ARUP

Cooks Cove Inlet Pty Ltd

Cooks Cove Planning Proposal

Concept Infrastructure Design

Ethane Pipeline Risk Assessment Report

Reference: PP-2022-1748

Issue 2 | 21 February 2023

COOK COVE

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Job number 252942-19

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Document Verification

Project title	Cooks Cove Planning Proposal Concept Infrastructure Design
Document title	Ethane Pipeline Risk Assessment Report
Job number	252942-19
Document ref	PP-2022-1748
File reference	

Revision	**Date**	**Filename**	Cooks Cove PHA Draft.docx		
Draft	19 December 2022	**Description**	First draft		
			Prepared by	**Checked by**	**Approved by**
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Issue 1	20 December 2022	**Filename**	211220 Cooks Cove PHA Issue 1.docx		
		Description	Issue		
			Prepared by	**Checked by**	**Approved by**
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Issue 2	21 February 2023	**Filename**	230221 Cooks Cove PHA Issue 2.docx		
		Description	Updated to reflect DPIE comments		
			Prepared by	**Checked by**	**Approved by**
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Issue Document Verification with Document ✓

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Summary

This report is a Preliminary Hazard Analysis (PHA) for the risk impact on a proposed development for Cooks Cove from the Moomba-Sydney Ethane pipeline in the vicinity of the site. The report has been prepared in accordance with Hazardous Industry Planning Advisory Paper (HIPAP) No.6 [1].

The APA Moomba-Sydney Ethane pipeline runs between the development and Cooks River. It transports liquefied ethane from Moomba in South Australia to Sydney and has a pressure of 8.2 MPa(g) at the location.

Based on a comprehensive review of pipeline safety literature [2], a set of failure scenarios were selected for the pipeline, varying from a small hole of 10-25 mm in diameter to a full-bore rupture (FBR). Immediate ignition of release gas would result in a jet fire that will continue until the section of pipeline is isolated, and the isolated inventory depleted. A delayed ignition may result in a flash fire or vapour cloud explosion depending on congestion and may be followed by a jet fire.

Based on generic failure rates for natural gas and liquefied flammable gas pipelines in the literature [2], the most appropriate data was used for the risk assessment. The 'long pipeline model' in DNV's *Safeti* v8.71 software was used. The resulting risk values were compared with the risk criteria in HIPAP No.10 [3].

The following results were obtained from the risk assessment:

- Individual risk of fatality levels of 0.5 x 10^{-6} p.a. and 1.0 x 10^{-6} p.a. are generated by the pipeline. This restricts some uses of the land, namely residential and sensitive uses as per the risk criteria.
- The societal risk, represented as an F-N curve, is below the upper limit of the risk tolerability band.
- Recommendations have been made to reduce risk to occupants of buildings and ensure occupiers of buildings do not engage in business activities that are inconsistent with the risk presented by the pipeline.

Notation

Report abbreviations

Abbreviation	Description
Arup	Arup Australia Pty Ltd
AS	Australian Standard
BoM	Bureau of Meteorology
CIA	Chemical Industry Association (UK)
DBYD	Dial Before You Dig
DoT	Department of Transport (USA)
DP	Deposited Plan
DPE	NSW Department of Planning and Environment
EGIG	European Gas Pipeline Incident Data Group
FBR	Full Bore Rupture
F-N	Cumulative Frequency vs. Number of fatalities
HAZID	Hazard Identification
HDD	Horizontal Directional Drilling
HDPE	High Density Polyethylene
HIPAP	Hazardous Industry Planning Advisory Paper
HP	High Pressure
HVL	Highly Volatile Liquids
kg/s	kilograms/ second
km	kilometres
KP	Kilometre Point (pipeline distance measurement)
kPa	kilopascals
kW/m^2	kilowatts per square metre
LFL	Lower Flammability Limit
LPG	Liquefied Petroleum Gas
LSIR	Location-Specific Individual Risk
m	metres
m/s	metres per second
MAE	Major Accident Event
MAHP	Major Accident Hazard Pipeline
MAOP	Maximum Allowable Operating Pressure
MIE	Minimum Ignition Energy
mg/m^3	milligrams per cubic metres
mJ	milli Joules
mm	millimetres
MSE	Moomba-Sydney Ethane pipeline
NG	Natural Gas
NSW	New South Wales
OGP	Offshore Oil & Gas producers Association
OSHA	Occupational safety and Health Agency (USA)

p.a.	per annum
PHA	Preliminary Hazard Analysis
PHMSA	Pipeline and Hazardous Materials Safety Administration (USA)
QRA	Quantitative Risk Assessment
SSD	State Significant Development
TNT	Tri-nitro Toluene
TPA	Third Party Activity
UFL	Upper Flammability Limit
UK HSE	United Kingdom Health & Safety Executive
UKOPA	United Kingdom Onshore Pipeline Operators' Association
v/v	volume/volume
VCE	Vapour Cloud Explosion

1. Introduction

This report has been prepared, on behalf of Cook Cove Inlet Pty Ltd, to support the public exhibition and assessment of the Cooks Cove Planning Proposal (PP-2022-1748), which was issued a Gateway Determination by the Department of Planning and Environment on 5 August 2022. The proposal seeks to amend Bayside Local Environmental Plan 2021 (BLEP 2021) to rezone and insert planning controls for certain land known as Cooks Cove within the BLEP 2021.

The Cooks Cove Planning Proposal aims to facilitate the long-planned transformation of 36.2 ha of underutilised and strategically important land at Arncliffe, located to the north of the M5 Motorway and adjacent the western foreshore of the Cooks River. The project seeks a renewed focus on delivering a contemporary logistics and warehousing precinct within a well-connected location, surrounded by enhanced open space provisions. The site forms part of the broader Bayside West 2036 Precincts and generally comprises the footprint of the former Kogarah Golf Club, now in part occupied by a temporary M6 Stage 1 construction compound.

This report applies to the Cooks Cove development zone only and addresses the risk of development of the Cooks Cove precinct in proximity to the Moomba Sydney Ethane Pipeline.

1.1 Cooks Cove Master Plan 2022

The Cooks Cove Master Plan 2022, as prepared by Hassell, represents an optimised and refined reference scheme, to guide best practice design and the preparation of detailed planning controls to achieve an attractive precinct with high amenity. Key features of the Cooks Cove Master Plan are:

- A net development zone of approximately 15 ha with up to 343,250 m^2 Gross Floor Area (GFA) comprising
  - 290,000 m^2 of multi-level logistics and warehousing
  - 20,000 m^2 for hotel and visitor accommodation uses
  - 22,350 m^2 for commercial office uses
  - 10,900 m^2 of retail uses.
- Multi-level logistics with building heights generally up to 5 storeys (approx. 48 m).
- A retail podium with commercial office and hotel above, up to a total of 12 storeys (approx. 51 m).
- Built form of a scale and composition which caters for the generation of approximately 3,300 new jobs.
- A surrounding open space precinct including:
  - A highly activated waterfront including the Fig Tree Grove outdoor dining and urban park precinct
  - An extension to the Bay to Bay Regional cycle link, 'Foreshore Walk', including active and passive recreational uses, together with environmental enhancements
  - Master planned and Council-owned 'Pemulwuy Park' – with an agreed embellishment outcome of passive open space and environmental enhancements to be delivered in stages post construction of the M6 Stage 1 Motorway.
- Complementary on and off-site infrastructure to be delivered by way of State and Local Voluntary Planning Agreements.

Figure 1: Proposed Cooks Cove Master Plan 2022 – Source: Hassell

1.2 Proposed planning control

The Planning Proposal Justification Report, as prepared by Ethos Urban, details the intention to insert new planning provisions covering the Cooks Cove development zone and adjoining lands, through the amendment of the BLEP 2021, accordingly removing this same area from State Environmental Planning Policy (Precincts—Eastern Harbour City) 2021 (formerly Sydney Regional Environmental Plan No. 33 – Cooks Cove).

Specifically, the Planning Proposal will:

- Seek new land use zones within the development zone, including a primary SP4 Enterprise zone across the majority of the Kogarah Golf Course freehold land, RE1 Public Recreation foreshore and passive open space zones and elements of SP2 Infrastructure.
- Impose an overall maximum building height of RL51 m with appropriate transitions to respond to aviation controls within limited sections of the site.
- Limit gross floor area (GFA) to the south of Marsh Street to 340,000 m^2, with a further 1.25:1 Floor Space Ratio (circa 3,243 m^2 of GFA) to the north of Marsh Street, to achieve the overall intended logistics, commercial, retail and short-term accommodation land uses.
- Other additional permitted uses and site-specific planning provisions.

- Reclassification of Lot 14 DP213314 and Lot 1 DP108492 (Council owned and the subject of Charitable Trusts), initially from 'community' to 'operational' to ensure appropriate access, improve utility of public open space and to create a contiguous boundary. Following rezoning and subdivision it is subsequently intended that Council reclassify residue RE1 parcels as 'community' by resolution.

The proposal is in response to Bayside West Precincts 2036 – Arncliffe, Banksia and Cooks Cove (released August 2018) and the subsequent Ministerial Directions under s9.1 of the EP&A Act, being Local Planning Directions 1.11 Implementation of Bayside West Precincts 2036 Plan and 1.12 Implementation of Planning Principles for the Cooks Cove Precinct.

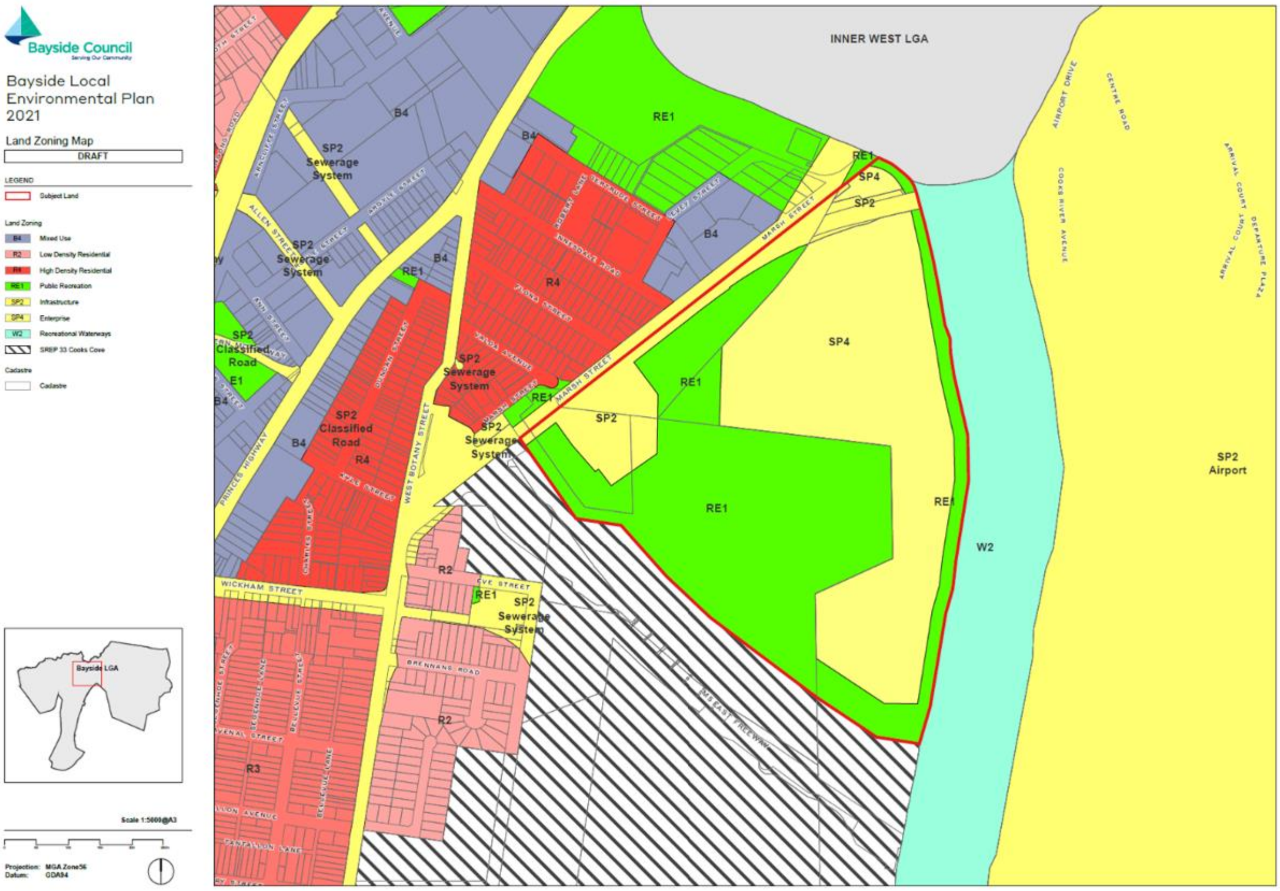

Figure 2: Proposed Draft Bayside LEP 2021 Zoning Map – Source: Ethos Urban

1.3 Site description

1.3.1 Cooks Cove

Cooks Cove is located in the suburb of Arncliffe within the Bayside Council Local Government Area (LGA). The site is located to the west of the Cooks River, approximately 10 km south of the Sydney Central Business District (CBD). The site enjoys adjacency to key trade-related infrastructure being immediately west of Sydney Kingsford Smith International Airport and approximately 6 km west of Port Botany.

Cooks Cove is strategically located within close proximity to a number of railway stations including Banksia, Arncliffe, Wolli Creek and the International Airport Terminal, which vary in distance from the site between 700m and 1.1km. The M5 Motorway, providing regional connectivity to the Sydney Metropolitan area, runs in an east-west direction immediately to the south of the site. The M8 and M6 Motorways are, and will be, constructed in tunnels approximately 60 metres beneath the adjoining Bayside Council 'Trust' lands. The Sydney Gateway project, presently under construction to the immediate north of Cooks Cove and Sydney Airport, will substantially improve future accessibility to the St Peters interchange and the wider M4/M5 WestConnex network, via toll free connections, as well as the Domestic Airport and Port Botany.

The Cooks Cove Development Zone is located to the north of the Southern and Western Suburbs Ocean Outfall Sewer (SWSOOS), and is generally bound by the Cooks River to the east and Marsh Street to the north and west. The site is approximately 36.2 ha and is owned and managed by a number of landowners, both public and private. Surrounding development includes the Sydney Airport International Terminal precinct, Mercure Sydney Airport, an area of low-density dwellings presently transitioning to medium-high density residential flat buildings, recreation and open space facilities and road and airport related infrastructure.

Kogarah Golf Club

Kogarah Golf Club was established in 1928, with the Club occupying the land subject to the Planning Proposal boundary since 1955. At this time, the Cooks River was reconfigured to its current alignment to accommodate the expansion of Sydney Airport. The land presents a highly modified environment, with relatively flat topography, gently moulded fairways and greens, separated by strips of vegetation and man-made water bodies. The golf course clubhouse, car park and maintenance facilities are in the northern corner of the site, adjacent the Cooks River. Access is provided via Levey Street. The members of Kogarah Golf Club will relocate from the site in May 2024 to new playing facilities.

Arncliffe Motorway Operations Complex

The temporary construction compound for the WestConnex M8 and M6 Stage 1 Motorway tunnelling works was originally established in June 2016. The temporary construction facility occupies approximately 7.5 ha and is expected to remain until 2025. At this time the facility will reduce to 1.5 ha to accommodate the permanent Arncliffe Motorway Operations Complex, located in the western corner of the site, adjacent Marsh Street. The complex will house ventilation and water treatment plant and maintenance equipment for both the M6 and M8 sub-grade motorways.

Easements and Affectations

The Sydney Desalination Plant pipeline runs through the development zone, north-south adjacent the Cooks River. The pipe has a diameter of 1.8 m and sits within an easement of 6-9 m in width. From south to north the pipeline is constructed in a combination of trench and above ground with mounded cover and then transitions to micro-tunnel and typical depth of circa 11m. The Moomba to Sydney Pipeline, containing ethane gas, follows a similar general alignment north-south adjacent the Cooks River. The pipe has a nominal 225 mm diameter, within an easement generally 5m wide and with the pipe located at a depth of 1.2 m-2.3 m.

2. Ethane Pipeline Risk Assessment

2.1 Background

Arup Australia Pty Ltd (Arup) was engaged on behalf of Cook Cove Inlet Pty Ltd to assess the level of risk arising from the Moomba-Sydney Ethane high pressure gas pipeline (MSE) in the vicinity of a proposed development in Arncliffe, NSW, on the site of the Kogarah Golf Club.

The assessment is necessary to confirm new proposed land uses for the site to satisfy the NSW Department of Planning and Environment (DPE) criteria for development in the vicinity of hazardous installations, as documented in Hazardous Industry Planning Advisory Paper No. *4 Risk Criteria for Land Use Safety Planning* (HIPAP 4) [3].

This document comprises the hazard analysis conducted in accordance with the requirements of HIPAP 6 *Hazard Analysis* [1].

2.2 Scope

The scope of the study included undertaking a risk assessment for the proposed development from the APA Moomba-Sydney Ethane (MSE) Pipeline in accordance with HIPAP No. 6 [1].

The scope of the PHA did not include the following:

- A Safety Management Study as required under AS 2885-2018 [4].
- Emergency management and incident response.

These are not normally addressed in a Preliminary Hazard Analysis (PHA), but only referred to as a requirement.

2.3 Objectives

The principal objective of the study was to perform a risk assessment covering the scope outlined in Section 1.2 and in accordance with the NSW HIPAP guidelines [1]. This included:

- Identification of gas release hazards from the MSE in the vicinity of the development;
- Development of appropriate and relevant representative gas release scenarios that may impact on the site;
- Quantification of the consequences of harmful effects for each representative scenario (fires, explosions, exposure to unignited gas), including the potential for impact on the proposed development;
- Quantification of the likelihood of occurrence of each representative scenario;
- Development and justification of assumptions for the risk assessment that are appropriate, with a focus on minimising uncertainty and obtaining a ‘cautious best estimate’ of risk to the proposed development; and
- Estimation of Location-Specific Individual Risk (LSIR) and Societal Risk for comparison with the DPE’s risk criteria for land use safety planning (HIPAP No.4 [3] and HIPAP No.10 [2]).

3. Description of Proposed Development and Surrounding Land Uses

3.1 Site Location and Zoning

The proposed development encompasses two lots (DP1231954, Lot 100 and DP1231486, Lot 31) occupied by the Kogarah Golf Club. The properties are located west of Sydney Airport directly across Cooks River, as shown in Figure 3. Marsh Street separates the two properties.

The proposal will require rezoning to allow retail, logistics, commercial and hotel activities. The location of these activities is shown in Figure 4 and the total number of people that may be present in those locations is provided in Table 1. Justification for the expected population in the development is provided in Appendix A.

Figure 3: Location of Proposed Development

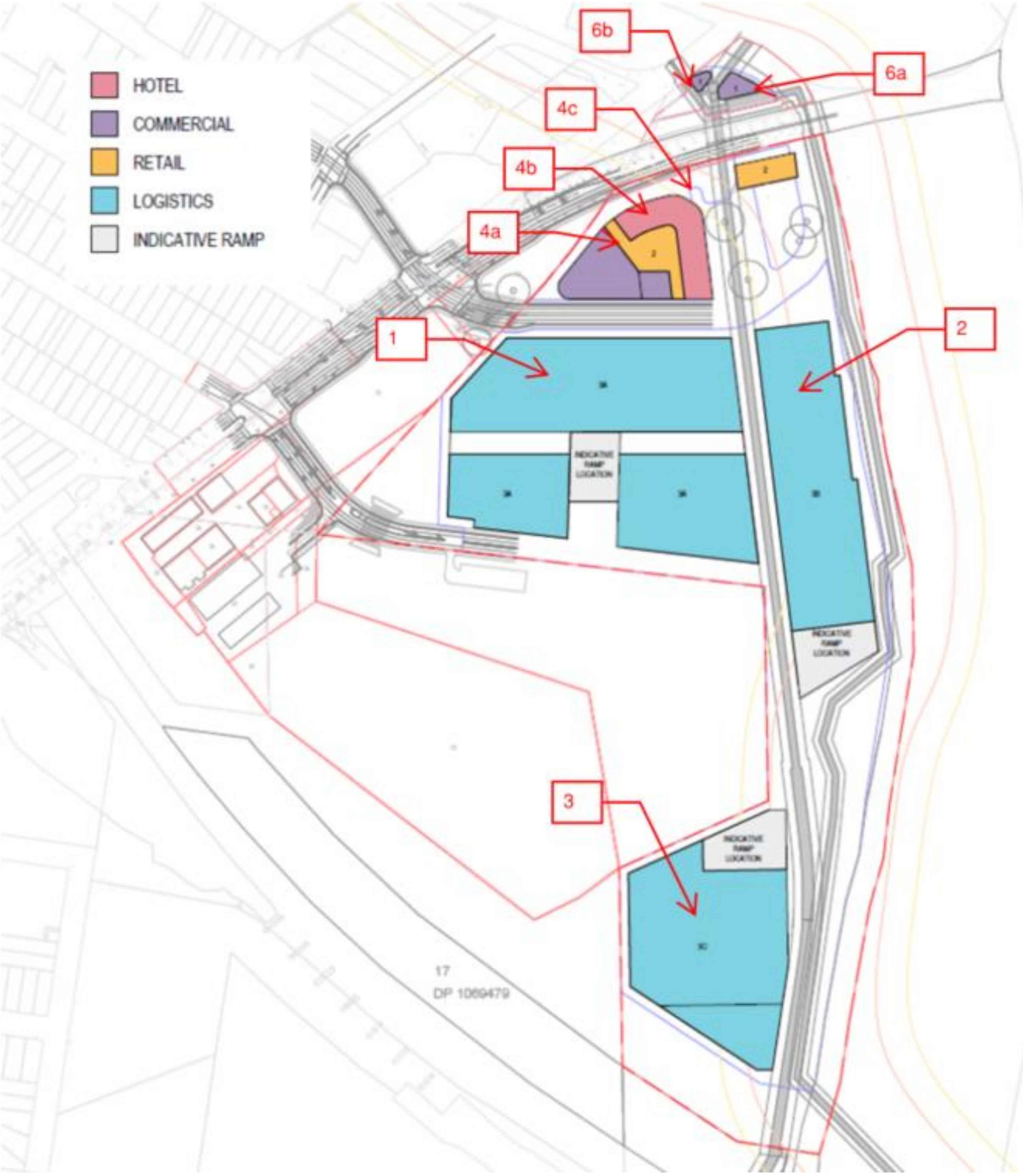

Figure 4 - Population in the Development and Land Uses

Table 1: Population distribution breakdown in the Development and Land Use

Name	Type	Day	Weekend	Night
1	LOGISTICS	1536	1536	384
2	LOGISTICS	767	767	191
3	LOGISTICS	835	835	208
4a	COMMERCIAL	716	0	0
4b	RETAIL	256	256	0
4c	HOTEL	549	549	424
5	RETAIL	143	143	0
6a	COMMERCIAL	107	0	0
6b	COMMERCIAL	40	0	0
Total		**4949**	**4086**	**1207**

3.2 Existing Facilities and Surrounding Land Uses

The lots identified for development are part of the Kogarah Golf Club. Parts of the golf course are now used as a location for infrastructure supporting the M8 Motorway Tunnel.

