HAZARD ANALYSIS

High Pressure Pipelines at 26 Tupia Street Botany

For Archicorp Pty Ltd

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Risk Engineering Solutions

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Summary

Arriscar Pty Ltd (Arriscar) was engaged by Archicorp to undertake a hazard analysis for the high-pressure pipelines in the vicinity of 26 Tupia Street Botany. This site is in the Bayside Council Local Government Area (LGA) in NSW and is proposed to be redeveloped into a 109 unit residential lot [1].

The scope of the hazard analysis included undertaking a hazard analysis for the high-pressure pipelines in the vicinity of the proposed development at 26 Tupia Street Botany, in accordance with HIPAP No. 6 [2] and the NSW Department of Planning, Industry and Environment's (DPIE's) specific requirements for the proposed redevelopment (Refer to Section 1.1). It included an assessment of the risks against the risk criteria for land use safety planning in HIPAP No. 10 [3].

The underground pipelines in the vicinity of the development include:

(a) The Jet A1 Pipeline - a high-pressure dangerous goods pipeline operated by Ampol Australia Pty Ltd (formerly Caltex Australia).

(b) Primary and Secondary Natural Gas Mains operated by Jemena.

The findings of the risk assessment are as follows:

- The maximum individual fatality risk is 0.5 x 10^{-6} p.a. and this only occurs at one location where the Jet A1, and Jemena Pipelines are in close proximity to each other (Refer to Figure 6). This risk criterion level only applies to sensitive land uses (schools, hospitals, etc.), which are not proposed at this location. Therefore, the proposed development satisfies the individual fatality risk criteria in HIPAP No.10 [3].
- All other individual risk levels comply with the corresponding quantitative risk criteria in HIPAP No.10 [3] (Refer to Sections 8.2 to 8.6).
- 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 (Refer to Section 8.7). This is particularly relevant where for a planning proposal where rezoning and population intensification may occur. Whilst the risk to the proposed development meets the quantitative individual and societal risk criteria, risk reduction measures are included in Section 9.2, consistent with the qualitative principles in HIPAP No.10 [3].
- The entirety of the F-N curve is in the 'Negligible' or 'ALARP' regions and complies with the DPIE's indicative societal risk criteria (Refer to Section 8.8).

Contents

List of Figures

List of Tables

Notation

Abbreviation	Description
ALB	Automatic Line Break
Arriscar	Arriscar Pty Ltd
AS	Australian Standard
BoM	Bureau of Meteorology
BSPD	British Standard Published Document
CH4	Methane
DA	Development Application
DBYD	Dial Before You Dig
DoP	Department of Planning (now DPIE)
DoT	Department of Transport (USA)
DP	Deposited Plan
DPIE	NSW Department of Planning, Industry 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
HVL	Highly Volatile Liquids
kg/s	Kilograms/ second
km	Kilometres
kPa	Kilo Pascals
kW/m^2	Kilo Watts per square metre
LEP	Local Environmental Plan
LFL	Lower Flammability Limit
LGA	Local Government Authority
LSIR	Location-Specific Individual Risk
m	metres
m/s	Metres per second
MAE	Major Accident Event

Abbreviation	Description
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
NG	Natural Gas
NSW	New South Wales
OGP	International Oil & Gas producers Association
OSHA	Occupational Safety and Health Agency (USA)
p.a.	per annum
PHMSA	Pipeline and Hazardous Materials Safety Administration (USA)
pmpy	Per million per year
QRA	Quantitative Risk Assessment
HA	Hazard Analysis
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
ALARP	As Low As Reasonably Practicable
DM	Deferred Matter
DCP	Development Control Plan
JUHI	Joint User Hydrant Installation
WHS	Workplace Health and Safety
DCVG	Direct Current Voltage Gradient
AS/NZS	Australian Standard/ New Zealand Standard
kL	Kilo-Litres
kPag	Kilo-Pascals gauge
SAOP	Safety Case – Operations
SAP-PM	Systems Applications and Products – Preventive Maintenance

Abbreviation	Description
UG	Underground
W/m^2	Watts/ square metre
CFR	Code of Federal Regulations (USA)

1 INTRODUCTION

1.1 Background

Archicorp Pty Ltd is proposing to be redeveloped land at 26 Tupia Street, Botany, into a 109 unit residential lot. The proposed site lies in the vicinity of high pressure dangerous goods pipelines.

Arriscar Pty Ltd (Arriscar) was engaged by Archicorp to undertake a hazard analysis for the high-pressure dangerous goods pipelines in the vicinity of 26 Tupia Street Botany, and assess the risk to the proposed development from the pipelines. This site is in the Bayside Council Local Government Area (LGA) in NSW and is proposed to be redeveloped into a 109 unit residential lot [1].

Undertaking a hazard analysis, including consultation with the pipeline operators, is a requirement of the Department of Planning, Industry and Environment (DPIE). The specific wording of DPIE's requirements is as follows:

1. report on the consultation outcomes with all operators of high pressure dangerous goods or gas pipelines within or in vicinity of the proposal area with regards to requirements under Australian Standard *AS 2885 Pipelines – Gas and liquid petroleum*;
2. a hazard analysis undertaken in accordance with the Department of Planning's Hazardous Industry Planning Advisory Paper No. 6, 'Hazard Analysis' and Multi-Level Risk Assessment (DoP, 2011). The hazard analysis must demonstrate that the proposed development would comply with the relevant qualitative and quantitative risk criteria detailed in the Department of Planning's Hazardous Industry Planning Advisory Paper No. 10, 'Land Use Safety Planning'.

1.2 Scope

The scope of the study included undertaking a hazard analysis for the high-pressure pipelines in the vicinity of 26 Tupia Street Botany, in accordance with HIPAP No. 6 [2] and DPIE's specific requirements for the proposed redevelopment (Refer to Section 1.1). It included an assessment of the risks against the risk criteria for land use safety planning in HIPAP No. 10 [3].

