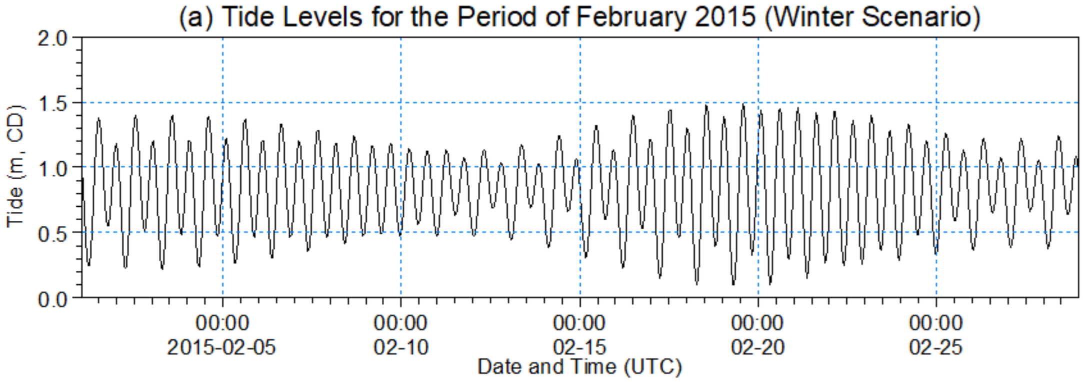
- a spill rate of 265.8 kg/s for a period of 2 minutes at the marine terminal near the berth

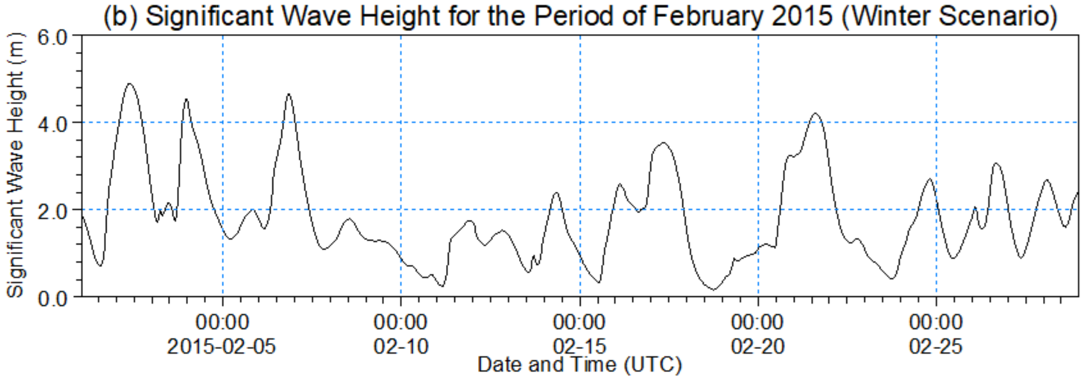
In order to identify typical seasons for modeling scenarios, which does not necessarily include extreme winds and waves attributed to hurricanes and post-tropical storms, historical records of tides and waves were evaluated. Hourly predicted tides by the GTM for the period 2000 to 2021 were analyzed and it was found that overall, the average monthly tide levels are consistent for this period. Hourly records of significant wave height for the period 1954 to 2018 at MSC50 M6013677 (offshore boundary of the model) were analyzed, and it was found that 2015 can represent a recent year with typical seasonal wave conditions compared to the 65 years for wave records. Table 4.1 presents and compares average monthly significant wave height for the period 1954 to 2018 and year 2015. This table indicates that overall, wave heights in 2015 are close to long-term wave heights. The following scenarios were modelled to take into account the effects of seasonality on fate and transport of sediment within the study area for short-term and long-term effects assessment:

- Typical Winter: February 2015 was selected as the typical winter conditions in the study area. Figure 4.1 presents boundary conditions used for this scenario. Average monthly Hs at the southern boundary of the model in February 2015 was 1.82 m.
- Typical Summer: July 2015 was selected as the typical summer conditions in the study area. Figure 4.2 presents boundary conditions used for this scenario. According to Table 4.1, average monthly Hs at the southern boundary of the model in July 2015 was 0.79 m.

Table 4.1 Average Monthly Significant Wave Heights (Hs) at MSC50 M6013677 for the Period 1954 to 2018 and the Year 2017

Month	Hs (1954 – 2018) (m)	Hs (2015) (m)	Difference (m)
January	1.87	2.38	0.51
February	1.00	1.82	0.82
March	0.72	0.56	-0.16
April	0.89	1.26	0.36
May	0.91	0.95	0.05
June	0.84	0.87	0.04
July	0.84	0.79	-0.04
August	0.97	0.88	-0.09
September	1.34	1.46	0.12
October	1.66	2.02	0.36
November	1.96	1.88	-0.08
December	2.25	2.11	-0.13





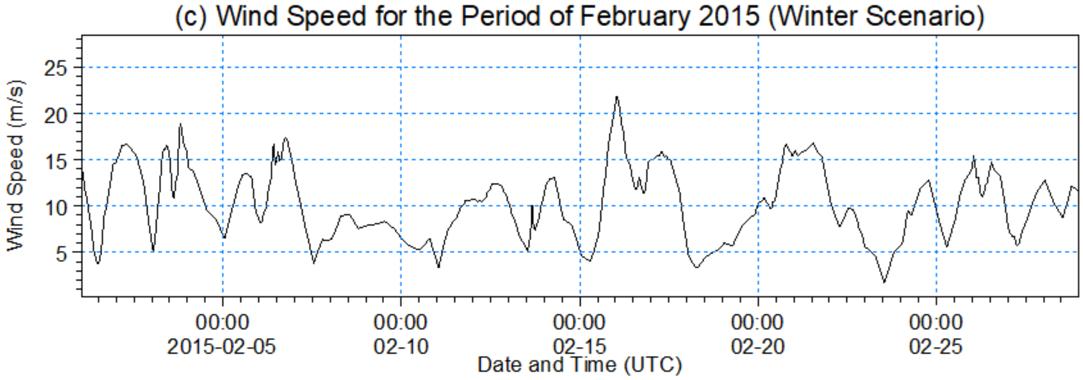
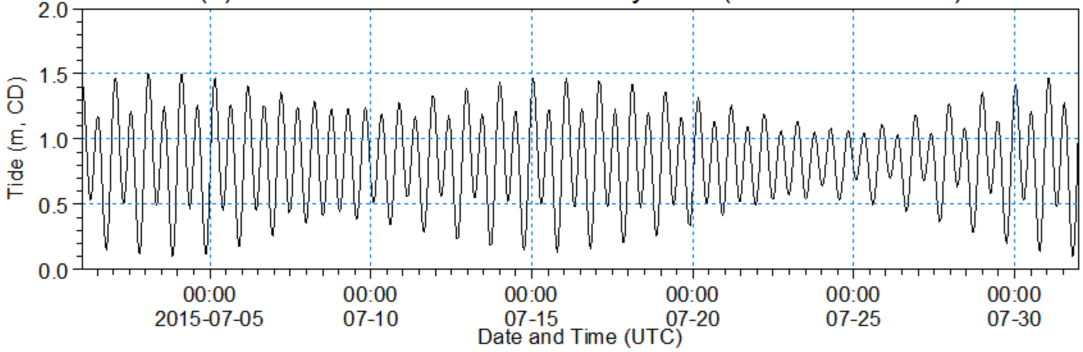
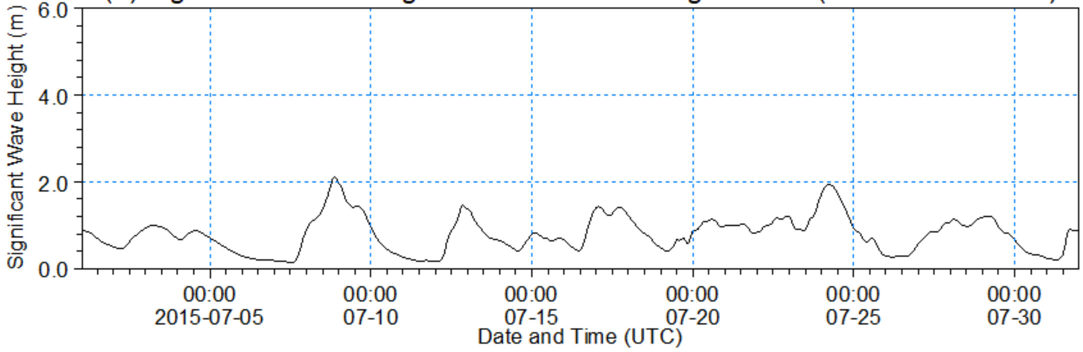


Figure 4.1 **Boundary Conditions Used in the Hydrodynamic and Fate and Transport Modelling for February 1 to March 1, 2015 (Typical Winter)**

(a) Tide Levels for the Period of July 2015 (Summer Scenario)



(b) Significant Wave Height for the Period of August 2015 (Summer Scenario)



(c) Wind Speed for the Period of July 2015 (Summer Scenario)

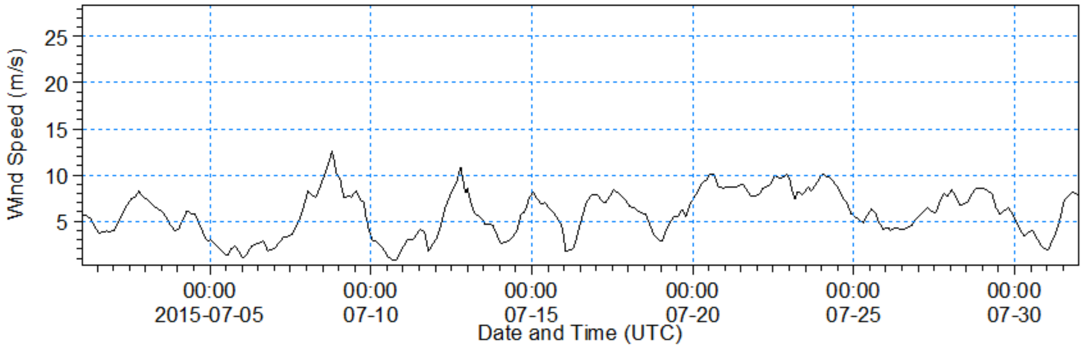


Figure 4.2 **Boundary Conditions Used in the Hydrodynamic and Fate and Transport Modelling for July 1 to August 1, 2015 (Typical Summer)**

4.2 Regulatory Framework for Ammonia

Canadian Council of Ministers of the Environment (CCME) has only a water quality guideline for total and un-ionized ammonia in freshwater (CCME, 2001a & 2001b) and no recommended guideline for marine waters. The British Columbia (BC) Approved Water Quality Guidelines provide long-term (chronic) and short-term (acute) guidelines for un-ionized ammonia in marine water (BCMOE, 2009). As no other provincial and federal regulatory guidelines are available for un-ionized ammonia in marine water, the British Colombia Ministry of Environment (BCMOE) guidelines were adopted for the study area in Newfoundland and Labrador. According to the guideline a 30-day average is used for the chronic condition effects assessment. The approved threshold for un-ionized ammonia is a function of water temperature, salinity and pH. Section 2.5 summarized the observed range of water temperature and salinity in the marine environment. Table 4.2 summarizes acute and chronic limits of un-ionized ammonia in typical winter and summer.

Table 4.2 Chronic and Acute Un-ionized Ammonia Limit in Marine Environments (BCMOE, 2009)

Season	Temperature (ºC)	pH	Salinity (PSU)	Acute milligrams per litre (mg/L)	Chronic (mg/L)
Winter	5	8.2	30	14.0	2.1
Summer	15	8.2	30	6.7	1.0

4.3 Modelling Results

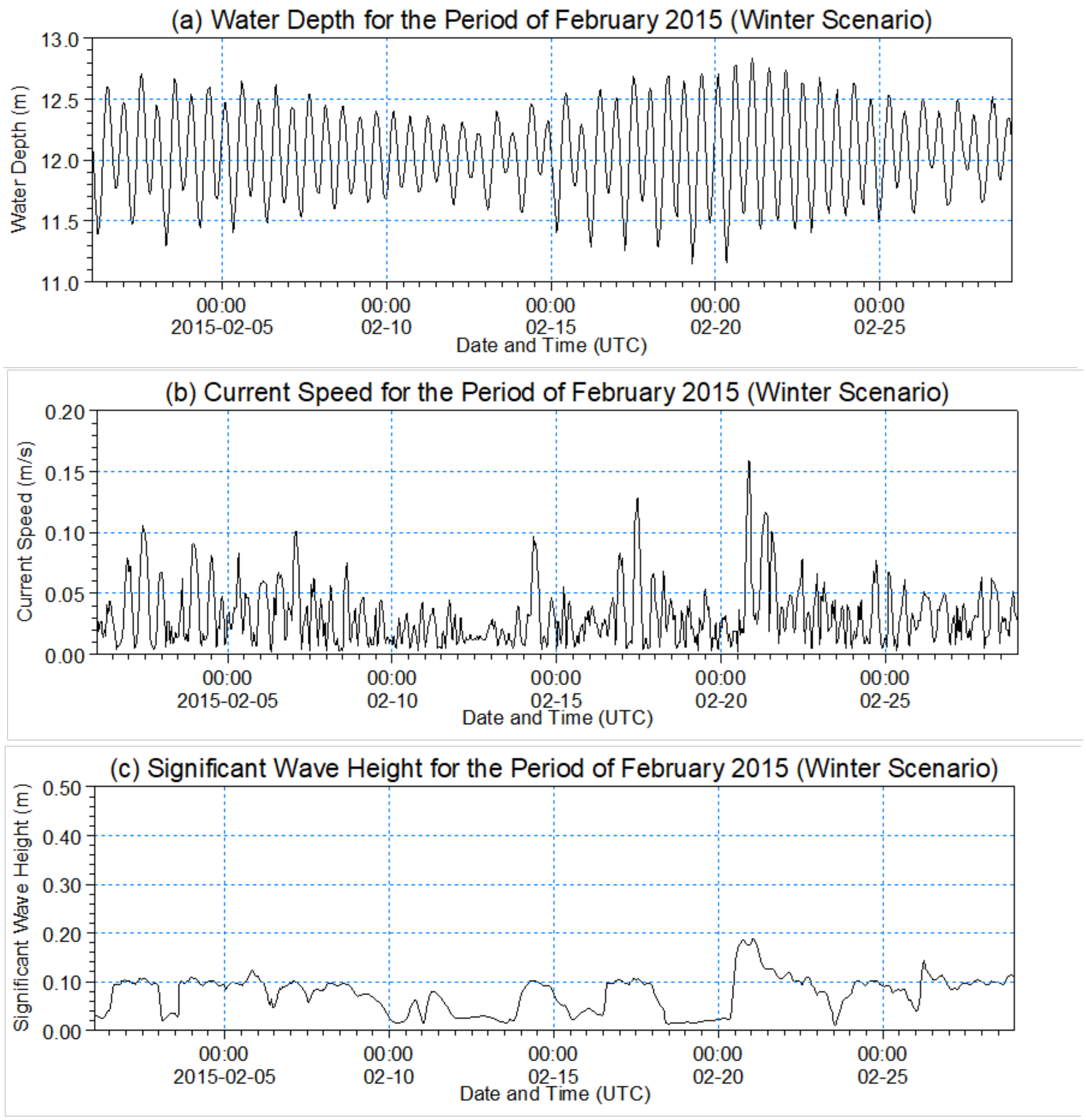
4.3.1 Fate and Transport of Ammonia in Winter

This section presents results of the ammonia spill at the marine terminal in winter. A one-month period of simulation in February 2015 was conducted to evaluate hydrodynamic and transport and fate of ammonia for short- and long- term effects. Maximum hourly and a 30-day averaged simulated concentrations were used to evaluate short-term (i.e., acute) and long term (i.e., chronic) effects on the marine environment. It was assumed that ammonia spills into the marine environment on the first day of February for a period of 2 minutes.

4.3.1.1 Hydrodynamic Conditions in Winter

This section presents key hydrodynamic model outputs at and near the spill location used in the fate and transport modelling. Figure 4.3 provides a time series of simulated water depth, current speed, and significant wave height at the spill location for February 2015 (i.e., winter scenario). A review of the hydrodynamic outputs indicates the following at the spill location in February 2015:

- Water depth at the spill location ranged from 11.2 m and 12.8 m with an average water depth of 12.1 m. Due to the proposed vessel draft, dredging may be conducted to increase water depth at the marine terminal; however, since the details are still unknown, as a conservative assumption, the existing shallower water depth was used for the purpose of ammonia fate and transport modelling as deeper water provides better mixing conditions for ammonia and lower concentrations.
- Current ocean water speed at the spill location ranged from 0 m/s to 0.16 m/s with an average current speed of 0.03 m/s. A review of simulated current at the spill location indicates that currents are weak inside the port. Figure 4.4 presents spatial variations of current speed during typical ebb and flood tides in winter.
- Significant wave height at the spill location ranged from 0 m to 0.19 m with an average significant wave height of 0.07 m. A review of simulated current at the spill location indicates that wave heights are weak inside the port and the port is well protected against incoming waves during this period. Figure 4.5 presents spatial variations of significant wave height at the time step when the maximum wave height was observed at the offshore boundary.


(a) Water Depth for the Period of February 2015 (Winter Scenario)

(b) Current Speed for the Period of February 2015 (Winter Scenario)

(c) Significant Wave Height for the Period of February 2015 (Winter Scenario)

Figure 4.3 Simulated Hydrodynamic Conditions at the Spill Location for February 2015

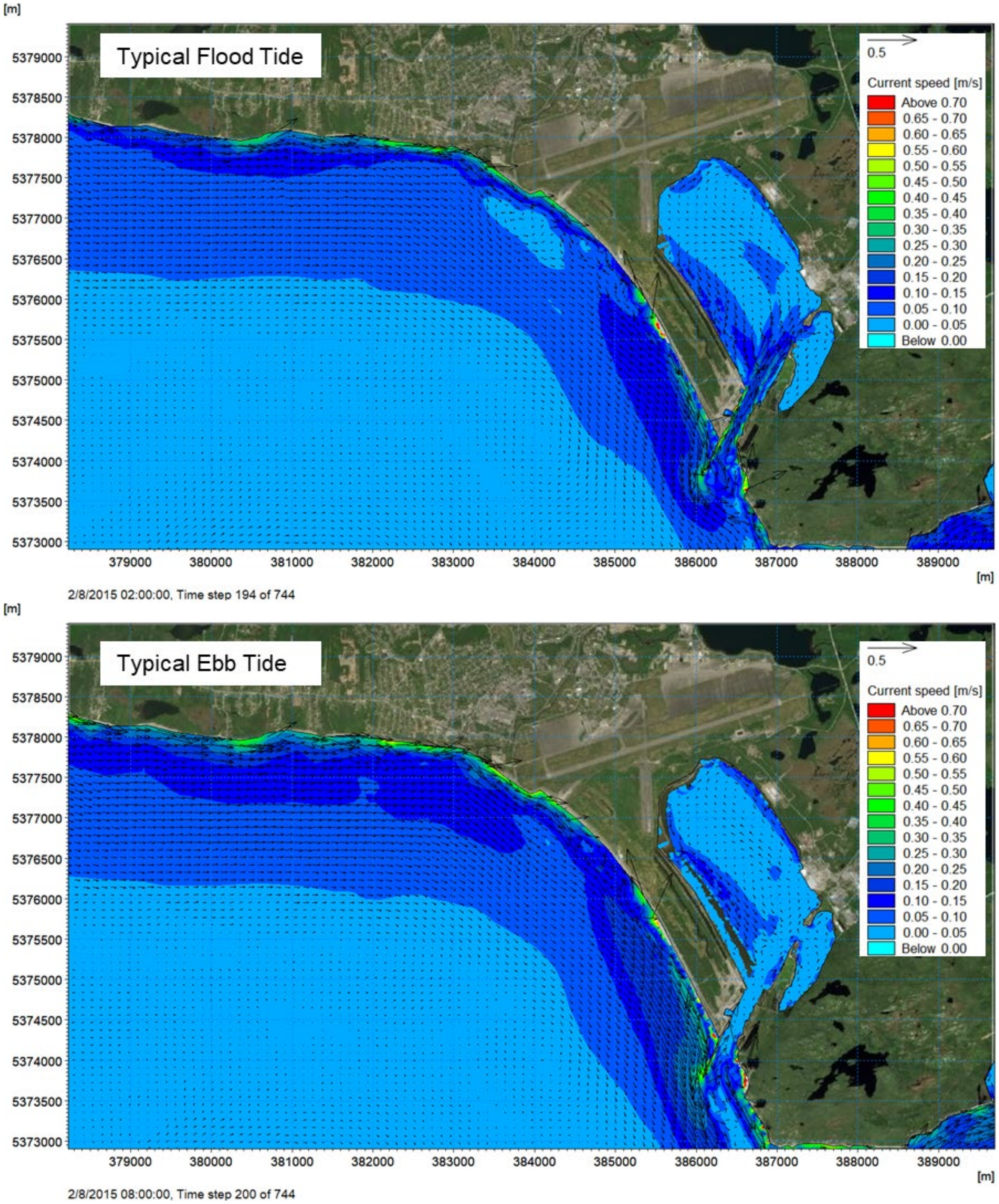
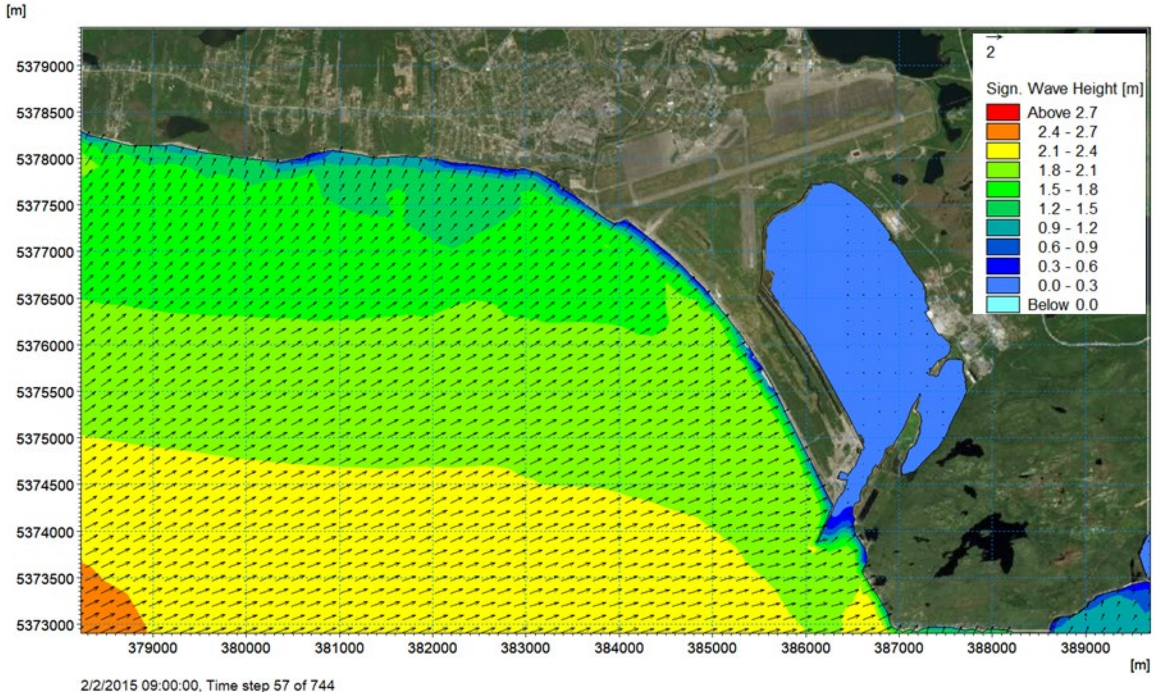


Figure 4.4 **Spatial variation of Current Speed During Typical Ebb and Flood Tides in Winter**



2/2/2015 09:00:00, Time step 57 of 744

Figure 4.5 Spatial Variation of Significant Wave Height on February 2, 2015

4.3.1.2 Ammonia Transport and Fate in Winter

Figure 4.6 presents the extent of an un-ionized ammonia plume and spatial variations of concentration 1 and 6 hr after the spill. A review of the results for each time period indicates a high concentration of un-ionized ammonia at and near the spill location immediately after the spill. Figure 4.7 presents the maximum extent of an un-ionized ammonia plume during a low tide event on February 2 (30 hr after the spill) and indicates that due to the effects of tides, un-ionized ammonia mixes with the marine water and extends east of the Port Harmon entrance a maximum concentration of 3 mg/L; and therefore, the plume extent is only limited to the areas in the port and does not extent into the bay. This figure also presents the extent and spatial variations of un-ionized ammonia during a flood tide on February 2 (26 hr after the spill) and indicates that the flood tide moves the plume inside the port. Figure 4.8 presents the extent of and spatial variations of un-ionized ammonia during an ebb tide on February 2 (42 hr after the spill) and indicates that ebb tides move the plume toward the entrance and east of the port entrance. This figure also presents the extent and spatial variations of an un-ionized plume at the end of one month of simulation and indicates that due to the tides and mixing process of un-ionized ammonia with the marine water during this period, un-ionized ammonia concentration reduces to less than 1 mg/L. A review of the modelling results in winter indicates that concentrations of un-ionized ammonia due to the spill reduced to less than 1 mg/L from February 15 and therefore, high concentrations would not persist in winter.