The surrounding land uses consist of mixed-use zones, low, medium, and high residential zones, public recreation zones and infrastructure zones.

There is one pipeline near the proposed site transporting hazardous material:

- A high-pressure ethane pipeline carrying liquid ethane from Moomba in South Australia to Sydney's Botany Industrial Park. Hereafter known as the Moomba-Sydney Ethane pipeline (MSE)

Land uses and the section of the pipeline considered in this study are shown in Figure 6.

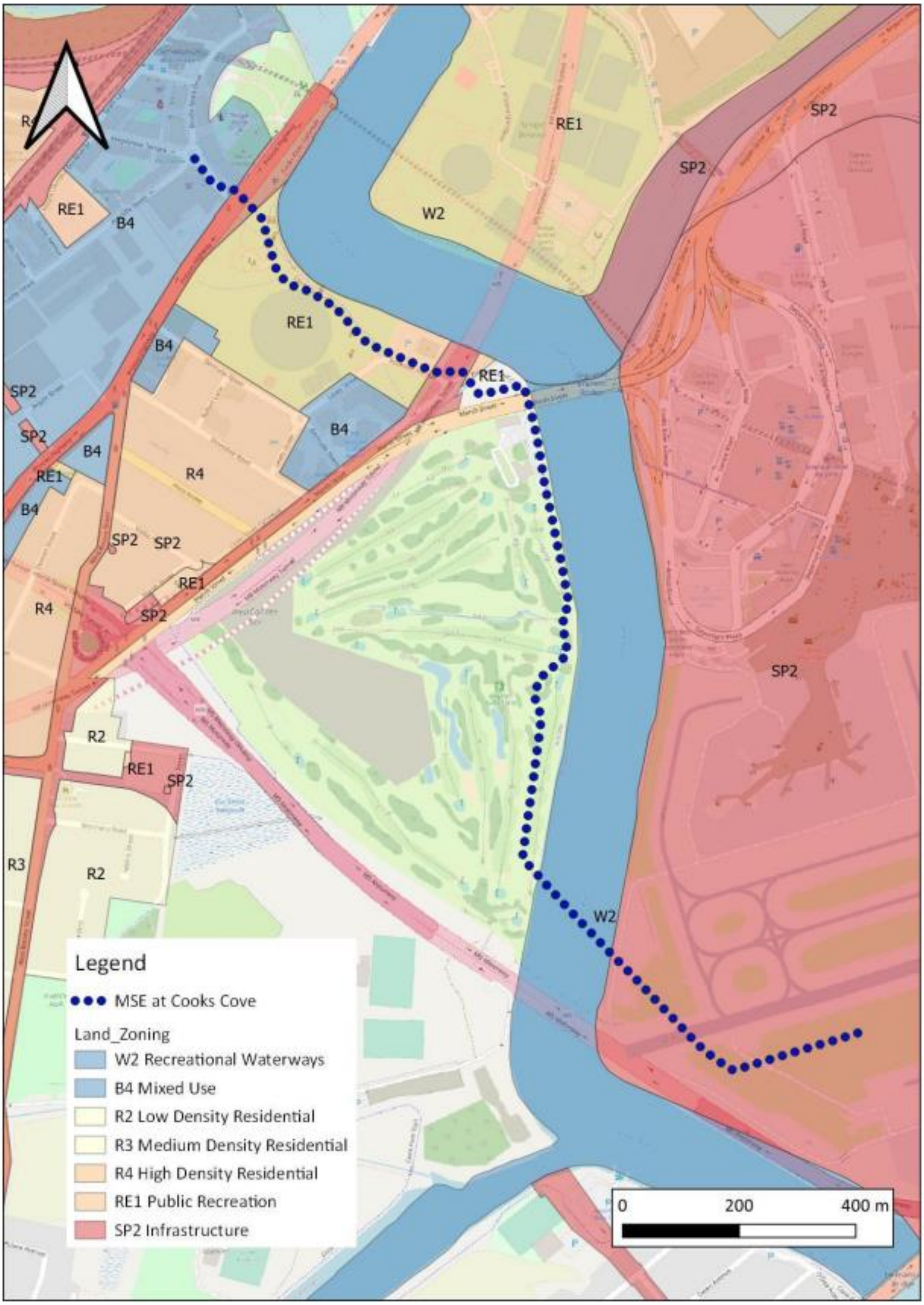

Figure 5: Surrounding Land Uses

3.2.1 Meteorological Data

Sydney airport observations have been processed to develop two sets of weather conditions for day (one hour after sunrise, and one hour before sunset) and night. The weather categories are identified by their Stability Class (A – F), and windspeed. Weather conditions used for the analysis are presented in Table 2 and Table 3.

Table 2 - Night-time Meteorology

Weather Category		**8.3D**	**4.2D**	**1.0D**	**3.3E**	**1.0F**	**Total**
Stability Class		D	D	D	E	F	
Wind speed [m/s]		8.3	4.2	1.0	3.3	1.0	
Temperature [°C]		17.6	16.7	16.8	15.3	15.9	
Relative Humidity		0.7	0.8	0.8	0.8	0.8	
Solar Radiation [kW/m^2]		0.0	0.0	0.0	0.0	0.0	
Direction	**N**	0.011	0.037	0.006	0.023	0.026	**0.104**
	NNE	0.030	0.028	0.003	0.012	0.013	**0.087**
	NE	0.012	0.019	0.002	0.008	0.010	**0.051**
	ENE	0.003	0.009	0.002	0.003	0.006	**0.022**
	E	0.005	0.016	0.002	0.004	0.006	**0.033**
	ESE	0.007	0.013	0.001	0.003	0.005	**0.029**
	SE	0.014	0.016	0.002	0.003	0.004	**0.039**
	SSE	0.025	0.014	0.001	0.003	0.004	**0.047**
	S	0.061	0.025	0.002	0.005	0.006	**0.100**
	SSW	0.027	0.015	0.001	0.004	0.004	**0.052**
	SW	0.012	0.015	0.002	0.006	0.006	**0.041**
	WSW	0.017	0.021	0.002	0.010	0.010	**0.059**
	W	0.025	0.031	0.004	0.016	0.018	**0.095**
	WNW	0.008	0.022	0.004	0.017	0.017	**0.068**
	NW	0.006	0.033	0.006	0.024	0.024	**0.093**
	NNW	0.004	0.029	0.004	0.025	0.019	**0.081**
	TOTAL	**0.269**	**0.343**	**0.045**	**0.166**	**0.177**	**1.000**

Table 3 - Day-time Meteorology

Weather Category		2.2B	8.5D	4.2D	1.6D	Total
Stability Class		B	D	D	D	
Wind speed [m/s]		2.2	8.5	4.2	1.6	
Temperature [°C]		21.9	21.0	19.5	18.4	
Relative Humidity		0.6	0.6	0.6	0.7	
Solar Radiation [kW/m^2]		0.6	0.5	0.4	0.3	
Direction	N	0.010	0.012	0.003	0.025	**0.050**
	NNE	0.007	0.038	0.002	0.016	**0.063**
	NE	0.006	0.060	0.001	0.017	**0.085**
	ENE	0.004	0.029	0.001	0.014	**0.049**
	E	0.009	0.019	0.002	0.027	**0.058**
	ESE	0.005	0.013	0.001	0.020	**0.039**
	SE	0.006	0.026	0.002	0.027	**0.060**
	SSE	0.010	0.034	0.002	0.023	**0.070**
	S	0.006	0.114	0.002	0.036	**0.158**
	SSW	0.003	0.032	0.002	0.013	**0.049**
	SW	0.003	0.007	0.002	0.010	**0.022**
	WSW	0.004	0.017	0.003	0.013	**0.037**
	W	0.008	0.034	0.005	0.028	**0.076**
	WNW	0.009	0.017	0.005	0.036	**0.067**
	NW	0.012	0.011	0.005	0.048	**0.076**
	NNW	0.008	0.008	0.003	0.021	**0.040**
	TOTAL	**0.010**	**0.287**	**0.219**	**0.484**	**1.000**

3.2.2 Surrounding Population

The surrounding residential population has been based on the 2021 Census [6]. Figure 6 shows Statistical Area 1 (SA1) boundaries and the population of those areas, with the total number of people living within the defined areas equalling 15,685. A breakdown of the population within this area is given in Table 4.

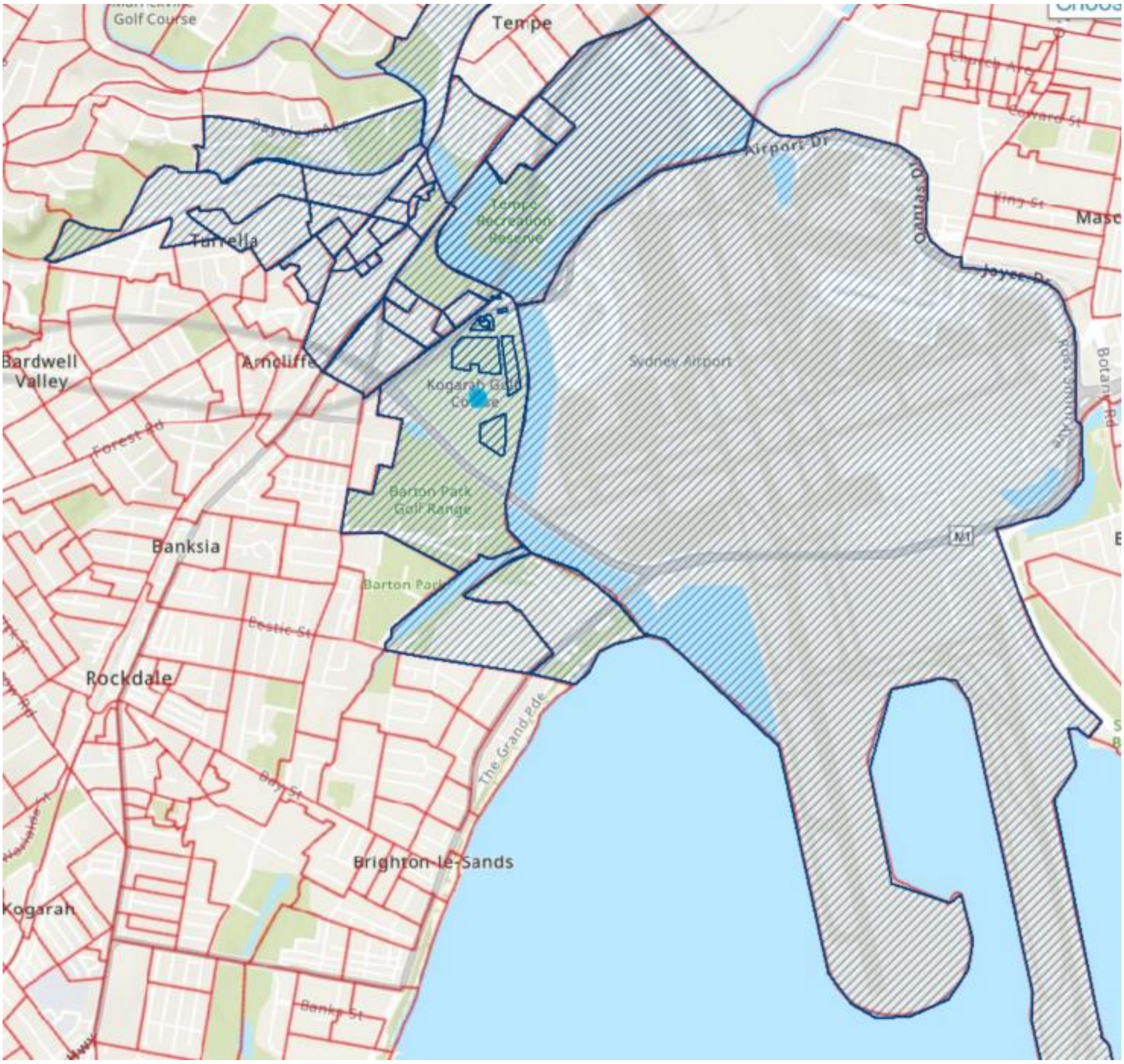

Figure 6 – Statistical Area 1 boundaries surrounding the Cooks Cove Development area.

Table 4: SA1 population data

ABS Population Reference	Population of Area (Number)
110701132501	19
11904166802	0
11904138001	493
11904138007	427
11904166803	426
11904167114	377

ABS Population Reference	Population of Area (Number)
11904167102	369
11904167108	375
11904167111	443
11904167117	391
11904166829	406
11904166809	582
11904166832	786
11902166241	298
11702163727	287
11702132811	490
11702132814	355
11702132812	238
11904167120	262
11904167103	303
11904167118	290
11904167119	570
11904167106	903
11904167115	1238
11904167112	763
11904167105	575
11904167113	469
11904167107	676
11904167109	936
11904167110	292
11904167104	616
11904167101	567
11904167116	310
11702132813	153

3.3 Ethane Pipeline License No. 15 (NSW) – Details for Cooks Cove Development Site.

Information obtained from APA about the MSE at the Cooks Cover development location is shown in Table 5.

Table 5 - MSE Details

Substance conveyed	**Ethane**
Measurement Length (ML)	59 0m (4.7 kW/m^2 Heat Radiation Zone) *Info only: 365 m (12.6 kW/m^2 Heat Radiation Zone)*
Length of pipeline	1375 km (approx)
Pipeline section under review	KP1365 to KP 1369 *[MLV at KP1344 Moorebank and at KP1368 Marsh St.]*
Outside diameter	219.1 mm
Depth of Cover	1200 mm (minimum)
Max. Allowable Operating Pressure	15.3 MPag (MAOP)
Normal Operating Pressure	8200 kPa (8.2 MPag)
Operating Temperature	20°C
Material Pumping Rate	30 tonne per hour
Location Class - Primary	T2 (predominant)
Location Class – Secondary	S
Critical Defect Length	322.7 mm (11.9 mm WT)
Hole size based on 10GJ/s release rate	92 mm
Hole size based on 1GJ/s release rate	36 mm

The following assessments of equipment with the potential to cause external damage to the MSE has been made for locations near the development:

Max equipment sizes without risk of a leak (B Factor 1.3):

- Excavator with General Purpose Teeth, will not cause leak
- Excavator with Tiger Teeth (Single Point Penetration) 25T
- Excavator with Twin Tiger Teeth (Both Points Penetrate), will not cause leak

Max equipment sizes without causing risk of Rupture (B Factor 1.3):

- Excavator with General Purpose Teeth, will not rupture
- Excavator with Twin Tiger Teeth (Single Point Penetration) 55T
- Excavator with Twin Tiger Teeth (Both Points Penetrate) 55T

4. Risk Assessment Methodology

4.1 Introduction

This analysis involves the quantitative estimation of the consequences and likelihood of accidents (a Quantitative Risk Assessment or QRA). For consequences to people, the most common risk measure is 'individual fatality risk' (the likelihood of fatality per year).

In developing the estimates for use in a QRA, it is important to ensure that any estimates fall on the side of conservatism, particularly where there is uncertainty in the underlying data and assumptions. This precautionary approach uses 'cautious best estimate' values, which, whilst conservative, are still realistic. This approach is consistent with the DPE's guidelines for undertaking this type of assessment [1].

Diagrammatically, the QRA process is as follows:

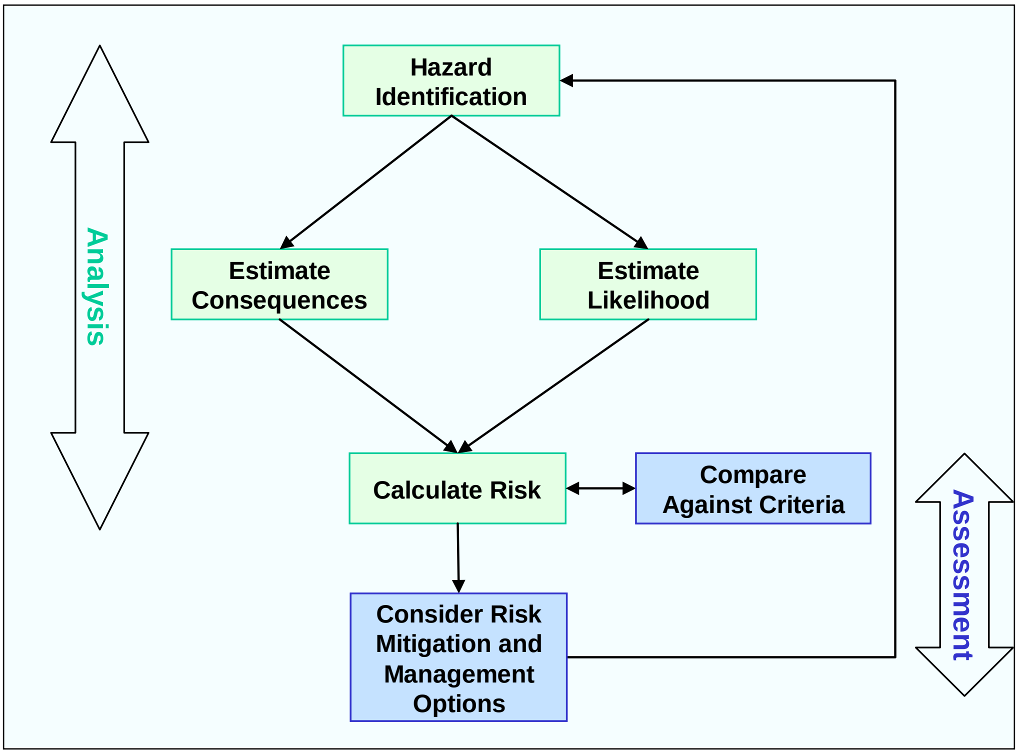

Figure 7 - Overview of QRA Process [1]

4.2 Methodology Overview

4.2.1 Hazard Identification and Register of Major Accident Events

A hazard is something with the potential to cause harm (e.g., thermal radiation from a fire, physical impact from a moving vehicle or dropped object, exposure to stored energy, etc.). As well as identifying the hazards that exist, it is also important to identify how these hazards could be realised.

For example, the Hazard identification (or HAZID) step for a QRA of a potentially hazardous pipeline would identify representative events that could result in a release of the material from the pipeline with the potential to cause harm (e.g., due to a subsequent ignition and fire/explosion). The representative potentially hazardous events are commonly described as 'Major Accident Events' (or MAEs). In the context of the QRA, an MAE is an event with the potential to cause off-site fatality or injury; off-site property damage; or, long-term damage to the biophysical environment (i.e. any outcome for which DPE has defined an acceptable risk criterion – Refer to Section 4.4)

There is no single definitive method for hazard identification (HAZID); however, it should be comprehensive and systematic to ensure critical hazards are not excluded from further analysis.

When identifying hazards for modelling in a QRA, it is necessary to capture the following information, either during the hazard identification process, or as part of the preparation for hazard consequence modelling:

- Hazardous materials and materials properties;
- Inventory of hazardous materials that could contribute to the accident;
- How the material is released (e.g., hole in a pipeline);
- The condition of the material prior to release (e.g., compressed gas at a specific temperature and pressure);
- The area/s into which the material is released (e.g., inside an enclosed area, etc.);
- Ambient conditions in the area where the material is released (e.g., air temperature, wind speed and direction, atmospheric stability);
- Locations of ignition sources around the release point; and
- Duration of release before it is isolated.

The above information was used to develop a detailed list of MAEs for the risk assessment. This QRA includes an estimate of the consequences and likelihood of each of these scenarios and aggregates the results to estimate the total risk.

4.2.2 Hazard Consequence Analysis

The physical consequences of a release of potentially hazardous material (e.g., flammable gas, flammable liquid, etc.) are generally dependent on:

- the quantity released;
- the rate of release; and,
- when ignition occurs for fire and explosion events.

The quantity of release depends on the inventory, size of release (viz. assumed equivalent hole diameter) and duration of release (how soon can the release be detected and isolated).

Meteorological conditions, such as wind speed, wind direction and weather stability class have an impact on the extent of the downwind and crosswind dispersion. Location-specific meteorological data is therefore required to undertake a QRA study. The representative wind directions, wind speeds and wind stability classes are normally determined from annual average of weather data available from the Bureau of Meteorology, for the local weather station.

In addition to wind speed, the Pasquill stability class has a significant impact on the vertical and crosswind dispersion of a released gas. Six wind stability classes (A to F) are normally used. Class A refers to more turbulent unstable conditions and Class F refers to more stable (inversion) conditions. Although the probability distribution of Pasquill stability classes is site-specific, it is generally observed that Class F conditions are more likely to occur during the night-time while Class D (neutral) conditions occur during the daytime (sunny conditions).

The wind direction, wind speed and stability class distribution used for the QRA is presented in Appendix A (Assumptions No. 3).

The Safeti 8.71 software package was used for all consequence modelling and the generation of the risk contours and societal risk curves.

4.2.3 Impairment Criteria

Impairment criteria have been developed for the effects of explosions and fires as outlined below. The impairment criteria adopted for the QRA are included in Appendix A (Section A.6)

Explosion

During a flash fire, acceleration of the flame front can occur due to the turbulence generated by obstacles within the combusting vapour cloud. When this occurs, an overpressure ('shock') wave is generated which has the potential to damage equipment and/or injure personnel.

The impact of explosion overpressure on humans takes two forms:

- For a person in the open, there could be organ damage (e.g., ear drum rupture or lung rupture), that may be considered to constitute serious harm.
- The person could be hit by a flying missile, caused by the explosion, and this can lead to serious injury or even fatality.

The vulnerability to explosion overpressure used in the analysis are summarised in Table 6 and Table 7.