The scope of the PHA did not include preparation of a Safety Management Study (SMS), which may be required under AS 2885-2008 [4]. Following consultation with the pipeline operators (Refer to Section 4.2), it was established that an SMS for the proposed redevelopment was not available for inclusion in the hazard analysis report.

1.3 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 [2]. This included:

- Identification of release events from the multi product fuel pipeline and natural gas mains in the vicinity of the proposed development;
- Development of appropriate and relevant representative release scenarios that may impact on the proposed development;
- 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;
- Generation of Location-Specific Individual Risk (LSIR) contours for comparison with the DPIE’s risk criteria for land use safety planning, viz. as per HIPAP No.4 [5] and HIPAP No.10 [3]; and
- Estimation of societal risk for comparison with the DPIE’s indicative risk criteria for land use safety planning, viz. as per HIPAP No. 4 [5] and HIPAP No.10 [3].

2 STUDY AREA

2.1 Existing Site and Surrounding Land Uses

The development at 26 Tupia Street Botany is in the Bayside Council LGA. The current use for the site is mixture of commercial and industrial.

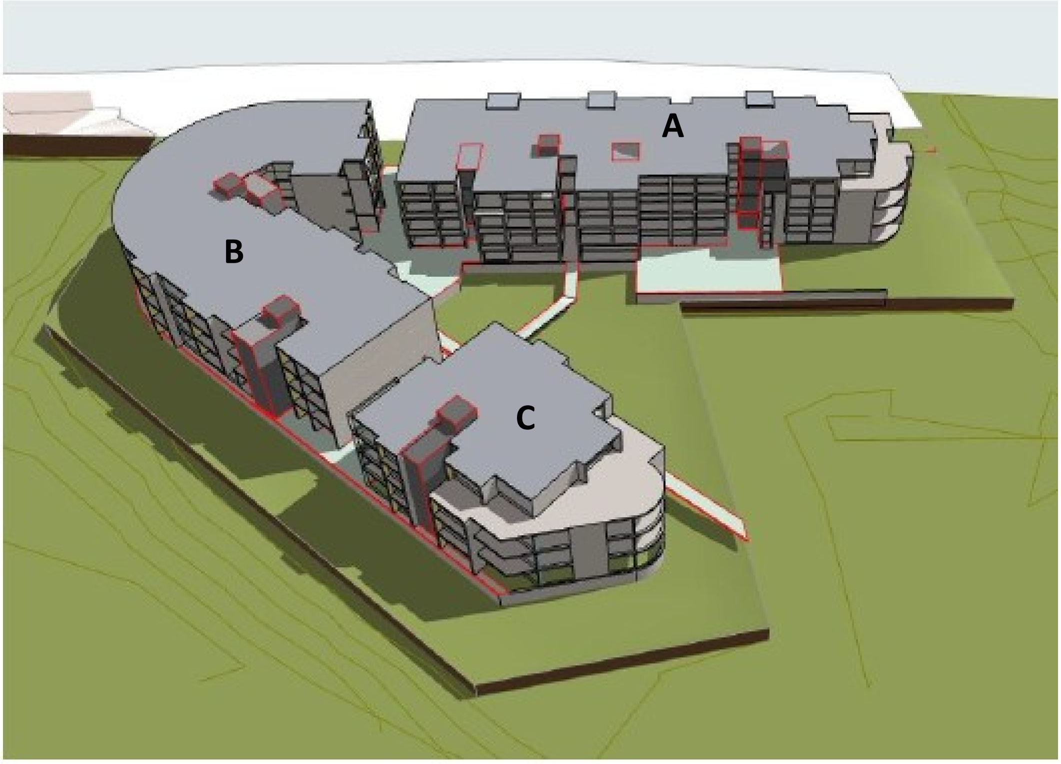
Figure 1 Current Land Use Zoning [6]

The current zoning for the lot is R3 Medium Density Residential [6]. The land surrounding the development is primarily zoned; RE1 Public Recreation, R2 Low Density Residential and R3 Medium Density Residential [6].

2.2 Proposed Site Location and Zoning

The proposed development is for three appartement buildings with onsite parking and landscaping as shown in Figure 2. Each building will 4 stories high with a mix of 1, 2 and 3 bedroom apartments as shown in Table 1.

Figure 2 Proposed Site Layout



The assumed population data for the various land uses is given in Appendix A.2 (Assumption No. 6 and Assumption No. 7).

Table 1 Apartment Distribution [1]

Building	Floor	No. Apartments		
		1 Bed	2 Bed	3 Bed
Building A	Ground	5	6	1
	1	3	8	1
	2	3	8	1
	3	2	6	2
Building B	Ground	3	7	1
	1	3	7	1
	2	3	7	1
	3	3	7	1
Building C	Ground	1	4	0
	1	0	5	0
	2	0	5	0
	3	0	3	1

2.3 Pipeline Locations

Three potentially hazardous pipelines have been identified in the vicinity of the proposed development. The most significant pipeline, as indicated by the DPIE in their planning circular [7], is the Jet A1 pipeline operated by Ampol. For completeness, the Jemena Primary and Secondary Natural Gas Mains have also been included as detailed in Section 4.

The location of the pipelines was determined through a review of 'Dial Before You Dig' (DBYD) information and a walk of the site to review pipeline marker locations. The pipeline locations used in the risk model are shown in Figure 3.