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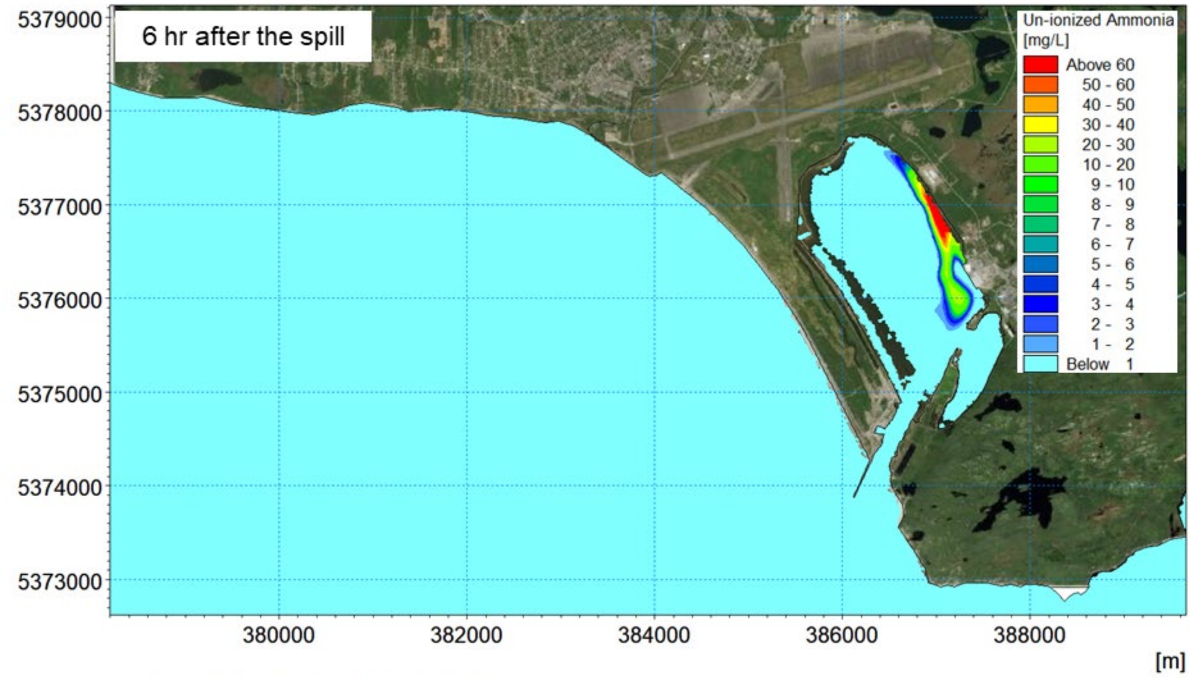

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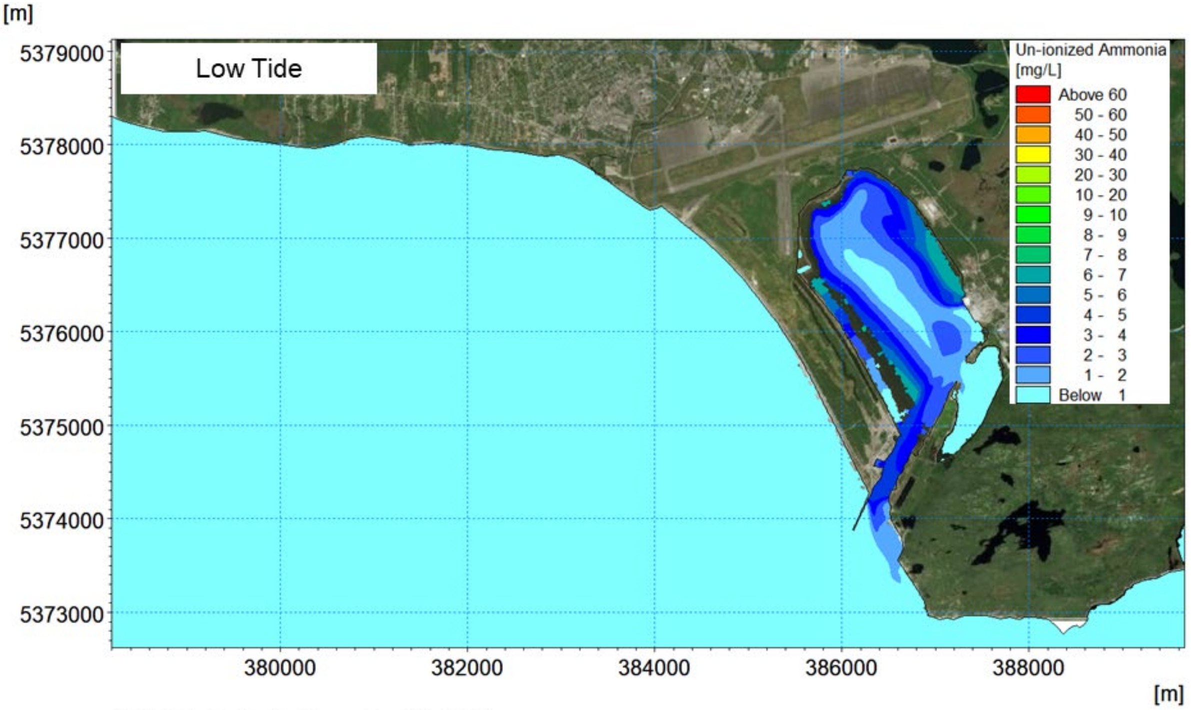
Figure 4.6 **Simulated Extent of Un-ionized Ammonia Plume in Winter After 1 and 6 hr from the Spill**



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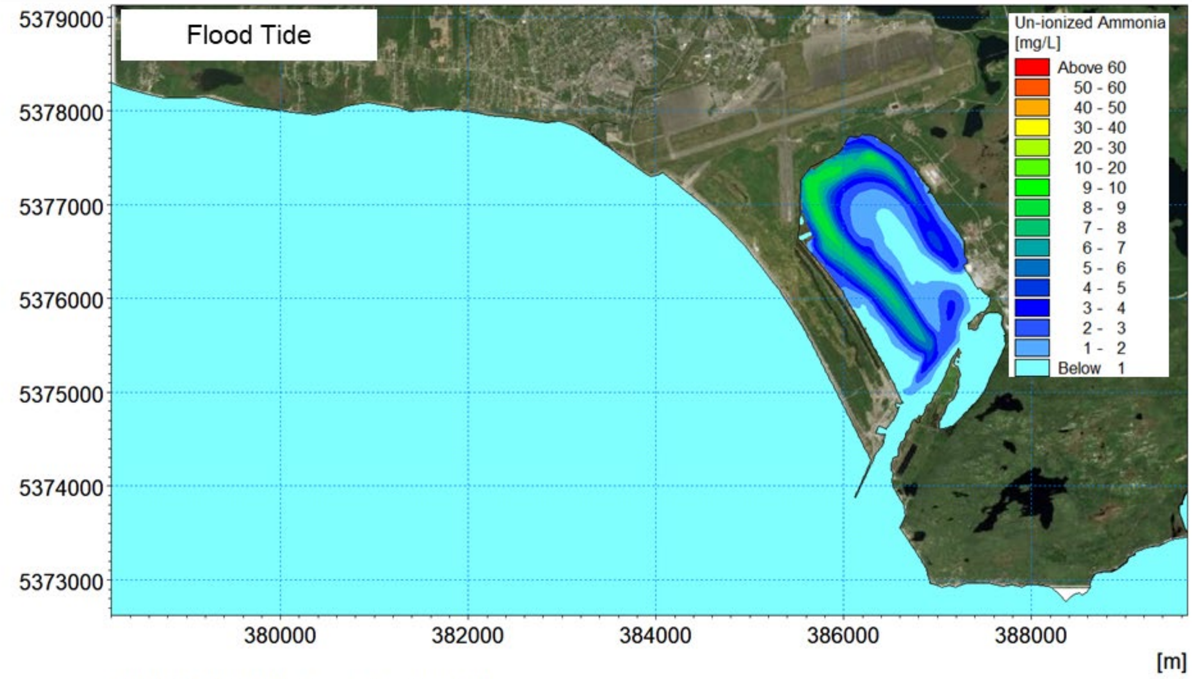

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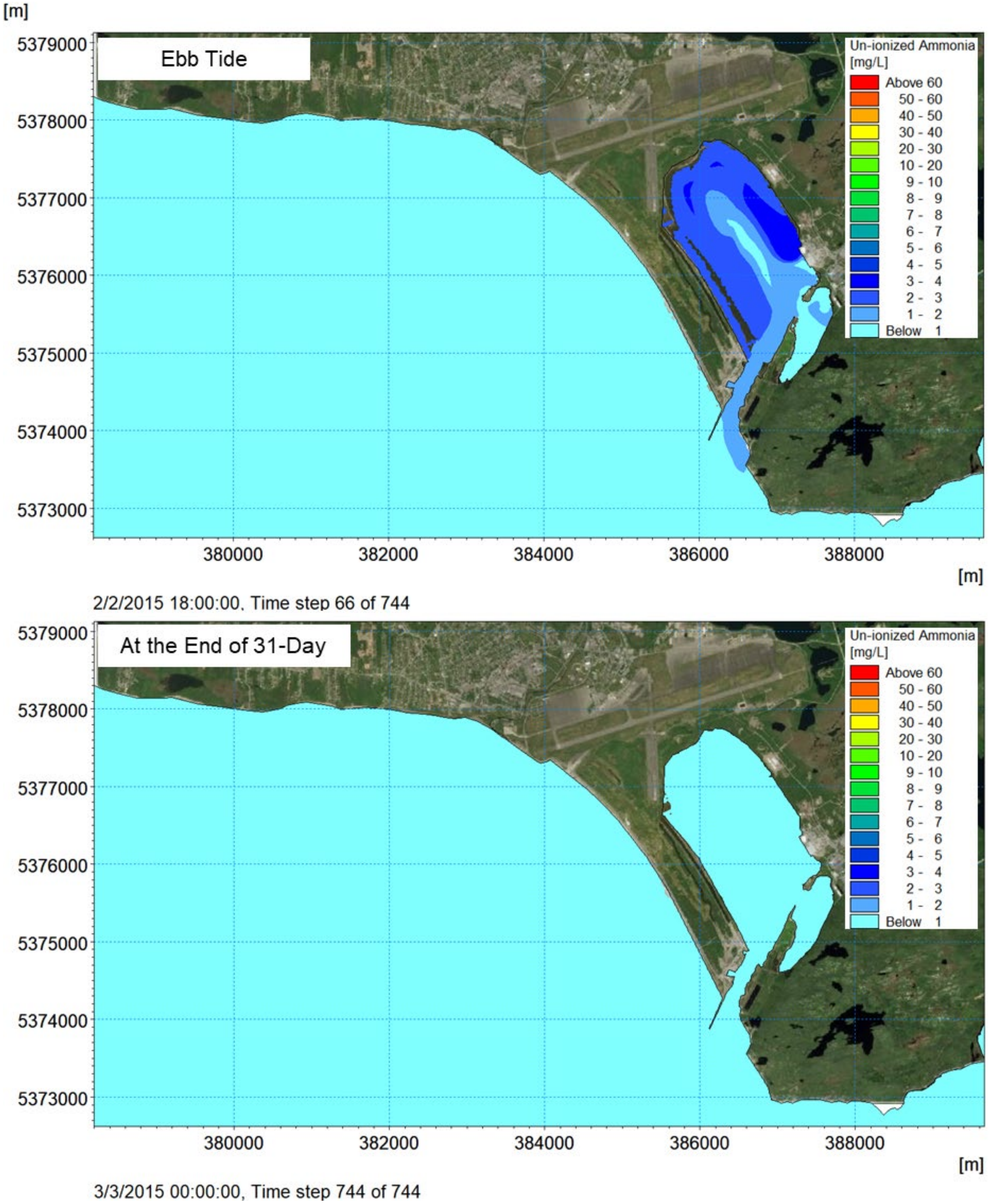
Figure 4.7 Simulated Maximum Extent of Un-Ionized Ammonia Plume in Winter During a Low Tide and Flood Tide



2/2/2015 18:00:00, Time step 66 of 744

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Figure 4.8 Simulated Maximum Extent of Un-Ionized Ammonia Plume in Winter During an Ebb Tide and at the End of 31 days Simulation

In order to understand the short- and long-term trend of un-ionized concentration, a time series of un-ionized ammonia concentration was extracted at the spill location and near the entrance of the port and presented on Figure 4.9. A review of the time series indicates a high short-term un-ionized ammonia concentration of 760.3 mg/L at the spill location immediately after the spill after and 4.3 mg/L at the port entrance 29 hours after the spill. The concentrations quickly reduce as a result of mixing with marine waters and tidal activity and reduces to 0.4 mg/L and 0 mg/L at the spill location and port entrance, respectively after one month of simulation in winter. Table 4.3 summarizes simulated acute (i.e., short-term) and chronic (i.e., long-term) un-ionized ammonia at the spill location and port entrance. As it is expected due to a high initial concentration at the spill location, the simulated un-ionized ammonia acute (760.3 mg/L) concentration in winter is higher than the BCMOE (2009) limit; however, the simulated un-ionized ammonia chronic (1.8 mg/L) concentration in winter reduces to lower than the BCMOE limit as Figure 4.9 shows a decreasing trend over time. At the port entrance, acute and chronic un-ionized ammonia concentrations of 4.3 mg/Land 0.3 mg/L, respectively are below the BCMOE limits and therefore, no exceedances were observed at the port entrance in winter. Although concentrations do vary within the port, generally concentrations are below the winter acute threshold of 14.0 mg/L approximately 1 day after the initial spill and below the chronic threshold of 2.1 mg/L 4 days after the initial spill.

Table 4.3 Acute and Chronic Concentration of Un-ionized Ammonia at the Spill Location and Port Entrance in Winter

Location	Acute (Maximum) Concentration (mg/L)	BCMOE Limit (mg/L)	Chronic (30-day average) Concentration (mg/L)	BCMOE Limit (mg/L)
Spill Location	**760.3** [1]	14.0 [2]	1.8	2.1 [2]
Port Entrance	4.3	14.0 [2]	0.3	2.1 [2]

Notes:
[1] **Bold font** indicates exceedance from BCMOE guidelines
[2] Obtained from BCMOE (2009) and summarized in Table 4.2

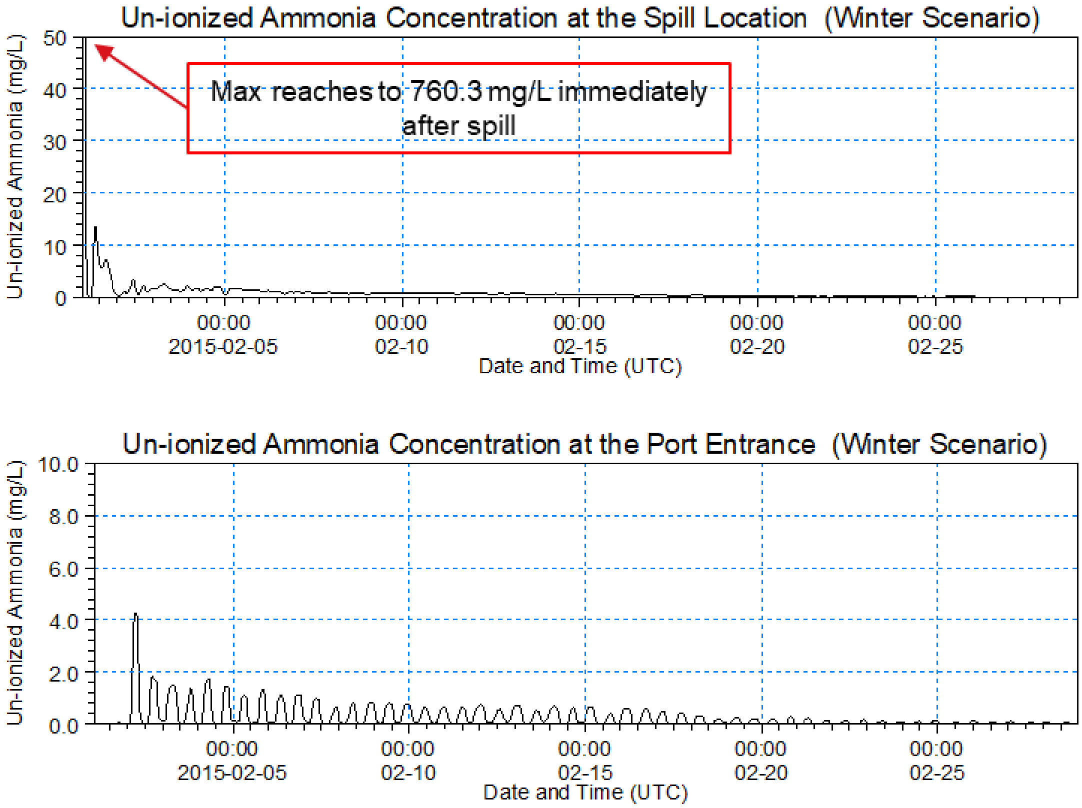

Figure 4.9 **Time Series of Un-ionized Ammonia Concentration at the Spill Location and the Port Entrance in Winter**

4.3.2 Fate and Transport of Ammonia in Summer

This section presents results of the ammonia spill at the marine terminal in summer. A one-month period of simulation in July 2015 was conducted to evaluate hydrodynamic and transport and fate of ammonia for short- and long- term effects. Maximum hourly and a 30-day averaged simulated concentrations were used to evaluate short-term (i.e., acute) and long term (i.e., chronic) effects on the marine environment. It was assumed that ammonia spills into the marine environment on the first day of July for a period of 2 minutes.

4.3.2.1 Hydrodynamic Conditions in Summer

This section presents key hydrodynamic model outputs at the spill location that were used in the fate and transport modelling. Figure 4.10 provides a time series of simulated water depth, current speed, and significant wave height at the spill location for July 2015 (i.e., summer scenario). A review of the hydrodynamic outputs indicates the following at the spill location in July 2015:

- Water depth at the spill location ranged from 11.3 m to 12.8 m with an average water depth of 12.1 m. Due to the proposed vessel draft, dredging may be conducted to increase water depth at the marine terminal; however, since the details are still unknown, as a conservative assumption, the existing conditions water depth was used for the purpose of ammonia fate and transport modelling as deeper water provides better mixing conditions for ammonia and lower concentrations.
- Current speed at the spill location ranged from 0 m/s to 0.09 m/s with an average current speed of 0.02 m/s. A review of simulated current at the spill location, indicates that currents are weak inside the port. Figure 4.11 presents spatial variations of current speed during typical ebb and flood tides in summer.
- Significant wave height at the spill location ranged from 0 m to 0.14 m with an average significant wave height of 0.05 m. A review of simulated current at the spill location, indicates that wave heights are inside the port and the port is well protected against incoming waves during this period. Figure 4.12 presents spatial variations of significant wave height at the time step when the maximum wave height was observed at the offshore boundary.

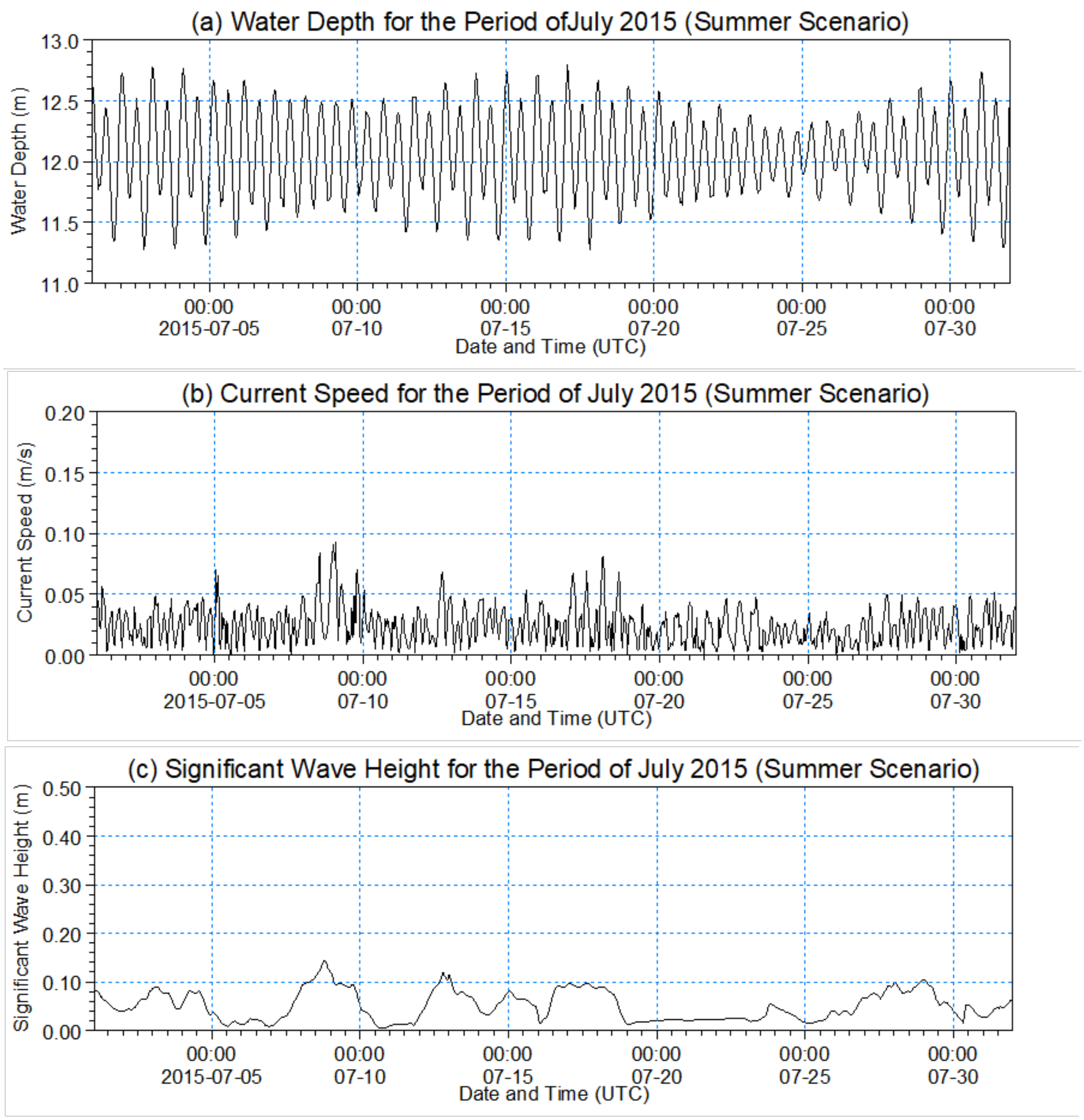

Figure 4.10 Simulated Hydrodynamic Conditions at the Spill Location for July 2015

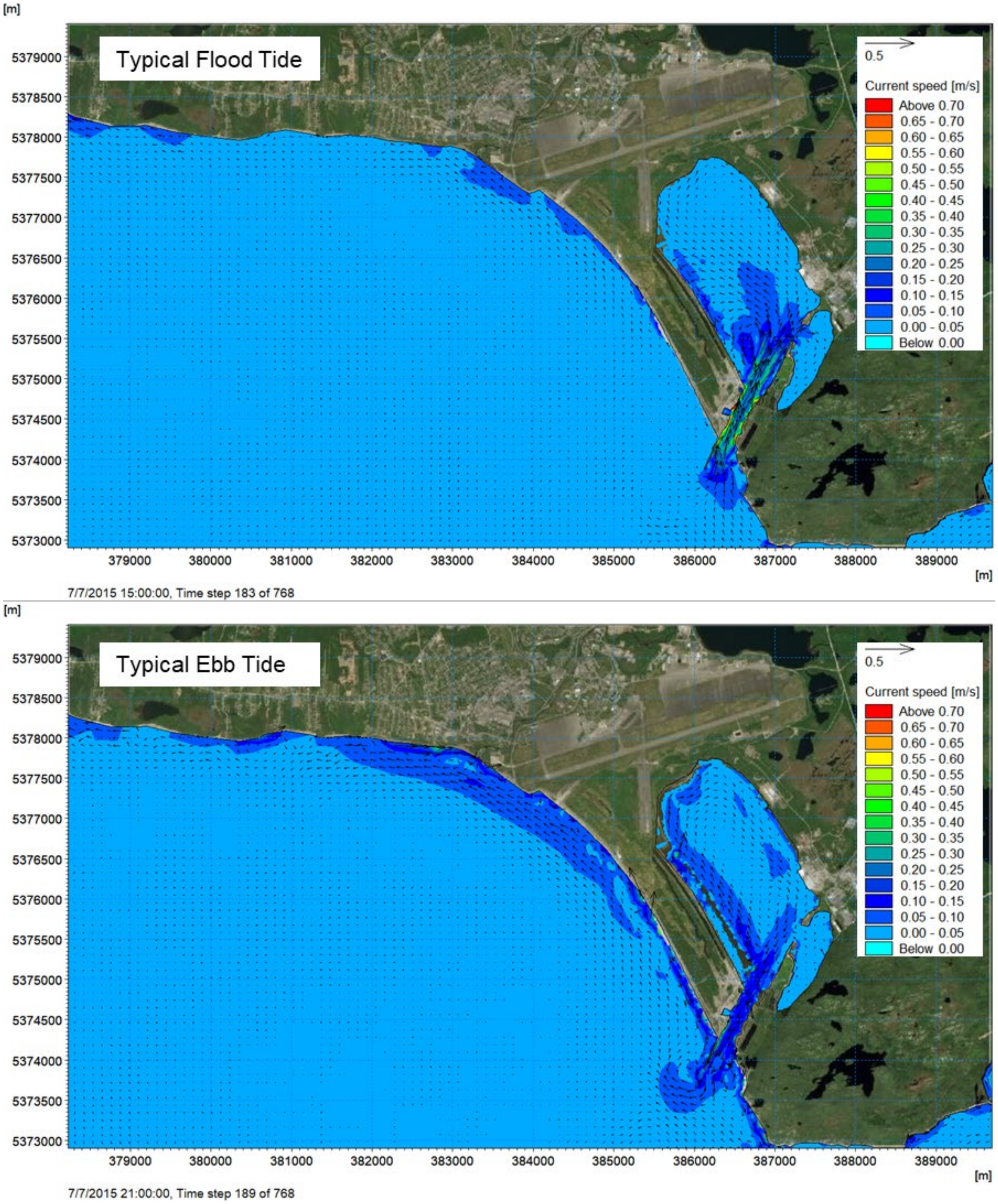

Figure 4.11 Spatial variation of Current Speed During Typical Ebb and Flood Tides in Summer

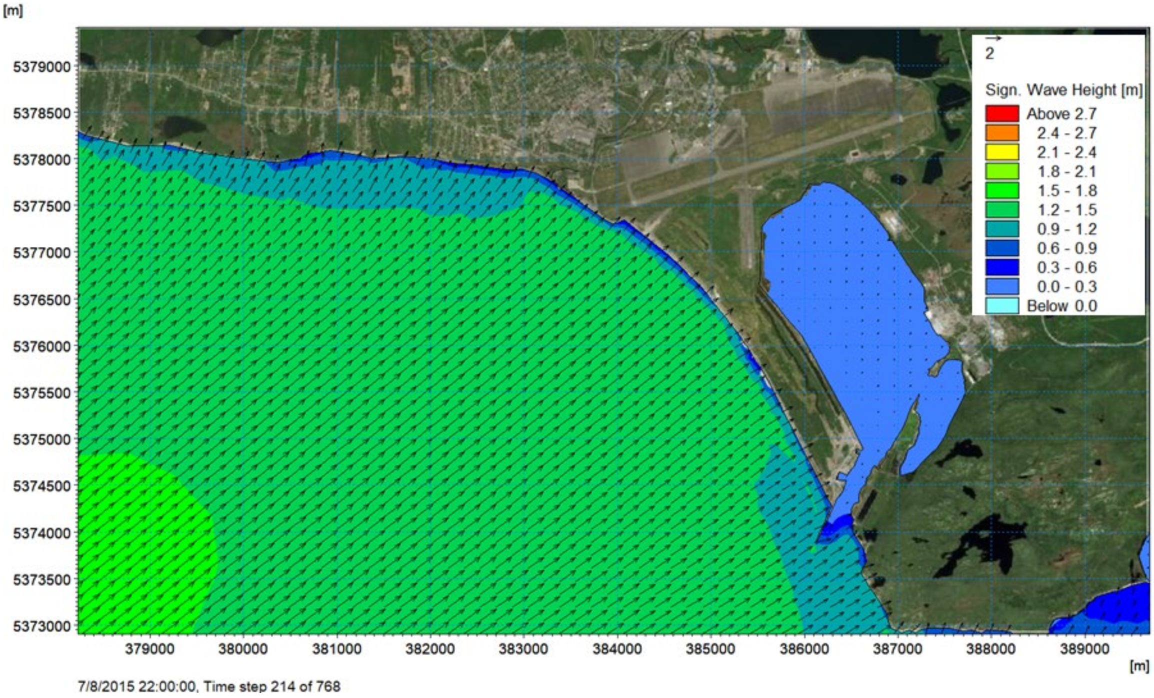

Figure 4.12 Spatial Variation of Significant Wave Height on July 8, 2015

4.3.2.2 Ammonia Transport and Fate in Summer

Figure 4.13 presents the extent of un-ionized ammonia plume and spatial variations of concentration 1 and 6 hr after the spill. A review of these two figures indicates a high concentration of un-ionized ammonia at and near the spill location immediately after the spill. Figure 4.14 presents the maximum extent of un-ionized ammonia plume during a low tide event on July 3 (76 hr after the spill) and indicates that due to the effects of tides, un-ionized ammonia mixes with the marine water and extends southwest of Port Harmon in the bay with a maximum concentration of 2 mg/L. This figure also presents the extent and spatial variations of un-ionized ammonia during a flood tide on July 3 (54 hr after the spill) and indicates that flood tide moves the plume inside the port. Figure 4.15 presents the extent of and spatial variations of un-ionized ammonia during an ebb tide on July 3 (63 hr after the spill) and indicates that ebb tides move the plume toward the entrance of the port in the bay. This figure also presents the extent and spatial variations of the un-ionized plume at the end of one month of simulation and indicates that due to the tides and mixing process of un-ionized ammonia with the marine water during this period, un-ionized ammonia concentration is reduced to less than 1 mg/L in the port. A review of the modelling results in summer indicates that concentration of un-ionized ammonia due to the spill reduced to less than 1 mg/L from July 18 and therefore, high concentrations do not persist in summer.