Table 6 - Probability of Fatality from Exposure to Peak Side on-Overpressure (Outdoor)

Overpressure (kPa)	Probability of Fatality	Source
30	1.0	Safeti software (default value)

Table 7 - Probability of Fatality from Exposure to Peak Side on-Overpressure (Indoor)

Overpressure (kPa)	Probability of Fatality	Source
10	0.025	Safeti software (default value)
30	1.0	Safeti software (default value)

Fire

The potential for injury or property damage from a fire is determined by the intensity of the heat radiation emitted by the fire and the duration of exposure to this heat radiation. Together, the combination of time and intensity is the thermal dose.

For individuals located outdoors, the probability of fatality is based on the following probit equation:

$$Y = -36.38 + 2.56\ln\left(I^{1.333}t\right)$$

Where Y is the probit value, I is the heat radiation intensity (W/m^2) and t is the exposure duration (seconds).

The probit value Y can be related back to a percentage of a population. Table 8 depicts the probability of fatality for various radiation intensities and a thirty second exposure.

Table 8 - Probability of Fatality for 30 Second Exposure for a Given Radiation Intensity

Heat Radiation Intensity (kW/m^2)	Probit	Probability of Fatality
4.7	1.19	0
12.6	4.55	0.32
15.9	5.35	0.63
23.0	6.61	0.94
35.0[1]	8.04	1.0

The dominant effect in a flash fire is direct engulfment by flame within the burning cloud. To estimate the magnitude of the flammable gas cloud, the furthest distance from the release location with a concentration equal or above the lower flammability limit (LFL) is estimated using a dispersion model.

4.2.4 Frequency and Likelihood Analysis

Once the consequences of the various accident scenarios have been estimated, it is necessary to estimate the likelihood of each scenario. In a QRA, the likelihood must be estimated in quantitative terms (i.e., occurrences per year). Exponential notation (e.g., 5.0×10^{-6} per year or 5E-06 per year) is normally used because the likelihood of a MAE is usually a low number (i.e. less than 1 chance in 1,000 to 10,000 per year).

The likelihood of each scenario is normally estimated from historical incident and failure data. This is only possible because data on such incidents and failures has been collected by various organisations over several years. Various databases and reference documents are now available that provide this data.

When using historical data to forecast the likelihood of a future event, it is important to ensure any specific conditions that existed at the time of the historical event are taken into account. For very low frequency events (i.e., where historical occurrences are very rare), it might not be possible to estimate the likelihood values directly from the historical data and other techniques such as fault tree analysis may be required.

The frequency analysis data and results are summarised in Section 5.3 and Appendix C.

4.2.5 Risk Analysis and Assessment

Risk analysis and assessment are separate tasks although they are often undertaken together. Risk analysis involves combining the consequence and likelihood estimates for each scenario and then summing the results across all the accident scenarios to generate a complete picture of the risk. The risk assessment step involves comparing the risk results against risk criteria.

Location-specific individual risk (LSIR) contours are usually used to represent off-site risk for a land-use safety QRA study. These iso-risk contours are superimposed on a plan view drawing of the site. Example risk levels that are typically shown as iso-risk contours include: 1×10^{-6} per year, 10×10^{-6} per year and 50×10^{-6} per year.

The iso-risk contours show the estimated frequency of an event causing a specified level of harm at a specified location, regardless of whether or not anyone is present at that location to suffer that harm. Thus, individual iso-risk contour maps are generated by calculating individual risk at every geographic location, assuming a person will be present and unprotected at the given location 100% of the time (i.e. peak individual risk with no allowance for escape or occupancy).

[1] The default vulnerability in Safeti is that 35 kW/m^2 results in 100% lethality, regardless of exposure time.

The assessment of risk results involves comparing the results against risk criteria. In some cases, this assessment may be a simple listing of each criterion together with a statement that the criterion is met. In other, more complex cases, the risk criteria may not be met, and additional risk mitigation controls may be required to reduce the risk.

The latest Safeti 8.71 software package was used to generate the iso-risk contours / transects and societal risk results (Refer to Section 7).

4.3 Study Assumptions

It is necessary to make technical assumptions during a risk analysis. These assumptions typically relate to specific data inputs (e.g., material properties, equipment failure rates, etc.) and modelling assumptions (e.g. release orientations, impairment criteria, etc.).

To comply with the general principles outlined in Section 2.2 of HIPAP No. 6 [1], all steps taken in the risk analysis should be:

"*traceable and the information gathered as part of the analysis should be well documented to permit an adequate technical review of the work to ensure reproducibility, understanding of the assumptions made and valid interpretation of the results*".

Therefore, details of the key assumptions adopted for the risk analysis are provided in Appendix A

4.4 Quantitative Risk Criteria

4.4.1 Residential and Sensitive Land Use Individual Fatality Risk Criteria for Development in the Vicinity of Potentially Hazardous Facilities

The individual fatality risk imposed by a proposed (or existing) industrial activity should be low relative to the background risk. This forms the basis for the following individual fatality risk criteria adopted by the NSW DPE [2] and [3].

The following criteria apply to residential and sensitive use development in the vicinity of existing industry [2]:

- *the half in a million per year individual fatality risk level is an appropriate criterion above which no intensification of sensitive use development should take place;*
- *the one in a million per year individual fatality risk level is an appropriate criterion above which no intensification of residential development should take place;*
- *residential intensification may be appropriate where mitigating measures can be implemented to reduce risk exposure to less than the one in a million per year individual fatality risk level, provided the pre-mitigation residual risk levels are below the 10 in a million per year individual fatality risk level; and*
- *no residential intensification should take place where pre-mitigation residual risk levels are in excess of the 10 in a million per year individual fatality risk level.*

Table 9 - Individual Fatality Risk Criteria – Other Land Uses

Land Use	Risk Criterion [per million per year]
Commercial developments, including offices, retail centres, warehouses with showrooms, restaurants, and entertainment centres	5
Sporting complexes and active open space areas	10
Industrial sites	50*

*HIPAP 4 allows flexibility in the interpretation of this criterion. For example, 'where an industrial site involves only the occasional presence of people, such as in the case of a tank farm, a higher level of risk may be acceptable'.

The DPE has adopted a fatality risk criterion of 1 x 10^{-6} per year (or 1 chance of fatality per million per year) for residential area exposure because this risk is very low in relation to typical background risks for individuals in NSW. For land uses such as hospitals, schools, child-care facilities, and old age housing, the criterion is one-half that for residential area, viz. 0.5 x 10^{-6} per year. "Sensitive" is the implied term for such uses in HIPAP 4 and the term sensitive is used in this study.

4.4.2 Injury Risk

The DPE has adopted risk criteria for levels of effects that may cause injury to people but will not necessarily cause fatality. Criteria are included in HIPAP No. 4 [3] for potential injury caused by exposure to heat radiation, explosion overpressure and toxic gas/ smoke/dust.

The DPE's suggested injury risk criterion for heat radiation is as follows:

- *Incident heat flux radiation at residential and sensitive use areas should not exceed 4.7 kW/m^2 at a frequency of more than 50 chances in a million per year.*

The DPE's suggested injury/damage risk criterion for explosion overpressure is as follows:

- *Incident explosion overpressure at residential and sensitive use areas should not exceed 7 kPa at frequencies of more than 50 chances in a million per year.*

The DPE's suggested injury risk criteria for toxic gas/ smoke/dust exposure are as follows:

- *Toxic concentrations in residential and sensitive use areas should not exceed a level which would be seriously injurious to sensitive members of the community following a relatively short period of exposure at a maximum frequency of 10 in a million per year.*
- *Toxic concentrations in residential and sensitive use areas should not cause irritation to eyes or throat, coughing or other acute physiological responses in sensitive members of the community over a maximum frequency of 50 in a million per year.*

4.4.3 Risk of Property Damage and Accident Propagation

Heat radiation exceeding 23 kW/m^2 may cause unprotected steel to suffer thermal stress that may cause structural damage and an explosion overpressure of 14 kPa can cause damage to piping and low-pressure equipment. The DPE's criteria for risk of damage to property and accident propagation are as follows [3]:

- *Incident heat flux radiation at neighbouring potentially hazardous installations or at land zoned to accommodate such installations should not exceed a risk of 50 in a million per year for the 23 kW/m^2 heat flux level.*
- *Incident explosion overpressure at neighbouring potentially hazardous installations, at land zoned to accommodate such installations or at nearest public buildings should not exceed a risk of 50 in a million per year for the 14 kPa explosion overpressure level.*

4.4.4 Societal Risk

It is possible that an incident at a hazardous facility may affect more than a single individual off-site, especially in the case of a full-bore rupture of a high-pressure gas pipeline, and the potential exists for multiple fatalities.

The societal risk concept evolved from the concept of 'risk aversion', i.e., society is prepared to tolerate incidents that cause single fatalities at a more frequent interval (e.g. motor vehicle accidents) than for incidents causing multiple fatalities (e.g. an aircraft accident).

Two parameters are required to define societal risk: (a) Number of fatalities that may result from an incident; and (b) the frequency (likelihood) of occurrence of the incident.

Societal risk can be represented by F-N curves, which are plots of the cumulative frequency (F) of various accident scenarios against the number (N) of casualties associated with the modelled incidents. In other words, 'F' represents the frequency of exceedance of number of fatalities, N.

The F-N plot is cumulative in the sense that, for each frequency on the plot, N is the number of fatalities that could be equalled **or exceeded**, and F is the frequency of exceedance of the specified number of fatalities.

The DPE's suggested societal risk criteria (Refer to Figure 8), recognise that society is particularly intolerant of accidents, which though infrequent, have a potential to create multiple fatalities. Below the negligible line, provided other individual criteria are met, societal risk is not considered significant. Above the intolerable level, an activity is considered undesirable, even if individual risk criteria are met. Within the 'As Low As Reasonably Practicable' (ALARP) region, the emphasis is on reducing risks as far as possible towards the negligible line. Provided other quantitative and qualitative criteria of HIPAP 4 [3] are met, the risks from the activity would be considered tolerable in the ALARP region.

In HIPAP 10 [2], the following is reported regarding the F-N criteria:

If a development proposal involves an intensification of population in the vicinity of a potential source of risk, then the incremental change in societal risk needs to be taken into account, even if individual risk criteria are met [Ref.2, Section 5.5.4]. The incremental societal risk should be compared against the indicative societal risk criteria in Section 5.4.2 of HIPAP No. 10 [Figure 8 *below]. If the incremental societal risk lies within the 'Negligible' region, then the development should not be precluded and if it lies within the 'Tolerable if ALARP' region, then options should be considered to relocate people away from the affected areas [Ref.2, Section 5.5.4]. If, after taking this step, there is still a significant portion of the societal risk plot within the 'Tolerable if ALARP' region, the proposed development should only be approved if benefits clearly outweigh the risks [Ref.2, Section 5.5.4].*

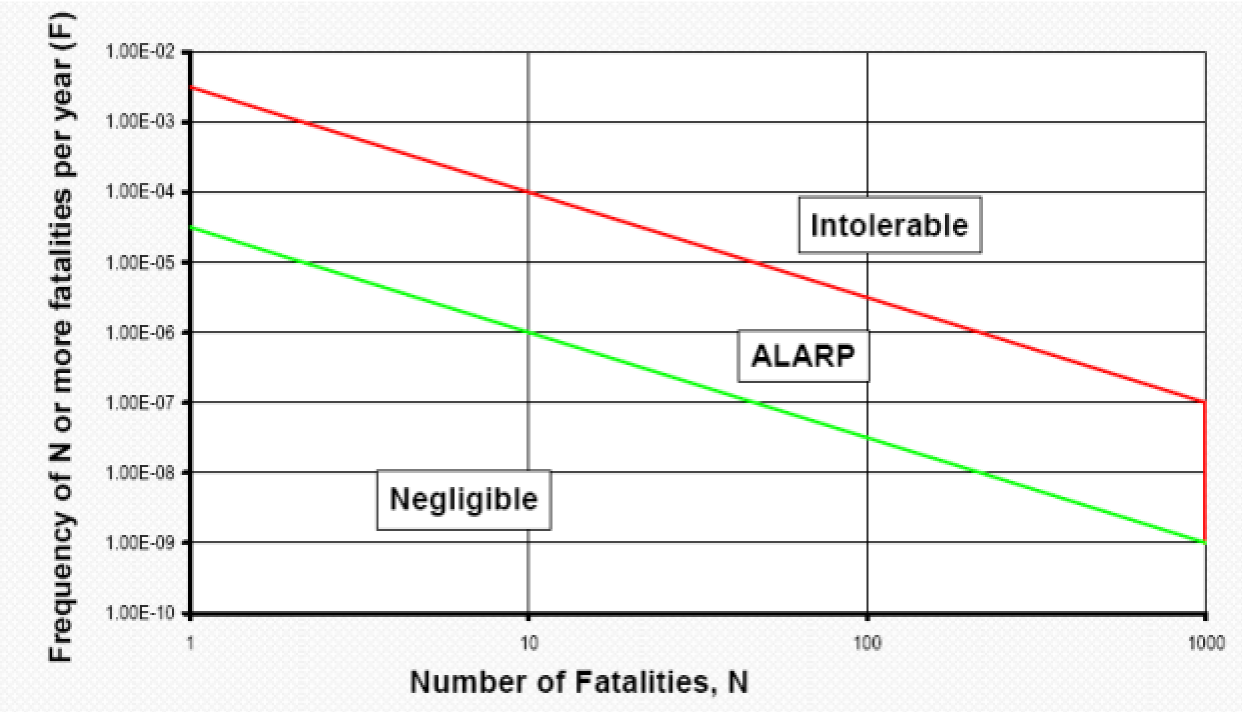

Figure 8 - Indicative Societal Risk Criteria

The F-N criterion in NSW imposes an absolute upper limit of N=1000 (i.e., an incident that could cause more than 1000 fatalities is not tolerable), regardless of how low the frequency is.

HIPAP No.4 [3] also states that the criteria in Figure 8 are an indicative criterion and provisional only and do not represent a firm requirement in NSW.

4.5 Qualitative Risk Criteria

Irrespective of the numerical value of any risk criteria for risk assessment purposes, it is essential that certain qualitative principles be adopted concerning the land use safety acceptability of a proposed development or existing activity. The qualitative risk criteria outlined in HIPAP No. 4 [3] encompass the following general principles:

- Avoidance of all 'avoidable' risks;

- Reduction, wherever practicable, of the risk from a major hazard, even where the likelihood of exposure is low;
- Containment, wherever possible, within the site boundary of the effects (consequences) of the more likely hazardous events; and
- Recognition that if the risk from an existing installation is already high, further development should not be permitted if it significantly increases that existing risk.

5. Hazard Identification

5.1 Introduction

The hazard identification was based on a review of the: information on the MSE pipeline; properties of ethane; and potential failure modes and consequences if a leak were to occur from a pipeline. These findings are presented as follows:

Section 5.2 - Properties of Ethane

Section 5.3 - Pipeline Failure Modes

Section 5.4 - Consequences of Gas Release

Section 5.5 - Control Measures

The representative MAEs carried forward to the consequence analysis are listed in Section 5.6.

5.2 Properties of Ethane

Ethane is principally used as a raw material for the manufacture of ethylene. It is modelled as 100% ethane in the QRA.

Physical properties are listed in Table 10.

Table 10 - Physical Properties of Ethane

Boiling Point	-88.6 °C
Autoignition Temperature	515 °C
Relative Density (Air=1)	1.05
Lower Flammability Limit in air (vol. %)	2.4%
Upper Flammability Limit in air (vol. %)	14.3%

Ethane is:

- A gas at ambient conditions;
- Flammable;
- A similar density to air at ambient temperatures; and
- Colourless and non-toxic.

Ethane is transported by pipeline as a liquefied gas under pressure.

5.3 Pipeline Failure Modes

Pipelines may leak due to various causes. The four principal failure modes that may result in a leak from an underground pipeline include [5]:

- **Mechanical failures,** including material defects or design and construction faults;
- **Corrosion,** including both internal and external corrosion;
- **Ground movement and other failure modes,** including ground movement due to earthquakes, heavy rains/floods or operator error, and other natural hazards such as lightning, etc.; and

- **Third Party Activity (TPA),** including damage from heavy plant and machinery, damage from drills/boring machines and hot tapping, etc.

The relative likelihood of each failure mode is shown in Appendix C for underground pipelines.

5.3.1 Mechanical Failure

Leaks due to mechanical failures are usually caused by a construction fault, a material fault / defect or design of the pipeline.

This failure mode is credible for the MSE; however, historical incident data for other pipelines (Refer to Appendix C) indicates this is generally a low likelihood failure mode, particularly for more recently manufactured pipelines (i.e., post 1980).

5.3.2 Corrosion

Leaks due to internal corrosion are generally a function of the material being transported, the wall thickness of the pipeline and the materials of construction.

Leaks due to external corrosion do not depend on the material being transported and are generally dependent on the soil type / conditions, pipeline coating and materials of construction, and the age of the pipeline.

This failure mode is credible for the MSE; however, historical incident data for other pipelines (Refer to Appendix C) indicates this is a low likelihood failure mode, particularly for pipelines with a higher wall thickness (i.e., > 10 mm) and more recently manufactured pipelines (i.e. post 1980)

5.3.3 Ground Movement and Other Failure Modes

Pipeline leaks may occur due to ground movement (e.g., following a landslide or earthquake). The potential also exists for ground movement in the vicinity of water crossings (water erosion) or as a result of construction activities (new road infrastructure and buildings).

Other external events, such as lightning strikes, operational errors and erosion may also lead to a leak.

This failure mode is credible for the MSE.

5.3.4 Third Party Activity

Most leaks due to Third Party Activity (TPA) are caused by construction vehicles and equipment (drills, etc.) or by farm machinery in rural areas. The leak typically occurs immediately upon contact; however, it may be delayed (i.e., if the TPA only weakens the pipeline such that it fails later).

Leaks due to TPA include those caused by horizontal directional drilling (HDD), which is commonly used to install utilities and services (communication cables, etc.).

Leaks due to TPA are particularly relevant when considering development in the vicinity of existing pipelines due to the potential for significant construction activities (e.g., new road infrastructure and buildings).

This failure mode is credible for the MSE.

5.4 Consequences of Gas Release

5.4.1 Asphyxiation

Although non-toxic, ethane has the potential to cause asphyxiation at higher concentrations due to oxygen depletion, particularly if exposure occurs in a confined space.

Ethane is a simple asphyxiant with low toxicity to humans. If a release does not ignite, then the potential exists for the gas concentration to be high enough to present an asphyxiation hazard to individuals nearby.

An atmosphere with marginally less than 21% oxygen can be breathed without noticeable effects. However, at 19.5% (which is OSHA's lower limit for confined space entry in 29 CFR 1915.12 [6]) there is a rapid onset of impairment of mental activity.

An oxygen concentration of about 15% will result in impaired coordination, perception, and judgment. This may prevent a person from performing self-rescue from a confined space.

The potential for unconsciousness and fatality is only significant at less than 10% oxygen. However, to reduce the oxygen concentration to 10% requires a relatively high concentration (viz. approximately 52% v/v, which equates to 641,000 mg/m^3 for ethane).

Oxygen deficiency from exposure to ethane should not be a major issue because the fire hazards are usually the dominant effects in most locations (the LFL for ethane is approximately one twentieth, or 5%, of the fatal asphyxiant concentration). Therefore, the potential for fatality from asphyxiation was not carried forward to the consequence, likelihood, and risk estimation steps of the QRA.

5.4.2 Jet Fire

Release of ethane from high pressure through a hole in a pipeline may create a jet plume. The gas plume extends several metres in the direction of discharge due to its momentum jet effect, entraining air. Ignition would result in a jet fire.

The potential for fatality due to exposure to heat radiation from a jet fire (including direct exposure to the jet) was included in the QRA.

5.4.3 Flash Fire

Ignition of an unconfined gas or vapour cloud will usually progress at low flame front velocities and will not generate a significant explosion overpressure. Unobstructed combustion of the gas cloud is referred to as a flash fire, which has the potential to cause injuries or fatalities for individuals within the ignited cloud.

A flash fire was included in the QRA as a potential outcome for all the gas releases. The potential for fatality due to direct exposure to a flash fire was included in the QRA.

5.4.4 Vapour Cloud Explosion

A high degree of confinement and congestion is required to produce high flame speeds (i.e., > 100 m/s) in a flammable gas or vapour cloud, due to promotion of turbulence and accelerated combustion. This may occur inside buildings and around obstacles (e.g., buildings, vehicles, trees etc.). The potential for fatality due to direct exposure to a vapour cloud explosion was included in the QRA.

5.4.5 Gas Ingress into Buildings

There is potential for flammable gas to be drawn into buildings through ventilation air intake, and through open doors or windows. If the gas concentration within the cloud is in the flammable region, an ignition within the building would result in a confined explosion with serious harm to occupants and structural damage. There is potential for fatalities, which has been included in the QRA. Refer to Assumptions No. 22 in Appendix A.

5.4.6 Toxic Smoke

Large quantities of smoke can be produced from hydrocarbon fires; however, this is rarely injurious for persons at ground level due to the buoyancy of the hot plume and its subsequent dispersion at heights well above ground level. Ethane is a relatively clean burning fuel and the potential for injury due to smoke exposure was not carried forward to the consequence, likelihood, and risk estimation steps of the QRA as the smoke plume would rise above the building roof height.

5.5 Control Measures

Under the NSW Pipelines Act (1967) and Pipeline Regulations (2013), a pipeline operator must ensure the design, construction, operation, and maintenance of a licensed pipeline is in accordance with the relevant provisions of Australian Standard AS 2885 [4] for gas and liquid petroleum pipelines.

A licensee must implement a pipeline management system that relates to the pipeline operated under the licence and is in accordance with the relevant provisions of AS 2885.

5.5.1 Prevention of Mechanical Failure

Operators of licensed pipelines under the NSW Pipelines Regulation 2013 are required to develop and implement systems and processes to ensure the pipeline structural integrity for the design life of the pipeline in accordance with Section 6 of AS 2885.3:2012 [7] as part of the pipeline management system.

Continual monitoring is required while the pipeline is in operation to ensure that pipeline structural integrity is maintained. They shall not be operated above the maximum allowable operating pressure (MAOP). Anomalies should be assessed, and defects repaired.

5.5.2 Corrosion Prevention

Operators of licensed pipelines under the NSW Pipelines Regulation 2013 are required to develop and implement systems and processes to ensure the pipeline structural integrity for the design life of the pipeline. (As per Section 6 of AS 2885.3:2012) as part of the pipeline management system. This should include corrosion protection systems.

Two key control measures are typically implemented by pipeline operators to minimise the likelihood of failure due to corrosion: cathodic protection systems and external pipe coatings.