Figure 3 Approximate Locations of Jet A1 Pipeline and Natural Gas Mains

3 Risk Assessment Methodology

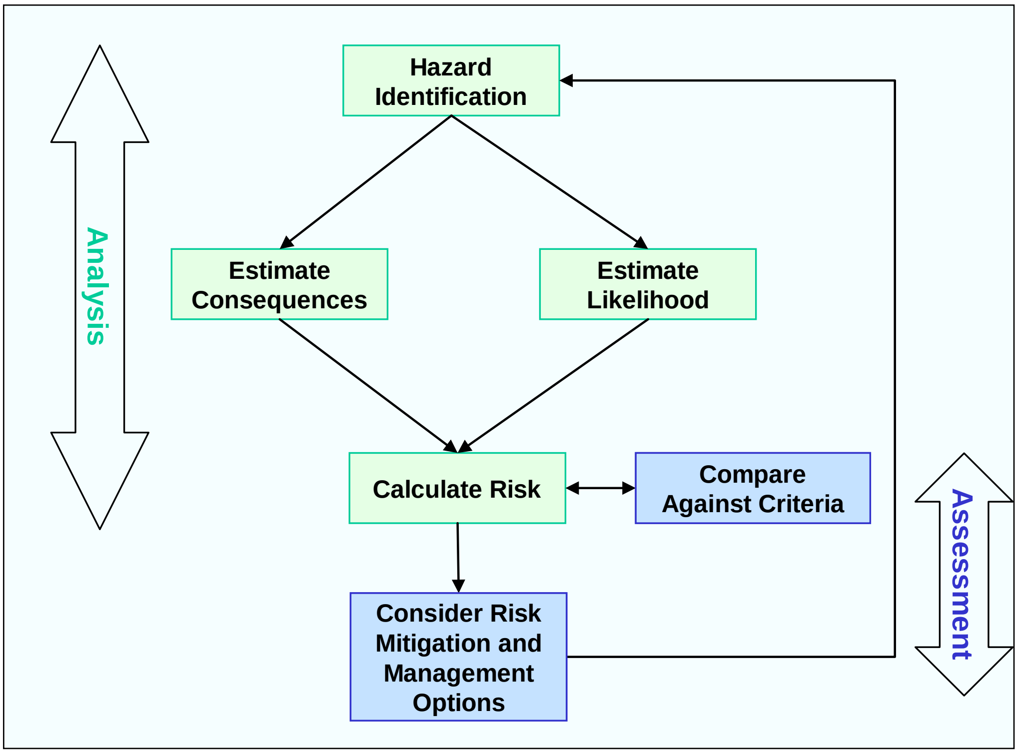
3.1 Introduction

This analysis involves the quantitative estimation of the consequences and likelihood of accidents (viz. a Quantitative Risk Assessment or QRA). For consequences to people, the most common risk measure is 'individual fatality risk' (viz. 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 DPIE's guidelines for undertaking this type of assessment [2].

Diagrammatically, the QRA process is as follows:

Figure 4 Overview of QRA Process [2]



3.2 Methodology Overview

3.2.1 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 hazard 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 DPIE has defined an acceptable risk criterion – Refer to Section 3.4).

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 material 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.

3.2.2 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,
- for fire and explosion events when ignition occurs.

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 Pasquil 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 Pasquil 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 (Assumption No. 3).

The latest SAFETI 8.61 software package was used for all consequence modelling and the generation of the risk contours and societal risk curves.

3.2.3 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.6.

Explosion

During a flash fire, acceleration of the flame front can occur due to the turbulence generated by obstacles within in 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 a flying missile, caused by the explosion, and this can lead to serious injury or even fatality.

The effects of exposure to explosion overpressure are summarised in Table 1 [2].

Table 2 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.

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.

The effects of exposure to thermal radiation are summarised in Table 2 [2]. The vulnerability criteria used in the risk analysis are included in Appendix A.6.

Table 3 Effects of Thermal Radiation

Heat Radiation [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.

The dominant effect in a flash fire is direct engulfment by flame within the combusting 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.

3.2.4 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 1000 to 10000 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 a number of 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 7 and Appendix C.

3.2.5 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 (p.a.), 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).

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.

SAFETI 8.61 software package was used to generate the iso-risk contours and societal risk results (Refer to Section 8).

3.3 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 [2], 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.

3.4 Quantitative Risk Criteria

3.4.1 Individual Fatality Risk

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 DPIE [3] and [5].

Table 4 Individual Fatality Risk Criteria

Land Use	Risk Criterion [per million per year]
Hospitals, schools, childcare facilities and old age housing developments	0.5
Residential developments and places of continuous occupancy, such as hotels and tourist resorts	1
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 DPIE 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 sensitive land uses such as schools, the criterion is one-half that for a residential area, viz. 0.5 x 10^{-6} pe year.

3.4.2 Injury Risk

The DPIE 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 [5] for potential injury caused by exposure to heat radiation, explosion overpressure and toxic gas/ smoke/dust.

The DPIE'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 DPIE'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 DPIE'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.*