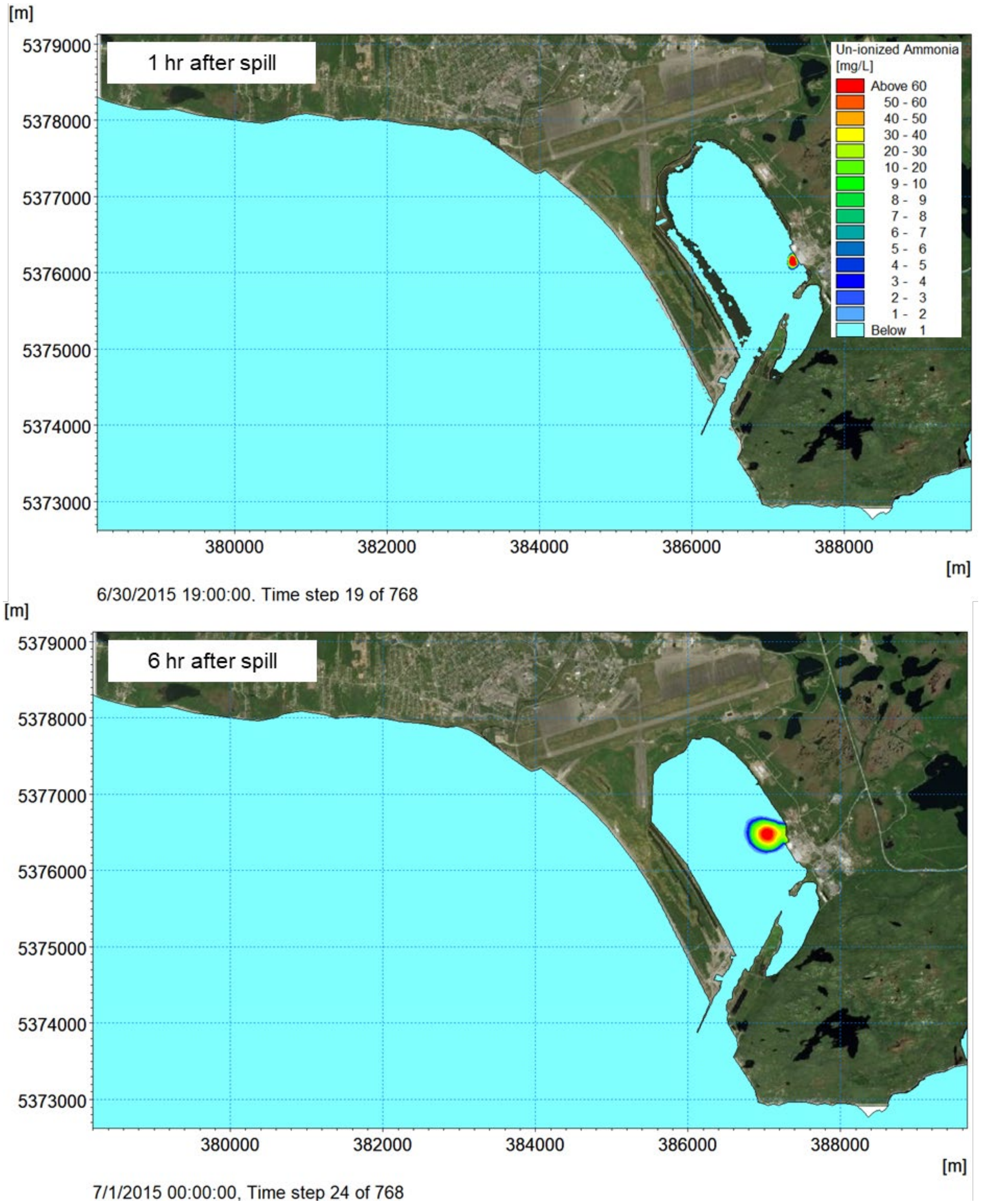

Figure 4.13 Simulated Extent of Un-ionized Ammonia Plume in Summer After 1 and 6 hr from the Spill

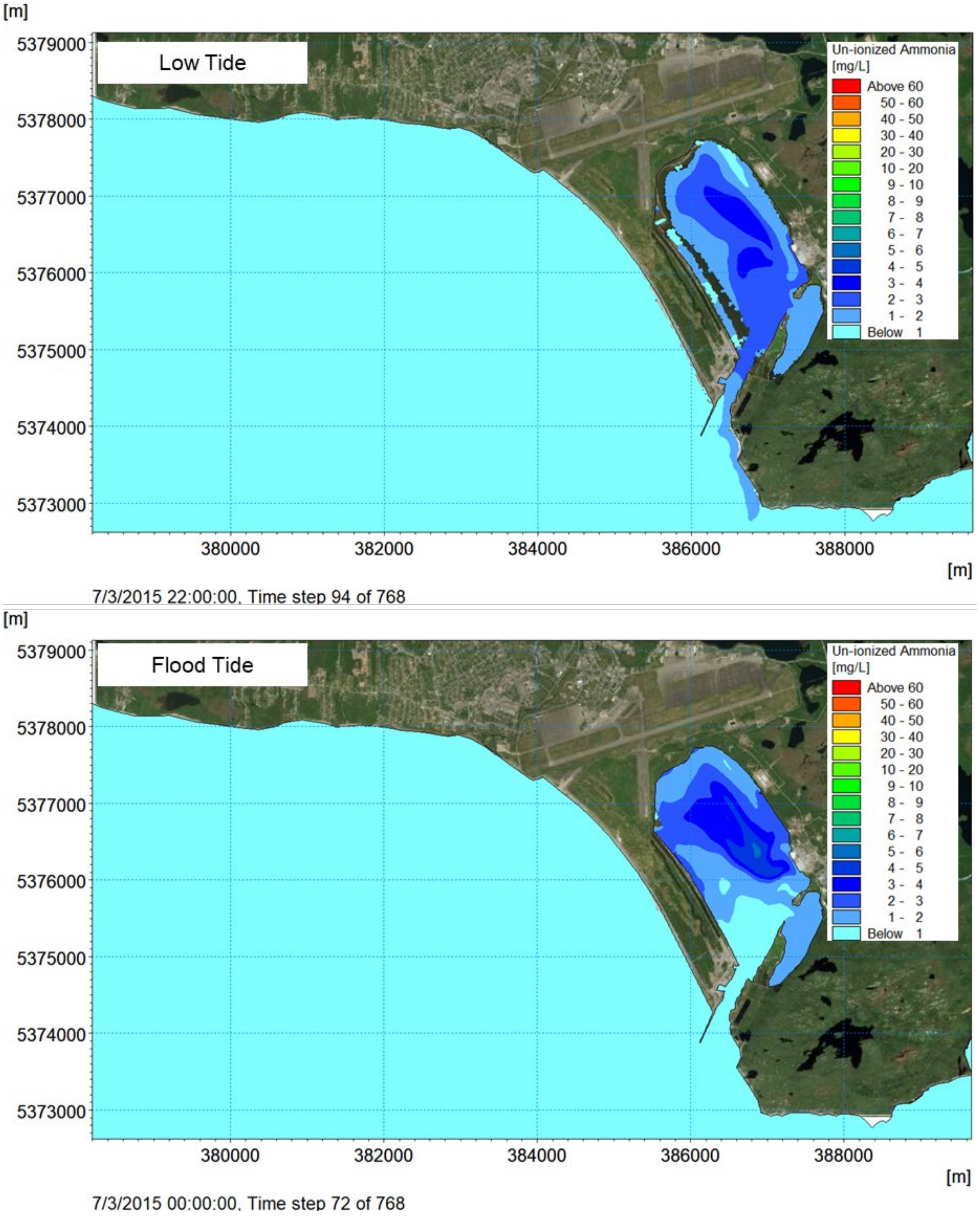

Figure 4.14 Simulated Maximum Extent of Un-Ionized Ammonia Plume in Summer During a Low Tide and Flood Tide

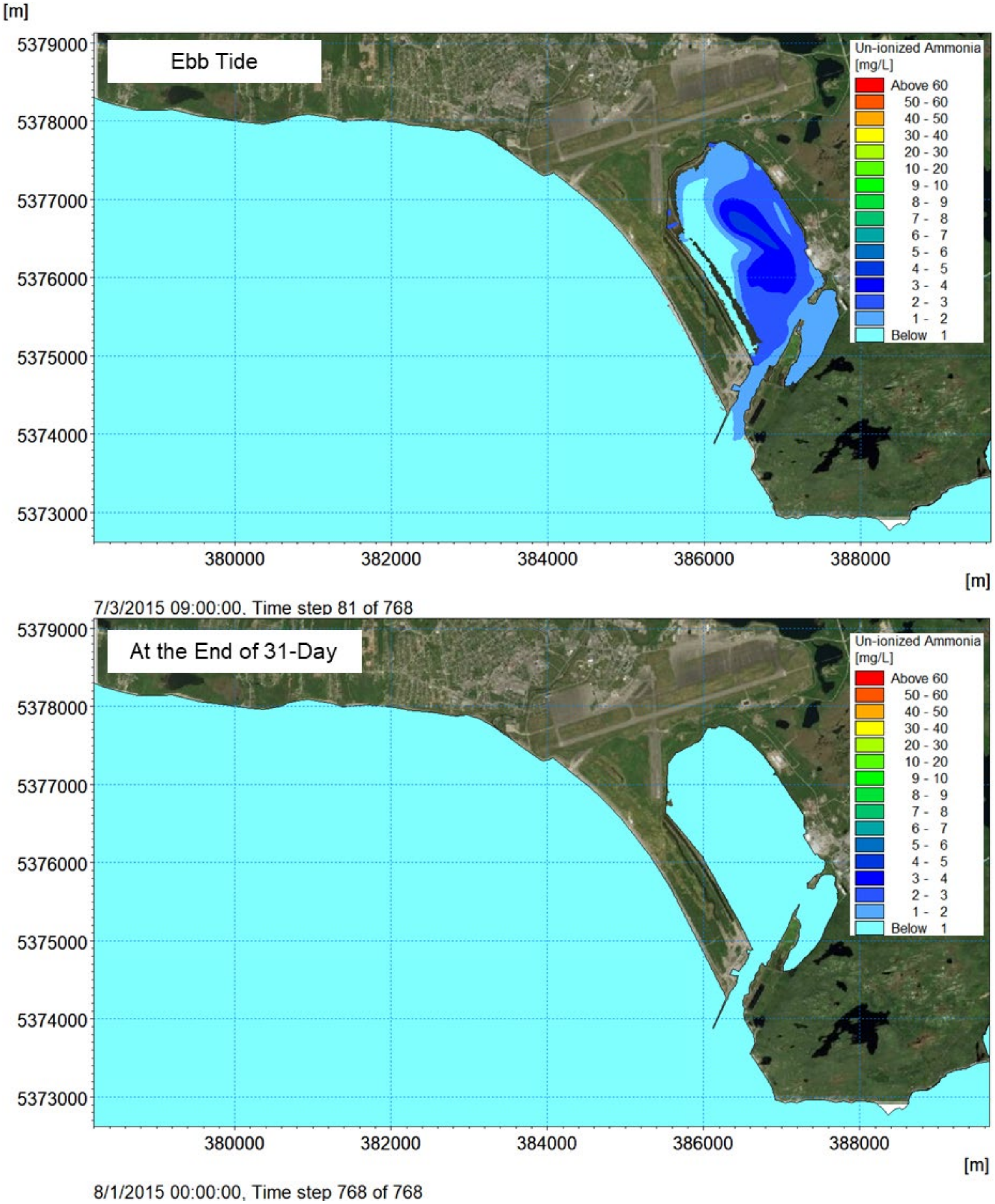

Figure 4.15 Simulated Maximum Extent of Un-Ionized Ammonia Plume in Summer During an Ebb Tide and at the End of One Month Simulation

In order to the understand short- and long-term trend of un-ionized concentration, a time series of un-ionized ammonia concentrations was extracted at the spill location and near the entrance of the port and presented on Figure 4.16. A review of the time series indicates a high short-term un-ionized ammonia concentration of 1,091.5 mg/L at the spill location immediately after the spill, and 2.3 mg/L at the port entrance 25 hours after the spill. The concentrations rapidly reduce as a result of mixing with the marine water and tidal activity and reduce to 0.42 mg/L and 0 mg/L at the spill location and port entrance, respectively, after one month of simulation in summer. Table 4.4 summarizes simulated acute (i.e., short-term) and chronic (i.e., long-term) un-ionized ammonia at the spill location and port entrance. As it is expected due to a high initial concentration at the spill location, simulated un-ionized ammonia acute (1,091.5 mg/L) and chronic (2.6 mg/L) concentrations in summer are higher than the BCMOE (2009) limits; however, it is expected that the long-term concentration reduces to lower than the BCMOE limit as Figure 4.16 shows a decreasing trend over time. At the port entrance, simulated acute (2.3 mg/L) and chronic (0.4 mg/L) concentrations of un-ionized ammonia are below the BCMOE limits. Although concentrations do vary within the port, generally concentrations are below the summer acute threshold of 6.7 mg/L approximately 2 days after the initial spill and below the chronic threshold of 1.0 mg/L 18 days after the initial spill.

Table 4.4 Ammonia Acute and Chronic Concentration of Un-ionized at the Spill Location and Port Entrance in Summer

Location	Acute (Maximum) Concentration (mg/L)	BCMOE Limit (mg/L)	Chronic (30-day average) Concentration (mg/L)	BCMOE Limit (mg/L)
Spill Location	**1,091.5** [1]	6.7 [2]	**2.6** [1]	1.0 [2]
Port Entrance	2.3	6.7 [2]	0.4	1.0 [2]

Notes:
[1] **Bold font** indicates exceedance from BCMOE guidelines
[2] Obtained from BCMOE (2009) and summarized in Table 4.2

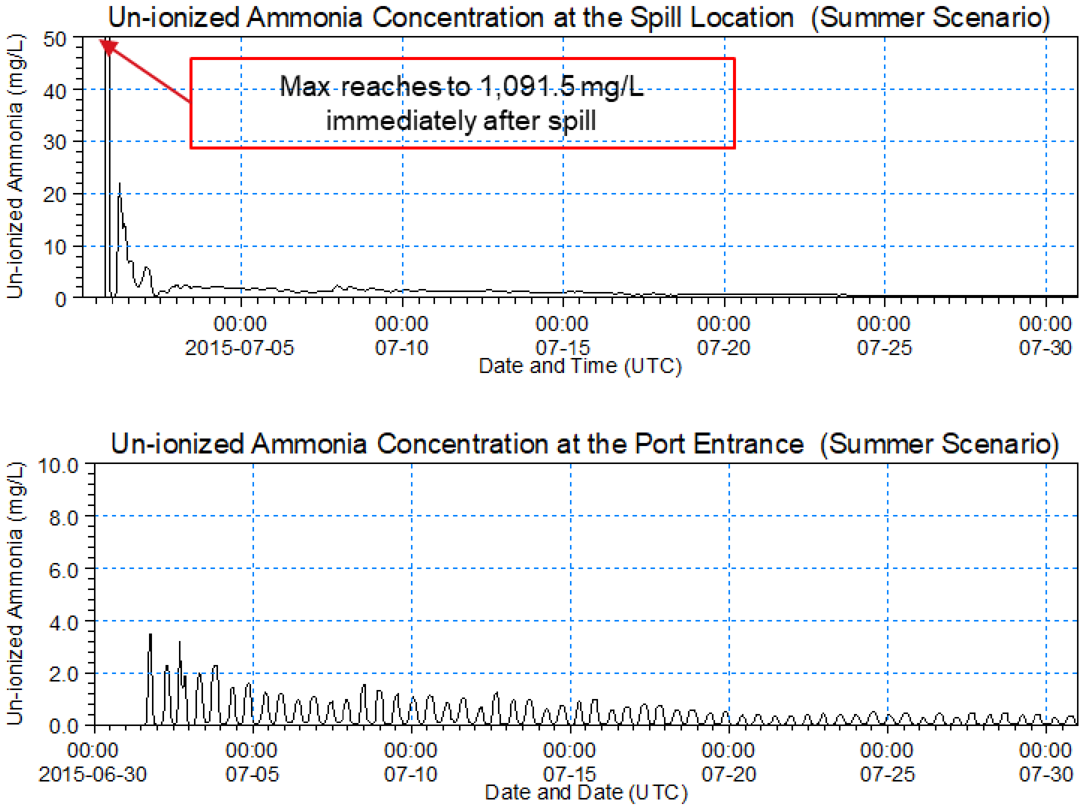

Figure 4.16 **Time Series of Un-ionized Ammonia Concentration at the Spill Location and the Port Entrance in Summer**

5.0 Summary and Conclusions

In this study, the fate and transport of anhydrous (un-ionized) ammonia in the marine environment due to an accidental spill during the loading process of a vessel at the marine terminal was modelled using the MIKE 21 coupled hydrodynamic and advection-dispersion model. The objective of the modelling was to estimate the extent of an un-ionized ammonia plume and spatial variations of concentration for short-term and long-term scenarios under typical winter and summer hydrodynamic conditions in the marine environment. In total two scenarios were modelled to evaluate the potential impacts of un-ionized ammonia under two seasonal conditions within the study area (winter and summer). February 2015 and July 2015 were selected as the months representing typical winter and summer, respectively. a spill rate of 265.8 kg/s for a period of 2 minutes in the marine terminal near the berth was modelled. As a conservative assumption, it was assumed that the spill occurred under the water and 100% of the spilled anhydrous ammonia mixed with the marine water. The key conclusions from the hydrodynamic and wave modelling results are summarized as follows:

- No field measurements for currents were available within the study area and therefore, a model calibration was not conducted for currents.
- Hydrodynamic conditions in winter may be impacted by strong winds and waves due to storm events in the bay but results of the hydrodynamic model indicate that the port is well protected against waves. Average water depth, significant wave height, and current speed for the simulation period of February 2015 (i.e., winter scenario) at the spill location were 12.1 m, 0.07 m, and 0.03 m/s, respectively.
- Summer was the calmest season. Average water depth, significant wave height, and current speed for the simulation period of July 2015 (i.e., summer scenario) at the spill location were 12.1 m, 0.05 m, and 0.02 m/s, respectively.

The key conclusions from the ammonia fate and transport modelling are summarized as follows:

- Results of the ammonia fate and transport modelling for all scenarios are summarized in Table 5.1. A review of the results indicates that the simulated un-ionized ammonia concentration only exceeds acute (i.e., maximum) BCMOE (2009) limit for marine water in winter and exceeds both acute (i.e., maximum) and chronic (30 day average) limits at the spill location. In addition, a review of the time series extracted at the spill location and entrance of Port Harmon indicates that concentrations reduce rapidly after the spill due to the tides and mixing process with the marine water and therefore, it is expected that the 2 minute accidental spill results in short-term elevated un-ionized ammonia concentrations in the port.
- A review of the simulated spatial and temporal variations of un-ionized ammonia in the port for winter scenario indicates that the simulated concentration of un-ionized ammonia reduces below the BCMOE acute limit of 14.0 mg/L approximately 1 day after the initial spill and reduces below the chronic limit of 2.1 mg/L approximately 4 days after the initial spill in winter.

- A review of the simulated spatial and temporal variations of un-ionized ammonia in the port for summer indicates that the simulated concentration of un-ionized ammonia reduces below the BCMOE acute limit of 6.7 mg/L approximately after 2 days from the initial spill and reduces below the chronic limit of 1.0 mg/L approximately 18 days after the initial spill in summer.
- The maximum extent of un-ionized ammonia was simulated at a low tide event 30 and 76 hours after the spill in winter and summer, respectively. A review of the maximum extent of the un-ionized plume indicates that the effects of the spill on the marine environment is only limited to the area inside the port.
- A review of BCMOE limits for un-ionized ammonia in marine waters indicates that the limit decreases by increasing temperature and therefore an accidental spill in summer is the worst-case spill scenario since the limits are lower and also currents are weaker within the study areas compared to other seasons.

Table 5.1 Acute and Chronic Concentration of Un-ionized Ammonia at the Spill Location and Port Entrance in Winter and Summer

Season	Location	Acute (Maximum) Concentration (mg/L)	BCMOE Limit (mg/L)	Chronic (30-day average) Concentration (mg/L)	BCMOE Limit (mg/L)
Winter	Spill Location	**760.3** [1]	14.0 [2]	1.8	2.1 [2]
	Port Entrance	4.3[,3]	14.0 [2]	0.3	2.1 [2]
Summer	Spill Location	**1,091.5** [1]	6.7 [2]	**2.6** [1]	1.0 [2]
	Port Entrance	2.3 [4]	6.7 [2]	0.4	1.0 [2]

Notes:

[1] **Bold font** indicates exceedance from BCMOE guidelines

[2] Obtained from BCMOE (2009) and summarized in Table 4.2

[3] Observed 29 hr after spill

[4] Observed 25 hr after spill

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Appendix 24-B

Quantitative Risk Assessment

Stantec

PROJECT NUJIO'QONIK
Quantitative Risk Assessment – Nujio'qonik Ammonia Production Facility Supporting Study

August 2023

Prepared for:

world energy
GH₂

Prepared by:

Stantec Consulting Ltd.

Project Number: 121417575

Revision: 1

Limitations and Sign-off

This document entitled Quantitative Risk Assessment – Nujio'qonik Ammonia Production Facility Supporting Study was prepared by Stantec Consulting Ltd. ("Stantec") for the account of World Energy GH2 (the "Client"). Any reliance on this document by any other party or use of it for any other purpose is strictly prohibited. The material in it reflects Stantec's professional judgment in light of the scope, schedule and other limitations stated in the document and in the contract between Stantec and the Client. The information and conclusions in the document are based on the conditions existing at the time the document was published and does not take into account any subsequent changes. In preparing the document, Stantec did not verify information supplied to it by the Client or others, unless expressly stated otherwise in the document. Any use which another party makes of this document is the responsibility and risk of such party. Such party agrees that Stantec shall not be responsible for costs or damages of any kind, if any, suffered by it or any other party as a result of decisions made or actions taken based on this document.

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04735 August 14 2023
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Executive Summary

World Energy Green H2 (WEGH2) retained Stantec Consulting Ltd. (Stantec) to complete a Quantitative Risk Assessment (QRA) associated with accidental releases from process activities at a proposed ammonia production facility (the Facility). The Facility will be located near the Port au Port peninsula, east of Stephenville, Newfoundland. The Facility is currently being designed to produce approximately 4,950 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 off-site risks associated with accidental releases. The risk is based on the likelihood and severity of the release scenarios, and can be compared against land use planning guidelines, to determine if facility operations would impose restrictions on current land use surrounding the Facility. Additionally, this study provides distances to selected consequence end points which can be used in the development of emergency response plans and as information for first responders.

The QRA included the following tasks:

1. Description of the proposed facility and how it is expected to operate.
2. Identification of potential major accident hazardous events.
3. Source characterization of several loss of containment (LOC) scenarios from several processes including:
    a. Hydrogen production and storage,
    b. Ammonia production,
    c. Ammonia separation, and
    d. Ammonia storage and piping to a marine terminal.
4. Consequence modeling to determine the extents of hazardous events for various combinations of release scenarios, 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 hazardous events 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 release scenarios involving the following hazards:

- Flash Fires (moving flame front resulting from the 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).
- Dispersion of an unignited toxic cloud, as a result of a liquid ammonia pool spill;

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 and release scenarios. The results of this modelling can be used to inform emergency responders and assist in the development of emergency response plans, and can also be used to identify areas of the process where additional mitigation might be beneficial in terms of 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 (CSChE). The criteria were adopted to aid in land use planning purposes, and are summarized in terms of the predicted individual risk levels as:

- **Zone A** – No land use other than the risk source; an annual individual risk greater than 100 in a million
- **Zone B** – Manufacturing, warehouses, and open space (parkland and golf courses); an annual individual risk between 10 and 100 in million
- **Zone C** – Low-density residential and commercial; an annual individual risk between 1 and 10 in a million
- **Zone D** – High-density residential and commercial; an annual individual risk between 0.3 and 1 in a million
- **Zone E** – Unrestricted development, including sensitive development such as hospitals and childcare; an annual individual risk less than 0.3 in a million.

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. The risk results were used to determine if there were potential conflicts with existing land use around the facility. Three cases were considered (representing different receptor locations). Estimates of individual risk were provided for the following:

- Sensitive institutional receptors
- Urban receptors
- Rural receptors

Based on comparison against the CSChE land-use-planning guidelines it is predicted that sole consideration of the proposed Facility is not predicted to result in unacceptable land use in the lands adjacent to it.

In review of the contributions to the individual risk, as provided above, releases of liquid ammonia from the storage vessels were found to be a large contributor. Passive mitigation measures that were considered in the risk modelling include:

- The storage tanks were considered "full containment" systems. This consists of a double-wall tank where both the outer and inner tanks are designed to be fully capable of holding the ammonia without compromising structural integrity or release of vapour. A loss of contents would only occur in the highly unlikely event that both the outer and inner tank were breached simultaneously.
- Tertiary containment in the form of a berm around the tanks, to prevent a liquid spill of ammonia from spreading.

The Facility will have the following additional mitigation measures, which will likely reduce the risk:

- Physical and electronic security systems will be implemented to protect all plant components from hazards and to minimize the potential for accidental release.
- The inclusion of robust instrumented systems designed to detect any releases of ammonia or hydrogen and to initiate shutdown procedures to isolate and minimize the discharge while also providing indications to personnel of potential danger and prompting egress from the affected area. The intent is to detect and react to any release before it has the potential to adversely affect people or the environment.
- Methodologies to address and react to any events that may occur. Most notably, those that would contain a release of ammonia and minimize the spread of vapors into the environment and surrounding communities. Ammonia vapors can be affectively contained by using water curtains produced by water monitors, sprinklers, foggers, or a combination of these. The ammonia vapors readily dissolve in the water and fall to earth where the water can be collected and treated. Additionally, liquid ammonia spills may be physically covered with tarps or other physical barriers to contain vapors while the liquid is collected for treatment.
- Community response procedures will be put in place to inform the local community of any situations arising from the plant. These measures will be developed in conjunction with local emergency management organizations and could include shelter in place orders and evacuation procedures for responding to extreme situations.

It is the intent of the Nujio'qonik project to design, build, and operate a safe facility, detailed studies of potential mishaps and accidents will be studied. Further refinement of response and mitigation plans will be developed and coordinated with the local communities. Inclusion of these additional mitigation methods would likely reduce the risk associated with operation of the Facility.

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Abbreviations

ACH	Air changes per hour
AEGL	Acute Exposure Guideline Levels
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASU	Air Separation Unit
BLEVE	Boiling liquid expanding vapour explosion
CDC	Center for Disease Control and Prevention
CSChE	Canadian Society for Chemical Engineering
ECCC	Environment and Climate Change Canada
EPA	Environmental Protection Agency
ERCB	Energy Resources Conservation Board
HSE	Health and Safety Executive
LFL	Lower flammability limit
LOC	Loss of containment
MAH	Major accident hazard
MEM	Multi-Energy method
MIACC	Major Industrial Accidents Council of Canada
NFPA	National Fire Protection Association
NIST	National Institute of Science and Technology
NSU	Nitrogen separation unit
PEM	Proton exchange membrane
QRA	Quantitative risk assessment
RMP	Risk management plan
SOEC	Solid oxide electrolyser cell

TDU	Thermal dose unit
TNO	Netherlands Organization for Applied Scientific Research
US EPA	United States Environmental Protection Agency
VCE	Vapour cloud explosion
WEGH2	World Energy GH2
WRC	Water Recycling Centre

1.0 Introduction

World Energy GH2 (WEGH2) retained Stantec Consulting Ltd. (Stantec) to complete a Quantitative Risk Assessment (QRA) associated with accidental release scenarios from process activities at a proposed ammonia production facility (the Facility). The Facility will be located in Stephenville, Newfoundland and Labrador. The Facility is currently being designed to produce approximately 4,950 tonnes/day (maximum) 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 off-site risks associated with accidental releases. The risk is based on the likelihood and severity of the release scenarios, and can be compared against land-use-planning guidelines to determine if facility operations would impose restrictions on current land use surrounding the Facility. Additionally, this study provides distances to selected consequence end points which can be used in the development of emergency response plans and as information for first responders.

This report outlines the modelling methodology and assumptions used to conduct the QRA and is divided into the following main sections:

- System/Installation Description
- Hazard Identification
- Consequence Modelling Analysis
- Quantitative Risk Assessment
- Modelling Sensitivity and Uncertainty
- Conclusions

2.0 System/Installation Description

WEGH2 will utilize air and water to produce nitrogen and hydrogen, respectively. The electricity to power the separation of water into hydrogen will be provided from nearby wind turbine sites (to be constructed). The hydrogen and nitrogen are then combined at high pressure and temperature through the Haber-Bosch process to produce anhydrous ammonia.

The facility location, relative to nearby communities, is shown in Figure 2.1. The community of Stephenville is northwest of the facility site, Stephenville Crossing is southeast of the facility site, and Little Port Harmon is to the west of the facility site. Little Port Harmon includes the region itself, as well as the Harmon Seaside Park community. Harmon Seaside Park is considered seasonal, operating approximately 21 weeks per year (Dave Pinsent, 2023).

A site plan for the proposed Facility is shown in Figure 2.2. A block flow diagram of the process is shown in Figure 2.3. The piping layout as currently proposed is shown in Figure 2.4.

The main processes in the facility include:

- Hydrogen production and storage. Hydrogen gas is separated from water through the use of proton exchange membrane electrolysers (PEMs) and solid oxide electrolyser cells (SOECs). Up to 20 tonnes of the produced hydrogen can be stored for future use.
- Nitrogen production, where nitrogen separation units (NSUs) will extract nitrogen from ambient air.
- Ammonia production, where pre-heaters and compression facilities are used to increase temperature and pressure of the combined hydrogen and nitrogen streams (including recycle). The combined stream is fed through a reactor (using the Haber-Bosch process), where ammonia is produced. The reactor outlet will contain unreacted hydrogen and nitrogen gas.
- Ammonia separation, where the outlet of the reactor, including ammonia and unreacted hydrogen and nitrogen, are cooled to separate ammonia as a liquid. Ammonia is sent to the storage vessels, while unreacted hydrogen and nitrogen are recycled to the ammonia production process.
- An ammonia storage and shipping system. The liquid ammonia is stored in refrigerated, atmospheric vessels, and can be pumped to a marine terminal. At the marine terminal, the ammonia can be transferred to a marine vessel via loading arms.

The facility will be brought online in three phases, each with its own process train (with processes as described above). Each phase will contribute one third of the total ammonia production (at 1,650 tonnes per day, up to approximately 4,950 tonnes per day at peak capacity).

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 based on the available design information provided by WEGH2. Summaries of the facility operating conditions for the main processes that were used for the QRA are provided in Appendix A.