The Moomba to Sydney Ethane Pipeline is inspected using ‘intelligent pigging’ and has a significant wall thickness (11.9 mm). It is equipped with a cathodic protection system and a double layered HDPE coating.

5.5.3 Prevention of Damage due to Ground Movement and Other Failures

Normal loads (e.g., due to the internal and external pressure, weight of soil, traffic loads, etc.) and occasional loads (e.g., due to flood, earthquake, transient pressures in liquid lines and land movement due to other causes) are considered during design of a pipeline (as per AS2885.1:2012). To comply with AS2885.1:2012 [8], additional depth of cover may also be required where the minimum depth of cover cannot be attained because of the action of nature (e.g., soil erosion, scour).

5.5.4 Prevention of Damage due to Third Party Activity

Operators of licensed pipelines under the NSW Pipelines Regulation 2013 are required to undertake a Safety Management Study (as per Section 11 of AS 2885.3:2012) to assess the risks associated with threats to the pipeline and to instigate appropriate measures to manage the identified threats.

Two key control measures are typically implemented by pipeline operators to minimise the likelihood of impact from TPA: the ‘Dial Before You Dig’ (DBYD) process and daily / weekly patrols.

Statistical data indicates that the pipelines in NSW are 100% cathodically protected with effectiveness between 95 and 100%, and that over 96% of parties contacted DBYD before any excavation work [9].

The probability of leak on impact depends on the pipeline wall thickness. The depth of cover may also reduce the likelihood of impact.

5.5.5 Mitigation Control Measures

Operators of licensed pipelines under the NSW Pipelines Regulation 2013 are required to develop and implement an Emergency Response Plan (as per Section 11 of AS 2885.3:2012) as part of the pipeline management system.

The Emergency Response Plan should detail the response and recovery strategies and procedures to address all pipeline related emergency events, including loss of containment; full-bore pipeline rupture; fires; and, natural events.

Leaks may be detected during visual inspections, incident notifications and/or by instrumented monitoring systems. If a leak is detected, then the HP pipelines can be isolated by closing automated and/or manual valves.

5.6 Major Accident Events for Risk Analysis

The list of MAEs included in the risk analysis is provided in Table 11.

Table 11 - List of MAEs

Major Accident Event (MAE)	Potential Consequences
Release of High-Pressure Ethane from APA Moomba-Sydney Ethane Pipeline	Jet Fire, Flash Fire or Explosion
Release of High-Pressure Ethane from Marsh Street MLV	Jet Fire, Flash Fire or Explosion

6. Consequence Analysis

6.1 Release of Flammable Liquid / Gas

6.1.1 Representative Hole Diameter

Representative hole diameters were selected for the consequence modelling. These were selected to align with the leak frequency data (Refer to Appendix C), which includes four-hole size categories: pinhole (≤ 25 mm); small hole (> 25 mm to ≤ 75 mm), large hole (> 75 mm to ≤ 110 mm); and rupture (> 110 mm). The representative hole diameter/s in each hole size category were selected based on a review of the available historical data (Refer to Appendix B.1):

- Leaks from underground pipelines in the pinhole size category tend to be larger for TPA incidents (i.e. typically c. 20 mm to 25 mm - Refer to Appendix D) than for the other failure modes (i.e. typically less than c. 10 mm). Therefore, two representative hole diameters were selected in this category: 25 mm for TPA and 10 mm for all other failure modes.
- There is insufficient historical incident data for ethane to determine the representative hole diameter/s in each hole size category. Therefore, the representative hole diameters were assumed to be the same as proposed by the UK HSE for LPG.

Table 12 - Representative Hole Diameters Selected for Consequence Analysis

Pipeline/s	Internal Diameter (mm)	Representative Hole Diameter (mm)			
		Pinhole (≤ 25 mm)	Small Hole (> 25 mm to ≤ 75 mm)	Large Hole (>75 mm to ≤ 110 mm)	Rupture (>110 mm)
MSE	202.9	10 or 25*	75	110	Full bore

*10 mm for all failure modes except TPA. 25 mm for TPA only.

6.1.2 Discharge Model

Release events were modelled using the 'Long Pipeline' model in Safeti. The estimated peak release rates are tabulated below for each representative hole size. Further detail on release rates, including the time varying release rates, are contained in Appendix D

Table 13 - Representative Hole Diameters Selected for Consequence Analysis

MAE	Hole Diameter (mm)	Peak Release Rate [kg/s]
Release of High-Pressure Ethane from MSE	10	3.5
	25	21.9
	75	96.7
	110	208
	FBR	656
Release of High-Pressure Ethane from Marsh Street MLV	25	21.1
	75	96.7
	110	208
	FBR	656

6.1.3 Height and Orientation of Release

The release of high-pressure gas or liquefied gas from a buried pipeline would result in a crater and gas would be released vertically from the crater [10]. The Safeti Gaspipe module determines a crater size and air entrainment for a release from a buried pipeline originating at ground level.

Above ground releases from the Marsh Street MLV station have been modelled as releases oriented 45° above the horizontal. This is to account for the large embankment at Marsh Street. Justification is provided in Assumptions No. 13.

6.1.4 Duration of Release

Ethane is flammable and any adverse impact of flammable hazards will occur quickly (fire or explosion); therefore, the duration of exposure is not as critical as it would be if there were a toxic material in the pipelines (i.e., where the adverse impact can significantly increase for longer exposure durations).

The isolation time and duration of release is not specified in the QRA as these will be significantly longer than the period of exposure required for an adverse effect to people (Refer to Section A.6) and the time required for each representative release case to reach steady state.

Duration of release becomes significant only from a fire escalation point and not required for risk assessment based on short duration exposure to fire.

6.2 Fire Modelling

Safeti was used to model all the representative fire events included in the risk analysis. The key data and assumptions used to model the representative fire events are included in Appendix A.4.

6.2.1 Jet Fire

Example distances to heat radiation levels of 4.7, 12.5, 23 and 35 kW/m^2 are tabulated in Appendix D for representative jet fire events included in the risk analysis.

6.2.2 Flash Fire

Example distances to the lower flammability limit (LFL) concentration are tabulated in Appendix D for representative flash fire events included in the risk analysis.

6.3 Vapour Cloud Explosion

When a flammable vapour cloud ignites, the flame front advances as the cloud burns. If there are obstacles in the path of the flame front, the level of turbulence increases causing accelerated burning and thus the flame front accelerates, reaching speeds of 100-200 m/s. The whole combustion process occurs over a period of less than a second, but this short burst of high-speed flame front results in a blast wave, resulting in a pressure above the atmospheric pressure on the target surface (referred to as blast overpressure).

The blast wave can cause damage to the structure and injury/ fatality to exposed individuals and is commonly called vapor cloud explosion (VCE).

The Multi-Energy model in Safeti was used to estimate the overpressure for a VCE. Results are provided in Appendix D.

7. Risk Analysis

7.1 Individual Risk of Fatality

The risk contour for individual risk of fatality at 1.0 x 10^{-6} (red) and 0.5 x 10^{-6} (yellow) per annum (p.a.) for the MSE is shown in Figure 9. The red contour corresponds to the individual risk criteria for residential and hotel developments according to HIPAP 4 (1.0 x 10^{-6} risk per year).

Figure 9: Location Specific Individual Risk Contours

7.2 Risk of Acute Toxic Injury or Irritation

No events with the potential to cause acute toxic injury or irritation were identified for inclusion in the risk analysis (Also refer to Section 5.4.6); therefore the proposed rezoning complies with the relevant DPE risk criteria (Refer to Section 4.4.2).

7.3 Risk of Property Damage and Accident Propagation (Exceeding 14 kPa or 23 kW/m^2)

Neither the cumulative risk of overpressure exceeding 14 kPa nor the cumulative risk of heat radiation exceeding 23 kW/m^2 reach 50 x 10^{-6} per annum. The property damage and accident propagation criteria are satisfied (Refer to Section 4.4.3).

7.4 Injury/Damage Risk Criterion for Explosion Overpressure

The DPE criteria for injury risk applies to the hotel development. The cumulative risk of injury (overpressure exceeding 7 kPa) does not reach 50 x 10^{-6} per annum; therefore, the proposed rezoning complies with the DPE injury/damage risk criterion for explosion overpressure (Refer to Section 4.4.2) within residential and sensitive use areas.

7.5 Injury Risk Criterion for Heat Radiation

The cumulative risk of injury (Heat radiation exceeding 4.7 kW/m^2) does not reach 50 x 10^{-6} per annum; therefore the proposed rezoning complies with the DPE injury risk criterion for heat radiation (Refer to Section 4.4.2) within residential and sensitive use areas.

7.6 Qualitative Risk Criteria

Irrespective of the numerical value of any risk criteria level for risk assessment purposes, it is essential that certain qualitative principles be adopted concerning the land use safety acceptability of a proposed development or existing activity. The proposed development is considered to comply with the qualitative risk criteria outlined in HIPAP No. 4, as follows:

- **Avoidance of all 'avoidable' risks** – The pipeline is an existing facility and cannot be relocated to avoid risk exposure. While redevelopment of current recreational space could theoretically be avoided, there are significant societal benefits from the redevelopment proposed such as generation of economic activity, generation of ongoing employment activity, locating logistics centres near Sydney Airport to reduce transport related issues.

- **Reduction, wherever practicable, of the risk from a major hazard, even where the likelihood of exposure is low**. This would require a review of the proposed development details to determine if refinements can be made to focus residential intensification in the Study Area further from the MSE.

- **Containment, wherever possible, within the site boundary of the effects (consequences) of the more likely hazardous events**. There are no further reasonably practicable means of containing the effects of hazardous release from the MSE.

- **Recognition that if the risk from an existing installation is already high, further development should not be permitted if it significantly increases that existing risk.** The risk levels within the development area from the MSE are below the criteria for commercial development, sporting complexes and active open space, and industrial development. Hence, the office, retail and logistics components of the development are unrestricted by the HIPAP 4 criteria. Components of the development subject to criteria for residential or sensitive use have been located in areas where the criteria are satisfied.

7.7 Societal Risk

An F-N curve depicting the societal risk from the Moomba- Sydney Ethane pipeline in the Study Area before and after the redevelopment is shown in Figure 10. There is a noticeable increase in societal risk at all points along the F-N curve below 300 fatalities, but when the Study Area is fully developed, the risk is still within the ALARP region.

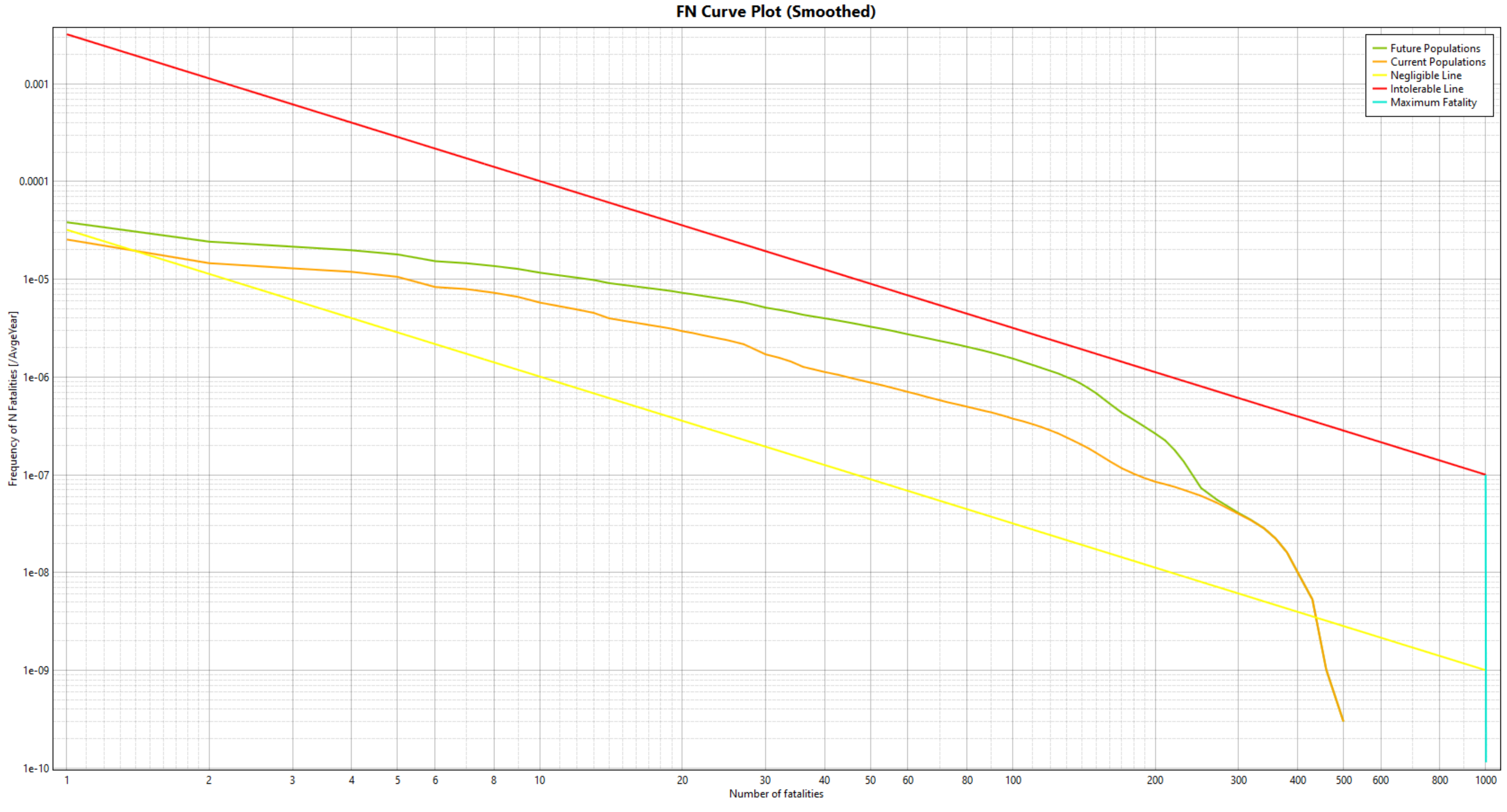

Figure 10: Societal Risk F-N Curve before and after development

8. Findings and Recommendations

8.1 Findings

The following findings were made from the risk assessment:

- The level of risk at the proposed hotel location is less than 1.0 x 10^{-6} p.a. The proposal for a hotel at the location satisfies the DPE criteria for residential use.
- The individual risk of fatality never exceeds 5.0 x 10^{-6} p.a. and therefore intensification of other land uses (business use) as proposed is consistent with DPE criteria.
- The societal risk, represented as an F-N curve, is within the ALARP region and below the upper limit of the risk tolerability band. This level of societal risk does not preclude the changes envisaged.

8.2 Recommendations

While the land uses proposed satisfy the DPE criteria for land use safety planning, the following recommendations are made to reduce risk so far as is reasonably practicable:

1. The construction of buildings should consider the hazards arising from the Moomba-Sydney Ethane (MSE) Pipeline and ensure in the event of a release and ignition of ethane from the MSE, there is adequate means of egress from the building to a place of safety, or alternatively, there is a suitable place of refuge within the building that remains tenable until the release is isolated.
2. In conjunction with recommendation 1, emergency response plans for the buildings should consider the potential hazards arising from the MSE.
3. Sensitive use activities such as children's activity centres, play gyms, etc. should be prevented within the buildings that encroach the 0.5 x 10^{-6} p.a. risk contour.

9. References

[1] NSW Department of Planning, “Hazardous Industry Planning Advisory Paper No.6 - Hazard Analysis,” Sydney, 2011.

[2] Health and safety Laboratory, “Research Report RR 1035 - Update of pipeline failure rates for land use planning assessments,” HSE Books, London, 2015.

[3] NSW Department of Planning, “Hazardous Industry Planning Advisory Paper No.10 - Land Use Safety Planning,” Sydney, 2011.

[4] NSW Department of Planning, “Hazardous Industry Planning Advisory Paper No.4 - Risk Criteria for Land Use Safety Planning,” Sydney, 2011.

[5] Standards Australia, “AS 2885.0 - Pipelines - Gas and Liquid Petroleum. Part 0 - General Requirements,” 2008.

[6] A. B. o. Statistics, “Search Census Data,” 2021. [Online]. Available: https://www.abs.gov.au/census/find-census-data/search-by-area.

[7] Occupational Safety and Health Administration, “Precautions and the order of testing before entering confined and enclosed spaces and other dangerous atmospheres.,” US Department of Labour, Washington, D.C, 1995.

[8] Standards Australia, “Pipelines - Gas and Liquid Petroleum Operations and Maintenance,” 2012.

[9] Standards Australia, “Pipelines - Gas and liquid petroleum Design and construction,” 2018.

[10] NSW Planning & Environment, “New South Wales 2017-18 Gas Networks Performance Report,” 2018.

[11] DNVGL, “SAFETI 8.2.3 Technical reference manual,” 2019.

[12] C. Symonds, “Experience with the Australian/New Zealand Pipeline Incident Database,” 2018.

Appendices

Appendix A

Assumptions

It is necessary to make technical assumptions during a risk analysis. These assumptions typically relate to specific data inputs (e.g. material properties, equipment failure rates, etc.) and modelling assumptions (e.g. release orientations, impairment criteria, etc.).

To comply with the general principles outlined in Section 2.2 of HIPAP No. 6, all steps taken in the risk analysis should be: "*traceable and the information gathered as part of the analysis should be well documented to permit an adequate technical review of the work to ensure reproducibility, understanding of the assumptions made and valid interpretation of the results*". Therefore, details of the key assumptions adopted for the risk analysis are provided in this Appendix.

Each assumption is numbered and detailed separately. The basis for each assumption is explained together with its potential impact on the risk results and the MAEs potentially affected. Key references are also listed for each assumption, where relevant.

It is important that the assumptions be supported by:

- experimental data in the literature, where available;
- actual operating experience, where available;
- similar assumptions made by experts in the field and a general consensus among risk analysts; and
- the engineering judgement of the analyst.

The main objectives are to minimise uncertainty in the risk estimate as far as is possible, and to ensure that the assumptions result in a 'conservative best estimate' of the risk. Such an approach is consistent with the following extract from Section 5 of HIPAP No. 6:

"*In the consequence analysis and throughout the hazard analysis, the analyst must be conscious of the uncertainties associated with the assumptions made. Assumptions should usually be made on a 'conservative best estimate' basis. That is, wherever possible the assumptions should closely reflect reality. However, where there is a substantial degree of uncertainty, assumptions should be made which err on the side of conservatism.*"

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A.1 Operational Data

Assumptions No. 1 - Pipeline Operating Conditions

Assumption No. 1 Pipeline Operating Conditions
Subject: Operational Data
Assumption/s: • All pipeline operating conditions (pressure, temperature, etc.) are as reported in Section 3.3
Justification and Impact/s of Assumption/s: • All operational data for the pipelines were provided by the pipeline owner (APA Group). • Operating conditions (particularly operating pressure) are required to undertake the release and dispersion modelling.
MAE/s Affected: • All.
Reference/s: • Data provided by APA Group.

Assumptions No. 2 - Pipeline Utilisation

Assumption No. 2 Pipeline Utilisation
Subject: Operational Data
Assumption/s: • The pipeline is utilised 100% of the time.
Justification and Impact/s of Assumption/s: • Utilisation data is required to undertake the release and dispersion modelling and to estimate the release frequency.
MAE/s Affected: • All.
Reference/s: • Data provided by APA Group.

A.2 Locational Data

Assumptions No. 3 - Representative Wind Speeds, Wind Directions and Stability Classes

Assumption No. 3	Representative Wind Speeds, Wind Directions and Stability Classes
Subject:	Locational Data

Assumption/s:

- Representative weather data is based upon 25 years of observations at Sydney Airport, BoM Station ID 066037.
- The probabilistic distribution of wind speed and wind direction for the representative stability classes is provided in Section 3.
- The data was split into daytime and night-time conditions.
- Night-time is considered the period from 1 hour before sunset, to one hour after sunrise. This approximates to 10 hours daytime and 14 hours night-time.

Justification and Impact/s of Assumption/s:

- Sydney Airport is the closest meteorological station to the study area and is located directly across Cooks River from the study area.
- Raw data from Sydney airport observations have been rationalised into a set of wind speed/weather stability classes for dispersion calculations.
- Wind will cause flames to tilt downwind. The higher the wind speed, the greater the tilt. The net effect of the tilt is to increase the heat radiation in the downwind direction. This is much more pronounced for pool fires than jet fires because jet fires have much greater momentum. An allowance for flame tilt is included in the Safeti models for pool fires and vertical jet fires. The Safeti model assumes horizontal jet fires are directed in the same direction as the wind.
- The downwind gas concentrations, and hence the hazard ranges for dispersion of flammable gas or vapour, vary with wind speed and weather stability class. Therefore, multiple representative wind speed and stability class categories are included in accordance with standard practice for undertaking a quantitative risk assessment (QRA).
- The day/night split of the weather data is required to allow for the fact that residential, commercial, and industrial occupancies change over a 24-hour period.

MAE/s Affected:

- All.

Reference/s:

- BoM meteorological data for Sydney Airport AWS.

Assumptions No. 4 - Surface Roughness Length

Assumption No. 4 Surface Roughness Length

Subject: Locational Data

Assumption/s:

- A conservative roughness length of 0.5 m is applicable for Cook\s Cove.

Justification and Impact/s of Assumption/s:

- The roughness length for different surface types, as listed in the Safeti user manual, is shown below in **Table 14**. The Cooks Cove development is located adjacent Botany Bay and Sydney airport to the East and South. These could be described as “open flat terrain”. In all other directions (from SSW through to ENE), there is significant suburban development.

Table 14 - Surface Roughness Length

Description	Roughness Length (m)
Open water, at least 5 km	0.0002
Mud flats, snow, no vegetation, no obstacles	0.005
Open flat terrain, grass, few isolated objects	0.03
Low crops; occasional large obstacles, x/h > 20	0.1
High crops, scattered large obstacles, 15 < x/h < 20	0.25
Parkland, bushes, numerous obstacles, x/h < 15	0.5
Regular large obstacle coverage (suburb, forest)	1
City centre with high- and low-rise buildings	3

- The surface roughness affects the dispersion analysis. As the surface roughness increases, a release of gas or vapour will disperse more quickly with increasing distance from the source. Therefore, it is necessary in Safeti to select a surface roughness length that is representative of the types of terrain and obstacles near the source of release.
- It is not possible to define different surface roughness lengths for different locations within a single Safeti model. Only a single representative value can be defined for the entire area.