3.4.3 Risk of Property Damage and Accident Propagation

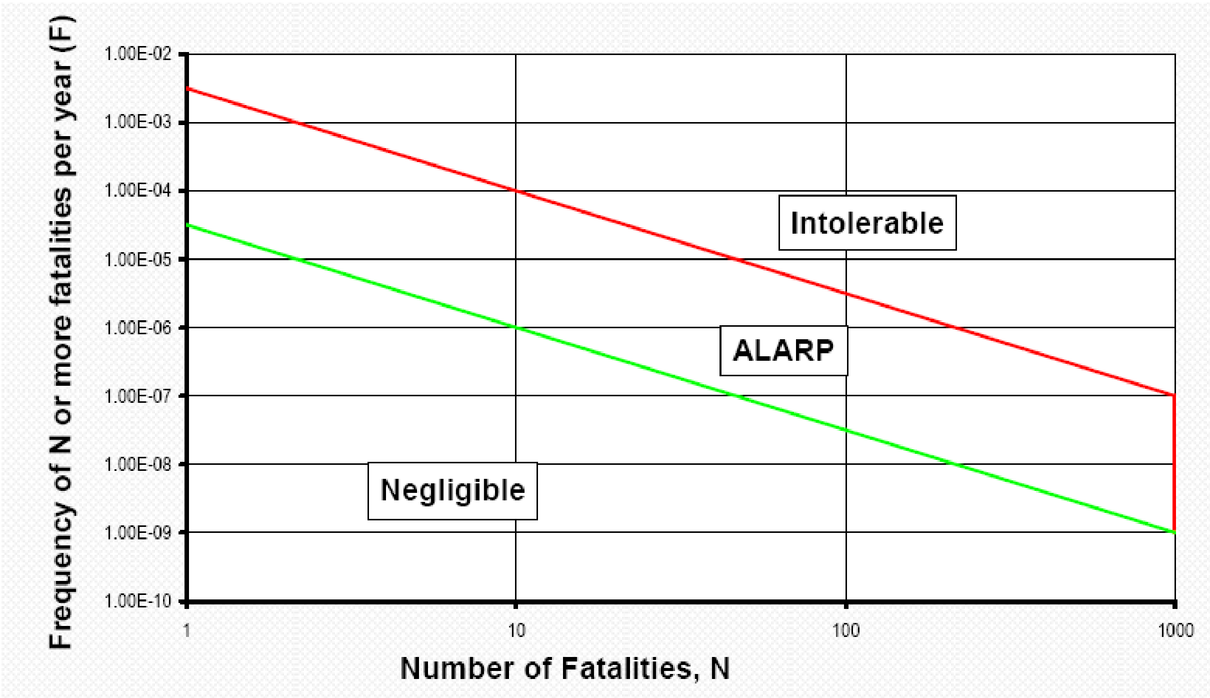
Heat radiation exceeding 23 kW/m^2 may cause unprotected steel to suffer thermal stress that may cause structural damage and an explosion overpressure of 14 kPa can cause damage to piping and low-pressure equipment. The DPIE's criteria for risk of damage to property and accident propagation are as follows [5]:

- *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/m² 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.*

3.4.4 Societal Risk

The DPIE's suggested societal risk criteria (Refer to Figure 5), 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 [5] are met, the risks from the activity would be considered tolerable in the ALARP region.

Figure 5 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.

It is reported in HIPAP No. 4 [5] that the criteria in Figure 5 are indicative criteria and provisional only and do not represent a firm requirement in NSW.

3.5 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 [5] 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.

4 OVERVIEW OF PIPELINES

4.1 Introduction

The proposed development is not a potential source of risk from DGs to the surrounding land uses; however, it is still appropriate to assess the risk from any existing potentially hazardous facilities (including high pressure DG pipelines) in the vicinity to ensure it is an appropriate land use in accordance with HIPAP No. 10 [3].

Two high-pressure dangerous goods pipelines pass the proposed site. These pipelines are operated by Ampol and Jemena and transport jet fuel and natural gas respectively.

Secondary natural gas mains and medium pressure natural gas mains also pass through, or adjacent to, proposed site. These are part of Jemena's natural gas distribution network and similar mains are common throughout suburban streets. Although not licenced pipelines, one larger secondary main may operate at pressures up to 1050 kPag. These larger secondary mains were also included in the QRA.

4.2 Consultation with Pipeline Operators

A DBYD enquiry was initiated in September 2020 [8] [9] and an initial response was received from Caltex and Jemena. This response (including maps showing approximate locations of the pipelines in the study area) was used to determine the scope of the follow-up consultation.

Operational data (MAOP, transfer rates, etc.) for the Jet A1 Pipeline was sought directly from Caltex (Refer to Section 4.3).

The primary and secondary natural gas mains are not licenced pipelines and the information supplied by Jemena in the DBYD response [8] [9] and in the Safety Case (SAOP) of Jemena Gas Assets (NSW) [10] was sufficient for the QRA. Additional consultation with Jemena was not undertaken.

4.3 Jet A1 Pipeline

The Jet A1 Pipeline is located on the north of the development and is located within the Sydney Water easement (Refer to Figure 3).

The Jet A1 Pipeline is approximately 9 km long and is used to transfer jet fuel from the Caltex Banksmeadow Terminal directly to the Sydney Kingsford Smith Airport Joint User Hydrant Installation (JUHI) [11].

Table 5 Jet A1 Pipeline

Pipeline Owner	**Caltex Petroleum**
Pipeline Name	Caltex Jet A1 Pipeline
Material/s Transferred	Jet Fuel
Licence No.	Licence with SafeWork NSW
Original Year of Construction	~ 1972
MAOP	10,000 kPag
Normal Operating Pressure	3,000 kPag
Operating Temperature	15 deg C
Flowrate	400 kL/hour
Pipeline Material	Steel grade X42
Pipeline Diameter	200 mm
Wall Thickness	Nom 6.35 mm
Depth of Cover	~ 1,000 mm
Cathodic Protection	Yes, Impressed Current
External / Internal Coating/s	Yellow Jacket external, no internal.
Leak Detection	Yes. Remote monitored 24x7 auto shut down.
Locations of Nearest Isolation Valves	Banksmeadow Terminal and JUHI
Inspections and Maintenance	Engineering inspection, SAP-PM routine maintenance
Control Measures for Third Party Activity (TPA)	DBYD, Signage, Weekly Patrols
Pigging	Yes. Frequency as per AS2885 part 3. Next due ~ 2023

4.4 Natural Gas Mains

The information tabulated below for the two natural gas mains included in the QRA is primarily based on information supplied by Jemena in the DBYD response [8] and information in the Safety Case (SAOP) of Jemena Gas Assets (NSW) [10]. Data for other similar secondary mains is also included where relevant.