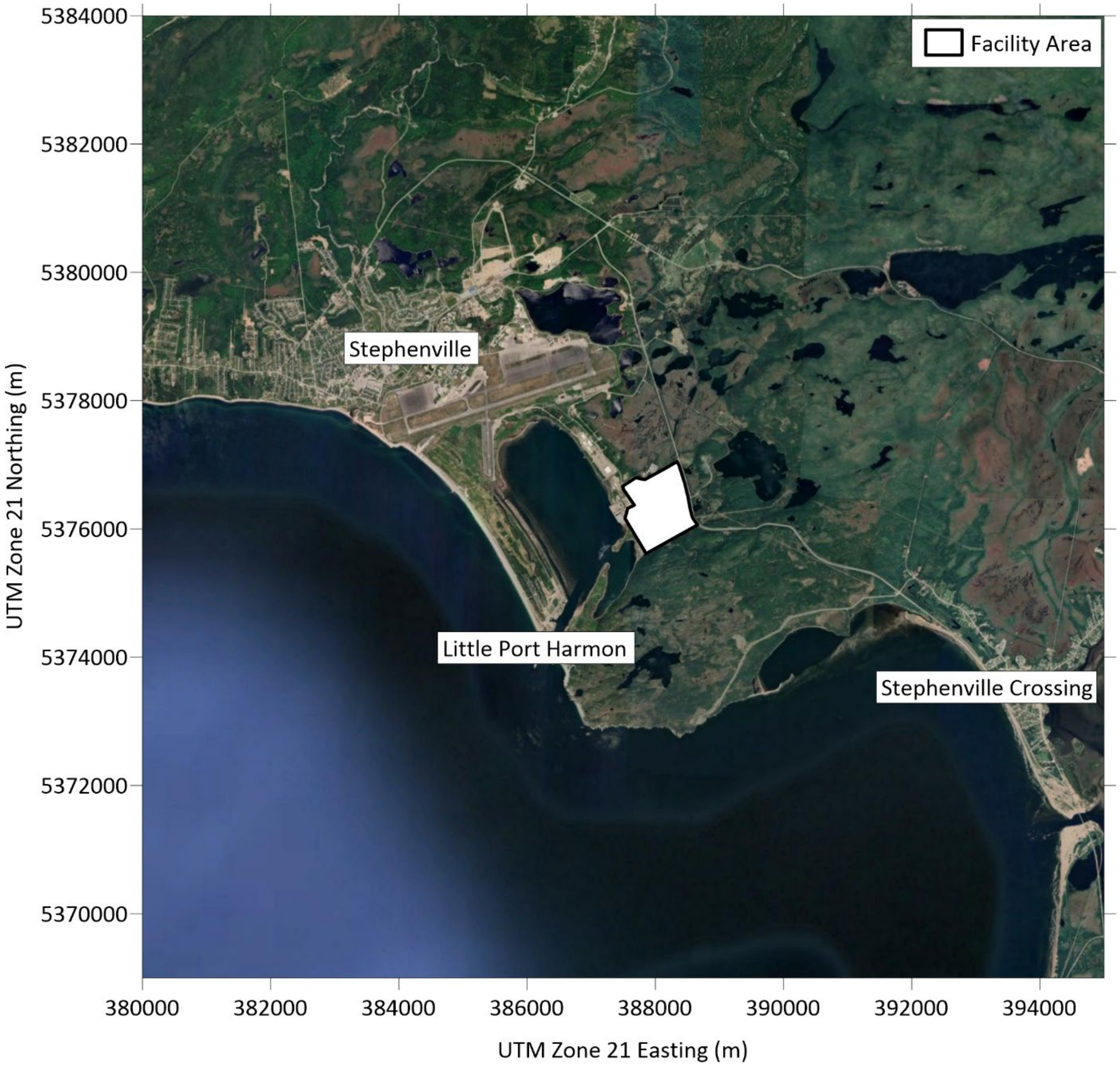


Figure 2.1 Project Location

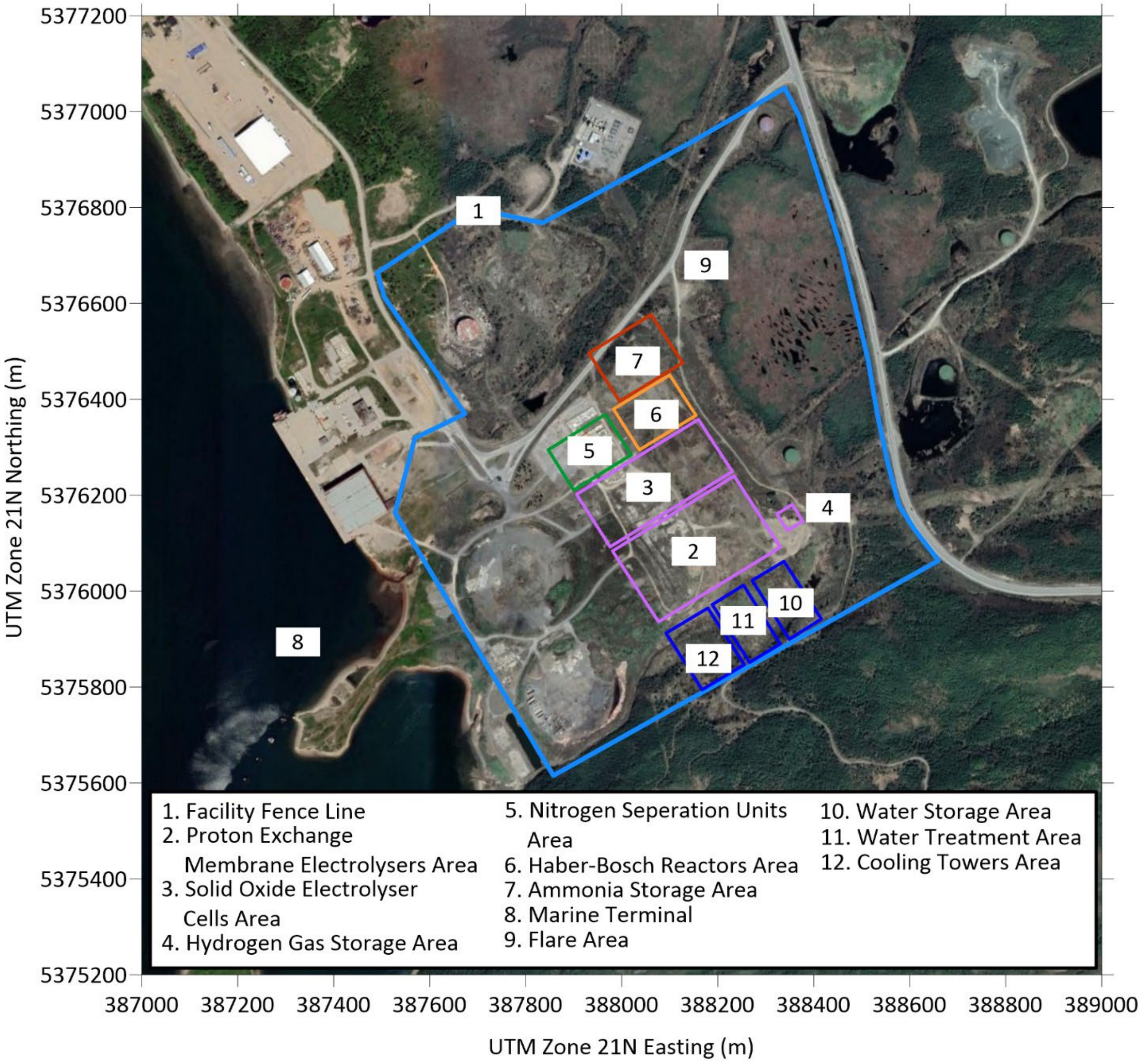


Figure 2.2 Project Site Plan

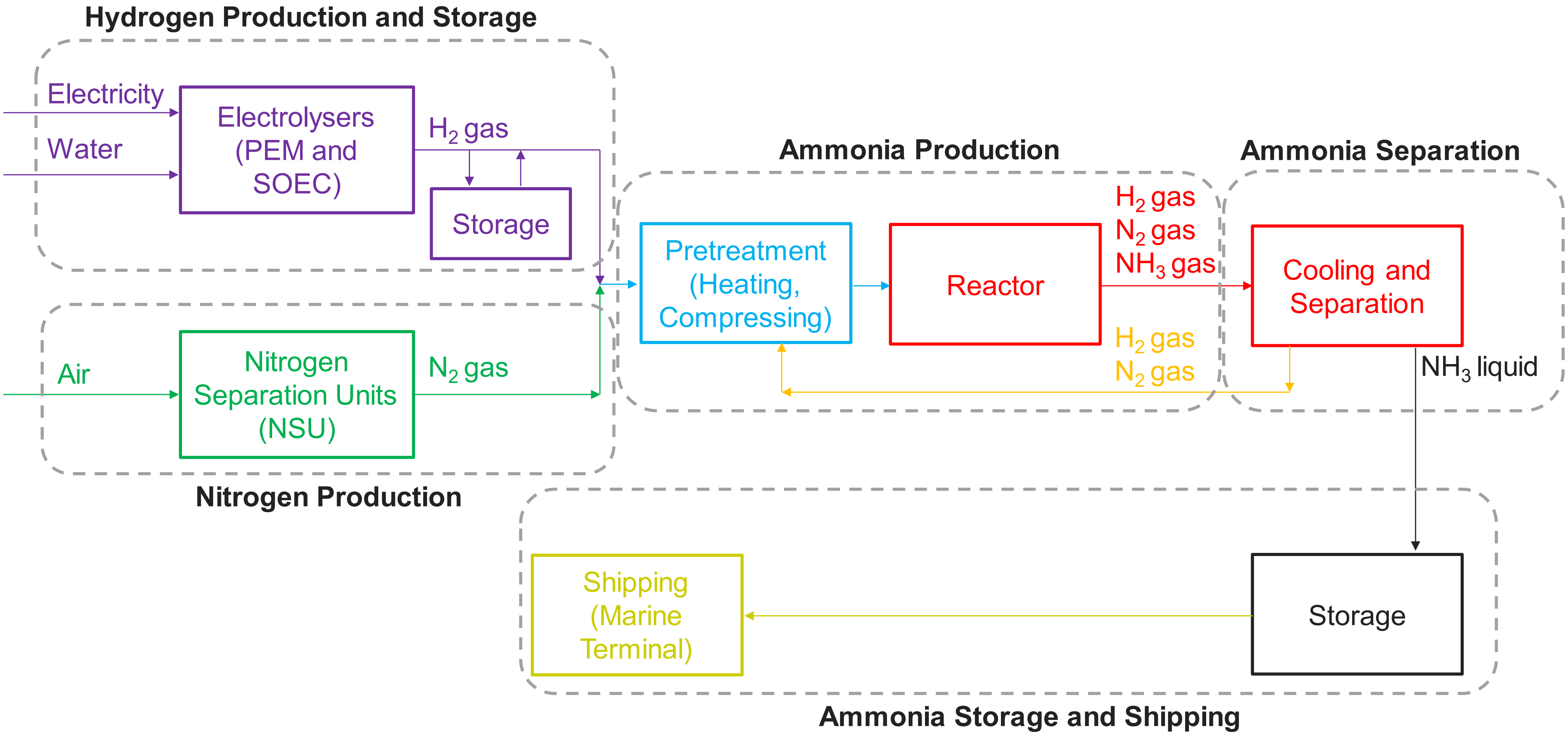


Figure 2.3 **Process Block Flow Diagram**

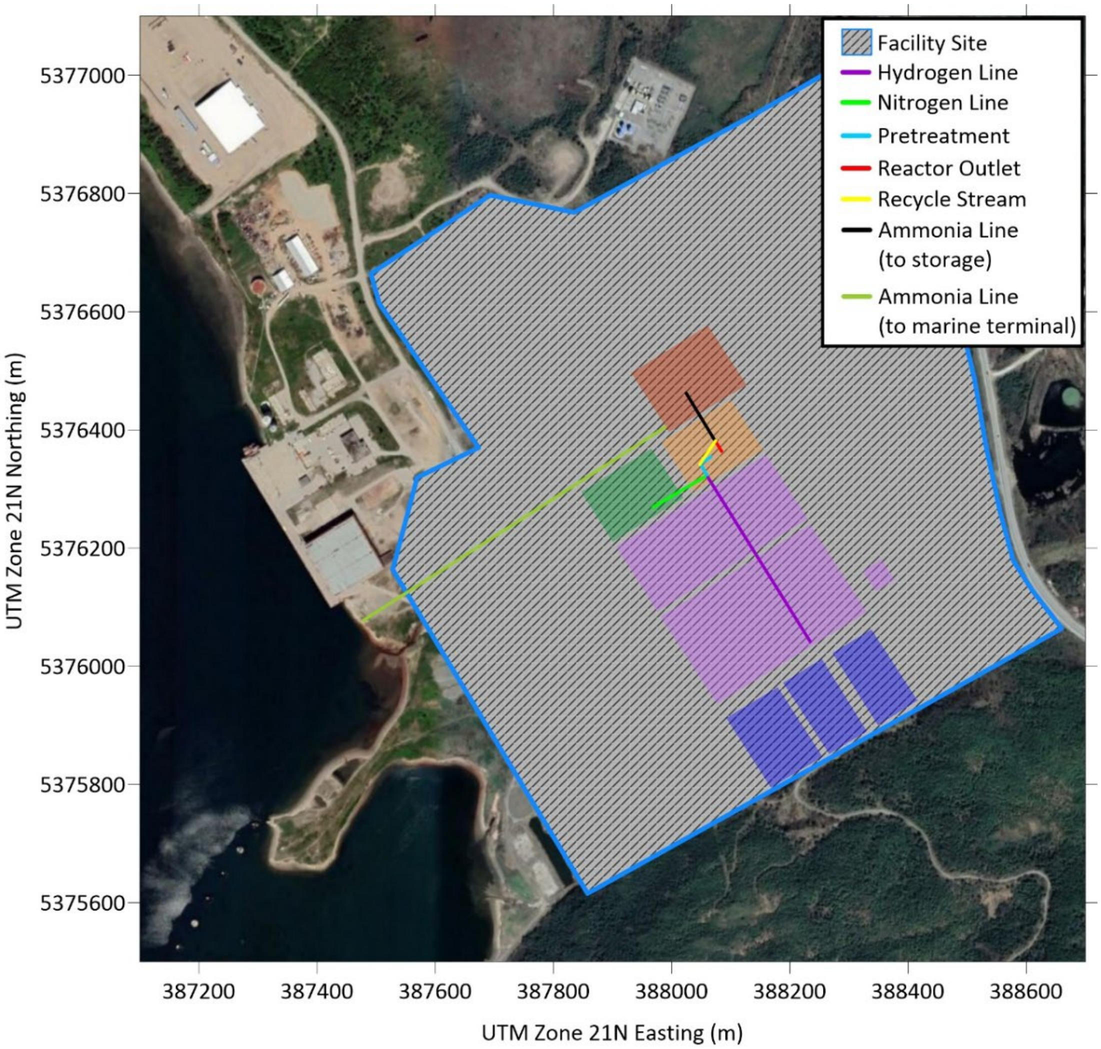


Figure 2.4 Hypothetical Piping Layout

2.1 Hydrogen Production and Storage

Each process train will include 32 PEM electrolysers (and one solid oxide electrolyser cell, SOEC) which separate process inlet water into hydrogen and oxygen. Electrolysers will be placed in an area on the south side of the facility, towards the center. The oxygen will be exhausted 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 30 bar(g) and 40°C. However, during upset conditions the system may operate at 50 bar(g). Each train may produce up to 293 tonnes of hydrogen gas per day.

Up to 20 tonnes of hydrogen gas may be stored in a high-pressure storage vessel. Each storage vessel can store approximately 12 m^3 at up to 1,000 bar(g).

2.2 Nitrogen Production

Nitrogen Separation Units (NSUs) will be used to separate nitrogen and oxygen from air, and are positioned northwest of the hydrogen production area. Each NSU will provide 1,357 tonnes of nitrogen gas per day through a 12-inch (304.8 mm) pipe at up to 8 bar(g) and 40°C.

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. The feed streams of hydrogen and nitrogen are mixed in a 14-inch (355.6 mm) diameter pipe, and then undergo a multi-stage compression cycle that brings the feed stream to 300 bar(g). During the pre-treatment, the unreacted hydrogen and nitrogen from the reactor output is recycled back into the reactor feed. A preheater brings the reactor feed to approximately 450°C. The fluid composition for the flow into each reactor has a 3:1 molar ratio of hydrogen to nitrogen gas. The inlet flow is delivered through a 16-inch (406.4 mm) pipe.

The reactor will produce ammonia. The ammonia production reaction is exothermic, and the temperature will be controlled such that the product stream maintains a temperature of 450°C. The outlet pipe is a 16-inch (406.4 mm) diameter pipe. The information provided by WEGH2 has indicated an isothermal and isobaric process, where there is no change in temperature or pressure through the process. This assumption will lead to an overestimate of pressure in some parts of the process. Systems at higher pressures generally produce larger consequences and therefore may overstate the risk.

The product stream is composed of approximately 30% ammonia by mass (or 18% by mole), and the remainder of the stream will be unreacted feed gas (3-to-1 molar ratio of hydrogen to nitrogen).

2.4 Ammonia Separation

The materials output from the reactor are sent to the ammonia separation section. Not all of the reactor input is converted to ammonia. The quantities of hydrogen and nitrogen that are not converted to ammonia are recycled back to the reactor inlet.

The ammonia separation process cools the reactor outputs to isolate ammonia for storage and export. The reactor outputs are put through a multi-stage separation cycle. The ammonia is recovered at -32°C and 5.5 bar(g), where it is sent to the storage vessels. The leftover hydrogen and nitrogen gases are returned to the system via a recycle stream to the reactor feed compression cycle.

2.5 Ammonia Storage and Shipping

Ammonia is sent to storage via a 6-inch (152 mm) diameter pipe for each process train. While the final design of the storage facility is not complete, the current storage design will have three refrigerated ambient pressure storage vessels per process train. Each storage vessel will store up to 35,000 m^3 of ammonia (approximately one marine tanker vessel volume). The storage vessel was assumed to be double walled and insulated to keep ammonia at -34°C and 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 storage location is just north of the facility center. The estimated storage vessel dimensions are 54 m diameter and 18.3 m in height. It was assumed that the ammonia storage will be surrounded by a berm large enough to contain 110% of the volume of one storage vessel.

Ammonia will be pumped from the storage area to a marine export terminal via a single 24-inch (609.6 mm) diameter pipe (connected to each process train), where the ammonia will be the unloaded onto an export ammonia tanker at approximately 1,400 m^3/h. The marine terminal is located at the south-west end of the facility.

2.6 Summary of Release Scenario Locations

The potential locations where loss of containment could occur are summarized in Table 2.1. A graphical representation of each scenario location is presented in Figure 2.5 for each process train. A loss of containment at leach scenario location could release a hazardous material, which will be discussed in the following section (Section 3).

Table 2.1 Release Scenario Location Summary

Process Region	Release Scenario Location	Scenario Description	Substance
Hydrogen Production and Storage	1	Loss of containment involving the electrolyser or the connection piping (3-inch diameter) to the header.	Hydrogen (gas)
	2	Loss of containment involving the hydrogen header (10-inch diameter).	Hydrogen (gas)
	3	Loss of containment involving the hydrogen storage vessel (12 m^3 per vessel)	Hydrogen (gas)
Ammonia Production	4	Loss of containment involving the hydrogen and nitrogen mixing piping (14-inch diameter).	Hydrogen (gas) Nitrogen (gas)
	5	Loss of containment involving the reactor inlet piping (16-inch diameter).	Hydrogen (gas) Nitrogen (gas)
	6	Loss of containment involving the reactor outlet piping (16-inch diameter).	Hydrogen (gas) Nitrogen (gas) Ammonia (gas)
Ammonia Separation	7	Loss of containment involving the recycle piping (24-inch diameter).	Hydrogen (gas) Nitrogen (gas)
	8	Loss of containment involving the piping from the separator to the ammonia storage vessels (6-inch diameter).	Ammonia (liquid)
Ammonia Storage and Shipping	9	Loss of containment involving the ammonia storage vessels (35,000 m^3 per storage vessel).	Ammonia (liquid)
	10	Loss of containment involving the piping to the marine terminal (24-inch diameter).	Ammonia (liquid)
	11	Loss of containment involving the marine loading arm (estimated as 24-inch diameter).	Ammonia (liquid)

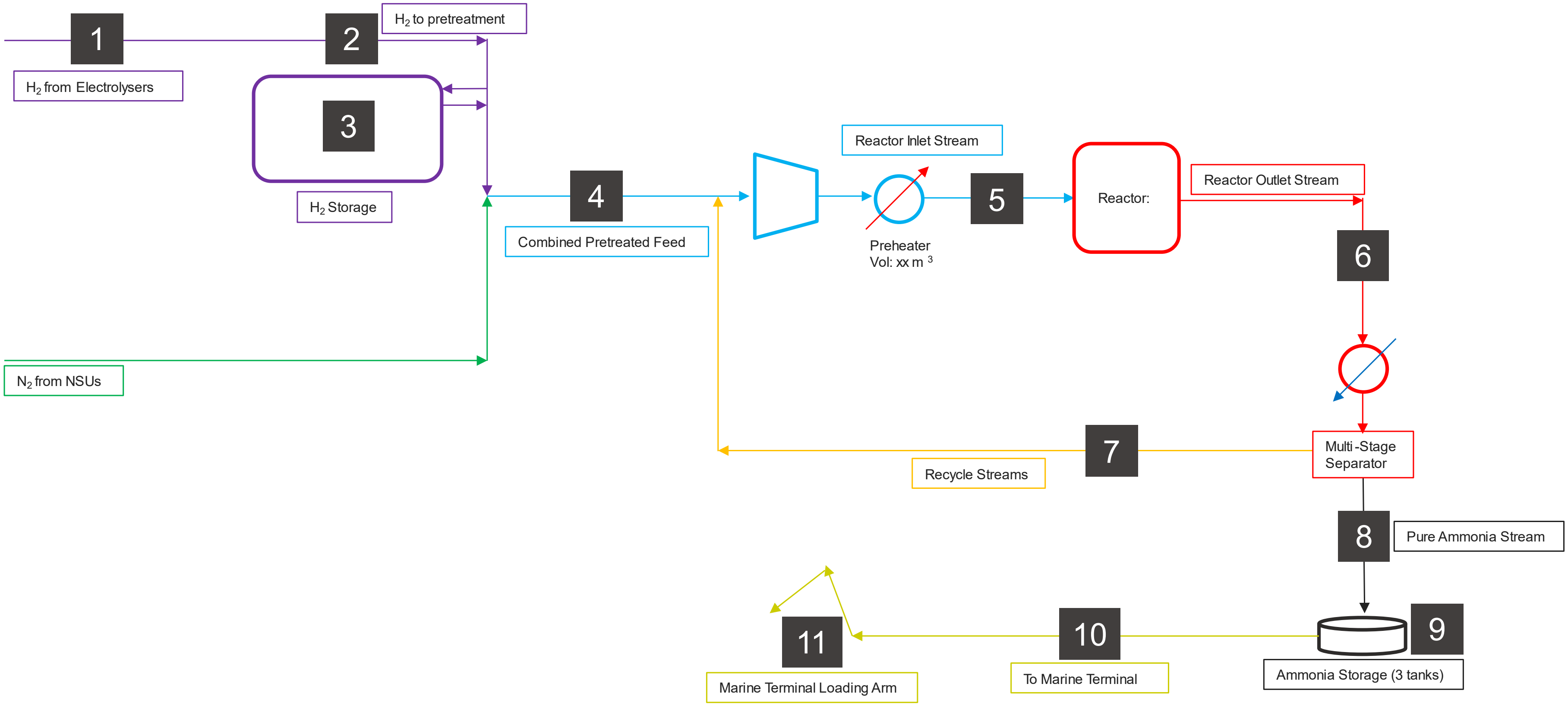


Figure 2.5 Release Scenario Locations (Single Process Train)

3.0 Hazard Identification

The primary hazards identified at the Facility are the flammability and toxicity of the substances handled. The potential hazardous events are summarized in Table 3.1.

Asphyxiation, due to displacement of oxygen, was identified. However, asphyxiation was not considered as the consequence extents were not expected to exceed flammability or toxicity.

Additionally, cold temperatures exposure was identified. While a release of pressurized gas could be initially quite cold due to rapid depressurization, the hazards associated with cold temperatures are not likely to extend offsite since the gas temperature would increase while the gas is mixed with ambient air, and so are not considered in this risk assessment

The specific hazardous events and an overview of potential effects are discussed in the following sections.

Table 3.1 Hazardous Event Summary

Hazardous Event	Cause	Consequence
Jet Fire	Immediate/Delayed ignition of hydrogen	Exposure to thermal radiation.
Flash Fire	Delayed ignition of the dispersing vapour cloud of hydrogen	Exposure to the travelling flame front and associated thermal radiation exposure.
Vapour Cloud Explosion	Significant structural congestion in the flammable region of the hydrogen vapour clouds, which causes flame speeds high enough to result in the formation of a pressure wave as the flame propagates through the flammable 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/Storage Vessel Explosion	An uncontrolled release of hydrogen gas fills the electrolyser enclosure and leads to an explosion of the process vessel. A sudden loss of containment from the hydrogen storage vessels.	Overpressure as a result of an explosion of the enclosure.
Toxic Vapour Cloud	Dispersion of an unignited cloud of ammonia, either from a gas release or from the volatilization of a liquid ammonia pool spill.	Toxic response to ammonia.

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 receptor.

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 Overview of the Relationship Between Thermal Radiation Intensity Exposure and Potential Effects

Radiation Intensity (kW/m^2)	**Representative 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. Thin steel insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure. Ignition of wood in the presence of flammable vapours.
25	Likely fatality for extended exposure and significant chance of fatality for instantaneous exposure. Spontaneous ignition of wood after long exposure. Unprotected steel will reach thermal stress temperature, potentially causing failures.
35	Cellulosic material will pilot ignite within one minute's exposure. Significant chance of fatality for people exposed instantaneously.
Note: Source: U.K. HSE (2013)	

Table 3.3 Burn Harm 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. The class of dispersion models typically used calculate time and ensemble average concentrations downwind of the release location. These models do not directly account for 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 and the variability about the time average 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 cause significant damage to buildings and structures, such as shattering of glass and structural failure, which can result in harm to the occupants. 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 process 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 Overview of the Relationship Between Overpressure and Potential 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 Process/Storage Vessel Explosion

A process/storage 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 or a catastrophic failure of a hydrogen storage vessel.

3.4 Toxic Vapour Cloud

Toxic vapour hazards from the Facility may occur due to the dispersion 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

3.5 Summary

Each component of the process may undergo an accidental loss of containment (referred to as a release scenario), which may result in a hazardous event (an event that puts individuals at risk of being exposed to a hazard). There are three potentially hazardous materials considered in this assessment: hydrogen gas, nitrogen gas, and ammonia (gas and liquid):

- **Hydrogen gas** will be produced from fresh water via the electrolysers, stored in vessels, and will be used directly in the reactors to produce ammonia. The primary hazard associated with an accidental release of hydrogen gas is due to its flammability and reactivity. The released gas could immediately ignite, forming a jet fire. Alternatively, the ignition could be delayed, leading to a potential flash fire, or delayed jet fire. Should the dispersing gas enter a congested area before ignition, a vapour cloud explosion could occur. Additionally, due to the storage and process pressures, a process/storage vessel explosion could occur.
- **Nitrogen gas** will be produced via the separation of air and is used 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. The conditions for asphyxiation and exposure to cold are expected to dissipate well within the property area, and so these hazards 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. Should ammonia be released as a gas, a toxic cloud may form. If ammonia is released as a liquid, a pool will form that releases toxic vapours into a cloud.

  Ammonia is also flammable and so presents an additional flammability hazard. However, the predicted toxic hazard extents are expected to cover a larger areas than the consequences of ammonia's flammability.

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 (release scenario), including the release temperature, the ratio of liquid to gas being released, and the release rate. Accidental release scenarios at the Facility may occur from failures of the ammonia storage vessels, hydrogen storage vessels, process vessels including the electrolysers, preheaters, reactors, or coolers, piping, valves, or other assets used and managed in the production process.

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

4.1.1 General Overview of Release Types

While detailed design of the Facility has not yet been completed, a review of the processes taking place at the Facility was completed to determine release scenarios (involving losses of containment) 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 10 minutes (ECCC 2020).

4.1.1.1 Hydrogen Production

Release scenarios related to hydrogen production included a hydrogen release from:

- The 3-inch diameter piping that connects the electrolyser to the hydrogen gas header.
- The 10-inch diameter header between the electrolysers and the reactor feed mixing (with nitrogen from the NSUs).

It was assumed that the electrolyser units would continue to produce hydrogen gas during a release. It was also assumed that isolation valves could be activated remotely after 15 minutes (900 seconds).

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.

The piping systems are also connected to 36 storage vessels that can store up to 20 tonnes of hydrogen gas (total). These vessels store hydrogen at pressures up to 1,000 bar(g), and could release hydrogen in the event of a rupture. The release scenarios considered were: a catastrophic rupture (emptying of the storage vessel in 10 minutes), a 50 mm rupture, 25 mm hole, 13 mm hole and a 6 mm leak. A vessel explosion due to a sudden loss of containment from the storage vessels was also considered.

In addition to releases from the electrolysers, storage vessels 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 release scenarios during ammonia production included:

- A release of hydrogen and nitrogen mixtures from the initial mixing 14-inch diameter piping.
- A release of hydrogen and nitrogen mixtures from the Haber-Bosch reactor inlet 16-inch diameter piping.
- A release of ammonia, hydrogen and nitrogen mixtures from the Haber-Bosch reactor outlet 16-inch diameter piping.

The initial mixing piping was modelled at a temperature of 40°C and 30 bar(g). The reactor inlet and outlet piping were modelled at a temperature of 450 °C, and at a pressure of 300 bar(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. The total flow rate for each reactor outlet was based on the total facility ammonia production rate of 4,950 tonnes/day (1,650 tonnes/day for each reactor).

It was assumed that the inlet and outlet piping associated with the reactor were not isolated from the reactor. As a result, a release from either the inlet or outlet piping would include gas from the reactor.

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. It was also assumed that isolation valves could be activated remotely after 15 minutes (900 seconds).

4.1.1.3 Ammonia Separation

The release scenarios during ammonia separation included releases of hydrogen and nitrogen from the recycle stream after the condenser from 24-inch piping.

The recycle stream conditions were assumed to be 40°C and 7.5 bar(g). 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. It was also assumed that isolation valves could be activated remotely after 15 minutes (900 seconds).

4.1.1.4 Ammonia Storage and Marine Terminal

Releases scenarios of pure liquid ammonia were considered from:

- the 6-inch diameter piping from the condensing unit to the storage system,
- an ammonia storage vessel,
- the 24-inch diameter piping from the storage vessels to the marine terminal, and
- the marine loading arm (assuming that all of the flow went to a single arm)

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 storage vessel 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. The marine loading arm was assumed to be able to be shutoff within 2 minutes of the release starting. Both the piping from the storage vessels to the marine terminal, and the marine loading arm, were only assumed to be active 30% of the time in the course of a year (during the loading of a shipping vessel).

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. It was also assumed that isolation valves could be activated remotely after 15 minutes (900 seconds).

For the ammonia storage vessel, releases considered were catastrophic (draining the storage vessel 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 are presented in Table 4.1. The release scenario locations in the table are consistent with the locations identified in Table 2.1. The release scenarios identified with each location are grouped by location.

The following sections discuss the hazard endpoints chosen for each hazardous event as a result of a release scenario.