MAE/s Affected:

- Dispersion modelling for all relevant MAEs.

Reference/s:

- Safeti software documentation.

Assumptions No. 5 - Location of High-Pressure Gas Pipelines

Assumption No. 5	Location of High-Pressure Gas Pipelines
Subject:	Locational Data
Assumption/s: • The location of the pipelines is sourced from the Australian Pipeline and Gas Association's (APGA) Australian Pipeline Database (APD).	

Justification and Impact/s of Assumption/s:
• The Australian Pipeline Database (APD) is made available to users to raise awareness of the location of high-pressure hydrocarbon pipelines and facilitate discussions between pipeline operators and stakeholders regarding the potential for planning and development decisions to trigger requirements in the Australian Standard, AS 2885, for pipeline Safety Management Studies.
• Use of the APD is conditional on several factors that are consistent with the objectives of this study, including:
  • The APD is to be used solely for the purpose of facilitating discussion regarding planning activity and decisions in the vicinity of pipelines. **This is consistent with the objectives of this study.**
  • The APD is not to be used for proving and construction activities. Dial Before You Dig enquiries must be made for these activities and any condition complied with. **It is not the intent of this study to provide detailed construction information.**
• When overlayed onto aerial photos, the APGA Pipeline database accuracy appears no less accurate than the accuracy expected of the consequence models and frequency estimates.	

MAE/s Affected: • All.	
Reference/s: • APGA Australian Pipeline Database	

Assumptions No. 6 - Residential Population (Day and Night)

Assumption No. 6	Residential Population (Day and Night)
Subject:	Locational Data
Assumption/s: • The current residential population of areas outside the development is based upon the Census of Population and Housing, 2021, obtained from the Australian Bureau of Statistics TableBuilder service. The population is based upon Statistical Area Level 1.	
Justification and Impact/s of Assumption/s: • The 2021 Census data is the latest available data.	
MAE/s Affected: • All societal risk calculations. Population density, along with the area of consequence distances, determines the F-N points of societal risk. • Locational specific risk is not impacted by these assumptions.	
Reference/s: • Census of Population and Housing, 2021, TableBuilder**.**	

Assumptions No. 7 - Development Population (Day and Night)

Assumption No. 7	Development Population (Day and Night)
Subject:	Locational Data

Assumption/s:

- There is one hotel employee per 100 $m^2$of hotel GFA. 80% of employees are present during the day, 20 % at night.
- There are 383 guests at the hotel, present 100% of the time.
- Office use buildings will have one employee per 25 $m^2$of office GFA, present during daytime only.
- Retail use buildings will have one employee per 25 $m^2$of retail GFA, present during daytime only.
- Logistics buildings will have one employee per 74 $m^2$of GFA. 80% of employees are present during the day, 20 % at night.

Justification and Impact/s of Assumption/s:

- The number of hotel employees was estimated based upon information contained within development applications for three comparable State Significant Developments:

Development	Jobs	GFA (m^2)	m^2/job	Note
Crown (SSD-6957)	3300	77500	23	This is denser than the two below, but presumably includes casino operations and much larger restaurant, entertainment, and gaming facility. For this reason, the Crown development is not an appropriate comparison with the Cooks Cove proposal.
301 and 305 Kent Street concept hotel development (SSD-9694)	80	11301	141	The number of jobs is stated as FTE, and hence total over all time periods (i.e. includes both day and night staff)
Intercontinental (SSD 7693)	390	40664	104	This is based on the existing site area and employment. Includes full time, part time and casual staff

- Hotel guests have been based on hotel occupancy of 85% and 1.5 guests per room.
- Other densities have been arrived at in consultation with DPE

MAE/s Affected:

- All societal risk calculations. Population density, along with the area of consequence distances, determines the F-N points of societal risk.
- Locational specific risk is not impacted by these assumptions.

Reference/s:

Environmental Impact Statement, New Ballroom Addition, Additions to the Roof Lounge and Comprehensive Hotel Upgrade, Intercontinental Hotel and Transport House, Macquarie Street, Sydney; BBC Consulting Planners.

301 & 305 Kent Street and 35–39 Erskine Street, Sydney Environmental Impact Statement; Architectus.

State Significant Development Application SSD 15_6957 Environmental Impact Statement; JBA Urban Planning Consultants Pty Ltd**.**

Assumptions No. 8 - Indoor / Outdoor distribution of people

Assumption No. 8 Indoor / Outdoor distribution of people

Subject: Locational Data

Assumption/s:

- 99% of the night-time population will be located indoors.
- 90% of the daytime population will be located indoors.
- All population is located at ground level.

Justification and Impact/s of Assumption/s:

- The default values recommended by the TNO [‘Purple Book’] for residential and industrial areas are tabulated below.

Table 15 - Proportion of Population Indoor and Outdoor During Day and Night [TNO]

Location	Day Time	Night Time
Indoor	93%	99%
Outdoor	7%	1%

- The % of the total population located indoors and outdoors was estimated from similar risk analyses (including some data provided by DPE). It is reported in these analyses that the % of people indoors and outdoors is 90% indoors and 10% outdoors during the day, which differs slightly from the TNO data, but is typically justified as being more applicable for Australian environmental conditions. Similarly, it is reported in these analyses that the % of people indoors and outdoors is 95 to 99% indoors and 1 to 5% outdoors during the night.

MAE/s Affected:

- All societal risk calculations

Reference/s:

- TNO, VROM, ***Guidelines for Quantitative Risk Assessment***, 'Purple Book', CPR18E, 3rd Edition.

A.3 Risks Analysis Methodology

Assumptions No. 9 - Location and Segmentation of Pipelines

Assumption No. 9	Location and Segmentation of Pipelines
Subject:	Risk Analysis Methodology
Assumption/s: • Representative release events are modelled using the 'Long Pipeline' model in Safeti, which distributes these events along the pipeline at set intervals.	
Justification and Impact/s of Assumption/s: • The 'Long Pipeline' model in Safeti is used to estimate the time-dependent release from a long pipeline. The 'Long Pipeline' model includes inputs for use in the risk calculations, such as pipeline burial depth, leak frequency, etc. • The interval at which representative incidents are distributed along the pipeline is selected automatically by the 'Long Pipeline' model based on the incident consequence.	
MAE/s Affected: • All.	
Reference/s: • Safeti software documentation**.**	

A.4 Consequence Analysis

Assumptions No. 10 - Representative Materials

Assumption No. 10	Representative Materials
Subject:	Consequence Analysis
Assumption/s: • Ethane is modelled as 100% ethane.	
Justification and Impact/s of Assumption/s: • The composition and materials used affect the magnitude of the consequences. Materials containing multiple components are simplified for modelling purposes by choosing a representative component to best approximate the variable composition. Modelling a representative material rather than a multi-component material reduces complexity, limits the potential for inconsistencies and ultimately has a minimal effect on the results. • The pipeline carries ethane which has been processed to serve as a petrochemical feed stock.	
MAE/s Affected: • All.	
Reference/s: • Data provided by APA Group.	

Assumptions No. 11 - Pressure and Flow for Release Modelling

Assumption No. 11	Pressure and Flow for Release Modelling
Subject:	Consequence Analysis

Assumption/s:

- A release of ethane from the Moomba to Sydney Ethane Pipeline is modelled at 8.2 MPag (Operating pressure), compared to an MAOP of 10 MPag.
- The mass flowrate of ethane through the pipeline is 30 tonnes per hour.
- Release events are modelled using the 'Long Pipeline' model in Safeti. Ten different release rates over the first 5 minutes of release are used for hole sizes 75 mm and above. The release rates are selected by Safeti so that the same mass is released in each segment.
- The release rates used for consequence modelling are dependent upon the type of consequence modelled:
  - The release rate for jet fires is the average rate over the first 30 seconds of the release – being equal to the assumed exposure to a jet fire (and hence worst case assuming immediate ignition).
  - Dispersion calculations are based on 10 different observer rates, equivalent to the 10 release rates and intervals as discussed above.
- For hole sizes less than 75 mm, the pipeline maintains a constant pressure at the release point. This also implies a constant release rate at the point of release.

Justification and Impact/s of Assumption/s:

- The release rate is dependent on the pressure and the MAOP is the maximum pressure permitted under an existing licence.
- The pressure used to model the release rates was based on the pipeline pressure near the proposed development, as advised by the pipeline owner.
- The long pipeline model assumes the input pressure is reduced by frictional losses along the pipeline length until the breach point. This results in a lower pressure at the release point that the operating pressure and hence also a lower release rate.
- Providing a flow will slow the rate of pressure reduction calculated by the long pipeline model.
- HIPAP 6 does not include guidance on the use of time dependent or multiple release rates. The Netherlands *Reference Manual Bevi Risk Assessments* states: "*In exceptional cases, it is possible to deviate from the approach set out above. In particular, this includes situations in which the duration of outflow is greater than 50 s and the outflow rate reduces significantly in the period from 0 to 1800 s. In such a situation it is possible to assume a time-dependent outflow, in which case at least five segments are defined*". The pressure in the pipeline drops rapidly for large hole sizes and the analysis uses 10 release rates, double the minimum recommended in the Bevi Manual.

MAE/s Affected:

- All.

Reference/s:

- Data provided by APA Group.

Assumptions No. 12 - Representative Hole Diameters for Release Modelling

Assumption No. 12	Representative Hole Diameters for Release Modelling
Subject:	**Consequence Analysis**

Assumption/s:

- **Consequence modelling is based on the following representative hole diameters:**

Table 16 - Representative Hole Diameters Selected for Consequence Analysis

Pipeline/s	Material	Internal Pipeline Diameter (mm)	Representative Hole Diameter (mm)			
			Pinhole	Small Hole	Large Hole	Rupture
			(≤ 25 mm)	(> 25 mm to ≤ 75 mm)	(> 75 mm to ≤ 110 mm)	(> 110 mm)
APA Ethane Pipeline	Ethane	202.9	10 or 25*	75	110	Full bore

* 10 mm for all failure modes except Third Party Activity (TPA). 25 mm for TPA only.

Justification and Impact/s of Assumption/s:

- The representative hole diameters were selected to align with the leak frequency data (Refer to Appendix CError! Reference source not found.), which includes four-hole size categories: p inhole (≤ 25 mm); small hole (> 25 mm to ≤ 75 mm), large hole (> 75 mm to ≤ 110 mm); and rupture (> 110 mm). The representative hole diameter/s in each hole size category were selected based on a review of the available historical data (Refer to Appendix B.1):
  - Leaks from underground pipelines in the pinhole size category tend to be larger for TPA incidents (i.e., typically c. 20 mm to 25 mm – Refer to Appendix C) than for the other failure modes (i.e., typically less than c. 10 mm). Therefore, two representative hole diameters were selected in this category: 25 mm for TPA and 10 mm for all other failure modes.
  - There is insufficient historical incident data for ethane to determine the representative hole diameter/s in each hole size category. Therefore, the representative hole diameters were assumed to be the same as proposed by the UK HSE for LPG (Refer to Appendix C.1.1). Ethane is transported as a liquefied flammable gas.

MAE/s Affected:

- All.

Reference/s:

- Refer to Appendix B.1

Assumptions No. 13 - Location of Release for Transmission Pipelines

Assumption No. 13	Location of Release for Transmission Pipelines
Subject:	Consequence Analysis

Assumption/s:

- High pressure gas releases would create a crater on the ground. The direction of release for underground pipeline failures from the crater is always vertical.
- The location of failure on the pipe can be taken as:
  - Top of the pipe (unobstructed releases); or
  - Middle of the pipe (on the side – obstructed releases).
- The release frequency is distributed between the two locations (37% from middle of pipe and 63% from top of pipe for all release cases except non-TPA events with a hole size less than or equal to 25mm, which are modelled as 100% from middle of pipe).
- Above ground releases at the Marsh Street valve station have been modelled angled 45° from the horizontal originating at a height of 1 m.

Justification and Impact/s of Assumption/s:

- The crater size depends on the location of the hole on the pipe and hence all three locations (top, middle and bottom) may be modelled (DNV, 2020). Top releases are taken as non-obstructed releases and middle/ bottom releases are taken as obstructed releases.
- Impingement reduces the momentum of the release, and the dispersion modelling is dominated by the representative wind conditions.
- The UK HSE [RR 1034] reports that some data from UKOPA includes the 'hole circumferential position' for releases from underground pipelines. Based on the 71 recorded incidents (All pipelines and materials) and average crater dimensions, an unobstructed release (c. ±71° from vertical) was estimated to occur for 63% of the releases and an obstructed release was estimated to occur for the balance (37% of releases). The distribution is not reported for different failure modes.
- Horizontal releases at 1 m are typical assumptions for QRA and the layout of the valve stations does not give rise to any compelling reason to deviate from this practice.
- The Marsh Street valve station is located close to a road embankment, which separates the valve station from most of the development. Horizontal releases directed towards the hotel and office components of the development would impinge the embankment. Making all releases from 45° from the horizontal better reflects the impact on the development. Parts of the development to the north of the valve station will still be within the 35 kW/m^2 radiation zone of substantial releases when modelled at 45°. Further distant on the north side is open space, so the reduction in length to hazardous radiation is unlikely to impact societal risk calculations. The buried pipeline is still the major contributor to individual risk.
- Diagrams below highlight the arrangement of the valve station, its location in relation to the embankment, and the width of the embankment (carrying six lanes of traffic).


NOVOTEL

MAE/s Affected:

- All.

Reference/s:
• Safeti software documentation. • UK HSE, 2015, *Review of the Event Tree Structure and Ignition Probabilities used in HSE's Pipeline Risk Assessment Code MISHAP*, Research Report (RR) 1034.

Assumptions No. 14 - Maximum Extent of Flash Fire

Assumption No. 14- Maximum Extent of Flash Fire
Subject: Consequence Analysis
Assumption/s: • The maximum extent of a flash fire is defined by the downwind and crosswind distances from the release location to a concentration equal to 100% of the lower flammability limit (LFL) concentration calculated using an 18.75 s averaging time.
Justification and Impact/s of Assumption/s: • Justification is provided in (Benintendi, 20171031, p. 341): For passive dispersion models, the shorter the averaging time, the higher the centreline concentration, and there is concern that flammable concentrations may exist beyond the 100% LFL contour determined for a specific averaging time. To take into account the different averaging times, the following empirical formula is recommended for converting concentrations from 10 minute averaging time to another (Hanna et al., 1993): $\frac{C_t}{C_{600}} = \left(\frac{600}{t}\right)^{0.2}$ …(1) where time is in seconds. C_t denotes time averaged concentration at the new averaging time of t seconds Hanna claims that experimentally: $C_{max} = 2 \times C_{600}$ …(2) where C_{max} is the maximum peak concentration in the plume. Substituting C_{max} from (2) with $C_{600}\left(\frac{600}{t}\right)^{0.2}$ from (1) and solving for t, it is yields *t = 18.75 s.* This time should be adopted to carry out worst case predictions for the extent of 100% LFL. It is the core averaging time for flammable dispersion in Safeti**.**
MAE/s Affected: • All MAEs with a flash fire as a potential outcome.
Reference/s: • Safeti software documentation. • Benintendi, R. (20171031). Process Safety Calculations. [[VitalSource Bookshelf version]]. Retrieved from vbk://9780081012291. • Hanna, S.R., Strimaitus, D.G., Chang, J., 1993. Hazard Response Modeling Uncertainty (A Quantitative Method) Vol 11 - Evaluation of Commonly Used Hazardous Gas Dispersion Models, Environics Division Air Force Engineering & Services Center, Engineering & Services Laboratory.

Assumptions No. 15 - Isolation Time and Duration of Release

Assumption No. 15Isolation Time and Duration of Release
Subject: Consequence Analysis
Assumption/s: • Isolation time and duration of release is not specified as these will be significantly longer than the period of exposure required for an adverse effect to people (Refer to Section A.6) and time required for each representative release case to reach steady state.
Justification and Impact/s of Assumption/s: • Ethane is flammable and any adverse impact will occur quickly (fire or explosion); therefore, the duration of exposure is not as critical as it would be if there were toxic materials in the pipeline (i.e., where the adverse impact can significantly increase for longer exposure durations). • The assumption is justified from the consequence calculations of the Long Pipeline Model, using a 20 sec. exposure time (user specified based on the Purple Book), compared to isolation valve closure times which typically vary from minutes (full bore rupture case) to hours (small to medium leaks).
MAE/s Affected: • All.
Reference/s: • Safeti software documentation. • TNO, VROM, *Guidelines for Quantitative Risk Assessment*, 'Purple Book', CPR18E, 3rd Edition.

Assumptions No. 16 - Shielding by Intervening Structures

Assumption No. 16Shielding by Intervening Structures
Subject: Consequence Analysis
Assumption/s: • The presence of intervening structures (e.g. buildings) does not shield other receptors from the heat radiation from a jet fire. • Only releases from the above ground section in relation to raised sections of Marsh Street have been modified to account for topography (refer **Assumptions No. 13**)
Justification and Impact/s of Assumption/s: • In the Safeti software, it is not possible to take account of the potential protection provided by intervening structures. • This analysis is taking place during the concept stage of development of a large growth area. There is insufficient information available to determine the location of large structures that could offer protection against radiant heat. • People located indoors are typically less vulnerable to fire, which is a relevant consideration for the societal risk assessment • The Marsh Street embankment will have a significant impact on the behaviour of above ground releases.
MAE/s Affected: • All MAEs with a pool fire or jet fire as a potential outcome, with the exception of releases from the above ground sections of pipeline.
Reference/s: • Safeti software documentation.

Assumptions No. 17 - 3D Explosion Model Parameters

Assumption No. 173D Explosion Model Parameters
Subject: Consequence Analysis
Assumption/s: • The maximum explosive mass in a flammable gas or vapour cloud is the maximum mass between the LFL and UFL concentration for that section of the cloud that overlaps a congested area. • The peak side-on overpressure resulting from an explosion is estimated using the Extended Explosion Modelling option in the Safeti software. • The severity of the blast is based on an unconfined blast strength of 4, with no specified obstruction region. • The blast strength is estimated based on the obstructed volume (%) and potential obstructions in each congested area. The following congested areas are included in the QRA: ◦ Buildings - A medium obstructed volume (60% for a residential building) and level of congestion is assumed to simulate entry of the gas or vapour into the building and the subsequent confined explosion. This equates to TNO Model curve number 4. • Only overpressure effects are included. Projectiles and whole-body displacement are not included.
Justification and Impact/s of Assumption/s: • The explosive mass and blast strength are key parameters for modelling the overpressure from a VCE. • There are no significantly congested locations in the study area; however, a confined explosion could occur if gas or vapour enters a building. • The open space between the buildings in the study area is not strictly a congested area; however, the presence of vehicles, trees etc. at ground level may contribute to flame acceleration and the formation of an overpressure if ignition occurs. Therefore, TNO Model curve number 4 was assumed to apply. • The 3D Obstructed Region Explosion Modelling option considers the interactions between the flammable cloud and obstructed regions that have been defined for the study area. This is more valid than simple models (e.g. TNT equivalence) which do not consider these interactions.
MAE/s Affected: • All MAEs with a VCE as a potential outcome.
Reference/s: • Centre for Chemical Process Safety, Estimating the flammable mass of vapour clouds", American Institute of Chemical Engineers, 1999. • TNO, VROM, 'Yellow Book'. • Safeti software documentation**.**

A.5 Likelihood Analysis

Assumptions No. 18 - Likelihood of Release (Loss of Containment)

Assumption No. 18- Likelihood of Release (Loss of Containment)
Subject: Likelihood Analysis
Assumption/s: • The likelihood of each representative release is provided in Appendix C.1.4 • The UK HSE pipeline failure rate data is the primary data used for the risk assessment.
Justification and Impact/s of Assumption/s: • The estimated likelihood of release (or loss of containment) is a critical and significant input for the risk analysis. The risk results are directly proportional to this input. • Generic failure rate data for cross-country pipelines from the UK, USA and Europe were reviewed. The UK data incorporates the European data. There are two sources of data from the UK: (a) HSE recommended data for land use safety planning (RR 1035); and (b) British Standards Institute PD 8010-3:2009+A1:2013. The HSE data is primarily used in this study, which is consistent with the NSW performance data. • The HSE data identifies four contributors to pipeline failure: (a) mechanical failure; (b) corrosion; (c) ground movement/other; and (d) Third Party Activity (TPA). Of these, mechanical, corrosion and TPA are similar to conditions in Australia and hence no frequency adjustments due to local conditions are justified. • The justification for the data used in this risk analysis is provided in Appendix C.1.1
MAE/s Affected: • All.
Reference/s: • Refer to Appendix C.1.1

Assumptions No. 19 - Ignition Probability

Assumption No. 19 -Ignition Probability
Subject: Likelihood Analysis
Assumption/s: • The probability of ignition for each representative release is provided in Appendix C.
Justification and Impact/s of Assumption/s: • The estimated probability of ignition is a critical and significant input for the risk analysis. The risk results are directly proportional to this input. • The justification for the data used in this risk analysis is provided in Appendix C**.**
MAE/s Affected: • All.
Reference/s: • Refer to Appendix C.

Assumptions No. 20 - Probability of VCE or Flash Fire

Assumption No. 20 – Probability of VCE or Flash Fire
Subject: Likelihood Analysis
Assumption/s: • Ignition of a free gas or vapour cloud is modelled as a flash fire in uncongested areas and as a vapour cloud explosion in congested areas. • Congested areas include buildings in the vicinity of the pipelines.
Justification and Impact/s of Assumption/s: • Ignition of a free gas cloud may demonstrate characteristics of a flash fire and/or an explosion. Safeti uses the delayed ignition probability resulting in either of the events. • Obstructed areas in the dispersing vapour cloud are defined by the user in the layout map. As the model calculates gas dispersion, it automatically calculates the consequence as vapour cloud explosion in congested areas and flash fires in uncongested areas. • The current version of Safeti, with the 3D obstructed area module, does not require a conditional probability of an explosion given ignition.
MAE/s Affected: • All MAEs with clouds in an obstructed region.
Reference/s: • Safeti software documentation. • TNO, VROM, *Guidelines for Quantitative Risk Assessment*, 'Purple Book', CPR18E, 3rd Edition.