The Mains are operated and maintained in accordance with a Safety Management Manual and the requirements of AS/NZS 4645 [10].

Table 6 Natural Gas Mains

Pipeline Owner	**Jemena**	**Jemena**
Pipeline Name	150 ST 3500 kPa [8]	450 ST 1050 kPa [8]
Material/s Transferred	Natural Gas	
Licence No.	Not Applicable (Primary and Secondary mains are not licensed pipelines)	
Original Year of Construction	*Information not provided*	
MAOP	3500 kPag [8]	1050 kPag [8]
Normal Operating Pressure	Primary mains typically operate at > 1750 kPag to 3500 kPag [10]	Secondary mains typically operate at > 545 kPag to 1050 kPag [10]
Operating Temperature	*Information not provided* (15 °C typical)	
Flowrate	*Information not provided*	
Pipeline Material	Steel (Typically Carbon Steel, API 5L Grade B or Grade X42 [12])	
Pipeline Diameter	150 mm	450 mm
Wall Thickness	*Information not provided* (4.78 mm typical)	
Depth of Cover	*Information not provided* (Note: Surveyed pipeline depths have observed to be marked on the roadways in various locations and found to be within 500mm to 1000mm in depth	
Cathodic Protection	*Information not provided* (Primary and Secondary mains are typically provided with CP, which is periodically monitored [10].	
External / Internal Coating/s	*Information not provided* (Typically coated with High-Density Polyethylene (HDPE) or Tri-laminate product and internally lined to reduce frictional loses and provide some internal corrosion protection [10])	
Leak Detection	*Information not provided*	
Locations of Nearest Isolation Valves	*Information not provided*	
Inspections and Maintenance	*Information not provided* (Integrity is assessed through integrity and performance assessments, such as Direct Current Voltage Gradient (DCVG) measurement [10])	*Information not provided* (Integrity is assessed through integrity and performance assessments [10])
Control Measures for Third Party Activity (TPA)	*Information not provided* (Typically includes DBYD, pipeline patrols and surveillance [10])	
Pigging	NA – Some Primary and all Secondary mains are not piggable [10]	

5 HAZARD IDENTIFICATION

5.1 Introduction

The hazard identification was based on a review of the: information on the Ampol Jet A1 Pipeline and the Natural Gas Mains (Refer to Section 4); properties of Jet Fuel and Natural Gas; 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 Potentially Hazardous Materials.

Section 5.3 - Pipeline Failure Modes.

Section 5.4 - Consequences of Liquid or 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 Potentially Hazardous Materials

5.2.1 Jet Fuel

Jet Fuel is typically a mixture of hydrocarbons (paraffins, cycloparaffins, aromatic and olefinic hydrocarbons with carbon numbers predominantly in the C9 to C16 range) and is typically modelled as n-Decane (C10) in a QRA.

Physical properties are listed in Table 6.

Table 7 Physical Properties of Jet Fuel and Decane

	Jet Fuel	Decane
Boiling Point	150 - 300 °C	174 °C
Flash Point	38 - 55 °C	46 °C
Autoignition Temperature	> 220 °C	201 °C
Relative Vapour Density (Air =1)	> 5	4.9
Lower Flammability Limit (vol. %)	1%	0.7%
Upper Flammability (vol. %)	6%	5.4%

Jet Fuel is:

- Liquid at ambient conditions with vapour that is heavier than air;
- Flammable; and
- Non-toxic with a characteristic hydrocarbon odour.

5.2.2 Natural Gas

Natural Gas is principally used as a fuel. It typically contains 95 to 97% methane (CH_4) and is modelled as methane in the risk analysis.

Physical properties are listed in Table 7.

Table 8 Physical Properties of Methane

Boiling Point	-162 °C
Flash Point	-218 °C
Autoignition Temperature	540 °C
Relative Density (Air =1)	0.55
Lower Flammability Limit in air (vol. %)	4.4%
Upper Flammability Limit in air (vol. %)	16.5%

Methane is:

- A gas at ambient conditions;
- A gas at typical operating conditions for Natural Gas pipelines;
- Flammable;
- Lighter than air at ambient temperatures; and
- Colourless, odourless and non-toxic (Note: Natural Gas is not odourless).

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 [13]:

- **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.1 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 Jet A1 Pipeline and the Natural Gas Mains; 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 Jet A1 Pipeline and the Natural Gas Mains; 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).

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 due to 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 Jet A1 Pipeline and the Natural Gas Mains; however, the local topography is such that this is expected to be lower likelihood than would apply for areas with more potential for ground movement.

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 at a later time).

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 Jet A1 Pipeline and the Natural Gas Mains.

5.4 Consequences of Liquid or Gas Release

5.4.1 Asphyxiation

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

Methane 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 [14]) 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 342,000 mg/m^3 for Methane).

Oxygen deficiency from exposure to Methane should not be a major issue because the fire hazards are usually the dominant effects in most locations (the LFL for methane is approximately one-tenth 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

A pressurised release of Gasoline or Jet Fuel may also form a jet fire. In these cases, the liquid jet is surrounded by a diffusion flame supported by the evaporating liquid. Impingement of the liquid jet will result in a pool fire (Refer to Section 5.4.3).

The SAFETI software uses a different correlation depending on the release conditions. For a liquid, or two-phase release, the Cook et. al. model is used.

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 Pool Fire

Combustion of Jet Fuel released from an orifice (e.g. hole in a pipeline) may create a pool fire.

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

5.4.4 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 of the Natural Gas release events. A flash fire was also included in the QRA as a potential outcome for the larger Jet Fuel releases from the Jet A1 Pipeline, but only for the case where the liquid does not 'rain out' at the source (i.e. does not impinge on the ground and/or the machinery that caused the leak – Refer to Section 6.1.3).

The potential for fatality due to direct exposure to a flash fire was included in the QRA.