Table 4.1 Potential Release Scenario Descriptions

Release Scenario Location	Scenario Description	Dimension (diameter for piping, volume for process/storage vessels)	Release Scenario	Release Description
1	Loss of containment within the electrolyzer, causing hydrogen gas to fill the enclosure.	100 vessel enclosures. 225 m^3 (per vessel enclosure)	1.1	Vessel explosion
	Loss of containment from the piping connecting each electrolyser to the main hydrogen header.	3-inch diameter (76.2 mm)	1.2	Guillotine Rupture
			1.3	Full Area Rupture
			1.4	25 mm Hole
			1.5	3 mm Leak
2	Loss of containment from the hydrogen gas header.	10-inch diameter (254 mm)	2.1	Guillotine Rupture
			2.2	Full Area Rupture
			2.3	85 mm Hole
			2.4	25 mm Hole
			2.5	4 mm Leak
3	Loss of containment from the hydrogen storage vessels.	36 storage vessels 12 m^3 (per vessel)	3.1	Vessel explosion
			3.2	Catastrophic Rupture (release in 10 minutes)
			3.3	50 mm Rupture
			3.4	25 mm Hole
			3.5	13 mm Hole
			3.6	6 mm Leak
4	Loss of containment from the hydrogen and nitrogen mixing piping.	14-inch diameter (356 mm)	4.1	Guillotine Rupture
			4.2	Full Area Rupture
			4.3	118.5 mm Rupture
			4.4	25 mm Hole
			4.5	4 mm Hole

Table 4.1 Potential Release Scenario Descriptions

Release Scenario Location	Scenario Description	Dimension (diameter for piping, volume for process/storage vessels)	Release Scenario	Release Description
5	Loss of containment from the reactor inlet piping.	16-inch diameter (406 mm)	5.1	Guillotine Rupture
			5.2	Full Area Rupture
			5.3	135.5 mm Rupture
			5.4	25 mm Hole
			5.5	4 mm Hole
6	Loss of containment from the reactor outlet piping.	16-inch diameter (406 mm)	6.1	Guillotine Rupture
			6.2	Full Area Rupture
			6.3	135.5 mm Rupture
			6.4	25 mm Hole
			6.5	4 mm Hole
7	Loss of containment from the recycle stream piping.	24-inch diameter (610 mm)	7.1	Guillotine Rupture
			7.2	Full Area Rupture
			7.3	203.2 mm Rupture
			7.4	25 mm Hole
			7.5	4 mm Hole
8	Loss of containment from the condensed ammonia piping.	6-inch diameter (152 mm)	8.1	Guillotine Rupture
			8.2	Full Area Rupture
			8.3	50.6 mm Rupture
			8.4	25 mm Hole
			8.5	4 mm Hole
9	Loss of containment from the ammonia storage vessel.	35,000 m^3 (per vessel)	9.1	Catastrophic Rupture (release in 10 minutes)
			9.2	1,000 mm Rupture
			9.3	300 mm Hole
10	Loss of containment from the marine terminal piping.	24-inch diameter (610 mm)	10.1	Guillotine Rupture
			10.2	Full Area Rupture
			10.3	203.2 mm Rupture
			10.4	25 mm Hole
			10.5	4 mm Hole
11	Loss of containment from the marine loading arm.	24-inch diameter (610 mm)	11.1	Guillotine Rupture
			11,2	Full Area Rupture
			11.3	203.2 mm Rupture
			11.4	25 mm Hole
			11.5	4 mm Hole

4.1.2 Flammable/Toxic Vapour Cloud Source Characterization

Source characterization modelling was completed to estimate the source properties occurring during the release scenarios involving hydrogen 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 were used to estimate the time-varying properties of the release, including the mass release rate, liquid mass fraction, source size and temperature. These source conditions in combination with the physical properties of the fluid (gas or liquid) are direct inputs used to predict the consequence extents of potential hazardous events that may result from an accidental release event.

The properties of the released fluid 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 4.2.

Table 4.2 Fluid Composition by Ammonia Production Process

Compound	Mole Fraction by Process Area					
	Hydrogen Production & Storage	Ammonia Production		Ammonia Separation		Ammonia Storage and Marine Export
		Reactor Inlet	Reactor Outlet	Recycle Stream	Liquid Ammonia Outlet	
H_2	1.00	0.67	0.618	0.67	0	0
N_2	0	0.33	0.215	0.33	0	0
NH_3	0	0	0.177	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 vapour and liquid phases are in thermodynamic equilibrium;
- The vapour and liquid phases are assumed to travel at the same velocity (i.e., there is no slip between the vapour and liquid phases); and,
- The fluid properties are estimated using the Peng-Robinson equation of state.

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

Depending on the source conditions during a release, the released fluid may rain-out or spill out forming a liquid pool in the vicinity of the release. In the event that pool formation is predicted, source conditions during a release were used as inputs to pool spill modeling to predict the spatial extents of the pool and the emission rate from the pool. The pool 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 vapours 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 level of turbulence over the pool, which is a strong function of the wind speed. However, other parameters, such as the ambient and substrate (ground) temperature, can have secondary effects on the evaporation rate.

The ambient temperature affects the rate of heat transfer to and from the pool and therefore 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 most of 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 or the hydrogen storage vessels.

For the electrolysers, 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.

For the hydrogen storage vessels, the high storage pressure (1,000 bar(g)) could create an overpressure wave if the container failed. This failure could result from vessel overfilling, or heating of the contents. Following the TNO Yellow Book, the energy involved in the explosion was estimated by considering the difference in internal energy between the pressurized fluid and ambient conditions (TNO, 2005).

4.2 Source Characterization 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 Production and Storage

The gas upstream of the reactor is composed of 100% hydrogen. The predicted release rates from the hydrogen header (Release Scenario Location 2) are shown in Figures B-1.

4.2.2 Ammonia Production

The gas upstream of the reactor is composed of 3:1 ratio of hydrogen to nitrogen. 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 (Release Scenario Locations 5 and 6) are shown in Figures B-2 and B-3, respectively.

4.2.3 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 vessel (Release Scenario Location 8) is shown in Figure B-4. The pool spill size with time is shown in Figure B-5. The evaporation rate from the pool is shown in Figure B-6.

4.2.4 Ammonia Storage and Shipping

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 vessels and the marine terminal (Release Scenario Location 10) are shown in Figure B-7. The time series of the pool spill effective radius is shown in Figure B-8. The evaporation rate from the pool is shown in Figure B-9.

The catastrophic release empties the storage vessel in approximately 600 seconds (10 minutes) and therefore has the largest flow rate. It was assumed that the ammonia vessels 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 vessel 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 vessels (Release Scenario Location 9) are shown in Figure B-10. The change in effective pool radius with time is shown in Figure B-11. The evaporation rate from the pool is shown in Figure B-12.

4.3 Consequence Modelling Methods

Consequence modelling estimates the physical effects of a hazardous event (as the result of a release scenario). The consequences associated with the release of a flammable fuel or toxic substance 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.

The following subsections describe the meteorological parameters that affect the consequence modelling, as well as describe how the individual hazardous events were modelled. Finally, the hazard endpoints of concern are described for each hazardous event.

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.
- Over land, 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). Over the ocean the formation of a stable temperature gradient is not restricted to nighttime hours. This stable gradient dampens vertical motion and results in a reduction in the level of turbulence.

Table 4.3 summarizes the combinations of atmospheric stability class and wind speed (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.

Table 4.3 Meteorological Conditions Used in the Consequence Modelling

Meteorology Code	Stability Class	Wind Speed		Description
		(m/s)	(kmph)	
A1.5	A	1.5	5.4	Over land typically occurs on warm, sunny days, late morning to mid-afternoon when the sun is at its peak. Unstable conditions are not restricted to daytime over the ocean
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 over land, slightly overcast
E5	E	5	18	
F2	F	2	7.2	Clear nights, over land, low to moderate wind speeds, Stable conditions are not restricted to night time over the ocean
F4	F	4	14.4	

Other meteorological factors for the dispersion modelling are as follows:

- An ambient temperature of 15°C was used.
- A relative humidity of 50%.
- A surface roughness of 90 cm.

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. For emergency response planning purposes, the LFL/2 is commonly used. ECCC considers the LFL concentration as the region within which fatalities, as a result of flame impingement, are possible (ECCC, 2020). This 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 common to estimate the chance of a fatality occurring based on the exposure to the toxic compound. 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). The consequence modelling was completed using the time varying behaviour of the release and the additional consideration of concentration fluctuations to estimate the toxic load.

The toxic load associated with exposure to a fluctuating concentration time-series can be defined by Equation 4.1 (U.K. HSE, 2010):

$$D = \int_{t=0}^{T} C^n dt$$ **Equation 4.1**

Where: *D* 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* (U.K. HSE, 2010)

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 (U.K. HSE, 2010):

$$\mathrm{Pr} = -35.9 + 1.85\ln(D)$$ **Equation 4.2**

Where *D* is the toxic load as defined in Equation 4.1.

The base case modelling will estimate the probability of fatality assuming that the affected individual is outdoors. This assumption will likely overstate the subsequent estimate of risk, as an offsite individual being indoors typically provide some additional protection from exposure. The probability of fatality can then be estimated using the following equation where the values of *a* and *b* are taken from Equation 4.2 as -35.9 and 1.85, respectively.

$$P(D) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{b\ln(D) + a - 5}{\sqrt{2}}\right)\right]$$ **Equation 4.3**

4.3.4.1 Indoor Receptor Concentrations

The indoor concentration was calculated to estimate the toxic load received by an individual sheltered indoors. A common and accepted approach to estimating indoor concentrations is to assume that the contaminated outdoor air enters a structure and mixes completely with the air inside the structure. This mixture is then assumed to leave at the same rate as the outdoor air that entered. This process can be represented as a stir tank reactor, in which the rate of indoor concentration changes can be derived from a mass balance expressed as,

$$\frac{dC_i}{dt} = a(C_o - C_i)$$ **Equation 4.4**

where,

C_i is the indoor concentration

C_o is the outdoor concentration

a is the number of building air changes in a specified unit of time

The average Alberta house has an air exchange rate of approximately 0.5 air changes per hour (ACH) (ERCB, 2010a), which is also reported generally by National Institute of Science and Technology (NIST, 1991). For public buildings, such as hospitals, a higher air change rate is expected. The value used in this assessment is 6 ACH, as provided by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE, 2017). The indoor concentration (C_i) was found by solving

Equation 4.4 numerically for a time-varying outdoor concentration (C_o), which was predicted with the SLAB model.

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:

$$D = \int_0^T I^{(4/3)}\, dt$$

Equation 4.5

where D is the dose (1 Thermal Dose Unit (TDU) = 1 $(\text{kW/m}^2)^{(4/3)}\text{s}$), 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 Equation 4.3 and assuming probit parameters of *a* = -14.9 and *b* = 2.56 (U.K. HSE, 2010).

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 Process/Storage Vessel Explosions

Process/storage 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 potentially impacting 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. For the hydrogen storage vessels, it was assumed that either an overfill or external fire impingement may result in a vessel burst scenario.

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.

For the hydrogen storage vessels, it was assumed that the pressure relief valves failed.

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

4.4 Consequence Modelling Results

A summary of the hazard endpoints of concern identified in the preceding sections is provided in Table 4.4. The extents to selected endpoint criteria (flammable extents, thermal radiation extents, overpressure consequences, and toxic exposure) are provided in the following list 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.

Table 4.4 Summary of Hazard Endpoints

Type of Hazardous Event	Hazard	Hazard Endpoints
Jet fire	Thermal Radiation	5 kW/m^2 (instantaneous)
		342 (kW/m^2)$^{4/3}$ s (TDU) (second degree burns)
Flash Fire	Potential for Ignition	Lower Flammability Limit, LFL
		50% of the LFL
Vapour Cloud Explosion/ Vessel Explosion	Overpressure	6.89 kPa
		25 kPa
Toxic Vapour Cloud	Inhalation of toxic substance	AEGL-2 Concentration (160 ppm – 1 hour)
		AEGL-3 Concentration (1,100 ppm – 1 hour)

The maximum distance to each hazard endpoint of concern is provided in Table 4.5 for each release scenario location considered (note, the maximum distance to each hazard endpoint of concern for each release scenario is provided in Appendix C). A summary of the results is provided below:

- **Hydrogen Production & Storage:** The maximum flammable and overpressure extents for these processes tended to occur during neutral or stable 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 head piping.

  Release scenarios involving the hydrogen gas header and hydrogen storage vessels could potentially extend offsite.

- **Ammonia Production:** The maximum extents for these processes tended to occur during neutral and stable atmospheric stability and moderate to high winds. The farthest thermal radiation extents occur with gas streams containing higher concentrations of hydrogen gas found in reactor inlet piping. For the reactor outlet stream, the hazard extents for inhalation of ammonia were the largest (despite only being 18% ammonia).

  Release scenarios involving ammonia gas releases from the reactor outlet piping could potentially extend offsite.

- **Ammonia Separation:** The maximum extents for this process tended to occur during neutral and stable atmospheric stability and moderate to high winds. The thermal radiation extents were similar to the reactor inlet stream (with a majority of hydrogen gas).

  Release scenarios involving liquid ammonia spills from the condensed ammonia piping could potentially extend offsite.

- **Ammonia Storage and Marine Terminal:** The hazard extents related to inhalation of ammonia tended to be largest for stable atmospheres and low to moderate windspeeds. The marine loading arm is fed from the same pipe as the shipping pipe from the ammonia storage vessels, however the reduced extents result from the shorter release duration, of two minutes.

  Release scenarios involving liquid ammonia spills from the ammonia storage vessels, marine terminal piping and marine loading arm could potentially extend offsite.

Table 4.5 Maximum Hazard Endpoint Extents for the Facility

			Maximum Distance to Hazard Endpoint (m)							
			Flammability		**Overpressure**		**Thermal Radiation**		**Inhalation**	
Process Location	**Release Scenario Location**	**Location Description**	**LFL**	**LFL/2**	**6.89 kPa**	**25 kPa**	**5 kW/m^2**	**342 TDU**	**AEGL-2**	**AEGL-3**
Hydrogen Production & Storage	1	Electrolyser	-	-	80	30	-	-	-	-
		Electrolyser Connection to Header	70	100	150	80	130	10	-	-
	2	Hydrogen Gas Header	230*	340*	440*	240*	400*	50	-	-
	3	Hydrogen Storage	220	350*	500*	250*	270*	70	-	-
Ammonia Production	4	Hydrogen and Nitrogen Mixing	60	140	150	70	90	10	-	-
	5	Reactor Inlet	70	120	230	110	230	10	-	-
	6	Reactor Outlet	70	100	230	110	220	10	480*	90
Ammonia Separation	7	Recycle Stream	130	290	320	160	180	10	-	-
Ammonia Storage & Marine Terminal	8	Condensed Ammonia Stream	-	-	-	-	-	-	2,730*	780*
	9	Ammonia Storage Vessel	-	-	-	-	-	-	20,000*,[1]	11,620*
	10	Marine Terminal Pipe	-	-	-	-	-	-	11,240*	2,990*
	11	Loading Arm	-	-	-	-	-	-	3,940*	1,100*

Note:

* refers to distances which may extend offsite (beyond the property boundary).

[1] Hazard endpoints were modelled to a maximum downwind distance of 20 km, to reflect the limits of meteorological persistence.

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 solely used to determine the acceptability of a facilities 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, if the consequences associated with uncontrolled releases are 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:

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

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 5.1 and Equation 5.2 can be used to estimate the individual risk for point sources (e.g., process/storage vessels) and line 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 5.1

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

Equation 5.2

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,
θ = 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 hazardous event (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.

Therefore, at a given point receptor (*R*), the individual risk is the sum of the risk contributions from each release scenario. The contributions of each release scenario are based on the failure frequency per year, which are described in Section 5.1.2.

5.1.1 Human Vulnerability

A summary of the thresholds for fatality used in the quantitative risk analysis are presented in Table 5.1. The probit equations (as defined in Section 4.3) relate the toxic or thermal load (how much of a toxic substance they have inhaled or how much thermal radiation they have been exposed to) to a probability of fatality (between 0 and 100%).

Table 5.1 Summary of Fatal Consequence Thresholds used for Quantitative Risk Analysis

Event Type	Fatality Threshold
Flash Fire	>LFL (100% Fatality)
Vapour Cloud Explosion/Process Vessel Explosions	>25 kPa overpressure (100% Fatality)
Fireball	Probit Equation[1]
Jet Fire	Probit Equation[1]
Ammonia Inhalation	Probit Equation[1]

Note:
[1] A probit equation defines the relationship between exposure and probability of fatality

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).

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
Hydrogen Storage	Catastrophic Release	6.00E-06	failures/yr	Hole sufficient to release the vessel contents within 10 minutes.
	Rupture	5.00E-06	failures/yr	50 mm Rupture
	Hole	5.00E-06	failures/yr	25 mm Hole
	Hole	1.00E-05	failures/yr	13 mm Hole
	Leak	4.00E-05	failures/yr	6 mm Leak
355.8 mm Piping (Mixing before reactor pre-treatment)	Guillotine Rupture	3.50E-08	failures/m/yr	(a)
	Full Rupture	3.50E-08	failures/m/yr	(b)
	Rupture	2.00E-07	failures/m/yr	118.6 mm Hole
	Hole	5.00E-07	failures/m/yr	25 mm Hole
	Leak	8.00E-07	failures/m/yr	4 mm Hole
406.4 mm Piping (Reacting Inlet, Reactor Outlet)	Guillotine Rupture	3.50E-08	failures/m/yr	(a)
	Full Rupture	3.50E-08	failures/m/yr	(b)
	Rupture	2.00E-07	failures/m/yr	118.6 mm Hole
	Hole	5.00E-07	failures/m/yr	25 mm Hole
	Leak	8.00E-07	failures/m/yr	4 mm Hole
609.6 mm Piping (Recycle Stream, 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
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

Table 5.2 Failure Frequencies used in the Quantitative Risk Analysis

Component	Failure	Frequency	Units	Additional Information
Ammonia Storage Vessel (Full Containment)	Catastrophic Release	5.00E-07	failures/yr	Hole sufficient to drain the vessel 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	Process Vessel Explosion	1.61E-05	failures/yr	
Hydrogen Storage Vessel	Storage Vessel Explosion	6.00E-06	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 outcomes following an accidental release. Figure 5.1 shows a simplified event tree template used in the current assessment for process/storage 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 event frequencies summarized in Table 5.2 to represent the total event likelihood.

Given that a release has occurred, the released fluid may ignite immediately or it may ignite at some time after the release starts (delayed ignition). For the fluids considered, delayed ignition may occur as the dispersing plume develops and encounters an ignition source. 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, it is recommended that the risk is defined using only the toxic hazard (TNO Purple Book, 2005).

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).

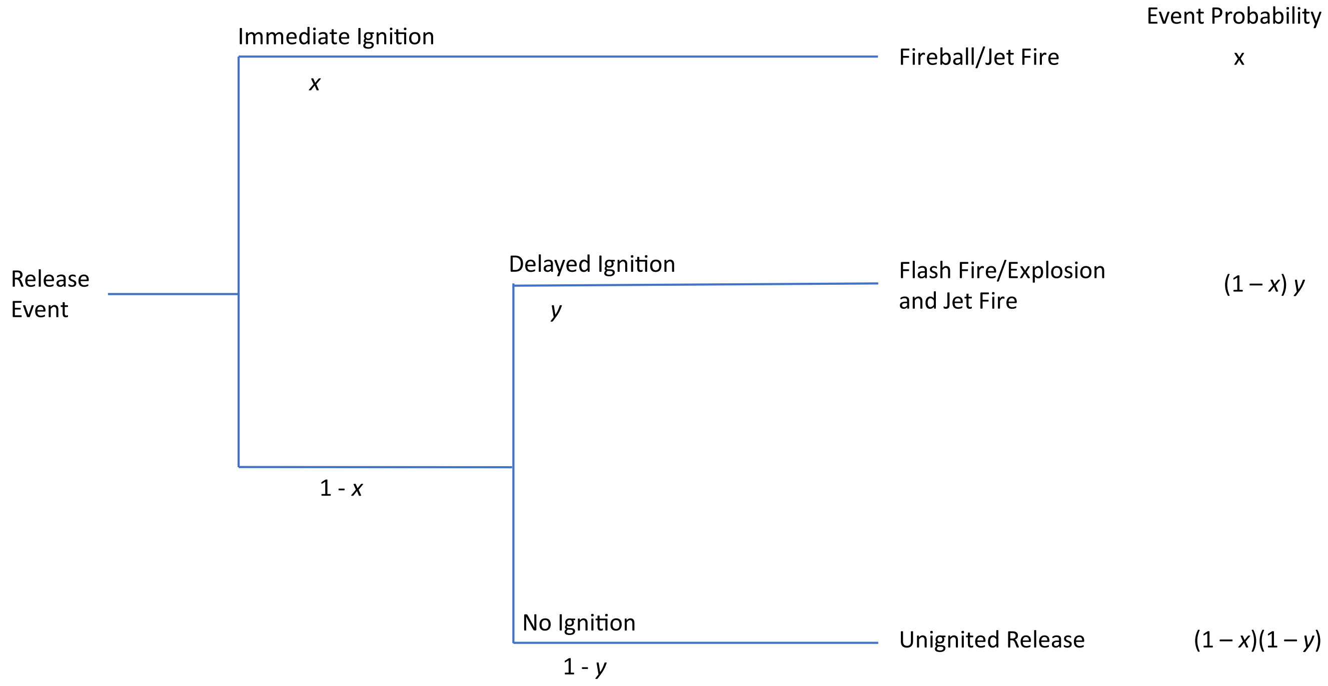


Figure 5.1 **Event Tree Template to Estimate the Conditional Event Probability**

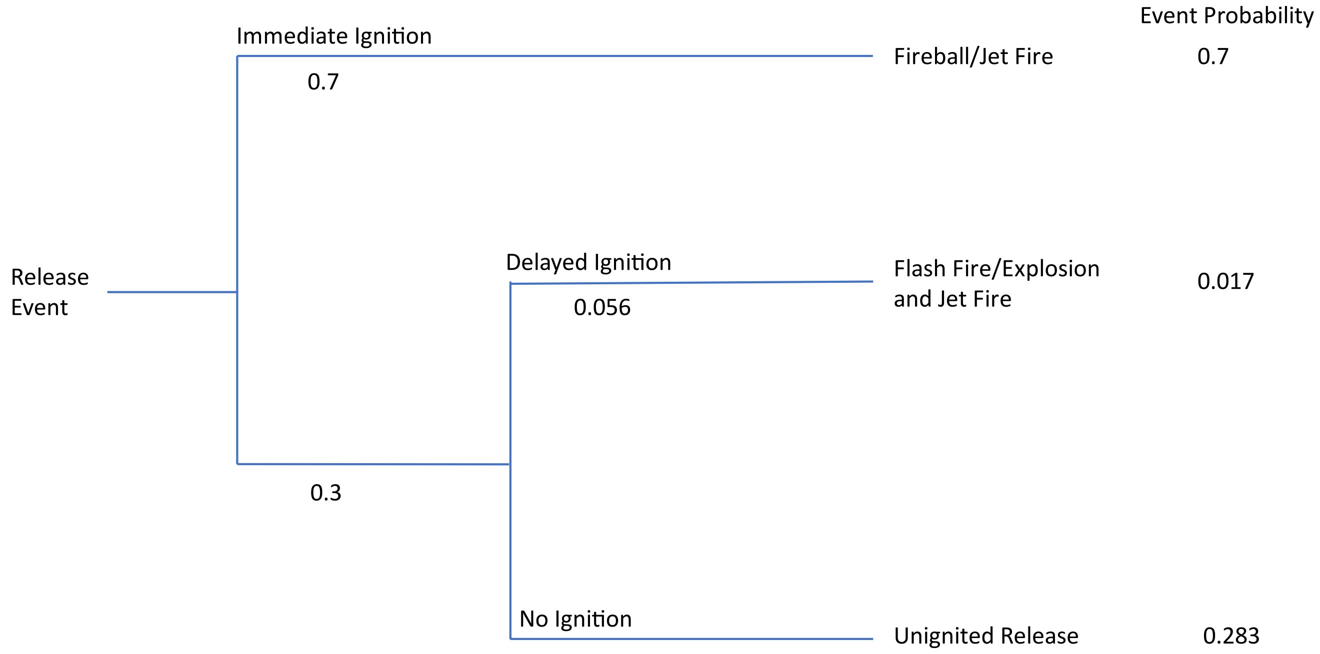


Figure 5.2 **Event Tree Example for Hydrogen Header Guillotine Rupture**

5.1.2.3 Additional Probabilities

Additional probabilities used in completing the assessment are:

- Probability of release orientation: piping and hydrogen storage vessel releases were assumed horizontal 100% of the time.
- Probability of release configuration: equal probability over the range of obstruction drags considered.
- Probability of receptor location:
  - Urban: 80% indoors, 20% outdoors (TNO, 1992)
  - Rural: 60% indoors, 40% outdoors (ERCB, 1993)

5.1.2.4 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.

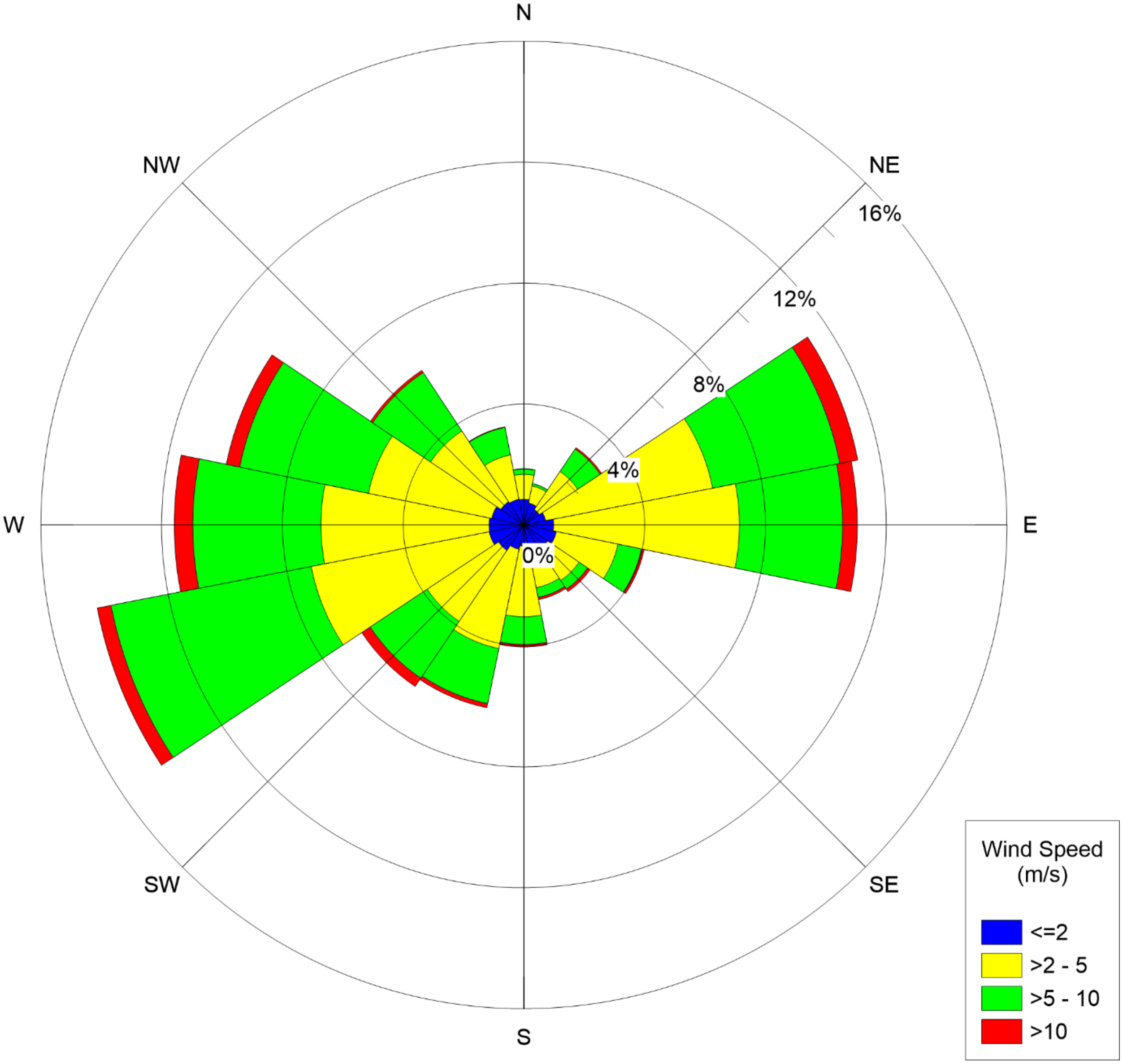
Meteorological Observation Site

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

The time series of windspeed and atmospheric stability class was used to calculate the frequency of atmospheric stability class and wind 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 Atmospheric Stability Class and Wind Conditions (Data from Lakes Environmental for 2020–- 2022)

Meteorology Code	Stability Class	Wind Speed (m/s)	Wind Speed (km/h)	Frequency of Occurrence
A1.5	A	1.5	5.4	0.02
B2	B	2	7.2	5.77
C2	C	2	7.2	4.83
C4	C	4	14.4	9.87
D2	D	2	7.2	5.34
D5	D	5	18	31.01
D10	D	10	36	13.62
E3	E	3	10.8	6.39
E5	E	5	18	4.25
F2	F	1.5	5.4	13.28
F4	F	3	10.8	5.62



Note: Direction is for "wind blowing from"

Figure 5.3 Wind Rose of the Project Site (Data from Lakes Environmental for 2020–-2022)

5.1.2.5 Knock-on (Domino) Effects

An accidental release from one portion of the facility could potentially trigger a release from another portion of the facility. For the purposes of this study, it was assumed that the facility’s final design will mitigate against knock-on effects.