A.6 Vulnerability Parameters

Assumptions No. 21 - Exposure to Heat Radiation from a Fire (Indoor or Outdoor)

Assumption No. 21Exposure to Heat Radiation from a Fire (Indoor or Outdoor)

Subject: Vulnerability Parameters

Assumption/s:

- For individuals located outdoors, the probability of fatality is based on the following probit equation [TNO 'Purple Book']:

$$Y = -36.38 + 2.56 \ln\left(I^{1.333} t\right)$$

  Where Y is the probit value, I is the heat radiation intensity (W/m^2) and t is the exposure duration (seconds).
- A maximum exposure duration of 30 seconds is applicable for individuals located outdoors in an urban setting. It is assumed after 30 seconds, the persons will have found shelter from heat radiation.
- The probability of fatality for an individual located outdoors (30 seconds exposure), as calculated using the above probit equation, is as follows:

Table 17 - Probability of Fatality for Exposure to Heat Radiation (Outdoor)

Heat Radiation Intensity (kW/m^2)	Probit	Probability of Fatality
4.7	1.19	0
12.6	4.55	0.32
15.9	5.35	0.63
23.0	6.61	0.94
35.0 *	8.04	1.0

* - Safeti assumes fatal injuries are incurred at 35 kW/m^2 and above, regardless of the exposure duration.

- For the calculation of societal risk:
  - The probability of fatality for individuals located outdoors is factored by 0.14 (Safeti default) to allow for the protection provided by clothing and the possibility of seeking shelter behind obstacles.
  - The probability of fatality for an individual located indoors is 0 at less than 35 kW/m^2 and 1.0 at 35 kW/m^2 or greater.

Justification and Impact/s of Assumption/s:

- The probit equation adopted for the risk analysis is generally consistent with the following data from HIPAP No. 4.

Table 18 - Effects of Thermal Radiation

Heat Radiation Intensity [kW/m^2]	Effect/s
1.2	Received from sun in summer at noon.
1.6	Minimum necessary to be felt as pain.
4.7	Pain in 15 to 20 seconds, 1st degree burns in 30 seconds. Injury (second degree burns) to person who cannot escape or seek shelter after 30s exposure.
12.6	High chance of injury. 30% chance of fatality for extended exposure. Melting of plastics (cable insulation). Causes the temperature of wood to rise to a point where it can be ignited by a naked flame after long exposure. Thin steel with insulation on the side away from the fire may reach a thermal stress level high enough to cause structural failure.
23.0	Fatality on continuous exposure. 10% chance of fatality on instantaneous exposure. Spontaneous ignition of wood after long exposure. Unprotected steel will reach thermal stress temperatures, which can cause failure. Pressure vessel needs to be relieved or failure would occur.
35.0	25% chance of fatality on instantaneous exposure.
60.0	Fatality on instantaneous exposure.

- It is reported in the TNO 'Purple Book' that people indoors are assumed to be protected from heat radiation until the building catches fire. The threshold for the ignition of buildings in the TNO 'Purple Book' is set at 35 kW/m^2 and if the building is set on fire, all the people inside the building are assumed to die (i.e. The probability of fatality indoors is 1 if the heat radiation exceeds 35 kW/m^2 and it is 0 if the heat radiation is less than 35 kW/m^2).

MAE/s Affected:

- All MAEs with a pool fire or jet fire as a potential outcome.

Reference/s:

- TNO, VROM, *Methods for the determination of possible damage*, 'Green Book', CPR16E.
- TNO, VROM, *Guidelines for Quantitative Risk Assessment*, 'Purple Book', CPR18E, 3rd Edition.

Assumptions No. 22 - Exposure to Flash Fire (Indoor or Outdoor)

Assumption No. 22 Exposure to Flash Fire (Indoor or Outdoor)
Subject: Vulnerability Parameters
Assumption/s: • For calculation of location-specific individual risk, the probability for fatality = 1 for any individual located within the flammable cloud (Distance to LFL concentration). • For calculation of societal risk, the probability for fatality for any individual located within the flammable cloud (Distance to LFL concentration) is 1 (outdoor) or 0.1 (indoor).
Justification and Impact/s of Assumption/s: • The assumed probabilities differ from the guidance in the TNO 'Purple Book' and the default values in the Safeti software. In both cases, the probability of fatality is set at 1 for all individuals (outdoor or indoor). This was considered too conservative. The probability of fatality indoors was set at 0.1 to take account of the possibility of open doors / windows and/or failure to evacuate.
MAE/s Affected: • All MAEs with a flash fire as a potential outcome.
Reference/s: • Safeti software documentation. • TNO, VROM, *Guidelines for Quantitative Risk Assessment*, 'Purple Book', CPR18E, 3rd Edition.

Assumptions No. 23 Exposure to Explosion Overpressure (Indoor or Outdoor)

Assumption No. 23 Exposure to Explosion Overpressure (Indoor or Outdoor)

Subject: Vulnerability Parameters

Assumption/s:

- The probability of fatality from exposure to the peak side-on overpressure from an explosion is as shown in **Table 19** (Person located outdoors) and **Table 20** (Person located indoors).

Table 19 - Probability of Fatality from Exposure to Peak Side on-Overpressure (Outdoor)

Overpressure (kPa)	Probability of Fatality	Source
30	1.0	Safeti software (default value)

Table 20 - Probability of Fatality from Exposure to Peak Side on-Overpressure (Indoor)

Overpressure (kPa)	Probability of Fatality	Source
10	0.025	Safeti software (default value)
30	1.0	Safeti software (default value)

For comparison, the description of explosion overpressure effects from HIPAP 4 are:

Table 21 - Effects of Explosion Overpressure

Overpressure [kPa]	Effect/s
0.3	Loud noise.
1.0	Threshold for breakage of glass.
4.0	Minimal effect in the open. Minor injury from window breakage in building.
7.0	Glass fragments fly with enough force to cause injury. Probability of injury is 10%. No fatality. Damage to internal partitions and joinery of conventional buildings, but can be repaired.
14.0	1% chance of ear drum rupture. House uninhabitable and badly cracked.
21.0	10% chance of ear drum rupture. 20% chance of fatality for a person within a conventional building. Reinforced structures distort. Storage tanks fail.
35.0	50% chance of fatality for a person within a conventional building and 15% chance of fatality for a person in the open. House uninhabitable. Heavy machinery damaged. Significant damage to plant.
70.0	100% chance of fatality for a person within a building or in the open. 100% loss of plant.

Justification and Impact/s of Assumption/s:
• When calculating location-specific individual injury or fatality risk contours (peak individual risk), all individuals must be considered to be located outdoors for 100% of the time since this is the underlying basis for the NSW DPE's individual risk criteria. Vulnerability parameters for individuals located indoors are only applicable for the calculation of societal risk. • The probability of fatality is higher for an individual located in a conventional building than when outdoors due to the higher chance of harm from collapse of the structure. • The NSW DPE's injury/damage risk criterion for explosion overpressure is as follows: "Incident explosion overpressure at residential and sensitive use areas should not exceed 7 kPa at frequencies of more than 50 chances in a million per year".
Incidents Affected:
• All incidents with a VCE as a potential outcome.
Reference/s:
• NSW Department of Planning and Infrastructure, Jan 2011, Hazardous Industry Planning Advisory Paper (HIPAP) No. 4, *Risk Criteria for Land Use Safety Planning*. • Safeti software documentation. • Oil & Gas Producers Association (OGP), Risk Assessment Data Directory, Report No. 434-14.1, *Vulnerability to Humans*, March 2010. • Chemical Industries Association (CIA), 2003, *Guidance for the location and design of occupied buildings on chemical manufacturing sites*, 2nd. ed.

Appendix B

Representative Hole Sizes

B.1 Representative Hole Diameters

Representative hole diameters were selected for the consequence modelling. These were selected to align with the leak frequency data, which includes four-hole size categories: pinhole (≤ 25 mm); small hole (> 25 mm to ≤ 75 mm), large hole (> 75 mm to ≤ 110 mm); and rupture (> 110 mm). The representative hole diameter/s in each hole size category were selected based on a review of the following available historical data.

B.1.1 Leak Data for Above Ground or Underground Cross-Country Pipelines – Various Materials

United Kingdom Onshore Pipeline Operators' Association (UKOPA), Major Accident Hazard Pipelines (1962-2014)

The definition of a Major Accident Hazard Pipeline (MAHP) from the Pipelines Safety Regulations 1996 (PSR 96) includes various materials (e.g., including natural gas at >8 bar, flammable liquids, etc.). The pipeline may be above or below ground.

The failure reports in the UKOPA database include the length and width of the failures. The failure area is also recorded for some events. The equivalent diameter of a circular opening with the same cross-sectional area was calculated.

The following table includes the recorded incidents where the hole size was reported [Cited by HSE in RR1035]. This data is almost exclusively for Natural Gas (NG) leaks, with only one leak from another material (Propylene).

Table 22 - Dimensions of Leaks for Above Ground or Underground Cross-Country Natural Gas or Propylene Pipelines (UKOPA - Reported Values Only)

Fault ID	Discovery Date	Product	Wall Thickness (mm)	Diameter (in)	Diameter (mm)	Equivalent Hole Diameter (mm)	Cause
1950	1998	NG	4.4	3.9	100	1.1	Corrosion
1948	1997	NG	4.4	3.9	100	11.3	Corrosion
400	1998	NG	Not Recorded	4	102	2.8	Corrosion
3112	2010	NG	4.4	4.5	114	1.1	Corrosion
1424	1990	NG	4.5	4.5	114	3.6	Corrosion
1998	2001	NG	4.8	5.9	150	24.5	Corrosion
2569	2005	NG	4.7	6.4	163	1.1	Corrosion
2979	2009	NG	4.3	6.4	163	17.8	Corrosion
728	1990	NG	6	6.6	168	1.1	Corrosion
425	2000	NG	6.6	8.6	218	1.1	Corrosion
417	1998	NG	5.2	8.6	218	3.2	Corrosion
402	1999	NG	5.2	8.6	218	3.6	Corrosion
422	1999	NG	6.6	8.6	218	3.6	Corrosion
1934	1993	NG	6.4	14	356	1.1	Corrosion

730	1994	NG	6.4	18	457	1.1	Corrosion
1460	2001	NG	6.35	12.7	323	3.6	Ground movement/ Other
1490	1989	NG	6.4	12.8	325	1.1	Ground movement/ Other
1489	1989	NG	6.4	12.8	325	3.6	Ground movement/ Other
1388	1998	NG	8	18	457	2.3	Ground movement/ Other
2923	2008	NG	9.52	18	457	3.4	Ground movement/ Other
2872	2000	NG	9.52	18	457	27.8	Ground movement/ Other
1972	1990	NG	4.5	3.5	89	3.6	Mechanical
1949	1997	NG	4.4	3.9	100	3.6	Mechanical
1947	1990	NG	4.4	4	102	3.6	Mechanical
1909	1989	NG	4.4	4	102	11.3	Mechanical
1913	1990	NG	4.4	4	102	11.3	Mechanical
1914	1990	NG	4.4	4	102	11.3	Mechanical
1916	1990	NG	4.4	4	102	11.3	Mechanical
1917	1990	NG	4.4	4	102	11.3	Mechanical
1919	1990	NG	4.4	4	102	11.3	Mechanical
363	1997	NG	Not recorded	5.9	150	1.1	Mechanical
1928	1990	NG	4.5	5.9	150	11.3	Mechanical
1973	1990	NG	4.5	5.9	150	11.3	Mechanical
2028	1990	NG	4.8	5.9	150	11.3	Mechanical
2078	1989	NG	5.6	5.9	150	11.3	Mechanical
1996	1993	NG	4.8	6.6	168	1.1	Mechanical
1875	1989	NG	5.2	6.6	168	11.3	Mechanical
1886	1990	NG	4.4	6.6	168	11.3	Mechanical
1887	1990	NG	4.4	6.6	168	11.3	Mechanical
1925	1989	NG	4.4	6.6	168	11.3	Mechanical
1926	1989	NG	4.4	6.6	168	11.3	Mechanical
1940	1990	NG	4.4	6.6	168	11.3	Mechanical
2069	1990	NG	6.4	8.6	218	3.6	Mechanical

1876	1989	NG	6.4	8.6	218	11.3	Mechanical
2055	1989	NG	6.4	8.6	218	11.3	Mechanical
1710	1989	NG	7.9	14	356	3.6	Mechanical
1842	1992	NG	9.5	17.7	450	1.1	Mechanical
1361	1994	NG	9.5	24	610	1.1	Mechanical
1117	1993	NG	12.7	36	914	160.1	Mechanical
1918	1990	NG	4.4	4	102	22.6	TPA
1987	1990	NG	4.8	6.6	168	23.9	TPA
2980	2009	NG	5.56	6.6	168	25	TPA
1645	1992	NG	7.1	8.6	218	5.5	TPA
366	1991	NG	4.8	8.6	218	24	TPA
2783	2006	NG	4.5	8.6	219	25	TPA
1560	1989	NG	6.4	12.8	325	56.2	TPA
1185	1998	NG	10.4	15.7	400	20	TPA
1193	1990	NG	9.5	16	406	25	TPA
3109	2009	Propylene	7.1	6.6	168	6.8	TPA

B.1.2 Leak Data for Underground Cross-Country Pipelines – Natural Gas

US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Reported Data for Underground Natural Gas Steel Pipelines (January 2010 to September 2017)

The dimensions of a leak are not always included in the US DoT database. The following tables include all recorded incidents where the hole size was reported.

The length and width of the hole is reported in the US DoT database; therefore, the equivalent diameter of a circular opening with the same cross-sectional area was calculated.

Table 23 - Dimensions of Rupture Events for Underground Natural Gas Steel Pipelines (US DoT - Reported Values Only)

MAOP		Pipe Diameter (in)	Rupture Length (in)	Rupture Width (in)	Approx. Rupture Area (sq.in)	% of Cross-Section Area	Equiv. Hole Diameter (mm)	Cause
(psig)	(kPag)							
15	205	1.66	1.5	1.5	1.8	81.7	38.1	Natural Force - High Winds
95	756	20	16	1	12.6	4.0	101.6	Corrosion - External
15	205	1	3.3	1	2.6	330.0	46.1	Excavation Damage
60	515	1.25	2	0.1	0.2	12.8	11.4	Excavation Damage
60	515	2	7.5	0.5	2.9	93.8	49.2	Material Failure of Pipe or Weld - Butt Weld

60	515	2.375	6.5	2.1	10.7	242.0	93.8	Material Failure of Pipe or Weld - Butt Weld
60	515	2.375	2	2	3.1	70.9	50.8	Excavation Damage
433	3087	4	10	0.2	1.6	12.5	35.9	Excavation Damage
60	515	6.625	12.5	0.5	4.9	14.2	63.5	Material Failure of Pipe or Weld - Pipe
78	639	16	16	16	201.1	100.0	406.4	Other Cause - Unknown

Table 24 - Dimensions of Puncture Events for Underground Natural Gas Steel Pipelines (US DoT - Reported Values Only)

MAOP		Pipe Diameter (in)	Puncture Axial Length (in)	Puncture Circumferential Length (in)	Approx. Puncture Area (sq.in)	% of Cross-Section Area	Equiv. Hole Diameter (mm)	Cause
(psig)	(kPag)							
60	515	0.75	0.5	0.5	0.2	44.4	12.7	Other Outside Force - Electrical arcing
260	1894	0.75	0.8	0.8	0.5	113.8	20.3	Excavation Damage
60	515	1.25	1.5	0.7	0.8	67.2	26.0	Excavation Damage
4	129	2	2	1	1.6	50.0	35.9	Excavation Damage
9.5	167	2	1	3	2.4	75.0	44.0	Excavation Damage
25	274	2	3.5	0.7	1.9	61.3	39.8	Incorrect Operation
52	460	2	0.5	0.5	0.2	6.3	12.7	Other Outside Force - Electrical arcing
60	515	2	1	0.5	0.4	12.5	18.0	Excavation Damage
60	515	2	0.5	0.5	0.2	6.3	12.7	Excavation Damage
60	515	2	1.5	0.7	0.8	26.3	26.0	Other Outside Force - Not Specified
35	343	2.375	1	1	0.8	17.7	25.4	Excavation Damage
440	3135	2.375	2.5	0.5	1.0	22.2	28.4	Excavation Damage
60	515	3	3	9.4	22.1	313.3	134.9	Excavation Damage
17	219	4	1.3	1.3	1.3	10.6	33.0	Excavation Damage
30	308	4	6	3	14.1	112.5	107.8	Excavation Damage
35	343	4	2	2	3.1	25.0	50.8	Excavation Damage
35	343	4	3	3	7.1	56.3	76.2	Excavation Damage
57	494	4	5	2	7.9	62.5	80.3	Excavation Damage
60	515	4	24	2	37.7	300.0	176.0	Excavation Damage
60	515	4	9	3	21.2	168.8	132.0	Excavation Damage

60	515	4	0.8	0.8	0.5	4.0	20.3	Excavation Damage
250	1825	4	5	3	11.8	93.8	98.4	Excavation Damage
285	2066	4	0.6	1.3	0.6	4.9	22.4	Excavation Damage
300	2170	4.5	1	12.6	9.9	62.2	90.2	Excavation Damage
10	170	6	6	6	28.3	100.0	152.4	Excavation Damage
35	343	6	3	3	7.1	25.0	76.2	Excavation Damage
60	515	6	6	6	28.3	100.0	152.4	Excavation Damage
60	515	6	6	6	28.3	100.0	152.4	Excavation Damage
60	515	6	6	6	28.3	100.0	152.4	Excavation Damage
60	515	6	0.5	0.5	0.2	0.7	12.7	Other Outside Force - Electrical arcing
150	1136	6	1.5	0.5	0.6	2.1	22.0	Excavation Damage
200	1480	6	1.2	1	0.9	3.3	27.8	Excavation Damage
200	1480	6	2	2	3.1	11.1	50.8	Excavation Damage
300	2170	6	0.5	0.5	0.2	0.7	12.7	Excavation Damage
400	2859	6	4	1	3.1	11.1	50.8	Excavation Damage
500	3549	6	1	0.5	0.4	1.4	18.0	Other Outside Force - Other Vehicle
60	515	6.58	1	1	0.8	2.3	25.4	Other Outside Force - Other Vehicle
300	2170	6.625	3	4	9.4	27.3	88.0	Excavation Damage
50	446	8	2.1	2.1	3.5	6.9	53.3	Excavation Damage
50	446	8	11	4	34.6	68.8	168.5	Excavation Damage
60	515	8	0.1	0.1	0.0	0.0	2.5	Excavation Damage
80	653	8	12	8	75.4	150.0	248.9	Excavation Damage
120	929	8	6.5	2.5	12.8	25.4	102.4	Excavation Damage
157	1184	8	3.9	3.2	9.8	19.5	89.7	Excavation Damage
300	2170	8	4	2	6.3	12.5	71.8	Excavation Damage
400	2859	8	2	6	9.4	18.8	88.0	Excavation Damage
870	6100	8	25.1	25.1	494.8	984.4	637.5	Excavation Damage
0.43	104	8.625	6	6	28.3	48.4	152.4	Excavation Damage

60	515	8.625	1	1	0.8	1.3	25.4	Other Outside Force - Not Specified
250	1825	8.625	1	5	3.9	6.7	56.8	Excavation Damage
15	205	10	5	5	19.6	25.0	127.0	Excavation Damage
50	446	10	1.5	0.5	0.6	0.8	22.0	Excavation Damage
60	515	10	0.3	13	3.1	3.9	50.2	Excavation Damage
60	515	10	1	3	2.4	3.0	44.0	Excavation Damage
150	1136	10	7.5	1.1	6.5	8.3	73.0	Excavation Damage
240	1756	10	2	2	3.1	4.0	50.8	Excavation Damage
82	667	10.75	3	2	4.7	5.2	62.2	Excavation Damage
33	329	12	11	4	34.6	30.6	168.5	Excavation Damage
60	515	12	3	3	7.1	6.3	76.2	Excavation Damage
100	791	12	2.3	2.5	4.5	4.0	60.9	Excavation Damage
100	791	12	3	3	7.1	6.3	76.2	Excavation Damage
225	1653	12	7	6.3	34.6	30.6	168.7	Excavation Damage
0.64	106	12.75	2.5	2.5	4.9	3.8	63.5	Other Outside Force - Not Specified
15	205	12.75	6	6	28.3	22.1	152.4	Excavation Damage
170	1273	14	6	3	14.1	9.2	107.8	Other Outside Force - Other Vehicle
58	501	16	2.5	5	9.8	4.9	89.8	Excavation Damage
188	1398	16	4	4	12.6	6.3	101.6	Excavation Damage
300	2170	16	1.1	3.5	3.0	1.5	49.8	Excavation Damage
150	1136	20	5	1	3.9	1.3	56.8	Excavation Damage
400	2859	26	0.2	0.2	0.0	0.0	5.1	Excavation Damage

Appendix C

Likelihood Analysis – Data and Results

C.1.1 Likelihood of Release from Underground Pipelines

The likelihood of a release (i.e., leak) from each underground pipeline was estimated based on a review of relevant data sources. The primary data sources included:

- Department of Industry, Resources and Energy, New South Wales, *2017-18 Licensed Pipelines Performance Report*. This includes data for all licensed pipelines in NSW for the 5-year period: 2013/14 to 2017/18; and
- UK Health and Safety Executive (HSE), 2015, *Update of Pipeline Failure Rates for Land Use Planning Assessments*, Research Report (RR) 1035.
- British Standards Institute, 2013, *Pipeline Systems – Part 3: Steel Pipelines on Land – Guide to the Application of Pipeline Risk Assessment to Proposed Developments in the Vicinity of Major Accident Hazard Pipelines Containing Flammables – Supplement to PD 8010-1:2004*, PD 8010-3:2009+A1:2013.
- US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Hazardous Liquid Pipeline Systems (January 2010 to September 2018).

The leak frequency data reported in RR1035 was adopted for the QRA as it is comparable to the NSW performance data and it includes the leak frequency for four-hole size categories (pinhole, small hole, large hole and rupture), four failure mode categories (mechanical failure, corrosion, ground movement / other and third party activity), and in some cases for varying pipe diameters and / or wall thicknesses.

The leak frequency data derived from the British Standards Institute PD 8010-3:2009+A1:2013 was not used since the leak rates (other than ruptures) are not clearly defined for all failure modes and the UK HSE does not accept the use of zero frequencies. Also, the rupture frequencies are disproportionally higher than for other hole sizes (unless factored down to account for concrete slab protection), which is not consistent with other data sources.