5.4.5 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.).

An explosion was included in the QRA as a potential outcome for the larger Jet Fuel releases, but only for the case where the liquid does not 'rain out' at the source (i.e. does not impinge on the ground and/or the machinery that caused the leak – Refer to Section 6.1.3). Similarly, an explosion was included in the QRA as a potential outcome for a natural gas leak.

The potential for fatality due to exposure to the overpressure from an explosion was included in the QRA.

5.4.6 Gas Ingress into Buildings

A high momentum natural gas release will disperse downwind as the momentum effect drops. If the high momentum release is oriented towards a building, there is potential for the flammable natural gas to be drawn into a building through ventilation air intakes and open windows. If the gas reaches lower flammability limit, an ignition within the building would result in a confined explosion with serious harm to occupants and structural damage.

5.4.7 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. Methane 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.

Large quantities of smoke can be produced from hydrocarbon fires, especially flammable liquids such as Jet Fuel; however, this is rarely injurious for persons at ground level due to the buoyancy of the hot plume and its subsequent dispersion well above ground level.

If a fire were to occur on the Jet A1 Pipeline, then smoke may ingress into the nearby high-rise buildings. This was not specifically carried forward in the risk analysis as the heat radiation effects will dominate the risk in the near field and ingress of gas / vapour into these buildings has been separately assessed for flash fires and vapour cloud explosions (as above).

5.4.8 Explosion in a Confined Space

If a leak of flammable vapour enters a confined space, then a confined explosion may occur if it is ignited.

Liquid migration through the ground is credible; however, this was not included in risk analysis as underground areas of buildings are typically sealed to prevent water ingress.

A leak of flammable gas or liquid from an underground pipeline also has the potential to enter underground services (e.g. sewer pipes) if there is inadequate segregation. This was the cause of major explosions in Mexico and Taiwan; however, these incidents occurred due to very specific circumstances (e.g. For the incident in Taiwan, a gas pipeline had been routed through a sewer and subsequently leaked inside the sewer due to corrosion. For the incident in Mexico, a fuel pipeline was in direct contact with a water pipe and a leak occurred between the two due to corrosion). Due to the very situational and localised nature of these events, this type of confined explosion has not been included in the risk analysis.

5.4.9 Incident Escalation in Pipeline Easement

A major fire on one pipeline may result in the failure of an adjacent pipeline. Underground pipelines are typically protected by the surrounding soil but may be exposed if a large release creates a crater.

The likelihood and consequences of propagation and escalation were estimated based on a review of historical incidents (Primarily from Ref. [15]) and the separation distances between the Jet A1 Pipeline and the Jemena Primary and Secondary Mains in the study area.

- **Historical Incidents** – In 2016, a review of buried pipeline rupture incidents identified only 2 propagation events from 17 pipeline rupture incidents due to an adjacent pipeline being exposed [15]. One of these events involved the rupture of natural gas pipeline with larger diameter (viz. 1,067 mm) and both a higher pressure (viz. greater than 6,000 kPa) than the primary and secondary mains in the study area.
- **Estimated Crater Dimensions** – The maximum crater radius and depth for full bore rupture of a 1050 kPa Secondary Natural Gas Main at a depth of 0.8 m in a clay soil was estimated to be c. 2.5m and c. 1.2 m, respectively (Note: It is not possible to estimate crater dimensions using SAFETI for the Jet A1 Pipeline). Based on this analysis and the separation distances (see below), even if a FBR of a secondary main were to occur, it is unlikely to expose a large section of the Jet A1 Pipeline.
- **Separation Distances** – There is only section of the Jet A1 Pipeline that is located in the same area as the 3500kPag Primary Natural Gas Main and 1050 kPa Secondary Natural Gas Main (Refer to Figure 3). All three pipelines run parallel to each other through Sir Joseph Banks Park until Tupia Street where the Jet A1 pipeline continues along the Sydney Water Easement and the natural gas mains run up Tupia Street toward Botany Road.
- **Escalation Potential** – Propagation from a Natural Gas Main to the Jet A1 Pipeline does not appear to be a credible event based on the observations above.

  Even if it is postulated that propagation from the Jet A1 Pipeline to a Natural Gas Main is credible (i.e. where a main is located near and above the Jet A1 Pipeline, such that it becomes exposed to a pool fire), then escalation is still not likely as the consequences of each pool / jet fire event are comparable and would be unlikely to occur simultaneously.

Based on this review, propagation and escalation was not considered a credible event for inclusion in the risk assessment.

5.5 Control Measures

Part 7.1 (Hazardous Chemicals) of the WHS Regulation applies to pipelines used to convey hazardous chemicals that are not regulated under the NSW Pipelines Act 1967 or the Gas Supply Act 1996. Division 9 under Part 7.1 of the WHS Regulation covers the: requirements for management of risk by the pipeline operator (Clause 389); duties of pipeline builders (390); and management of risks to health and safety by the pipeline operator (Clause 391).

The Ampol Jet A1 Pipeline is regulated by SafeWork NSW under the NSW Work, Health and Safety (WHS) Regulation [7]. The Jet A1 Pipeline is operated and maintained in accordance with AS/NZS 2885 [11]

The Primary Mains System operation complies with AS2885 to ensure “continued pipeline integrity during the life of the pipeline” to prevent risk to community safety, property and environmental damage and loss of gas supply, as indicated in the Jemena Distribution Network Safety Case [10].

Due to the lower operating pressures, AS/NZS 2885 does not apply for the Secondary Natural Gas Mains. These mains are operated and maintained in accordance with AS/NZS 4645 [10]. Part 1 of AS/NZS 4645:2018 [16] includes the network management requirements for the life cycle of a gas distribution network (including operation and maintenance) and Part 2 [17] specifies the requirements for design, construction and testing of steel pipes.