5.1.3 Risk Acceptability Criteria

The Canadian Society for Chemical Engineering (CSChE) has developed risk exposure guidelines for land use planning purposes (Major Industrial Accidents Council of Canada, MIACC, 2008), and these guidelines were used for this quantitative risk analysis. 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. These recommendations define five zones, with associated recommended land use, based on the estimated individual risk:

- **Zone A** – No land use other than the risk source; an annual individual risk greater than 100 in a million
- **Zone B** – Manufacturing, warehouses, and open space (parkland and golf courses); an annual individual risk between 10 and 100 in million
- **Zone C** – Low-density residential and commercial; an annual individual risk between 1 and 10 in a million
- **Zone D** – High-density residential and commercial; an annual individual risk between 0.3 and 1 in a million
- **Zone E** – Unrestricted development, including sensitive institutions development such as hospitals and childcare; an annual individual risk less than 0.3 in a million.

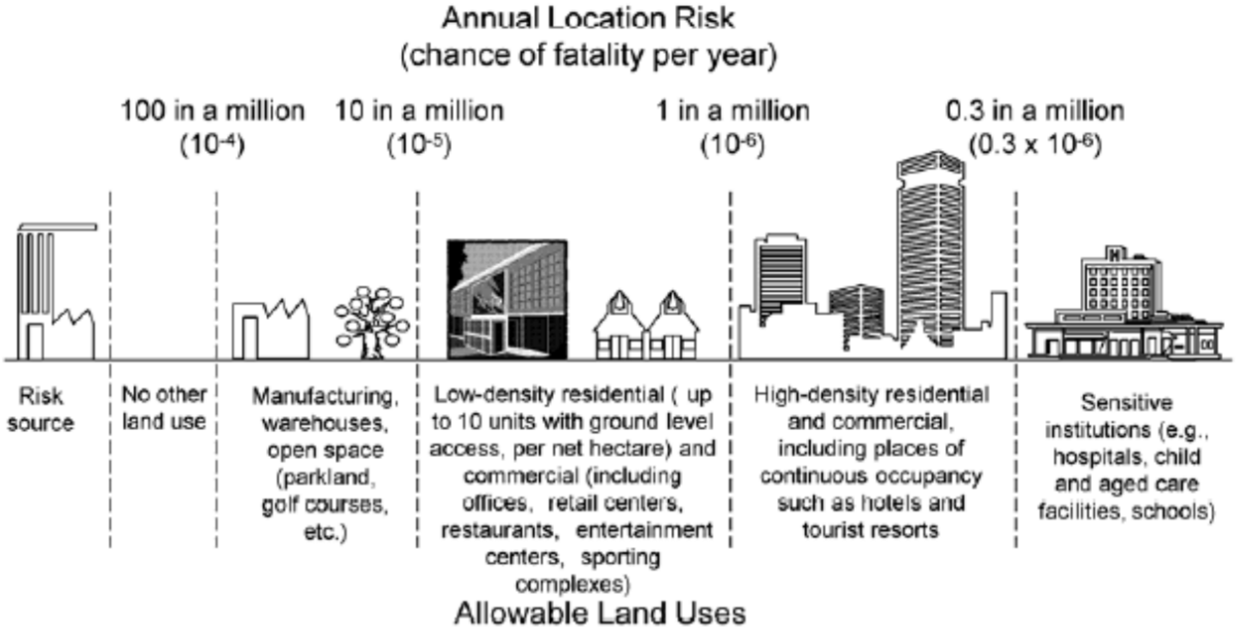


Figure 5.4 Individual Risk Exposure Guidelines used for Quantitative Risk Analysis (Source: Canadian Society for Chemical Engineering, 2008)

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. An additional risk criteria of 0.3 in 1,000,000 chance of fatality per annum is specified, within which sensitive institutions such as hospitals, schools, childcare centres, and nursing homes would not be considered acceptable land use. Sensitive institutions surrounding the facility are indicated in Figure 5.5. As indicated in Figure 2.1, the facility is surrounded by the communities of Stephenville, Little Port Harmon, and Stephenville Crossing.

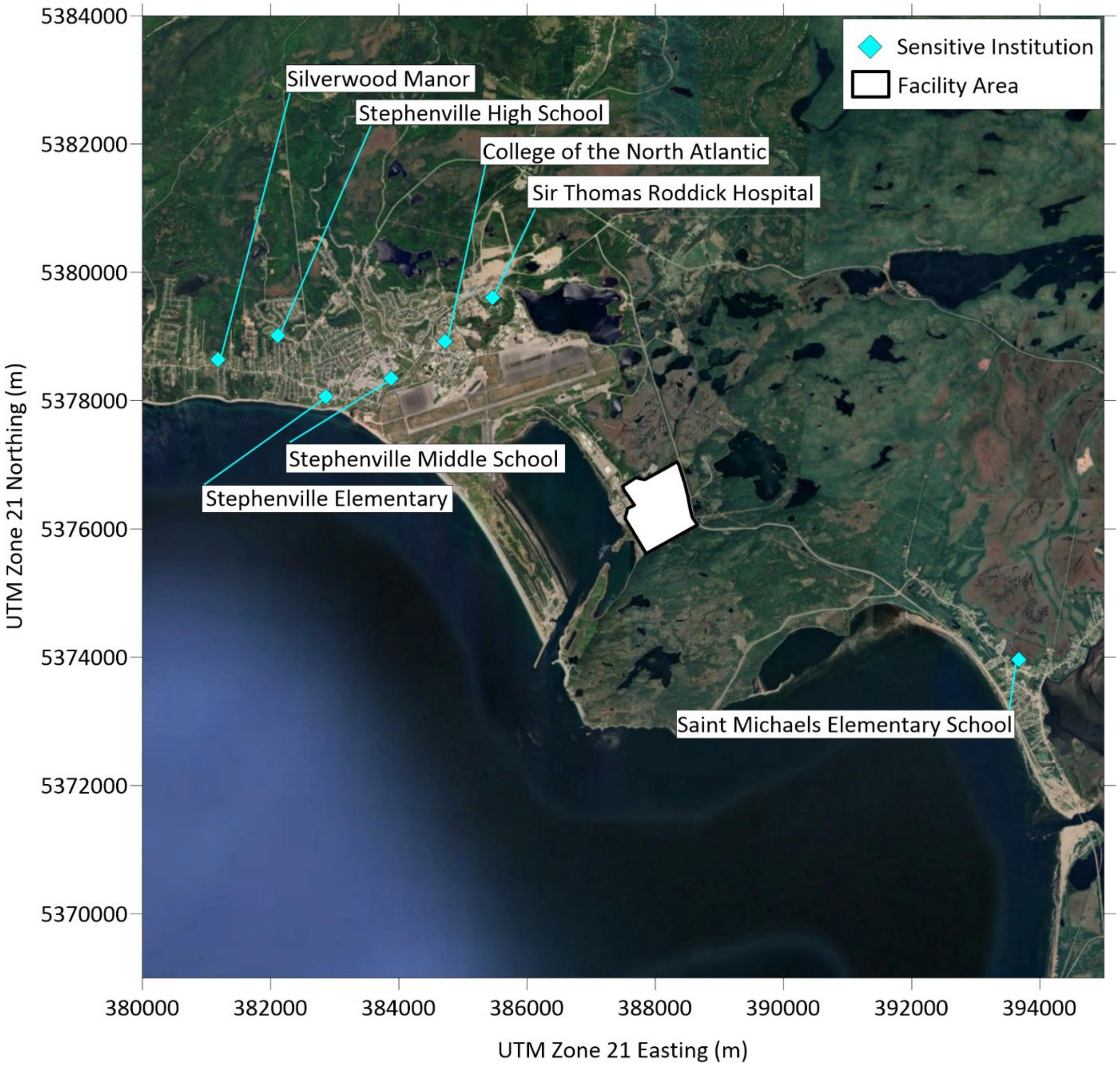


Figure 5.5 Project Location Relative to Sensitive Institutions

5.2 Quantitative Risk Assessment Results

Risk contour intervals shown in the following figures align with the Individual Risk land use planning Guidelines recommended by the Canadian Society for Chemical Engineering (CSChE). The most stringent threshold recommended by the CSChE is 0.3 chances in a million of a fatality (Zone E, no coloration). This guideline level represents an acceptable level of risk for vulnerable populations, such as schools, day care centres, hospitals, and long-term care facilities.

The risk calculations include the contribution of each release scenario by considering (following methodologies discussed in Section 5.1):

- The consequence modelling results summarized in Section 4.4 and Appendix C for the release scenarios summarized in Table 4.1,
- The failure frequencies (per year) for the various Facility assets as provided in Table 5.2, and
- The meteorological frequencies of occurrence for the Project location summarized in Table 5.3
- Indoor/Outdoor probabilities as discussed in Section 5.1.2.3.

These considerations are formed into risk estimates using either of Equation 5.1 or Equation 5.2, depending on the source type. The results are then summed over each release scenario to provide an estimate of individual risk at each receptor considered.

The results predicted are reflective of additional assumptions that may overstate the risk, including:

- There has been no communication with individuals or organizations related to the nature of the hazard and potential actions that can be taken in the event of the release (for example sheltering in place adjustment of a structures ventilation rates)
- No consideration for the "active" mitigation of the liquid pool release by facility personal, external first responders or automated physical processes.
- There is no consideration that individuals may be warned (callout system) or evacuated (if viable)

The individual risk is provided for the following:

- Sensitive institutional receptors
- Urban receptors
- Rural receptors

In addition to the indoor/outdoor probability assumption, the ACH is assumed to vary with receptor as discussed in Section 4.3.4.1. The sensitive institutional receptors are assumed to have an air exchange rate of 6 ACH, and the residential receptors are assumed to have an air exchange rate of 0.5 ACH.

The individual risk associated with sensitive institutional receptors is provided in Figure 5.6. The results presented indicate that the sensitive institutional receptors are located in Zone E, which allows this type of land use.

The individual risk associated with urban receptors is shown in Figure 5.7. The results presented indicate that urban receptors are located outside (further from the risk source) of Zone D which allow high density residential land use.

The individual risk associated with rural receptors is shown in Figure 5.8. The results presented indicate that there is a portion of Harmon Seaside Park within Zone C. Zone C supports continuous low density residential land (up to 10 units per net hectare). The unit density associated with Harmon Seaside Park is estimated to exceed 10 units per hectare but the occupancy is seasonal and has been stated to be about 41% of the year. With consideration of the seasonal nature of the occupancy and that the receptor (individual) is not at the park for 100% of the year, the receptor within Harmon Seaside Park with the largest predicted individual risk is below the Zone D threshold of 1.0 chances in a million of fatality per year. This indicates that, with consideration of the seasonal nature of its occupancy, the Harmon Seaside Park is appropriate land use at its current location.

The results shown in the three figures indicate that the revised land use imposed by the facility does not conflict with the existing land use in the area.

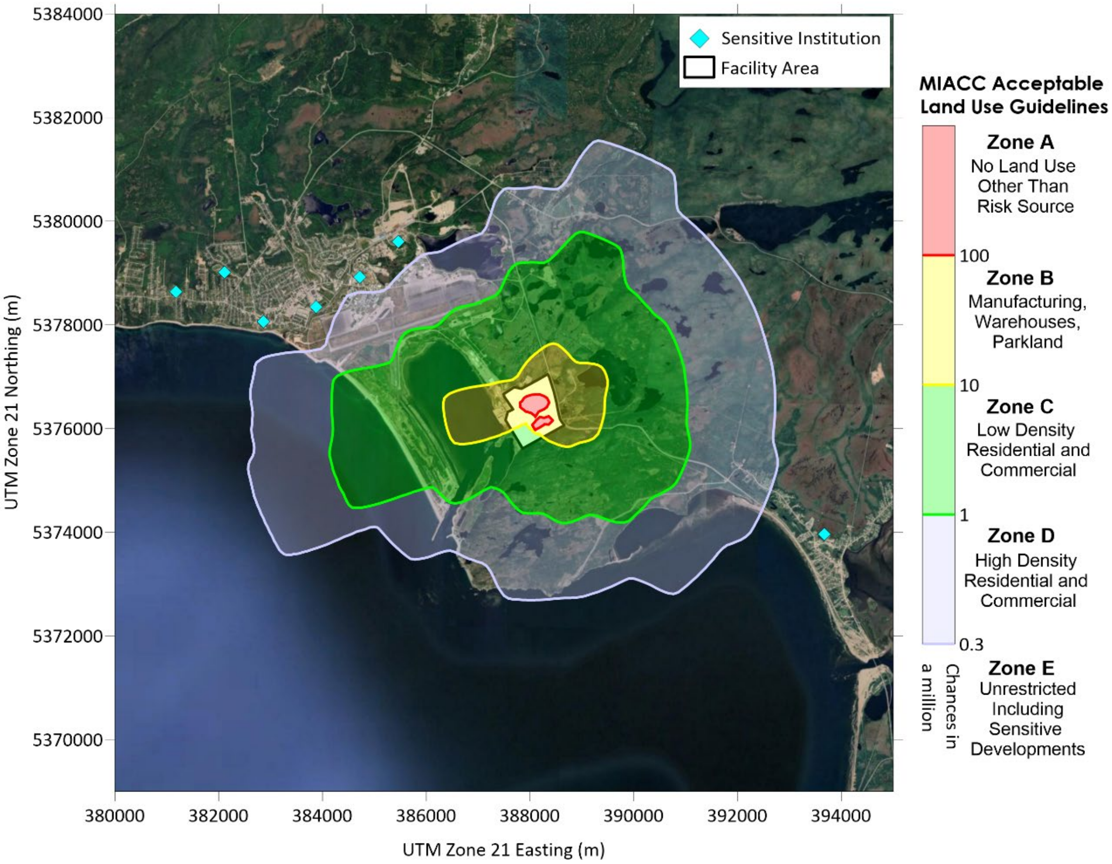


Figure 5.6 **Predicted Individual Fatality Risk Contours for the Project when Considering Sensitive Institutions (Individual is Outdoors 20% of the Time, 6 air changes per hour)**

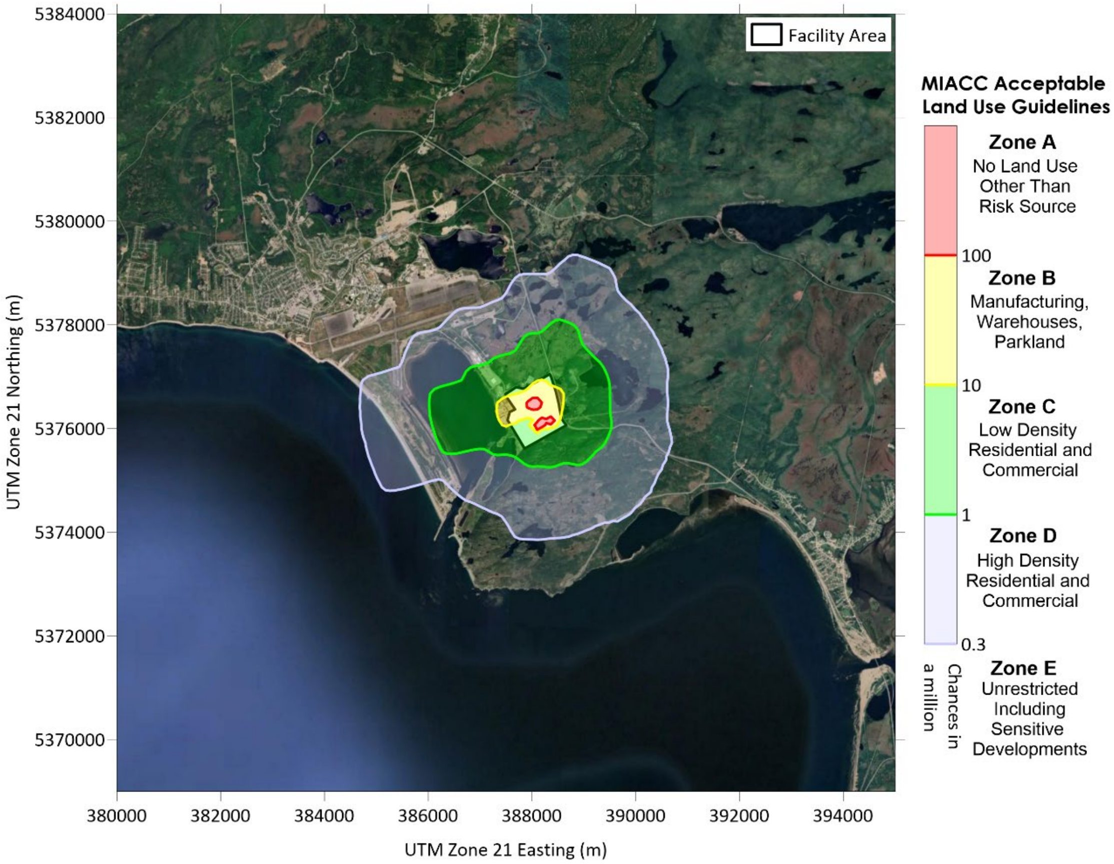


Figure 5.7 Predicted Individual Fatality Risk Contours for the Project when Considering Urban Areas (Individual is Outdoors 20% of the Time, 0.5 air changes per hour)

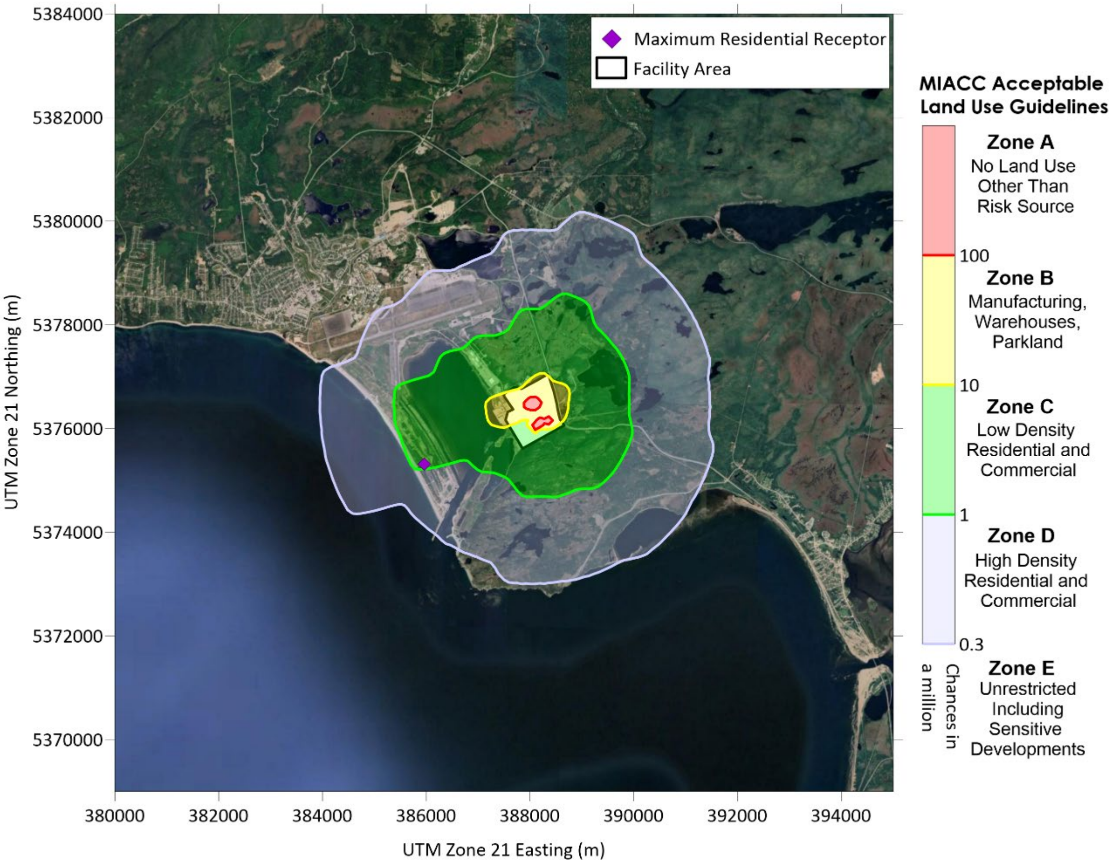


Figure 5.8 **Predicted Individual Fatality Risk Contours for the Project when Considering Rural Areas (Individual is Outdoors 40% of the Time, 0.5 air changes per hour)**

In review of the contributions to the individual risk, as provided above, releases of liquid ammonia from the storage vessels were found to be a large contributor. Passive mitigation measures that were considered in the risk modelling include:

- the storage tanks were considered "full containment" systems. This consists of a double wall tank where both the outer and inner tanks are designed to be fully capable of holding the ammonia without compromising structural integrity or release of vapor. A loss of contents would only occur in the highly unlikely event that both the outer and inner tank were breached simultaneously.
- tertiary containment in the form of a berm around the tanks, to prevent a liquid spill of ammonia from spreading.

The Facility will have the following additional mitigation measures, which will likely reduce the risk:

- security systems will be implemented to protect all plant components from hazards and to minimize the potential for accidental release.
- the inclusion of robust instrumented systems designed to detect any releases of ammonia or hydrogen and to initiate shutdown procedures to isolate and minimize the discharge while also providing indications to personnel of potential danger and prompting egress from the affected area. The intent is to detect and react to any release before it has the potential to adversely affect people or the environment.
- methodologies to address and react to any events that may occur. Most notably, those that would contain a release of ammonia and minimize the spread of vapors into the environment and surrounding communities. Ammonia vapors can be affectively contained by using water curtains produced by water monitors, sprinklers, foggers, or a combination of these. The ammonia vapors readily dissolve in the water and fall to earth where the water can be collected and treated. Additionally, liquid ammonia spills may be physically covered with tarps or other physical barriers to contain vapors while the liquid is collected for treatment.
- community response procedures will be put in place to inform the local community of any situations arising from the plant. These measures will be developed in conjunction with local emergency management organizations and could include shelter in place orders and evacuation procedures for responding to extreme situations.

It is the intent of the Nujio'qonik project to design, build, and operate a safe facility, detailed studies of potential mishaps and accidents will be studied. Further refinement of response and mitigation plans will be developed and coordinated with the local communities. Inclusion of these additional mitigation methods would likely reduce the risk associated with operation of the Facility.

6.0 Modelling Sensitivity and Uncertainty

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

- Uncertainty in emissions estimation;
- 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 there is uncertainty in the obstruction drag coefficient. As a result, this parameter 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 conjunction with associated frequencies.

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 (likely to be overstated) 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 the Nujio’qonik Ammonia Production Facility. The source modelling considered time varying releases from pressurized storage and facility piping (including the transport terminal piping). Consequence modelling considered the impacts of hazardous events as a result of release scenarios.

The release scenario locations were developed through a review of the processes associated with the facility and in discussions held with the WEGH2 team.

The primary hazards identified were the flammability and toxicity of the substances handled onsite. The flammable hazardous events considered included flash fires, jet fires, storage vessel explosions, enclosure explosions, and vapor cloud explosions. Toxic hazardous events considered included toxic cloud dispersion as a result of liquid ammonia spills evaporating. Release scenarios considered ranged from catastrophic ruptures (less likely) to 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 led to the farthest maximum extents due to the toxic inhalation hazard of the vapourizing and dispersing ammonia.

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. The risk results were used to determine if there were potential conflicts with existing land use around the facility. Three cases were considered (representing different receptor locations). Estimates of individual risk were provided for the following:

- Sensitive institutional receptors
- Urban receptors
- Rural receptors

Based on comparison against the CSChE land-use-planning guidelines it is predicted that sole consideration of the proposed Facility is not predicted to result in unacceptable land use in the lands adjacent to it.

In review of the contributions to the individual risk, as provided above, releases of liquid ammonia from the storage vessels were found to be a large contributor. Passive mitigation measures that were considered in the risk modelling include:

- the storage tanks were considered “full containment” systems.
- tertiary containment in the form of a berm around the tanks.

The Facility will have the following additional mitigation measures, which will likely reduce the risk:

- security systems will be implemented to protect all plant components from hazards and to minimize the potential for accidental release.
- the inclusion of robust instrumented systems designed to detect any releases of ammonia or hydrogen and to initiate shutdown procedures to isolate and minimize the discharge while also providing indications to personnel of potential danger and prompting egress from the affected area. The intent is to detect and react to any release before it has the potential to adversely affect people or the environment.
- methodologies to address reaction to any events that may occur. Most notably, those that would contain a release of ammonia and minimize the spread of vapors into the environment and surrounding communities. Ammonia vapors can be affectively contained by using water curtains produced by water monitors, sprinklers, foggers, or a combination of these. The ammonia vapors readily dissolve in the water and fall to earth where the water can be collected and treated. Additionally, liquid ammonia spills may be physically covered with tarps or other physical barriers to contain vapors while the liquid is collected for treatment.
- community response procedures will be put in place to inform the local community of any situations arising from the plant. These measures will be developed in conjunction with local emergency management organizations and could include shelter in place orders and evacuation procedures for responding to extreme situations.

It is the intent of the Nujio’qonik project to design, build, and operate a safe facility, detailed studies of potential mishaps and accidents will be studied. Further refinement of response and mitigation plans will be developed and coordinated with the local communities. Inclusion of these additional mitigation methods would likely reduce the risk associated with the Facility.

8.0 Closure

This report has been prepared for the sole benefit of World Energy GH2 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 World Energy GH2.

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

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.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	293
Fluid Pressure	Bar (g)	30 - 50
Fluid Temperature	°C	40
Pipe Diameter (Individual Electrolyzer)	Inches	3
Pipe Diameter (Electrolyzer Header)	Inches	10

Table A.2 Operating Conditions for Hydrogen and Nitrogen Supply Mixing

Operating Parameter	Unit of Measurement	Value (per train)
Nitrogen Flow Rate (from NSUs)	Tonnes per day	1,357
Hydrogen Flow Rate (from Electrolyzers)	Tonnes per day	293
Fluid Pressure	Bar (g)	30
Fluid Temperature	°C	40
Pipe Diameter	Inches	14

Table A.3 Operating Conditions for Hydrogen and Nitrogen Supply Process to Reactor

Operating Parameter	Unit of Measurement	Value (per train)
Nitrogen Flow Rate (from NSUs)	Tonnes per day	1,357
Nitrogen Flow Rate (from Recycle Stream)	Tonnes per day	3,166
Hydrogen Flow Rate (from Electrolyzers)	Tonnes per day	293
Hydrogen Flow Rate (from Recycle Stream)	Tonnes per day	684
Fluid Pressure	Bar (g)	300
Fluid Temperature	°C	450
Pipe Diameter	Inches	16

Table A.4 Operating Conditions for Ammonia Reactor Outlet Process

Operating Parameter	Unit of Measurement	Value (per train)
Nitrogen Flow Rate	Tonnes per day	3,166
Hydrogen Flow Rate	Tonnes per day	684
Ammonia Flow Rate	Tonnes per day	1,650
Fluid Pressure	Bar (g)	300
Fluid Temperature	°C	450
Pipe Diameter	Inches	16

Table A.5 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	3,166
Hydrogen Flow Rate	Tonnes per day	684
Fluid Pressure	Bar (g)	7.5
Fluid Temperature	°C	40
Pipe Diameter	Inches	24

Table A.6 Operating Conditions between Ammonia Condenser and Ammonia Storage

Operating Parameter	Unit of Measurement	Value (per train)
Ammonia Flow Rate	Tonnes per day	1,650
Fluid Pressure	Bar (g)	5.5
Fluid Temperature	°C	-32
Pipe Diameter	Inches	6

Table A.7 Ammonia Storage Vessel Operating Conditions

Operating Parameter	Unit of Measurement	Value (per train)
Ammonia Storage Capacity	Cubic metres	105,000 (35,000 per storage vessel)
Storage Pressure	Bar (g)	Ambient Pressure
Storage Temperature	°C	-34
Vessel Diameter	Metres	54
Vessel Height	Metres	18.288
Containment Berm Radius	Metres	114

Table A.8 Operating Conditions for Marine Export Pipeline

Operating Parameter	Unit of Measurement	Value (per train)
Ammonia Flow Rate	Cubic Metres per Hour	1,400
Fluid Pressure	Bar (g)	0.25
Fluid Temperature	°C	-34
Pipe Diameter	Inches	24

Appendix B

Time-Varying Source Characterization Results

Appendix B Time-Varying Source Characterization Results

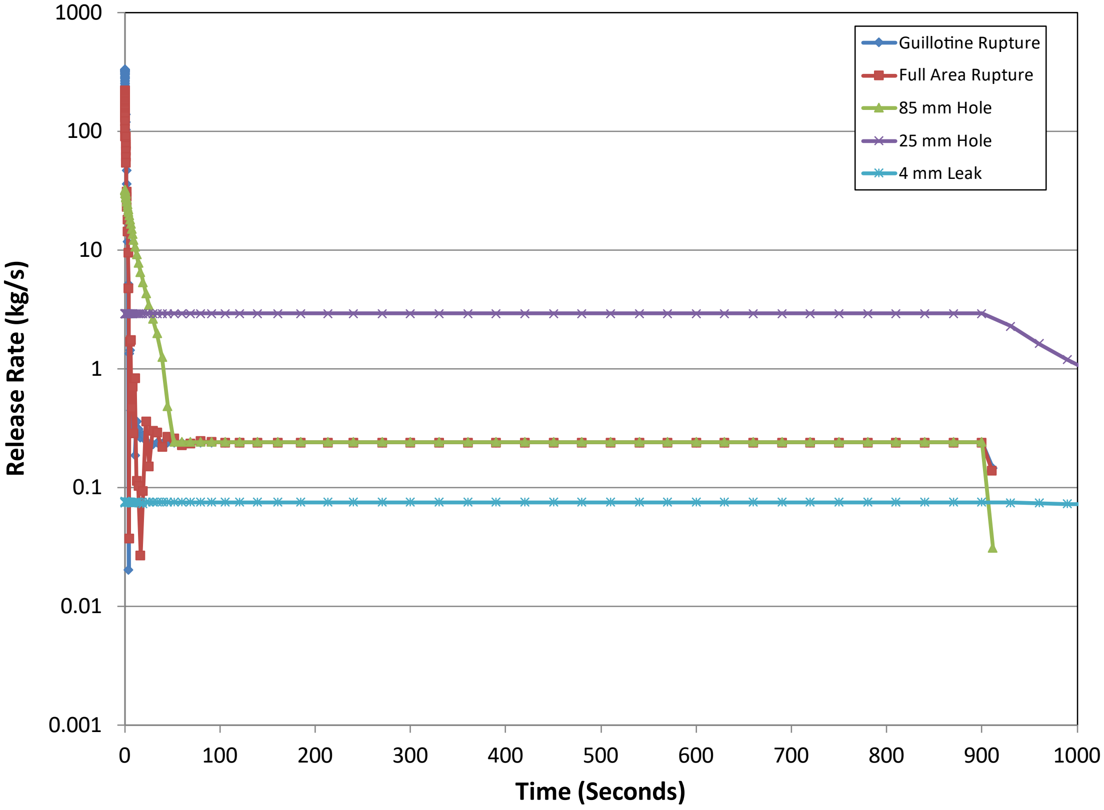

Figure B.1 Release Rate Time Series for the Hydrogen Header (Release Scenario Location 2) for Different Release Sizes