The leak frequency data reported in RR1035 has been based on:

- An analysis of pipeline failure data from multiple organisations, including:
  - CONCAWE (CONservation of Clean Air and Water in Europe);
  - UKOPA (United Kingdom Onshore Pipeline Operators' Association); and
  - EGIG (European Gas pipeline Incident Group).
- A conservative, yet realistic, analysis of the available data. For example:
  - For failure mode categories where zero failures have occurred, assumptions have been made to estimate the chance of a failure, even if not seen historically (over the observation period).
  - Only the most recent 22 years of historical incident data was analysed to ensure a consistent pipeline population and to remove the older incident data, which may not be as representative of current practice.
  - Incident data for pipelines carrying products at elevated temperatures was excluded from the analysis.
  - Although the location of failures (e.g., rural or urban) may be recorded in the various databases, it is recognised that there is insufficient data to estimate the leak frequency for different locations.
  - The recommended failure rates for specific materials have been derived from the most appropriate dataset (e.g., for a specific substance the failure rates for corrosion may derived from the

CONCAWE products dataset, whilst the mechanical failure rates may be derived from the UKOPA dataset).

NSW Performance Report

The average leak frequency from the 2018 NSW Performance Report for all licensed pipelines in NSW for the 5-year period 2013/14 to 2017/18 is 8.2E-05 per km per year.

UK HSE (RR1035)

The is no leak frequency data specifically for ethane in RR1035. The data for natural gas (methane), ethylene and LPG (propane and butane) was reviewed. The data for LPG was selected as it is slightly more conservative for the larger leak diameters and is more applicable for a liquefied gas.

The total leak frequency data reported in Section 7.6 of RR1035 for underground LPG pipelines is slightly more conservative (e.g. 2.1E-04 per km per year for a pipeline with wall thickness ≥ 5 mm to < 10 mm) and was adopted in the QRA for the underground HP Ethane pipeline (Refer to Table 25).

Table 25 - Leak Frequencies for Underground LPG Pipelines

Failure Mode	Pipeline Diameter (mm)	Wall Thickness (mm)	Leak Frequency (per km per yr)				
			Pinhole (≤ 25 mm)	Small Hole (> 25 mm to ≤ 75 mm)	Large Hole (> 75 mm to ≤ 110 mm)	Rupture (> 110 mm)	Total Leak Frequency
Mechanical Failure	All	All	5.7E-05	1.3E-05	6.7E-06	8.3E-06	8.5E-05
Corrosion	All	< 5	1.6E-04	8.9E-07	4.5E-07	1.3E-06	1.6E-04
		5 to < 10	8.4E-05	2.4E-07	4.8E-07	7.3E-07	8.6E-05
		10 to < 15	4.5E-06	1.3E-08	2.6E-08	3.9E-08	4.6E-06
		≥ 15	4.3E-07	1.2E-09	2.5E-09	3.7E-09	4.4E-07
Ground Movement / Other	All	All	1.2E-05	2.5E-06	1.5E-07	2.5E-06	1.7E-05
TPA	All	All	2.2E-05	2.4E-06	1.0E-07	1.0E-07	2.5E-05
Total Leak Freq. =	All	5 to < 10	1.7E-04	1.8E-05	7.4E-06	1.2E-05	**2.1E-04**
% =			82.4	8.7	3.5	5.5	100

British Standards Institute (PD 8010-3:2009+A1:2013)

The data and approach included in Annex B of PD 8010-3:2009+A1:2013 was used to estimate the leak frequencies for the Moomba to Sydney Ethane Pipeline (Refer to Table 26). The data applicable for a pipeline with a wall thickness of 8.1 mm, manufactured after 1980, was used.

Leak frequency data is not reported for internal corrosion; therefore, the total leak frequencies reported in Table 26 may be underestimated.

For leaks (other than ruptures) due to 'Ground Movement / Other', the estimated leak frequency was assumed to be distributed evenly across the other hole sizes (Note: There is no guidance in PD 8010-3:2009+A1:2013 on how to distribute the non-rupture events).

For leaks (other than ruptures) due to 'TPA', the estimated leak frequency was assumed to be distributed across the smaller hole sizes and weighted to the smaller hole size categories (Note: There is no guidance in PD 8010-3:2009+A1:2013 on how to distribute the non-rupture events).

The rupture frequency due to 'TPA' was derived from the generic pipeline failure frequency, which was modified in accordance with the relevant parameters for the Moomba to Sydney Ethane Pipeline (i.e.

location, design factor, wall thickness and depth of cover). As this pipeline has concrete slab protection and marker tapes, the base rupture frequency was reduced by a factor of 0.125 (Table A.0, p.31).

Table 26 - Approx. Leak Frequencies for Underground Ethane Pipeline

Failure Mode	Approx. Leak Frequency (per km per yr)				
	Pinhole (≤ 25 mm)	Small Hole (> 25 mm to ≤ 75 mm)	Large Hole (> 75 mm to ≤ 110 mm)	Rupture (> 110 mm)	Total Leak Frequency
Mechanical Failure	8.0E-06	3.2E-06	0.0E+00	0.0E+00	1.1E-05
Corrosion	3.2E-05	1.1E-05	3.0E-06	0.0E+00	4.6E-05
Ground Movement / Other	4.9E-07	4.9E-07	4.9E-07	6.6E-08	1.5E-06
TPA	6.1E-06	4.0E-06	2.0E-06	8.1E-06	2.0E-05
Total Leak Freq. =	4.7E-05	1.9E-05	5.5E-06	8.1E-06	**7.9E-05**
% =	59.0	23.7	7.0	10.3	100

US Department of Transportation (DoT)

The US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Hazardous Liquid Pipeline Systems (January 2010 to September 2018) include incidents for ethane pipelines; however, the total length of the ethane pipelines is not available (i.e. it is not possible to determine the leak rate per km per year).

To enable a comparison with the UK data, the data for all Highly Volatile Liquids (Except Ammonia) was analysed and the leaks categorised using the same representative hole sizes as reported in the UK (i.e. RR1035 and PD8010). The results are reported in Table 27.

Period of Recorded Incident Data =	8.75	years	(Jan 2010 to Sept 2018)
Total Length of All HVL Pipelines =	102663	km	Note: Average for 2010 to 2017 for ALL HVLs

Table 27 - Leak Frequencies for Underground HVL Pipelines (Excluding Ammonia)

Failure Mode	Approx. Leak Frequency (per km per yr)					Comments
	Pinhole (≤ 25 mm)	Small Hole (> 25 mm to ≤ 75 mm)	Large Hole (> 75 mm to ≤ 110 mm)	Rupture (> 110 mm)	Total Leak Frequency	
Mechanical Failure	3.9E-05	0.0E+00	0.0E+00	0.0E+00	3.9E-05	Excludes pipelines manufactured prior to 1980.
Corrosion	5.6E-06	0.0E+00	0.0E+00	1.1E-06	6.7E-06	Excludes external corrosion (other than SCC).
Ground Movement / Other	5.6E-06	2.2E-06	1.1E-06	5.6E-06	1.4E-05	
TPA	8.9E-06	6.7E-06	2.2E-06	8.9E-06	2.7E-05	
Total Leak Freq. =	5.9E-05	8.9E-06	3.3E-06	1.6E-05	**8.7E-05**	
% =	67.9	10.3	3.8	17.9	100	

Australia /New Zealand Pipeline Incident Database

A comparison with limited Australian data between 2000 and 2018 extracted from the report "Experience with the Australian/New Zealand Pipeline Incident Database" [11] has been undertaken. The report [11] does not provide explicit rates for loss of containment from pipelines but provides data from which some conclusions may be drawn. These are:

- Total km of pipelines within a given interval (Table 28), and
- Total number of leaks and ruptures in the period 2000 to 2018. A total of 17 are reported in the database.

Table 28 - Australian Pipeline Population by Half Decade [11]

Period		km of Pipeline				Pipeline Population
Start	End	Interval (yr)	Start of period	End of period	Average during period	(km.yr)
2000	2005	5	26000	29000	27500	137,500
2005	2010	5	29000	32000	30500	152,500
2010	2015	5	32000	36000	34000	170,000
2015	2018	3	36000	36000	36000	108,000
					Total	**568,000**

From Table 28 and the total of 17 release incidents, the expected total release frequency is

$$f = \frac{N}{km.y} = \frac{17}{568{,}000} = 2.99 \times 10^{-5}\ \text{km}^{-1}\text{y}^{-1}$$

The value selected for the release of ethane from the MSE is 2.124×10^{-4} km^{-1}y^{-1}. This is conservative when compared to the Australia /New Zealand Pipeline Incident Database.

C.1.2 Likelihood of Release from Aboveground Pipelines

Above ground sections of pipeline considered in this study have been limited to the valve station at Marsh Street. The above ground equipment is contained within a secure compound. For this reason, the failure frequencies have been obtained from the UK HSE Document "Failure Rate and Event Data for use within Risk Assessments (06/11/17)", specifically item FR 3.1.2 "Above Ground Pipelines in a Gas Installation". These values are replicated in Table 29.

Table 29 - Item Failure Rates (UK HSE)

Failure Category	Failure Rate (per m per year)
Rupture (>110mm diameter)	6.5×10^{-9}
Large Hole (>75 –≤110mm diameter)	3.3×10^{-8}
Small Hole (>25 mm – ≤75 mm diameter)	6.7×10^{-8}
Pin Hole (≤25 mm diameter)	1.6×10^{-7}

C.1.3 Ignition Probability

The ignition probabilities adopted in the risk analysis are listed below. This was based on a review of relevant ignition probability data and ignition probability correlations (Refer to Sections C.1.3.1 - C.1.3.3).

Ethane

1. The total ignition probability was based on OGP Scenario 3, which is release rate dependent (Refer to Section C.1.3.1).

No historical ignition data was identified for ethane pipelines; however, it is typically grouped with other liquefied gases such as propane.

2. The total ignition probability was split 50:50 for immediate ignition: delayed ignition.

   The OGP data assumes an immediate ignition probability of 0.001. A 50:50 split was assumed for the QRA.

Ignition data is usually reported by hole size rather than failure mode and inconsistent reporting of immediate ignition due to TPA (which is sometimes reported to be the highest immediate ignition probability and sometimes not) means it was not possible to estimate the immediate ignition probability based on failure mode.

C.1.3.1 Ignition Probability Data for Above Ground or Underground Cross-Country Pipelines – Various Materials

United Kingdom Onshore Pipeline Operators' Association (UKOPA), Major Accident Hazard Pipelines (1962-2014)

The definition of a Major Accident Hazard Pipeline (MAHP) from the Pipelines Safety Regulations 1996 (PSR 96) includes various materials (e.g., including natural gas at >8 bar, flammable liquids, etc.). The pipeline may be above or below ground.

There were 9 out of 192 (4.7%) product loss incidents that resulted in ignition.

Table 30 - Ignition Probability - UKOPA

Hole Size Class #	Total Number of Incidents	Number of Incidents with Ignition	Total Ignition Probability	Total Ignition Probability
Full Bore and Above	7	1	0.14	0.09
110mm – Full Bore	4	0	0.0	
40mm – 110mm	7	1	0.14	0.03
20mm – 40mm	23	0	0.0	
6mm – 20mm	31	3	0.10	0.05
0 – 6mm	118	4	0.03	
Unknown	2	0	0.0	0.0
Total =	192	9	0.047	0.047

OGP, Ignition Probabilities for Pipe-Gas-LPG-Industrial (Scenario 3: Gas or LPG release from onshore pipeline in an industrial or urban area)

The following data applies for releases of flammable gases, vapours or liquids significantly above their normal (Normal Atmospheric Pressure (NAP)) boiling point from onshore cross-country pipelines running through industrial or urban areas.

The OGP Data applies for cross-country pipelines. Although not explicitly stated, it is assumed the pipeline may be above ground or underground.

These curves represent "total" ignition probability. The method assumes that the immediate ignition probability is 0.001 and is independent of the release rate.

Table 31- Ignition Probability – OGP Scenario 3

Release Rate (kg/s)	Total Ignition Probability
0.1	0.0010
0.2	0.0017
0.5	0.0033
1	0.0056

2	0.0095
5	0.0188
10	0.0316
20	0.0532
50	0.1057
100	0.1778
200	0.2991
500	0.5946
1000	1.0000

C.1.3.2 Ignition Probability Data for Underground Cross-Country Pipelines – Flammable or Combustible Liquids

US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Hazardous Liquid Pipeline Systems (January 2010 to September 2018)

Reporting of data is required by 49 CFR Part 195. An accident report is required for each failure in a pipeline system subject to this part in which there is a release of the hazardous liquid or carbon dioxide transported resulting in any of the following:

(a) Explosion or fire not intentionally set by the operator.

(b) Release of 5 gallons (19 litres) or more of hazardous liquid or carbon dioxide, except that no report is required for a release of less than 5 barrels (0.8 cubic meters) resulting from a pipeline maintenance activity if the release is:

(1) Not otherwise reportable under this section;

(2) Not one described in §195.52(a)(4);

(3) Confined to company property or pipeline right-of-way; and

(4) Cleaned up promptly;

(c) Death of any person;

(d) Personal injury necessitating hospitalisation;

(e) Estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding $50,000.

Table 32 - Ignition Probability – US DoT

Liquid	Leak			Mechanical Puncture			Other			Rupture			Total		
	# with Ignition	# with no ignition	Prob. of Ignition	# with Ignition	# with no ignition	Prob. of Ignition	# with Ignition	# with no ignition	Prob. of Ignition	# with Ignition	# with no ignition	Prob. of Ignition	# with Ignition	# with no ignition	Prob. of Ignition
HVLs *	0	46	0.0	0	7	0.0	4	2	0.7	5	5	0.5	9	60	0.13

* Highly Volatile Liquids (Includes ethane).

C.1.3.3 Ignition Probability Data for Underground Cross-Country Pipelines – Gases Other Than Natural Gas

UK HSE (RR 1034) - Typical Event Tree Probabilities for Flammable Gas other than Natural Gas

The following data is proposed in RR 1034 for the HSE's computer program MISHAP to calculate the level of risk around Major Accident Hazard Pipelines (MAHPs), particularly in land use planning (LUP) assessments. A MAHP may be above or below ground; however, the MISHAP model appears to be primarily for underground pipelines. The probabilities are not reported for varying hole sizes and appear to be only applicable for larger release events.

For MISHAP, the risk associated with VCE events is negligible because the development of MISHAP (and its predecessors) was based on areas with low congestion and confinement (e.g. rural pipelines), which are not conducive for creating the large flammable clouds required by VCE. It is acknowledged in RR 1034 that this may require further review.

Table 33 - Ignition Probability – UK HSE (RR 1034)

Outcome	Probability of Outcome		
	R12 Materials with a MIE < 0.2 mJ (1)	R12 Materials with a MIE ≥ 0.2 mJ (2)	R11 and Low Reactive Materials (3)
Immediate ignition, fireball and jet fire	0.350	0.300	0.250
Delayed ignition and jet fire	0.325	0.210	0.188
Delayed ignition, flash fire and jet fire	0.096	0.145	0.167
No ignition	0.229	0.345	0.396

(1) For example: ethylene

(2) For example: butane, ethane and propane

(3) For example: ammonia, carbon monoxide

C.1.3.4 Ignition Probability Data for Underground Cross-Country Pipelines – Natural Gas

Acton M R and Baldwin P J - Ignition Probability for High Pressure Gas Transmission Pipelines (7th International Pipeline Conference, IPC2008-64173, Sept 29 – Oct 3, 2008)

Note: Cited in IGEM/TD/2, Assessing the Risks from High Pressure Natural Gas Pipelines and HSE CRR 1034.

An analysis of historical data for rupture incidents shows the ignition probability increases linearly with pd^2. The correlation derived for rupture releases takes the form:

$$P_{ign} = 0.0555 + 0.0137\,pd^2;\ 0 \le pd^2 \le 57$$

$$P_{ign} = 0.81;\ pd^2 > 57$$

P_{ign} = probability of ignition

p = pipeline operating pressure (bar)

d = pipeline diameter for ruptures (m)

The probability of ignition P_{ign}, calculated as detailed above, is then generally apportioned as 0.5 for immediate ignition and 0.5 for delayed ignition, where delayed ignition occurs after 30 seconds.

This correlation is for ignition by all causes and is applicable to underground cross-country pipelines carrying high pressure natural gas. It does not take the location of the pipeline (e.g. rural or urban) or the cause of failure (e.g. external) into consideration. The following data was combined to derive the correlation:

- Transmission pipeline incident data recorded between 1970 and 2004; and
- US Office of Pipeline Safety Office (OPS) data between 2002 and 2007.

The authors state that the total ignition probability for releases caused by external interference, such as excavating machinery, is much lower than releases caused by other means (viz. 0.11 vs. 0.34 for pipeline ruptures from 1970 to 2004).

For puncture releases (all causes), the same ignition probability relationship may be applied, with d equal to the release hole diameter and with the pd^2 value halved, reflecting the difference between the two sources following a rupture and the single source contributing to a puncture release.

Table 34 - Ignition Probability – Acton & Baldwin

Pipeline Diameter (mm)	Operating Pressure (bar)	Equivalent Hole Diameter (mm)	pd^2	Probability of Immediate Ignition	Probability of Delayed Ignition	Total Ignition Probability
433.6	148.95	FBR	28.00	0.220	0.220	0.439
		110	1.80	0.034	0.034	0.068
		75	0.84	0.031	0.031	0.061
		25	0.09	0.028	0.028	0.056
		10	0.01	0.028	0.028	0.056
836.8	50	FBR	35.01	0.268	0.268	0.535
		110	77.03	0.030	0.030	0.060
		75	52.52	0.029	0.029	0.057
		25	0.03	0.028	0.028	0.056
		10	0.01	0.028	0.028	0.056

EGIG (9th Report, 2015), Natural Gas Transmission Pipelines (1971-2013)

Although the pipeline definition does not preclude above ground pipelines, the data is predominantly for underground natural gas transmission pipelines with a maximum operating pressure > 15 bar.

In the period 1970 - 2013, only 5% of the gas releases recorded as incidents in the EGIG database ignited.

Table 35 - Ignition Probability – EGIG

Hole Size Class		Total Ignition Probability
Rupture (FB and Above)	All diameters	0.139
	<= 16 inches	0.103
	> 16 inches	0.32
Hole (>20 mm to FB)		0.023
Pinhole / Crack (Up to 20 mm)		0.044

UK HSE (RR 1034) - Typical Event Tree Probabilities for Natural Gas

The following data is proposed in RR 1034 for the UK HSE's computer program MISHAP. This program is used by the UK HSE to calculate the level of risk around Major Accident Hazard Pipelines (MAHPs), particularly in land use planning (LUP) assessments.

A MAHP may be above or below ground; however, the MISHAP model appears to be primarily for underground pipelines. The probabilities are not reported for varying hole sizes or operating pressures (i.e. are not release rate dependent) and appear to be only applicable for larger release events (i.e. ruptures).

For example, the literature cited in RR 1034 indicates an overall ignition probability between 0.2 and 0.5 for larger releases of natural gas, depending on the degree of confinement. On this basis, the total ignition probability proposed in CR 1034 for natural gas is 0.44.

It is reported in RR 1034 that the risk associated with VCE events is negligible because the development of MISHAP (and its predecessors) was based on areas with low congestion and confinement (e.g. rural pipelines), which are not conducive for creating the large flammable clouds required for a VCE. It is acknowledged in RR 1034 that this may require further review.

The proposed conditional probability value for delayed remote ignition is zero. It is reported in RR 1034 that this is "to take into account the reasoning that natural gas is unlikely to form a significant vapour cloud due to its buoyant nature".

Table 36 - Ignition Probability – UK HSE (RR 1034)

Outcome	Probability of Outcome
Immediate ignition, fireball and jet fire	0.250
Delayed ignition and jet fire	0.188
Delayed ignition, flash fire and jet fire	0.000
No ignition	0.563

Note: Some of the sources cited in RR 1034 with an overall ignition probability between 0.2 and 0.5 are relatively old (c. mid 1980s - See below). This data would also appear to confirm that the total ignition probability proposed for natural gas in MISHAP is for a worst-case rupture event on a larger transmission pipeline.

Table 37 - Ignition Probability – Data Cited by UK HSE (RR 1034)

Data source	Ignition probability	
World-wide, Townsend & Fearnehough (1986)	Leaks	0.1
	Ruptures	0.5
US Gas, Jones (1986)	Ruptures	0.26
	All sizes	0.16
European Gas, European Gas Pipeline Incident Data Group (1988)	Pinholes / cracks	0.02
	Holes	0.03
	Ruptures < 16”	0.05
	Ruptures ≥ 16”	0.35
	All sizes	0.03

C.1.4 Likelihood of Representative Release Scenarios and Ignition Probabilities

The estimated likelihood of each representative release scenario from sections of pipeline are listed in Table 38 and Table 39.

Table 38 - Release Frequency – Underground Sections of Ethane Pipeline (MSE)

Leak Scenario	Release Frequency (per km per year)			Probability of scenario compared to total
	TPA	All Other Failure Modes	Total Release Frequency	
10mm MID	-	1.53E-04	1.53E-04	0.7200
10mm TOP	-	0.00E+00	0.00E+00	0.0000
25mm MID	2.20E-05	-	2.20E-05	0.1036
25mm TOP	0.00E+00	-	0.00E+00	0.0000
75mm MID	2.40E-06	5.94E-06	8.34E-06	0.0393
75mm TOP	0.00E+00	1.01E-05	1.01E-05	0.0476
110mm MID	1.00E-07	2.70E-06	2.80E-06	0.0132
110mm TOP	0.00E+00	4.60E-06	4.60E-06	0.0217

FBR	1.00E-07	1.15E-05	1.16E-05	0.0547
Total	2.46E-05	1.88E-04	**2.124E-04**	1.0000

Table 39 - Release Frequency – Aboveground Sections of Ethane Pipeline (MSE)

Leak Scenario	Failure Rate (per m per year)
Full Bore Rupture (FBR) Horizontal	6.5×10^{-9}
110 mm Horizontal	3.3×10^{-8}
75 mm Horizontal	6.7×10^{-8}
25 mm Horizontal	1.6×10^{-7}

The probability of ignition for the various release scenarios has been based upon release rate according to OGP Ignition Probability Scenario 3. This is replicated in Table 40.