5.5.1 Prevention of Mechanical Failure

Systems and processes to ensure the pipeline structural integrity for the design life of a pipeline such as the Ampol Jet A1 Pipeline are included in Section 6 of AS/NZS 2885.3:2012 [18] and are included as part of the pipeline management system. Similar requirements for the natural gas distribution mains are included in Part 2 of AS/NZS 4645:2018 [17].

The Jet A1 Pipeline is inspected using 'intelligent pigging' and repaired as required (Refer to Section 4.3).

5.5.2 Corrosion Prevention

Systems and processes to ensure the pipeline structural integrity for the design life of a pipeline such as the Ampol Jet A1 Pipeline are included in Section 6 of AS/NZS 2885.3:2012 [18]. Similar requirements for the natural gas distribution mains are included in Part 2 of AS/NZS 4645:2018 [17]. These 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 Jet A1 Pipeline is inspected using 'intelligent pigging' (Refer to Section 4.3). It is coated and equipped with a cathodic protection system (Refer to Section 4.3).

The Primary and Secondary Natural Gas Mains are cathodically protected. These mains are typically coated with High-Density Polyethylene (HDPE) or a Tri-laminate product and are internally lined to reduce frictional loses and provide some internal corrosion protection [10].

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 AS/NZS 2885.1:2018 and AS/NZS 4645:2018). 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).

All the pipelines are located on relatively flat stable land within road corridors or easements. The potential for ground movement is low.

5.5.4 Prevention of Damage due to Third Party Activity

Section 11 of AS 2885.3:2012 [18] requires a Safety Management Study to be undertaken 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 periodic patrols.

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

Section 11 of AS 2885.3:2012 [18] requires the development and implementation of an Emergency Response Plan as part of the pipeline management system. Similar requirements for the natural gas distribution mains are included in Section 9 of AS/NZS 4635.1:2018 [16].

An Emergency Response Plan should typically 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 pipelines can be isolated by closing automated and/or manual valves (Refer to Sections 4.3 and 4.4).

5.6 MAEs for Risk Analysis

The list of MAEs included in the risk analysis is provided in Table 8.

Table 9 List of MAEs

MAE	Potential Consequences
Release of Jet Fuel from Ampol Jet A1 Pipeline *	Pool Fire, Jet Fire, Flash Fire and/or Explosion
Release of Natural Gas from Jemena Secondary Main (450 mm Diameter)	Jet Fire, Flash Fire and/or Explosion
Release of Natural Gas from Jemena Primary Main (150 mm Diameter)	Jet Fire, Flash Fire and/or Explosion

* Modelled as Decane (As representative material for Jet Fuel)

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) 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.

Table 10 Representative Hole Diameters Selected for Consequence Analysis

Pipeline/s	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)
Jet A1 Pipeline	200	10 or 25*	75	110	Full bore
Natural Gas Mains	450	10 or 25*	75	110	Full bore
	150	10 or 25*	75	110	Full bore

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

6.1.2 Rate of Release

Release events were modelled using SAFETI. The estimated release rates are tabulated below for each representative hole size.

Table 11 Representative Hole Diameters Selected for Consequence Analysis

MAE	Hole Diameter (mm)	Release Rate [kg/s]
Release of Jet Fuel from Ampol Jet A1 Pipeline	10	3.4
	25	21.5
	75	88.9*
	110	88.9*
	FBR	88.9*
Release of Natural Gas from Jemena Primary Main (150 mm Diameter)	10	0.45
	25	2.77
	75	25.0
	110	53.8
	FBR	100

MAE	Hole Diameter (mm)	Release Rate [kg/s]
Release of Natural Gas from Jemena Secondary Main (450 mm Diameter)	10	0.14
	25	0.86
	75	7.7
	110	16.6
	FBR	277

* Limited to transfer rate.

6.1.3 Height and Orientation of Release

The SAFETI software does not permit entry of a release height below 0 m; therefore, all releases from the underground pipeline were modelled at a release height of 0 m (i.e. ground level). This is not a significant factor for the typical burial depth (Refer to Section 4.3).

A release of high-pressure gas or liquid from a buried pipeline would result a crater and would be orientated upwards from the crater [19].

6.1.4 Duration of Release

Jet Fuel and Methane are 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 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 Appendix A.6) and the time required for each representative release case to reach steady state.

6.2 Fire Modelling

The latest SAFETI software package (Version 8.61) 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 Pool Fire

Example distances to heat radiation levels of 4.7, 14, 21 and 35 kW/m^2 are tabulated in Appendix B.2.1 for the representative pool fire events included in the risk analysis.

6.2.2 Jet Fire

Example distances to heat radiation levels of 4.7, 12.5, 23 and 35 kW/m^2 are tabulated in Appendix 0 for representative jet fire events included in the risk analysis.

The worst-case jet fire is a full-bore rupture (FBR) of the 450 mm Secondary Natural Gas Main due to its relatively large diameter and release rate.

6.2.3 Flash Fire

Example distances to the upper flammability limit (UFL), lower flammability limit (LFL) and ½LFL concentrations are tabulated in Appendix B.2.3 for representative flash fire events included in the risk analysis.

Only the 'horizontally' orientated releases of natural gas have the potential to exceed the LFL or ½LFL concentrations at ground level. These distances are relatively large for the FBR events (e.g. up to several hundred metres for FBR of the 450 mm diameter main); however, the potential hazard area for a flash fire is limited by the relatively narrow plume widths.

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 3-D obstruction model in SAFETI was used to estimate the overpressure for a VCE and a medium level of congestion (Equivalent to TNO Model curve number 4) was assumed to simulate entry of the gas or vapour into a building and the subsequent confined explosion. The maximum calculated overpressure using TNO Model curve number 4 is 10 kPa.