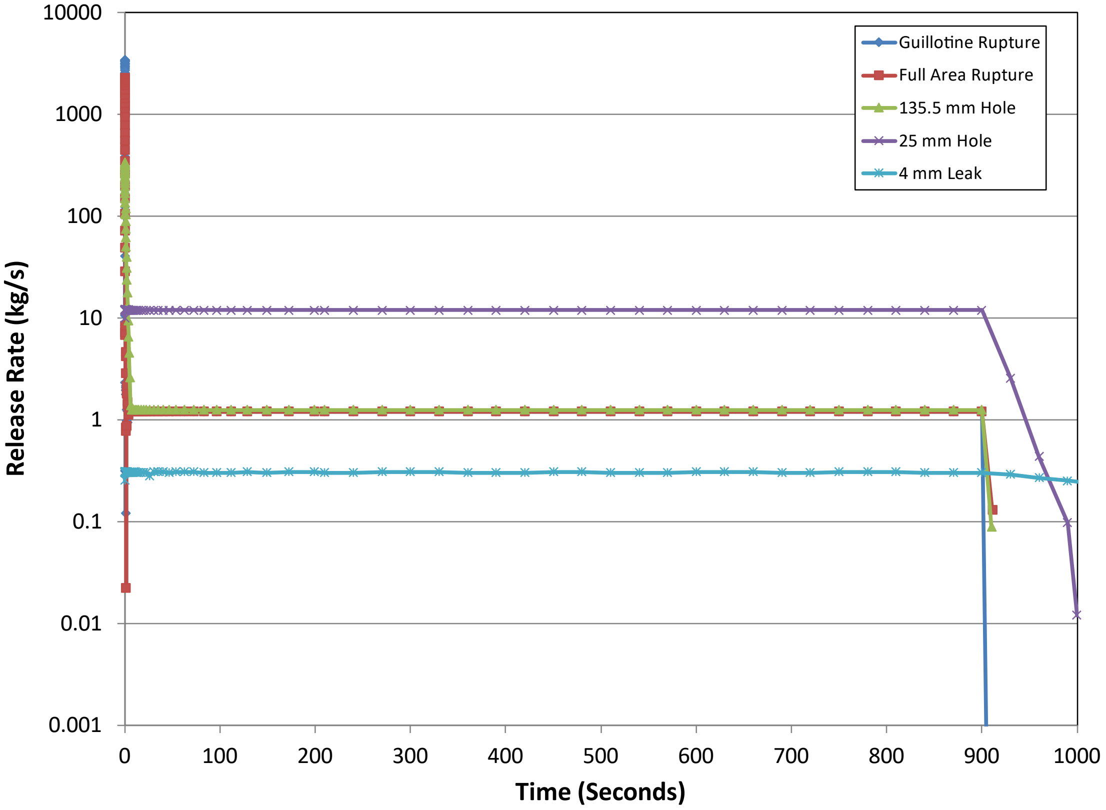

Figure B.2 **Release Rate Time Series for the Reactor Inlet (Release Scenario Location 5) for Different Release Sizes**

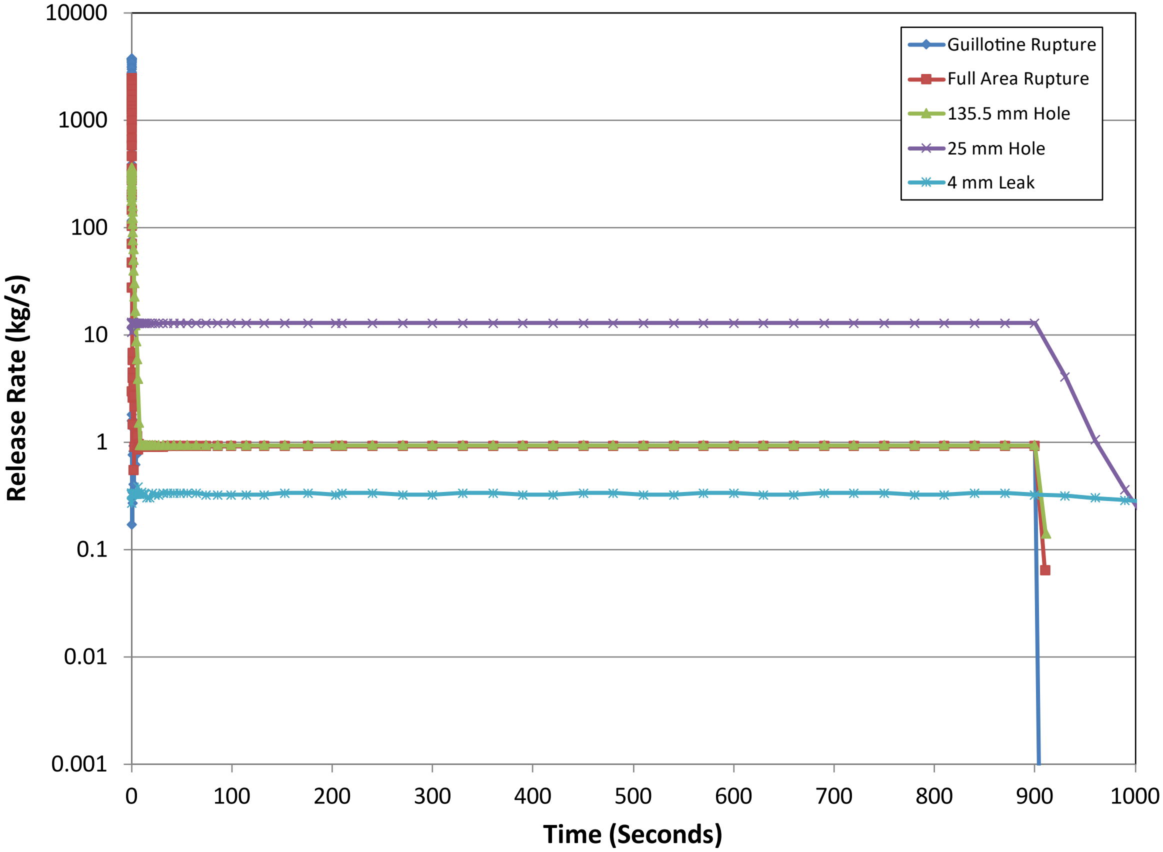

Figure B.3 **Release Rate Time Series for Process Gas from the Reactor (Release Scenario Location 6) for Different Release Sizes**

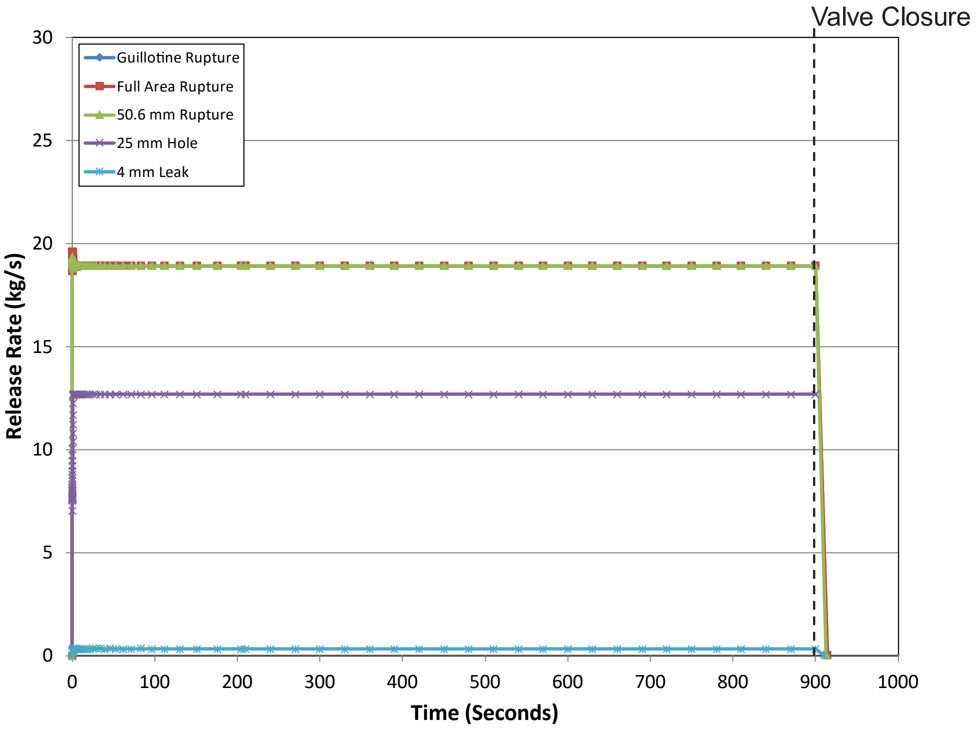

Figure B.4 Release Rate Time Series for Liquid Ammonia between Process Cooler and Ammonia Storage Vessel (Location 8)

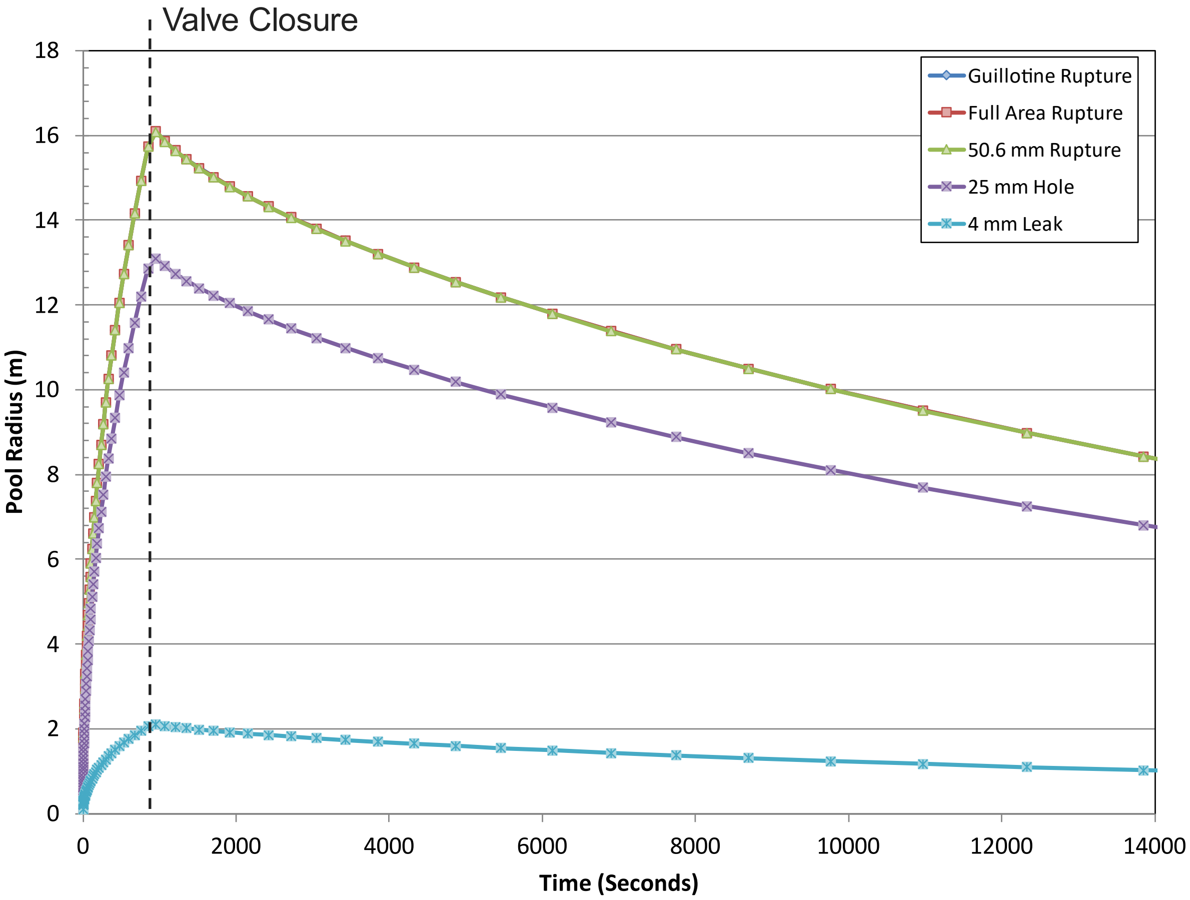

Figure B.5 **Pool Radius Time Series for Liquid Ammonia Spill from Pipe between Process Cooler and Ammonia Storage Vessel (Release Scenario Location 8)**

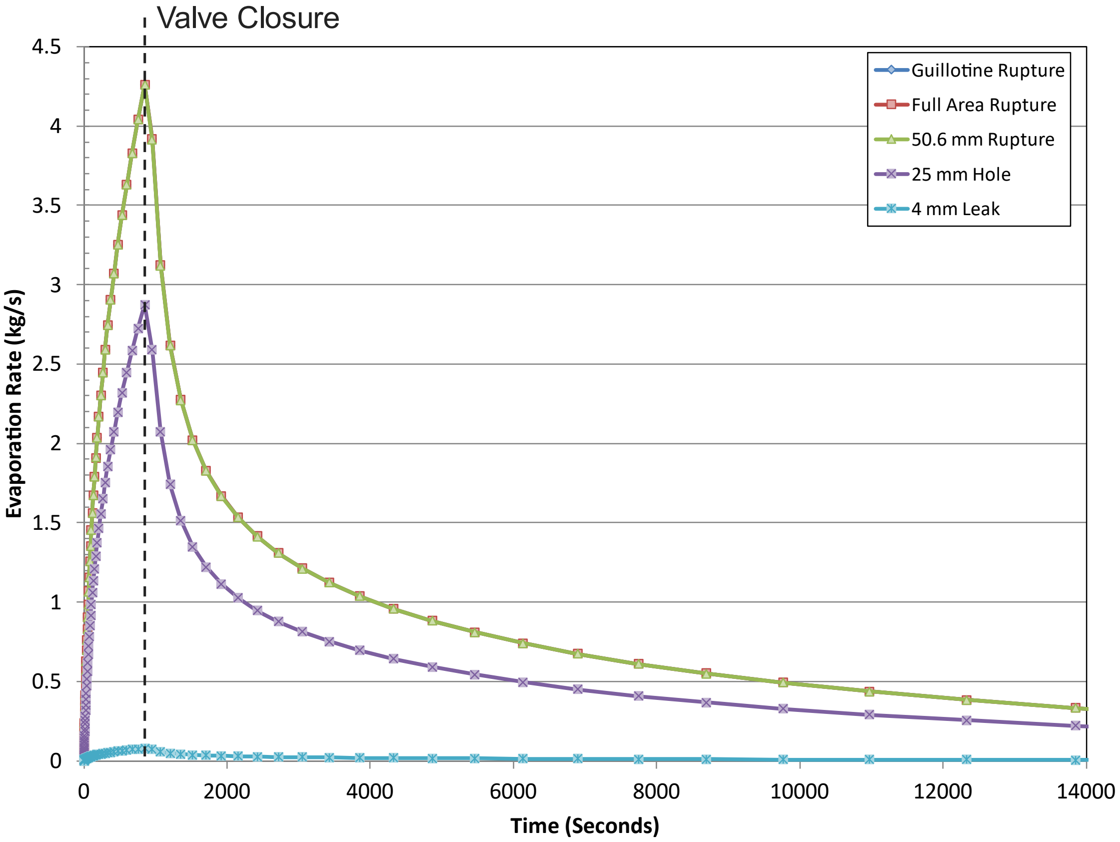

Figure B.6 Evaporation Rate from Ammonia Pool during Ammonia Release from Ammonia Separation Piping (Release Scenario Location 8)

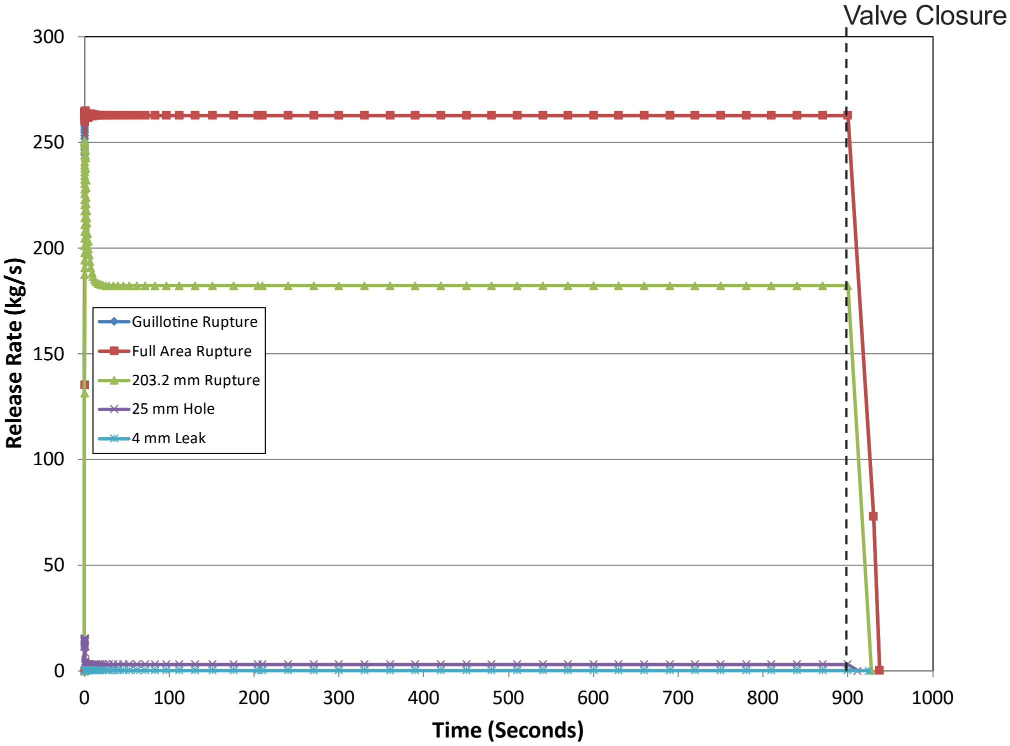

Figure B.7 **Release Rate Time Series for Liquid Ammonia between Ammonia Storage Vessel and Marine Terminal (Release Scenario Location 10)**

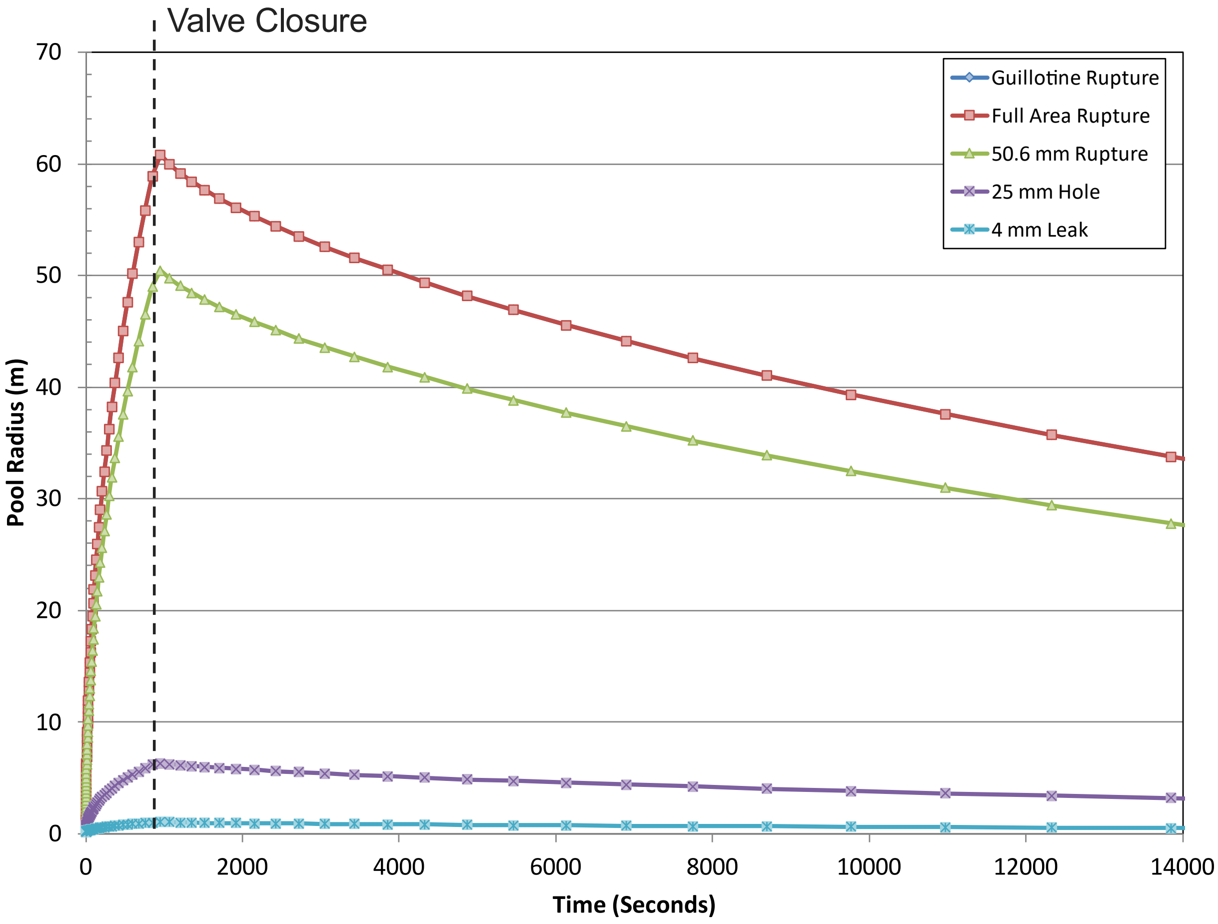

Figure B.8 **Pool Radius Time Series for Liquid Ammonia Spill from Pipe between Ammonia Storage Vessel and Marine Terminal (Release Scenario Location 10)**

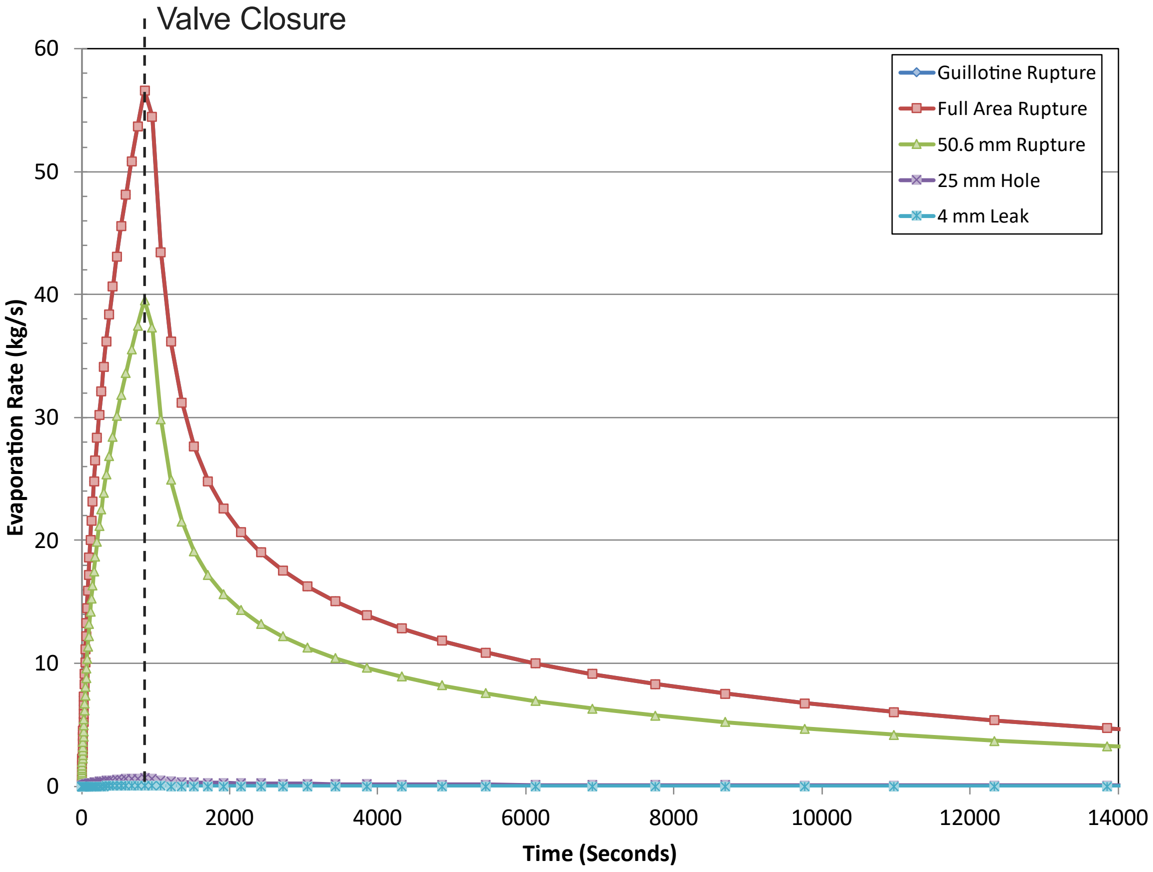

Figure B.9 Evaporation Rate from Ammonia Pool during Ammonia Release from Marine Terminal Piping (Release Scenario Location 10)

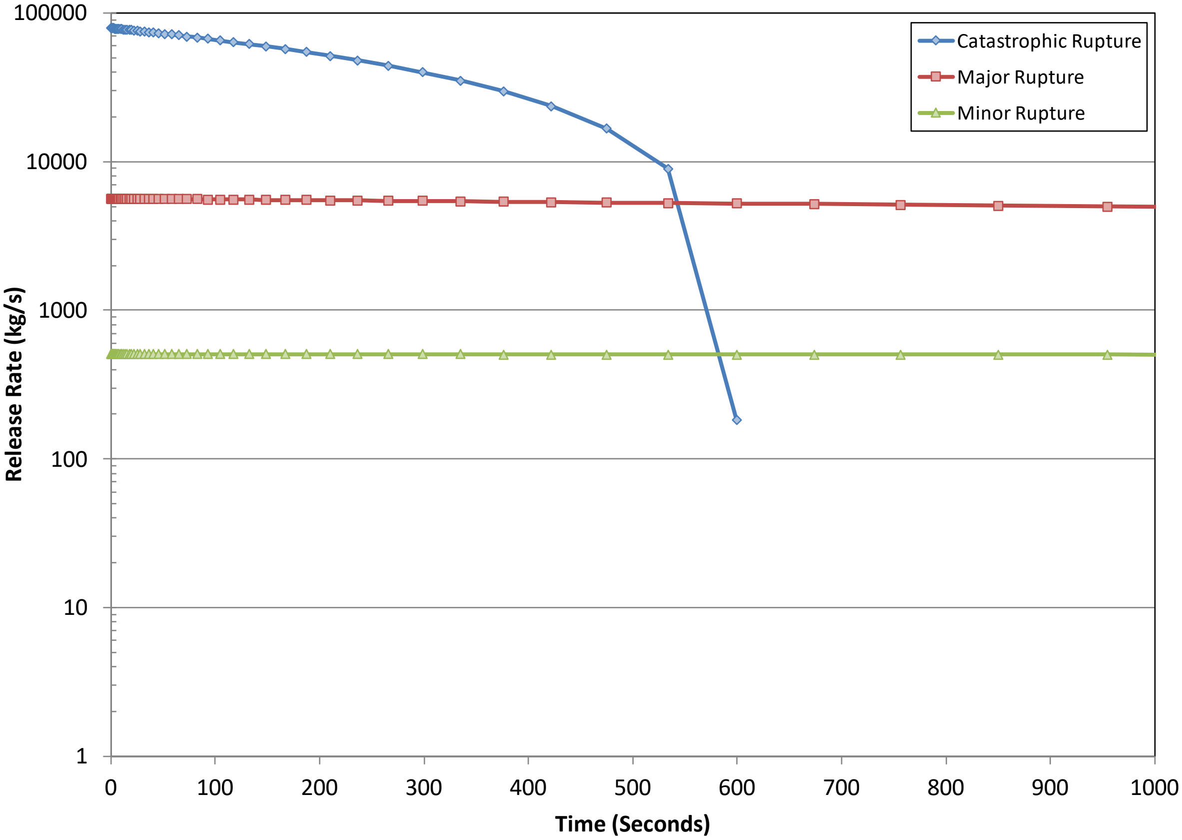

Figure B.10 **Mass Release Rates for Liquid Ammonia Spills from the Ammonia Storage Vessel (Release Scenario Location 9)**