Table 40 - Ignition Probability – OGP Scenario 3

Release Rate (kg/s)	Total Ignition Probability
0.1	0.0010
0.2	0.0017
0.5	0.0033
1	0.0056
2	0.0095
5	0.0188
10	0.0316
20	0.0532
50	0.1057
100	0.1778
200	0.2991
500	0.5946
1000	1.0000

Appendix D

Consequence Results

D.1 Jet Fire Results

Table 41 - Distance downwind to defined radiation levels for day conditions

Scenario ID	Weather	Flame length (m)	Distance downwind to 4.7 kW/m² (m)	Distance downwind to 12.6 kW/m² (m)	Distance downwind to 23 kW/m² (m)	Distance downwind to 35 kW/m² (m)
Marsh St MLV 25mm	2.2B	40.52	67.10	45.31	33.86	16.77
Marsh St MLV 25mm	8.5D	29.29	65.47	45.96	36.17	31.41
Marsh St MLV 25mm	4.2D	33.79	66.07	43.89	35.56	29.24
Marsh St MLV 25mm	1.6D	43.84	67.37	45.66	30.83	6.62
Marsh St MLV 75mm	2.2B	84.45	147.20	98.65	75.05	47.66
Marsh St MLV 75mm	8.5D	61.04	139.23	95.16	74.00	64.67
Marsh St MLV 75mm	4.2D	70.43	143.68	94.47	75.58	61.44
Marsh St MLV 75mm	1.6D	91.36	148.53	100.28	72.07	28.13
Marsh St MLV 110mm	2.2B	111.63	199.57	133.42	102.99	71.02
Marsh St MLV 110mm	8.5D	80.68	181.05	122.31	95.61	83.19
Marsh St MLV 110mm	4.2D	93.09	189.74	124.87	99.84	81.02
Marsh St MLV 110mm	1.6D	120.76	201.49	135.88	100.19	50.99
Marsh St MLV FBR	2.2B	135.51	245.77	164.19	127.59	90.95
Marsh St MLV FBR	8.5D	97.94	213.14	142.46	112.83	96.85
Marsh St MLV FBR	4.2D	113.01	224.83	148.45	118.38	94.56
Marsh St MLV FBR	1.6D	146.60	248.25	167.32	124.81	69.54
10mm MID	2.2B	21.03	33.01	21.29	13.11	6.44
10mm MID	8.5D	15.20	36.25	26.14	21.58	18.72
10mm MID	4.2D	17.54	35.36	22.93	18.50	15.17
10mm MID	1.6D	22.75	32.62	18.78	8.35	3.93
25mm MID	2.2B	44.57	76.32	48.47	31.02	16.68
25mm MID	8.5D	32.22	80.90	55.75	43.69	36.86
25mm MID	4.2D	37.17	80.13	51.63	40.67	32.74
25mm MID	1.6D	48.22	75.54	43.71	22.01	10.08
75mm MID	2.2B	76.98	142.41	86.63	53.97	28.49
75mm MID	8.5D	55.64	136.80	90.50	69.82	60.34
75mm MID	4.2D	64.20	142.91	92.62	71.10	55.48
75mm MID	1.6D	83.28	139.15	76.79	37.52	15.67
75mm TOP	2.2B	71.18	123.64	68.07	33.18	11.87

75mm TOP	8.5D	51.44	121.17	78.34	61.81	52.37
75mm TOP	4.2D	59.36	117.64	74.86	51.43	32.29
75mm TOP	1.6D	77.00	125.01	63.45	23.81	7.43
110mm MID	2.2B	97.65	182.44	108.34	65.29	32.87
110mm MID	8.5D	70.58	169.39	109.95	86.25	73.55
110mm MID	4.2D	81.44	171.98	112.79	84.11	62.43
110mm MID	1.6D	105.64	181.45	99.44	48.98	19.75
110mm TOP	2.2B	91.94	155.53	83.67	37.94	13.24
110mm TOP	8.5D	66.45	152.37	97.96	77.70	64.41
110mm TOP	4.2D	76.68	148.45	93.19	61.94	37.85
110mm TOP	1.6D	99.46	157.09	77.57	26.23	8.26
FBR	2.2B	128.78	244.11	156.44	107.81	71.38
FBR	8.5D	93.07	211.12	139.36	109.66	93.73
FBR	4.2D	107.40	241.71	156.49	121.20	96.15
FBR	1.6D	139.31	243.10	147.86	91.79	28.27

Table 42 - Distance downwind to defined radiation levels for night conditions

Scenario ID	Weather	Flame length (m)	Distance downwind to 4.7 kW/m^2 (m)	Distance downwind to 12.6 kW/m^2 (m)	Distance downwind to 23 kW/m^2 (m)	Distance downwind to 35 kW/m^2 (m)
Marsh St MLV 25mm	8.3D	29.37	65.46	45.87	35.97	31.36
Marsh St MLV 25mm	4.2D	33.79	66.02	43.87	35.54	29.22
Marsh St MLV 25mm	1.0D	48.05	67.27	45.26	21.01	2.81
Marsh St MLV 25mm	3.3E	36.17	66.64	44.39	35.48	27.21
Marsh St MLV 25mm	1.0F	48.05	67.48	45.40	21.43	2.91
Marsh St MLV 75mm	8.3D	61.21	139.11	94.84	73.85	64.48
Marsh St MLV 75mm	4.2D	70.43	143.54	94.40	75.52	61.37
Marsh St MLV 75mm	1.0D	100.14	149.40	101.01	62.62	9.79
Marsh St MLV 75mm	3.3E	75.39	145.38	95.99	76.15	59.07
Marsh St MLV 75mm	1.0F	100.14	149.95	101.35	63.30	9.99
Marsh St MLV 110mm	8.3D	80.90	180.88	121.89	95.37	82.88
Marsh St MLV 110mm	4.2D	93.09	189.54	124.76	99.75	80.91
Marsh St MLV 110mm	1.0D	132.37	202.85	137.36	90.83	4.98
Marsh St MLV 110mm	3.3E	99.65	197.07	130.09	103.59	82.24
Marsh St MLV 110mm	1.0F	132.37	203.63	137.83	91.65	4.98
Marsh St MLV FBR	8.3D	98.21	212.98	142.03	112.74	96.48
Marsh St MLV FBR	4.2D	113.01	224.58	148.32	118.27	94.42
Marsh St MLV FBR	1.0D	160.69	249.99	169.37	115.07	26.10
Marsh St MLV FBR	3.3E	120.97	235.76	155.97	123.93	97.98
Marsh St MLV FBR	1.0F	160.69	250.99	169.96	116.04	27.01
10mm MID	8.3D	15.24	36.27	26.07	21.45	18.49
10mm MID	4.2D	17.54	35.34	22.92	18.49	15.16
10mm MID	1.0D	24.94	30.17	12.55	3.89	2.12
10mm MID	3.3E	18.77	34.43	22.69	17.41	12.51
10mm MID	1.0F	24.94	30.28	12.63	3.91	2.13
25mm MID	8.3D	32.31	81.16	55.76	43.53	36.81
25mm MID	4.2D	37.17	80.05	51.59	40.64	32.70
25mm MID	1.0D	52.86	70.65	31.67	10.41	5.04
25mm MID	3.3E	39.79	78.17	51.33	38.63	28.11
25mm MID	1.0F	52.86	70.94	31.93	10.51	5.07
75mm MID	8.3D	55.79	136.97	90.32	69.78	60.24
75mm MID	4.2D	64.20	142.75	92.54	71.03	55.40
75mm MID	1.0D	91.28	131.30	60.01	18.45	7.33

75mm MID	3.3E	68.72	144.44	94.61	69.70	50.88
75mm MID	1.0F	91.28	131.95	60.56	18.71	7.40
75mm TOP	8.3D	51.58	120.96	77.89	61.68	52.03
75mm TOP	4.2D	59.36	117.52	74.78	51.35	32.20
75mm TOP	1.0D	84.40	119.63	50.98	10.28	3.23
75mm TOP	3.3E	63.54	120.61	73.11	45.61	23.18
75mm TOP	1.0F	84.40	120.25	51.48	10.37	3.25
110mm MID	8.3D	70.77	169.42	109.62	86.25	73.31
110mm MID	4.2D	81.44	171.77	112.68	84.01	62.31
110mm MID	1.0D	115.80	171.99	79.97	24.72	8.97
110mm MID	3.3E	87.17	176.86	113.60	79.94	53.67
110mm MID	1.0F	115.80	172.91	80.72	25.11	9.06
110mm TOP	8.3D	66.64	152.06	97.84	77.46	63.89
110mm TOP	4.2D	76.68	148.28	93.08	61.83	37.76
110mm TOP	1.0D	109.02	157.08	68.16	14.48	4.52
110mm TOP	3.3E	82.07	152.29	90.57	54.11	25.53
110mm TOP	1.0F	109.02	157.94	68.23	14.75	4.55
FBR	8.3D	93.33	211.77	139.33	109.85	93.63
FBR	4.2D	107.40	241.40	156.34	121.06	96.01
FBR	1.0D	152.70	236.73	129.29	65.22	34.33
FBR	3.3E	114.96	248.12	162.57	122.58	93.62
FBR	1.0F	152.70	237.89	130.20	65.92	34.65

D.2 Flash Fire Results

Table 43 - Maximum distance to LFL at any height for day conditions

Scenario ID	Weather	Max flash fire distance for all heights (m)	Height at max flash fire distance for all heights (m)
Marsh St MLV 25mm	2.2B	16.26	15.50
Marsh St MLV 25mm	8.5D	13.19	10.77
Marsh St MLV 25mm	4.2D	14.86	13.37
Marsh St MLV 25mm	1.6D	16.32	16.03
Marsh St MLV 75mm	2.2B	39.48	32.74
Marsh St MLV 75mm	8.5D	31.28	19.74
Marsh St MLV 75mm	4.2D	37.02	23.27
Marsh St MLV 75mm	1.6D	44.28	36.91
Marsh St MLV 110mm	2.2B	54.90	29.49
Marsh St MLV 110mm	8.5D	43.77	22.32
Marsh St MLV 110mm	4.2D	52.38	26.41
Marsh St MLV 110mm	1.6D	64.58	51.74
Marsh St MLV FBR	2.2B	67.52	54.48
Marsh St MLV FBR	8.5D	54.15	26.62
Marsh St MLV FBR	4.2D	64.44	31.21
Marsh St MLV FBR	1.6D	77.52	63.47
10mm MID	2.2B	0.94	9.43
10mm MID	8.5D	1.34	6.41
10mm MID	4.2D	1.16	8.36
10mm MID	1.6D	0.90	10.31
25mm MID	2.2B	2.35	21.45
25mm MID	8.5D	3.36	13.54
25mm MID	4.2D	2.97	18.34
25mm MID	1.6D	2.32	24.35
75mm MID	2.2B	7.29	59.28
75mm MID	8.5D	10.96	35.42
75mm MID	4.2D	9.78	46.86
75mm MID	1.6D	7.86	67.92
75mm TOP	2.2B	0.94	9.43
75mm TOP	8.5D	1.34	6.41
75mm TOP	4.2D	1.16	8.36
75mm TOP	1.6D	0.90	10.31
110mm MID	2.2B	10.87	84.35
110mm MID	8.5D	16.65	44.91
110mm MID	4.2D	14.76	68.80
110mm MID	1.6D	11.98	67.30
110mm TOP	2.2B	10.87	84.35
110mm TOP	8.5D	16.65	44.91
110mm TOP	4.2D	14.76	68.80
110mm TOP	1.6D	11.98	67.30
FBR	2.2B	11.61	58.38
FBR	8.5D	15.75	39.63

FBR	4.2D	13.36	49.42
FBR	1.6D	12.79	71.49

Table 44 - Maximum distance to LFL at any height for night conditions

Scenario ID	Weather	Max flash fire distance for all heights (m)	Height at max flash fire distance for all heights (m)
Marsh St MLV 25mm	8.3D	13.17	10.80
Marsh St MLV 25mm	4.2D	14.80	13.31
Marsh St MLV 25mm	1.0D	16.48	16.58
Marsh St MLV 25mm	3.3E	13.02	12.20
Marsh St MLV 25mm	1.0F	8.83	8.79
Marsh St MLV 75mm	8.3D	31.21	19.84
Marsh St MLV 75mm	4.2D	36.66	26.82
Marsh St MLV 75mm	1.0D	47.25	29.58
Marsh St MLV 75mm	3.3E	35.16	23.40
Marsh St MLV 75mm	1.0F	25.80	22.55
Marsh St MLV 110mm	8.3D	43.59	22.41
Marsh St MLV 110mm	4.2D	51.78	26.30
Marsh St MLV 110mm	1.0D	67.50	32.59
Marsh St MLV 110mm	3.3E	49.17	27.00
Marsh St MLV 110mm	1.0F	36.96	29.66
Marsh St MLV FBR	8.3D	53.96	26.75
Marsh St MLV FBR	4.2D	63.64	31.06
Marsh St MLV FBR	1.0D	81.20	36.98
Marsh St MLV FBR	3.3E	59.53	31.08
Marsh St MLV FBR	1.0F	43.56	34.15
10mm MID	8.3D	1.33	6.44
10mm MID	4.2D	1.15	8.15
10mm MID	1.0D	0.80	10.85
10mm MID	3.3E	1.13	9.28
10mm MID	1.0F	0.86	11.44
25mm MID	8.3D	3.33	13.57
25mm MID	4.2D	2.95	18.27
25mm MID	1.0D	2.08	26.32
25mm MID	3.3E	2.77	19.79
25mm MID	1.0F	1.93	24.81
75mm MID	8.3D	10.84	35.56
75mm MID	4.2D	9.72	46.58
75mm MID	1.0D	7.02	76.79
75mm MID	3.3E	9.00	50.42
75mm MID	1.0F	6.48	67.42
75mm TOP	8.3D	1.33	6.44
75mm TOP	4.2D	1.15	8.15
75mm TOP	1.0D	0.80	10.85
75mm TOP	3.3E	1.13	9.28
75mm TOP	1.0F	0.86	11.44
110mm MID	8.3D	16.44	45.04
110mm MID	4.2D	14.66	68.44

Scenario ID	Weather	Max flash fire distance for all heights (m)	Height at max flash fire distance for all heights (m)
110mm MID	1.0D	10.66	108.86
110mm MID	3.3E	13.68	57.40
110mm MID	1.0F	49.06	66.06
110mm TOP	8.3D	16.44	45.04
110mm TOP	4.2D	14.66	68.44
110mm TOP	1.0D	10.66	108.86
110mm TOP	3.3E	13.68	57.40
110mm TOP	1.0F	49.06	66.06
FBR	8.3D	15.49	38.57
FBR	4.2D	13.30	49.03
FBR	1.0D	12.91	86.34
FBR	3.3E	14.30	53.72
FBR	1.0F	14.11	80.49

D.3 Explosion Results

Table 45: Explosion details, day conditions

Scenario ID	Weather	Distance downwind to 0.07 bar (m)	Distance downwind to 0.1 bar (m)	Distance downwind to 0.14 bar (m)	Distance downwind to 0.21 bar (m)	Distance downwind to 0.3 bar (m)	Explosion centre at 0.07 bar (m)	Explosion centre at 0.1 bar (m)	Explosion centre at 0.14 bar (m)	Explosion centre at 0.21 bar (m)	Explosion centre at 0.3 bar (m)
Marsh St MLV 25mm	2.2B	16.42	13.70	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 25mm	8.5D	15.53	13.19	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 25mm	4.2D	16.10	13.52	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 25mm	1.6D	16.56	13.78	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 75mm	2.2B	45.21	38.76	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV 75mm	8.5D	43.31	37.67	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV 75mm	4.2D	44.73	38.49	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV 75mm	1.6D	57.11	49.86	Not reachable	Not reachable	Not reachable	40	40	0	0	0
Marsh St MLV 110mm	2.2B	71.86	62.60	Not reachable	Not reachable	Not reachable	50	50	0	0	0
Marsh St MLV 110mm	8.5D	58.06	50.41	Not reachable	Not reachable	Not reachable	40	40	0	0	0

Scenario ID	Weather	Distance downwind to 0.07 bar (m)	Distance downwind to 0.1 bar (m)	Distance downwind to 0.14 bar (m)	Distance downwind to 0.21 bar (m)	Distance downwind to 0.3 bar (m)	Explosion centre at 0.07 bar (m)	Explosion centre at 0.1 bar (m)	Explosion centre at 0.14 bar (m)	Explosion centre at 0.21 bar (m)	Explosion centre at 0.3 bar (m)
Marsh St MLV 110mm	4.2D	71.18	62.21	Not reachable	Not reachable	Not reachable	50	50	0	0	0
Marsh St MLV 110mm	1.6D	84.58	74.17	Not reachable	Not reachable	Not reachable	60	60	0	0	0
Marsh St MLV FBR	2.2B	86.15	75.07	Not reachable	Not reachable	Not reachable	60	60	0	0	0
Marsh St MLV FBR	8.5D	72.08	62.72	Not reachable	Not reachable	Not reachable	50	50	0	0	0
Marsh St MLV FBR	4.2D	85.62	74.76	Not reachable	Not reachable	Not reachable	60	60	0	0	0
Marsh St MLV FBR	1.6D	99.12	86.78	Not reachable	Not reachable	Not reachable	70	70	0	0	0
75mm MID	8.5D	25.67	19.03	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	2.2B	36.45	25.24	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	8.5D	32.47	22.95	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	4.2D	34.01	23.84	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	1.6D	37.00	25.56	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	2.2B	36.45	25.24	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	8.5D	32.47	22.95	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	4.2D	34.01	23.84	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	1.6D	37.00	25.56	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	2.2B	37.75	25.99	Not reachable	Not reachable	Not reachable	10	10	0	0	0

Scenario ID	Weather	Distance downwind to 0.07 bar (m)	Distance downwind to 0.1 bar (m)	Distance downwind to 0.14 bar (m)	Distance downwind to 0.21 bar (m)	Distance downwind to 0.3 bar (m)	Explosion centre at 0.07 bar (m)	Explosion centre at 0.1 bar (m)	Explosion centre at 0.14 bar (m)	Explosion centre at 0.21 bar (m)	Explosion centre at 0.3 bar (m)
FBR	8.5D	38.28	26.30	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	4.2D	39.13	26.79	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	1.6D	39.11	26.78	Not reachable	Not reachable	Not reachable	10	10	0	0	0

Table 46: Explosion details, night conditions

Scenario ID	Weather	Distance downwind to 0.07 bar (m)	Distance downwind to 0.1 bar (m)	Distance downwind to 0.14 bar (m)	Distance downwind to 0.21 bar (m)	Distance downwind to 0.3 bar (m)	Explosion centre at 0.07 bar (m)	Explosion centre at 0.1 bar (m)	Explosion centre at 0.14 bar (m)	Explosion centre at 0.21 bar (m)	Explosion centre at 0.3 bar (m)
Marsh St MLV 25mm	8.3D	15.5386	13.192	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 25mm	4.2D	16.0911	13.5104	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 25mm	1.0D	16.6335	13.823	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 25mm	3.3E	15.8361	13.3635	Not reachable	Not reachable	Not reachable	10	10	0	0	0
Marsh St MLV 75mm	8.3D	43.3565	37.6976	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV 75mm	4.2D	44.7187	38.4826	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV 75mm	1.0D	57.3435	49.9953	Not reachable	Not reachable	Not reachable	40	40	0	0	0

Scenario ID	Weather	Distance downwind to 0.07 bar (m)	Distance downwind to 0.1 bar (m)	Distance downwind to 0.14 bar (m)	Distance downwind to 0.21 bar (m)	Distance downwind to 0.3 bar (m)	Explosion centre at 0.07 bar (m)	Explosion centre at 0.1 bar (m)	Explosion centre at 0.14 bar (m)	Explosion centre at 0.21 bar (m)	Explosion centre at 0.3 bar (m)
Marsh St MLV 75mm	3.3E	44.7654	38.5095	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV 75mm	1.0F	33.4025	27.7241	Not reachable	Not reachable	Not reachable	20	20	0	0	0
Marsh St MLV 110mm	8.3D	58.1122	50.4383	Not reachable	Not reachable	Not reachable	40	40	0	0	0
Marsh St MLV 110mm	4.2D	71.1891	62.2116	Not reachable	Not reachable	Not reachable	50	50	0	0	0
Marsh St MLV 110mm	1.0D	85.01	74.4136	Not reachable	Not reachable	Not reachable	60	60	0	0	0
Marsh St MLV 110mm	3.3E	59.688	51.3465	Not reachable	Not reachable	Not reachable	40	40	0	0	0
Marsh St MLV 110mm	1.0F	48.4493	40.6326	Not reachable	Not reachable	Not reachable	30	30	0	0	0
Marsh St MLV FBR	8.3D	72.1512	62.7661	Not reachable	Not reachable	Not reachable	50	50	0	0	0
Marsh St MLV FBR	4.2D	85.6307	74.7714	Not reachable	Not reachable	Not reachable	60	60	0	0	0
Marsh St MLV FBR	1.0D	111.275	98.0245	Not reachable	Not reachable	Not reachable	80	80	0	0	0
Marsh St MLV FBR	3.3E	73.9715	63.8151	Not reachable	Not reachable	Not reachable	50	50	0	0	0
Marsh St MLV FBR	1.0F	61.4346	52.3531	Not reachable	Not reachable	Not reachable	40	40	0	0	0
75mm MID	8.3D	25.7068	19.0521	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	8.3D	32.5284	22.9835	Not reachable	Not reachable	Not reachable	10	10	0	0	0

Scenario ID	Weather	Distance downwind to 0.07 bar (m)	Distance downwind to 0.1 bar (m)	Distance downwind to 0.14 bar (m)	Distance downwind to 0.21 bar (m)	Distance downwind to 0.3 bar (m)	Explosion centre at 0.07 bar (m)	Explosion centre at 0.1 bar (m)	Explosion centre at 0.14 bar (m)	Explosion centre at 0.21 bar (m)	Explosion centre at 0.3 bar (m)
110mm MID	4.2D	33.9677	23.813	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	1.0D	40.8839	27.7989	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	3.3E	33.7959	23.7139	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm MID	1.0F	74.8182	60.0663	Not reachable	Not reachable	Not reachable	40	40	0	0	0
110mm TOP	8.3D	32.5284	22.9835	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	4.2D	33.9677	23.813	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	1.0D	40.8839	27.7989	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	3.3E	33.7959	23.7139	Not reachable	Not reachable	Not reachable	10	10	0	0	0
110mm TOP	1.0F	74.8182	60.0663	Not reachable	Not reachable	Not reachable	40	40	0	0	0
FBR	8.3D	38.3924	26.363	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	4.2D	39.0831	26.761	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	1.0D	40.5124	27.5848	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	3.3E	39.5642	27.0383	Not reachable	Not reachable	Not reachable	10	10	0	0	0
FBR	1.0F	36.5666	25.3108	Not reachable	Not reachable	Not reachable	10	10	0	0	0