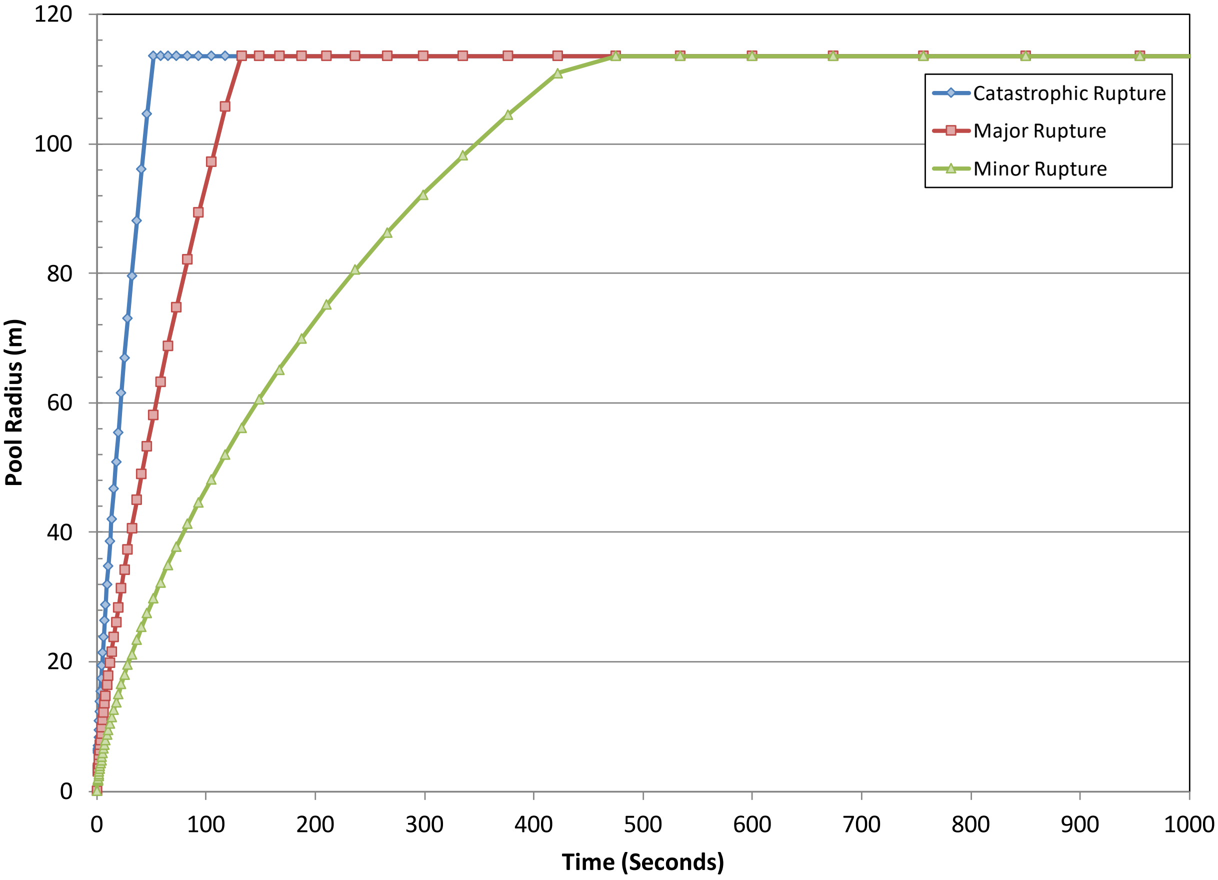

Figure B.11 Time Series of Ammonia Pool Spill Radius for Ammonia Storage Vessel Releases (Release Scenario Location 9)

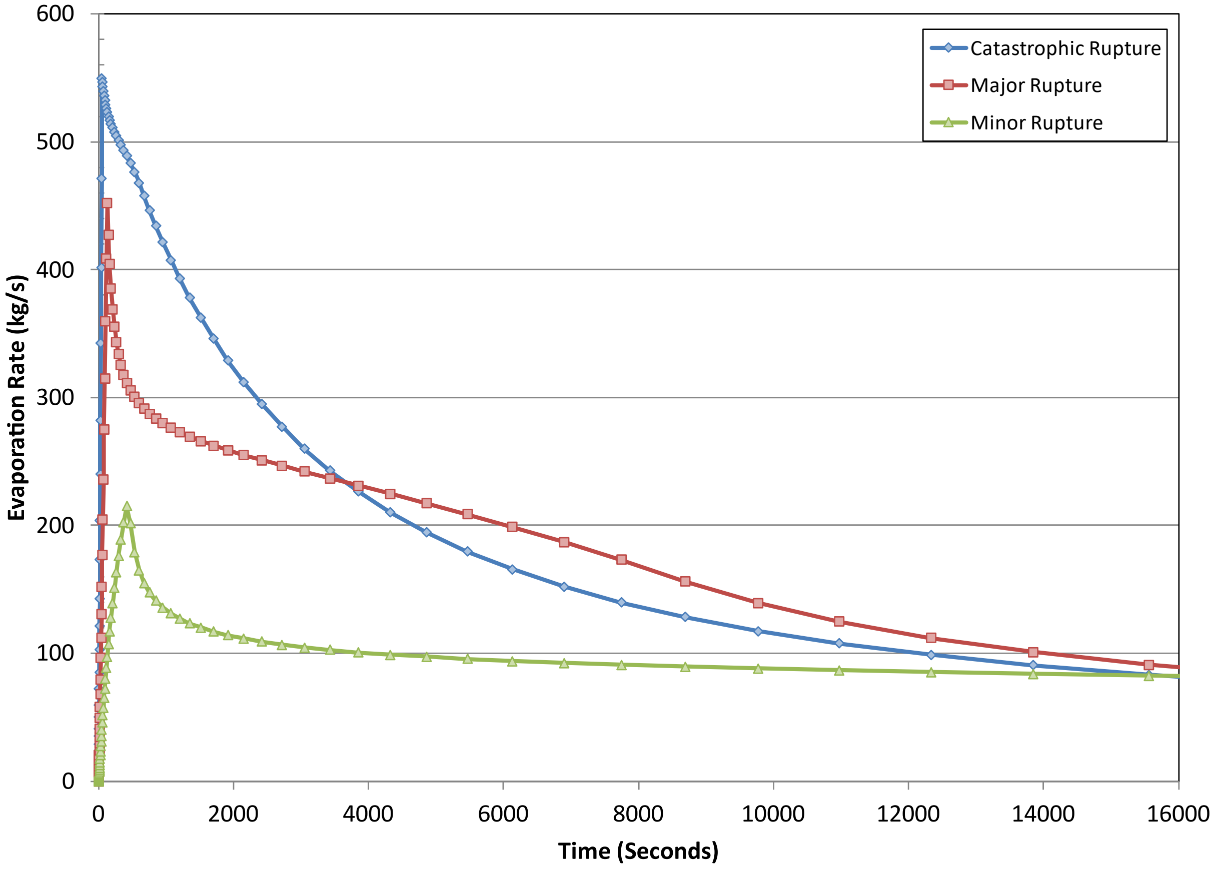

Figure B.12 Evaporation Rate from Ammonia Pool during an Ammonia Release from a Storage Vessel (Release Scenario Location 9)

Appendix C

Consequence Results Tables

Appendix C Consequence Results Tables

Table C.1 Maximum Downwind Extent to LFL for each Release Scenario

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	B2	C2	C4	D2	D5	D10	E3	E5	F2	F4
Hydrogen Production & Storage	Electrolyser Connection to Header	1.2	Guillotine Rupture	38	41	41	47	39	48	69	37	42	34	39
		1.3	Full Area Rupture	33	34	34	41	34	42	59	33	37	31	34
		1.4	25 mm Hole	34	38	39	47	38	58	69	39	48	36	42
		1.5	3 mm Leak	10	10	14	10	13	14	10	16	18	10	16
	Hydrogen Gas Header	2.1	Guillotine Rupture	111	113	113	128	112	133	213	114	126	108	121
		2.2	Full Area Rupture	97	101	102	116	99	119	179	101	112	96	107
		2.3	85 mm Rupture	77	79	79	136	79	176	226	86	149	79	89
		2.4	25 mm Hole	48	51	49	84	49	106	103	81	147	49	86
		2.5	4 mm Leak	13	15	15	15	16	19	15	20	24	14	20
	Hydrogen Storage Vessel	3.2	Catastrophic Release	131	134	136	148	134	158	201	139	157	141	156
		3.3	50 mm Rupture	114	117	117	132	116	156	219	121	137	119	134
		3.4	25 mm Hole	83	86	86	134	86	168	184	89	149	88	101
		3.5	13 mm Hole	59	62	62	117	62	124	123	68	123	61	69
		3.6	6 mm Leak	34	36	37	48	37	58	56	53	71	37	51

Table C.1 Maximum Downwind Extent to LFL for each Release Scenario

Process Location	**Location Description**	**Release Scenario**	**Release Description**	**Maximum Downwind Distance to Hazard Extent (m)**										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Production	Hydrogen and Nitrogen Mixing	4.1	Guillotine Rupture	29	29	29	39	27	53	39	49	43	26	27
		4.2	Full Area Rupture	28	28	29	37	29	52	39	49	43	28	29
		4.3	118.6 mm Rupture	38	39	41	44	39	48	56	42	57	37	63
		4.4	25 mm Hole	19	20	21	19	21	22	22	21	23	20	22
		4.5	4 mm Leak	0	0	0	0	0	0	0	0	0	0	0
	Reactor Inlet	5.1	Guillotine Rupture	39	43	46	48	39	43	52	41	37	36	37
		5.2	Full Area Rupture	47	49	51	54	46	51	54	41	43	42	43
		5.3	135.5 mm Rupture	51	52	52	59	52	62	73	52	57	51	57
		5.4	25 mm Hole	28	31	32	36	31	39	39	31	42	31	31
		5.5	4 mm Leak	5	5	5	7	5	7	7	5	7	5	5
	Reactor Outlet	6.1	Guillotine Rupture	42	51	51	42	46	43	49	39	48	39	49
		6.2	Full Area Rupture	52	52	53	53	51	52	56	43	48	43	49
		6.3	135.5 mm Rupture	51	53	53	59	52	62	73	53	57	51	56
		6.4	25 mm Hole	27	28	28	29	28	32	32	28	31	27	28
		6.5	4 mm Leak	5	5	5	5	5	5	5	4	5	4	4

Table C.1 Maximum Downwind Extent to LFL for each Release Scenario

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Separation	Recycle Stream	7.1	Guillotine Rupture	42	44	46	71	41	89	91	32	127	32	34
		7.2	Full Area Rupture	41	42	43	69	38	89	89	33	127	32	34
		7.3	203.2 mm Rupture	63	64	66	96	66	112	96	67	128	66	69
		7.4	25 mm Hole	10	10	12	10	12	12	10	12	13	12	12
		7.5	4 mm Leak	0	0	0	0	0	0	0	0	0	0	0

Table C.2 Maximum Downwind Extent to LFL/2 for each Release Scenario

Process Location	**Location Description**	**Release Scenario**	**Release Description**	**Maximum Downwind Distance to Hazard Extent (m)**										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Hydrogen Production & Storage	Electrolyser Connection to Header	1.2	Guillotine Rupture	51	53	54	63	53	64	**97**	52	59	48	56
		1.3	Full Area Rupture	43	44	46	56	46	58	**88**	46	53	42	49
		1.4	25 mm Hole	43	47	47	72	46	91	**103**	51	79	44	53
		1.5	3 mm Leak	15	16	23	18	27	23	18	34	34	22	**41**
	Hydrogen Gas Header	2.1	Guillotine Rupture	122	124	124	143	124	149	**317**	129	146	123	136
		2.2	Full Area Rupture	108	113	113	128	112	134	**276**	117	131	109	123
		2.3	85 mm Rupture	84	88	86	221	87	277	**341**	96	252	88	99
		2.4	25 mm Hole	54	81	91	144	91	187	168	152	**258**	56	196
		2.5	4 mm Leak	19	23	28	23	33	31	23	43	47	29	**51**
	Hydrogen Storage Vessel	3.2	Catastrophic Release	159	164	164	182	164	196	307	169	193	169	189
		3.3	50 mm Rupture	127	131	131	203	129	251	348	139	223	139	157
		3.4	25 mm Hole	94	97	97	224	97	277	299	133	261	103	154
		3.5	13 mm Hole	72	87	92	201	87	224	216	131	238	74	153
		3.6	6 mm Leak	48	63	77	88	76	109	99	116	143	48	127

Table C.2 Maximum Downwind Extent to LFL/2 for each Release Scenario

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Production	Hydrogen and Nitrogen Mixing	4.1	Guillotine Rupture	37	37	38	56	37	78	58	**91**	74	33	36
		4.2	Full Area Rupture	38	39	41	54	39	78	57	**91**	74	38	41
		4.3	118.6 mm Rupture	51	53	56	63	72	69	89	83	106	52	**141**
		4.4	25 mm Hole	31	32	38	37	44	46	39	47	44	32	**62**
		4.5	4 mm Leak	7	7	7	5	8	7	0	8	8	7	8
	Reactor Inlet	5.1	Guillotine Rupture	52	53	54	59	52	66	68	**73**	59	51	55
		5.2	Full Area Rupture	56	57	59	64	57	66	**79**	73	59	58	61
		5.3	135.5 mm Rupture	68	72	73	78	72	84	103	72	89	71	**118**
		5.4	25 mm Hole	51	52	53	81	53	96	84	54	**111**	52	56
		5.5	4 mm Leak	10	12	12	13	12	14	13	12	14	10	12
	Reactor Outlet	6.1	Guillotine Rupture	56	58	56	59	58	59	69	52	79	56	**93**
		6.2	Full Area Rupture	58	59	59	66	59	68	81	59	79	61	**93**
		6.3	135.5 mm Rupture	71	73	74	79	73	86	**103**	73	82	72	93
		6.4	25 mm Hole	43	44	46	67	46	76	69	46	**86**	44	48
		6.5	4 mm Leak	10	10	12	10	12	12	10	10	12	10	10

Table C.2 Maximum Downwind Extent to LFL/2 for each Release Scenario

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Separation	Recycle Stream	7.1	Guillotine Rupture	58	61	61	113	56	146	138	44	213	44	48
		7.2	Full Area Rupture	53	54	57	113	52	146	138	47	213	46	51
		7.3	203.2 mm Rupture	96	99	99	188	99	224	188	103	286	96	107
		7.4	25 mm Hole	18	19	19	21	21	24	21	21	29	19	26
		7.5	4 mm Leak	7	5	9	4	10	0	0	5	0	0	5

Table C.3 Maximum Downwind Distance to Thermal Radiation Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)	
				5 kW/m^2	342 (kW/m^2)$^{3/4}$ (TDU)
Hydrogen Production & Storage	Electrolyser Connection to Header	1.2	Guillotine Rupture	129	8
		1.3	Full Area Rupture	60	7
		1.4	25 mm Hole	39	2
		1.5	3 mm Leak	5	0
	Hydrogen Gas Header	2.1	Guillotine Rupture	398	47
		2.2	Full Area Rupture	189	40
		2.3	85 mm Rupture	124	24
		2.4	25 mm Hole	41	5
		2.5	4 mm Leak	7	0
	Hydrogen Storage Vessel	3.2	Catastrophic Release	267	66
		3.3	50 mm Rupture	199	44
		3.4	25 mm Hole	117	22
		3.5	13 mm Hole	64	9
		3.6	6 mm Leak	30	2
Ammonia Production	Hydrogen and Nitrogen Mixing	4.1	Guillotine Rupture	78	5
		4.2	Full Area Rupture	93	5
		4.3	118.6 mm Rupture	65	6
		4.4	25 mm Hole	16	1
		4.5	4 mm Leak	3	0
	Reactor Inlet	5.1	Guillotine Rupture	129	10
		5.2	Full Area Rupture	232	12
		5.3	135.5 mm Rupture	165	14
		5.4	25 mm Hole	38	4
		5.5	4 mm Leak	7	0

Table C.3 Maximum Downwind Distance to Thermal Radiation Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)	
				5 kW/m^2	342 (kW/m^2)$^{3/4}$ (TDU)
Ammonia Production (cont'd)	Reactor Outlet	6.1	Guillotine Rupture	192	9
		6.2	Full Area Rupture	218	9
		6.3	135.5 mm Rupture	144	11
		6.4	25 mm Hole	33	3
		6.5	4 mm Leak	6	0
Ammonia Separation	Recycle Stream	7.1	Guillotine Rupture	175	11
		7.2	Full Area Rupture	128	9
		7.3	203.2 mm Rupture	57	10
		7.4	25 mm Hole	8	0
		7.5	4 mm Leak	1	0

Table C.4 Maximum Downwind Distance to 6.89 kPa Overpressure Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	B2	C2	C4	D2	D5	D10	E3	E5	F2	F4
Hydrogen Production & Storage	Electrolyser	1.1	Vessel Explosion	77										
	Electrolyser Connection to Header	1.2	Guillotine Rupture	137	139	141	142	139	144	149	141	142	137	141
		1.3	Full Area Rupture	126	124	127	128	126	129	133	127	127	122	126
		1.4	25 mm Hole	134	136	138	141	136	147	149	134	143	133	137
		1.5	3 mm Leak	42	43	47	39	46	43	34	46	51	44	48
	Hydrogen Gas Header	2.1	Guillotine Rupture	366	374	377	386	377	389	417	372	379	374	382
		2.2	Full Area Rupture	344	344	349	356	349	367	387	342	349	343	351
		2.3	85 mm Rupture	328	332	329	369	329	406	444	328	356	324	336
		2.4	25 mm Hole	216	217	217	271	216	289	239	217	336	214	219
		2.5	4 mm Leak	54	56	56	51	59	56	46	59	67	58	67
	Hydrogen Storage Vessel	3.2	Catastrophic Release	452	454	457	466	457	472	497	454	467	457	472
		3.3	50 mm Rupture	416	418	421	432	419	434	494	416	429	417	428
		3.4	25 mm Hole	333	331	331	371	331	407	422	331	347	332	341
		3.5	13 mm Hole	244	244	244	327	243	328	293	242	307	242	243
		3.6	6 mm Leak	149	159	151	177	148	187	153	146	198	146	146
		3.1	Vessel Explosion	75										

Table C.4 Maximum Downwind Distance to 6.89 kPa Overpressure Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Production	Hydrogen and Nitrogen Mixing	4.1	Guillotine Rupture	91	107	93	111	83	129	97	149	132	87	97
		4.2	Full Area Rupture	94	109	93	112	86	128	97	149	132	86	98
		4.3	118.6 mm Rupture	147	149	152	148	149	141	146	143	137	139	143
		4.4	25 mm Hole	78	76	78	69	78	72	64	77	76	77	77
		4.5	4 mm Leak	1	1	1	1	1	1	1	1	1	1	1
	Reactor Inlet	5.1	Guillotine Rupture	76	93	79	116	68	109	81	129	113	76	82
		5.2	Full Area Rupture	77	94	79	94	69	108	79	129	112	74	73
		5.3	135.5 mm Rupture	214	216	217	221	217	222	229	214	218	216	219
		5.4	25 mm Hole	154	153	151	146	148	146	132	142	147	139	137
		5.5	4 mm Leak	24	24	24	24	24	24	23	23	23	23	23
	Reactor Outlet	6.1	Guillotine Rupture	73	81	88	74	97	83	64	102	119	71	123
		6.2	Full Area Rupture	69	79	88	76	96	84	73	102	107	76	123
		6.3	135.5 mm Rupture	214	217	217	221	217	224	229	216	218	217	221
		6.4	25 mm Hole	138	133	128	119	129	119	109	123	118	121	119
		6.5	4 mm Leak	21	21	21	21	21	21	19	17	17	17	17

Table C.4 Maximum Downwind Distance to 6.89 kPa Overpressure Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Separation	Recycle Stream	7.1	Guillotine Rupture	151	149	148	233	147	251	208	144	297	146	174
		7.2	Full Area Rupture	148	148	146	232	147	251	208	148	297	144	147
		7.3	203.2 mm Rupture	241	239	242	294	242	306	263	239	322	239	238
		7.4	25 mm Hole	43	43	43	39	44	42	37	43	42	44	44
		7.5	4 mm Leak	1	1	1	1	1	1	1	1	1	1	1

Table C.5 Maximum Downwind Distance to 25 kPa Overpressure Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Hydrogen Production & Storage	Electrolyser	1.1	Vessel Explosion	32										
	Electrolyser Connection to Header	1.2	Guillotine Rupture	66	67	67	69	67	71	76	66	68	64	67
		1.3	Full Area Rupture	59	59	59	62	59	63	67	58	61	58	59
		1.4	25 mm Hole	64	66	67	71	66	73	79	66	68	64	67
		1.5	3 mm Leak	19	21	23	18	22	21	17	22	24	21	23
	Hydrogen Gas Header	2.1	Guillotine Rupture	174	181	182	191	182	194	218	174	181	173	181
		2.2	Full Area Rupture	163	164	167	174	167	182	202	159	164	158	164
		2.3	85 mm Rupture	151	153	152	179	152	202	241	153	177	149	158
		2.4	25 mm Hole	99	101	101	127	101	141	123	103	169	99	104
		2.5	4 mm Leak	26	27	27	24	28	27	22	28	33	27	31
	Hydrogen Storage	3.2	Catastrophic Release	212	214	217	223	216	228	249	216	226	218	229
		3.3	50 mm Rupture	194	196	198	207	197	211	251	197	207	197	207
		3.4	25 mm Hole	154	153	153	181	153	204	214	153	167	154	162
		3.5	13 mm Hole	113	113	113	158	112	162	149	113	151	112	114
		3.6	6 mm Leak	68	72	69	82	69	88	73	68	96	68	68
		3.1	Vessel Explosion	75										

Table C.5 Maximum Downwind Distance to 25 kPa Overpressure Hazard Extents

Process Location	**Location Description**	**Release Scenario**	**Release Description**	**Maximum Downwind Distance to Hazard Extent (m)**										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Production	Hydrogen and Nitrogen Mixing	4.1	Guillotine Rupture	42	47	41	54	38	66	49	71	62	38	42
		4.2	Full Area Rupture	43	47	41	54	38	66	49	71	62	38	43
		4.3	118.6 mm Rupture	71	71	72	73	71	67	71	66	64	63	67
		4.4	25 mm Hole	36	36	36	33	37	34	32	36	36	36	36
		4.5	4 mm Leak	1	1	1	1	1	1	1	1	1	1	1
	Reactor Inlet	5.1	Guillotine Rupture	33	41	33	51	31	54	42	61	52	31	33
		5.2	Full Area Rupture	34	41	33	46	31	54	41	61	52	31	33
		5.3	135.5 mm Rupture	96	97	98	101	97	102	108	97	99	97	99
		5.4	25 mm Hole	68	68	67	66	67	67	59	64	67	63	63
		5.5	4 mm Leak	11	11	11	11	11	11	11	11	11	11	11
	Reactor Outlet	6.1	Guillotine Rupture	34	38	38	37	43	42	33	47	57	32	59
		6.2	Full Area Rupture	33	37	39	38	43	43	38	47	56	33	59
		6.3	135.5 mm Rupture	96	97	97	101	97	102	107	97	99	97	99
		6.4	25 mm Hole	61	59	58	53	58	53	49	56	53	54	54
		6.5	4 mm Leak	9	9	9	9	9	9	9	8	8	8	8

Table C.5 Maximum Downwind Distance to 25 kPa Overpressure Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Separation	Recycle Stream	7.1	Guillotine Rupture	66	66	66	108	64	121	108	64	149	63	71
		7.2	Full Area Rupture	64	66	64	108	64	121	107	66	149	63	66
		7.3	203.2 mm Rupture	113	113	114	139	114	148	127	113	158	113	114
		7.4	25 mm Hole	21	21	21	18	21	19	17	21	19	21	21
		7.5	4 mm Leak	1	1	1	1	1	1	1	1	1	1	1

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.6 Maximum Downwind Distance to AEGL-2 Inhalation Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Production	Reactor Outlet	6.1	Guillotine Rupture	66	80	116	85	154	126	88	179	232	10	329
		6.2	Full Area Rupture	66	80	118	85	154	126	88	179	234	10	330
		6.3	135.5 mm Rupture	70	80	118	85	193	124	90	262	215	479	420
		6.4	25 mm Hole	85	218	88	257	88	318	249	96	434	91	101
		6.5	4 mm Leak	40	47	66	51	88	70	51	99	102	74	166
Ammonia Storage and Marine Terminal	Condensed Ammonia Stream	8.1	Guillotine Rupture	213	272	468	334	847	563	413	1,473	1,170	2,271	2,731
		8.2	Full Area Rupture	213	272	468	334	847	563	413	1,473	1,169	2,269	2,731
		8.3	76.2 mm Rupture	213	272	468	334	846	563	413	1,473	1169	2,269	2,731
		8.4	25 mm Hole	174	221	374	267	681	452	333	1,167	926	1,899	2,118
		8.5	4 mm Leak	32	37	57	42	97	64	54	146	117	319	233
	Ammonia Storage Vessel	9.1	Catastrophic Release	1,804	3,399	7,795	6,443	12,815	11,570	9,242	20,000	20,000	20,000	20,000
		8.2	Major Rupture	1,809	3,092	7,001	5,521	11,535	9,723	7,434	17,865	20,000	20,000	20,000
		9.3	Minor Rupture	1,682	2,311	4,871	3,533	7,744	5,974	4,358	16,192	14,642	20,000	20,000

Table C.6 Maximum Downwind Distance to AEGL-2 Inhalation Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Storage and Marine Terminal (cont’d)	Marine Terminal Pipe	10.1	Guillotine Rupture	828	1,077	2,067	1,462	3,199	2,419	1,744	5,727	5,616	9,288	11,244
		10.2	Full Area Rupture	828	1,077	2,067	1,462	3,201	2,419	1,744	5,727	5,615	9,291	11,244
		10.3	203.2 mm Rupture	682	883	1,671	1,182	2,567	1,961	1,416	4,748	4,479	7,761	8,848
		10.4	25 mm Hole	87	107	173	127	312	208	157	509	404	909	874
		10.5	4 mm Leak	16	19	28	22	44	31	27	64	52	134	98
	Loading Arm	11.1	Guillotine Rupture	326	419	751	536	1,221	894	653	2,179	1,919	3,439	3,936
		11.2	Full Area Rupture	327	419	751	536	1,222	894	653	2,179	1,919	3,442	3,937
		11.3	203.2 mm Rupture	267	344	604	431	1,008	723	529	1,763	1,529	2,766	3,163
		11.4	25 mm Hole	37	43	67	49	116	78	62	178	142	333	287
		11.5	4 mm Leak	8	9	13	9	18	13	12	24	21	48	34

Table C.7 Maximum Downwind Distance to AEGL-3 Inhalation Hazard Extents

Process Location	**Location Description**	**Release Scenario**	**Release Description**	**Maximum Downwind Distance to Hazard Extent (m)**										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Production	Reactor Outlet	6.1	Guillotine Rupture	14	30	32	31	43	43	31	51	70	8	88
		6.2	Full Area Rupture	14	30	32	31	43	43	31	51	70	8	88
		6.3	135.5 mm Rupture	27	29	41	30	52	41	30	63	62	80	91
		6.4	25 mm Hole	51	51	54	68	55	77	63	55	91	54	59
		6.5	4 mm Leak	15	15	19	16	20	20	16	23	26	20	31
Ammonia Storage and Marine Terminal	Condensed Ammonia Stream	8.1	Guillotine Rupture	69	87	147	103	272	177	128	449	357	637	777
		8.2	Full Area Rupture	69	87	147	103	272	177	128	449	357	637	777
		8.3	76.2 mm Rupture	69	87	146	103	272	177	128	449	357	636	776
		8.4	25 mm Hole	58	72	119	84	219	143	104	357	283	535	608
		8.5	4 mm Leak	12	13	19	14	31	22	15	44	37	91	68
	Ammonia Storage Vessel	9.1	Catastrophic Release	539	1,008	2,277	1,893	3,604	3,316	2,671	5,394	6,204	5,730	10,638
		9.2	Major Rupture	542	907	2,053	1,621	3,218	2,807	2,172	4,682	6,533	5,821	11,618
		9.3	Minor Rupture	516	684	1,398	988	2,181	1,728	1,252	4,301	4,014	6,016	8,415

Table C.7 Maximum Downwind Distance to AEGL-3 Inhalation Hazard Extents

Process Location	Location Description	Release Scenario	Release Description	Maximum Downwind Distance to Hazard Extent (m)										
				A1.5	**B2**	**C2**	**C4**	**D2**	**D5**	**D10**	**E3**	**E5**	**F2**	**F4**
Ammonia Storage and Marine Terminal (cont’d)	Marine Terminal Pipe	10.1	Guillotine Rupture	256	331	614	418	937	737	519	1,642	1,628	2,431	2,993
		10.2	Full Area Rupture	256	331	614	418	937	737	519	1,642	1,627	2,432	2,993
		10.3	203.2 mm Rupture	214	274	499	339	763	601	424	1,378	1,312	2,052	2,377
		10.4	25 mm Hole	29	36	57	41	101	67	50	157	124	261	254
		10.5	4 mm Leak	5	7	9	7	14	10	7	21	16	38	28
	Loading Arm	11.1	Guillotine Rupture	104	132	227	158	384	278	198	654	578	948	1,103
		11.2	Full Area Rupture	104	132	227	158	384	278	198	656	578	949	1,102
		11.3	203.2 mm Rupture	87	109	186	129	318	226	162	532	463	768	893
		11.4	25 mm Hole	13	15	22	16	37	26	18	54	44	96	83
		11.5	4 mm Leak	3	3	4	3	5	4	2	8	5	14	10