7 FREQUENCY AND LIKELIHOOD ANALYSIS

7.1 Likelihood of Liquid or Gas Release

The likelihood of a liquid or gas release (i.e. leak) from each of the pipelines is tabulated in Table 11 (Also refer to Appendix C.1) and was estimated based on a review of relevant data sources. The primary data sources included:

- Department of Industry, Resources and Energy, New South Wales, *2018-19 Licensed Pipelines Performance Report* [20]. This includes data for all licensed pipelines in NSW for the 5-year period: 2014/15 to 2018/19.
- UK Health and Safety Executive (HSE), Research Report (RR) 1035 [13].
- British Standards Institute (2013) [21].

Table 12 Leak Frequencies

MAE	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
Release of Jet Fuel from Ampol Jet A1 Pipeline	5.4E-05	2.7E-05	2.2E-05	8.8E-06	**1.12E-04**
Release of Natural Gas from Jemena Secondary Main (450 mm Diameter)	3.5E-04	4.9E-06	2.7E-07	2.6E-06	**3.6E-04**
Release of Natural Gas from Jemena Primary Main (150 mm Diameter)	4.9E-04	4.9E-06	2.7E-07	2.6E-06	**5.0E-04**

7.2 Probability of Ignition

The ignition probabilities adopted in the risk analysis are listed in and were based on a review of relevant ignition probability data and ignition probability correlations (Refer to Appendix C).

Table 13 Ignition Probabilities

MAE	Hole Diameter (mm)	Release Rate [kg/s]	Total Ignition Probability	Immediate Ignition Probability	Delayed Ignition Probability
Release of Jet Fuel from Ampol Jet A1 Pipeline	10	3.4	0.0096	0.0048	0.0048
	25	21.5	0.0324	0.0162	0.0162
	75	89*	0.0670	0.0335	0.0335
	110	89 *	0.0670	0.0335	0.0335
	FBR	89 *	0.0670	0.0335	0.0335
Release of Natural Gas from Jemena Secondary Main (450 mm Diameter)	10	0.14	0.0013	0.0006	0.0006
	25	0.86	0.0049	0.0025	0.0025
	75	7.70	0.0257	0.0129	0.0129
	110	16.6	0.0458	0.0229	0.0229
	FBR	167.7	0.2599	0.1300	0.1300

MAE	Hole Diameter (mm)	Release Rate [kg/s]	Total Ignition Probability	Immediate Ignition Probability	Delayed Ignition Probability
Release of Natural Gas from Jemena Primary Main (150 mm Diameter)	10	0.45	0.0034	0.0017	0.0017
	25	2.8	0.0138	0.0069	0.0069
	75	25	0.0700	0.0350	0.0350
	110	53.8	0.1262	0.0631	0.0631
	FBR	100	0.1932	0.0966	0.0966

* Limited to transfer rate.

7.3 Likelihood of Representative MAEs

The likelihood of each representative release scenario included in the risk analysis is tabulated in Appendix C.3.

8 RISK ANALYSIS

8.1 Individual Risk of Fatality

The 0.5 x 10^{-6} per annum (p.a.) cumulative individual fatality risk contour for the Jet A1 Pipeline and the Natural Gas Mains is shown in Figure 6. This value is the risk criterion for sensitive land uses in HIPAP No.10 [3].

A cumulative individual fatality risk of 1 x 10^{-6} p.a., which is the risk criterion for residential land uses in HIPAP No.10 [3], is not reached at any location in the vicinity of the development.

Figure 6 Cumulative Individual Fatality Risk

It is noted that the individual fatality risk presented in Figure 6 accounts for dangerous goods risk associated with pipelines only and does not include any potential risk associated with handling of dangerous goods at Port Botany. Based on the individual fatality risk presented in the Port Botany Land Use Safety Study [22], the cumulative individual fatality risk of 1 x 10^{-6} p.a. does not reach the subject site for either the existing or postulated future cases modelled in that study.

8.2 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 5.4.7); therefore the proposed development complies with the relevant DPIE risk criteria (Refer to Section 3.4.2).

8.3 Risk of Property Damage and Accident Propagation (Exceeding 14 kPa)

The cumulative risk of property damage and accident propagation (Overpressure exceeding 14 kPa) does not reach 50 x 10^{-6} p.a. This criterion does not apply to the proposed development (Refer to Section 3.4.3).

8.4 Risk of Property Damage and Accident Propagation (Exceeding 23 kW/m^2)

The cumulative risk of property damage and accident propagation (Heat radiation exceeding 23 kW/m^2) does not reach 50 x 10^{-6} p.a. This criterion does not apply to the proposed development (Refer to Section 3.4.3).

8.5 Risk of Injury (Exceeding 7 kPa)

The cumulative risk of injury (Overpressure exceeding 7 kPa) does not reach 50 x 10^{-6} p.a.; therefore, the proposed development complies with the relevant DPIE risk criterion (Refer to Section 3.4.2).

8.6 Risk of Injury (Exceeding 4.7 kW/m^2)

The cumulative risk of injury (Heat radiation exceeding 4.7 kW/m^2) does not reach 50 x 10^{-6} p.a.; therefore, the proposed development complies with the relevant DPIE risk criterion (Refer to Section 3.4.2).

8.7 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 pipelines are existing facilities and cannot be relocated to avoid risk exposure.
- Reduction, wherever practicable, of the risk from a major hazard, even where the likelihood of exposure is low – Risk reduction measures are proposed in Section 9.2.
- Containment, wherever possible, within the site boundary of the effects (consequences) of the more likely hazardous events – The effects (consequences) of the more likely hazardous events (i.e. the smallest representative hole sizes) are generally limited to the roadways in which they are located (Refer to Appendix B.2).
- 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 to the proposed development meets the individual and societal risk criteria, and risk reduction measures proposed

8.8 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 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).

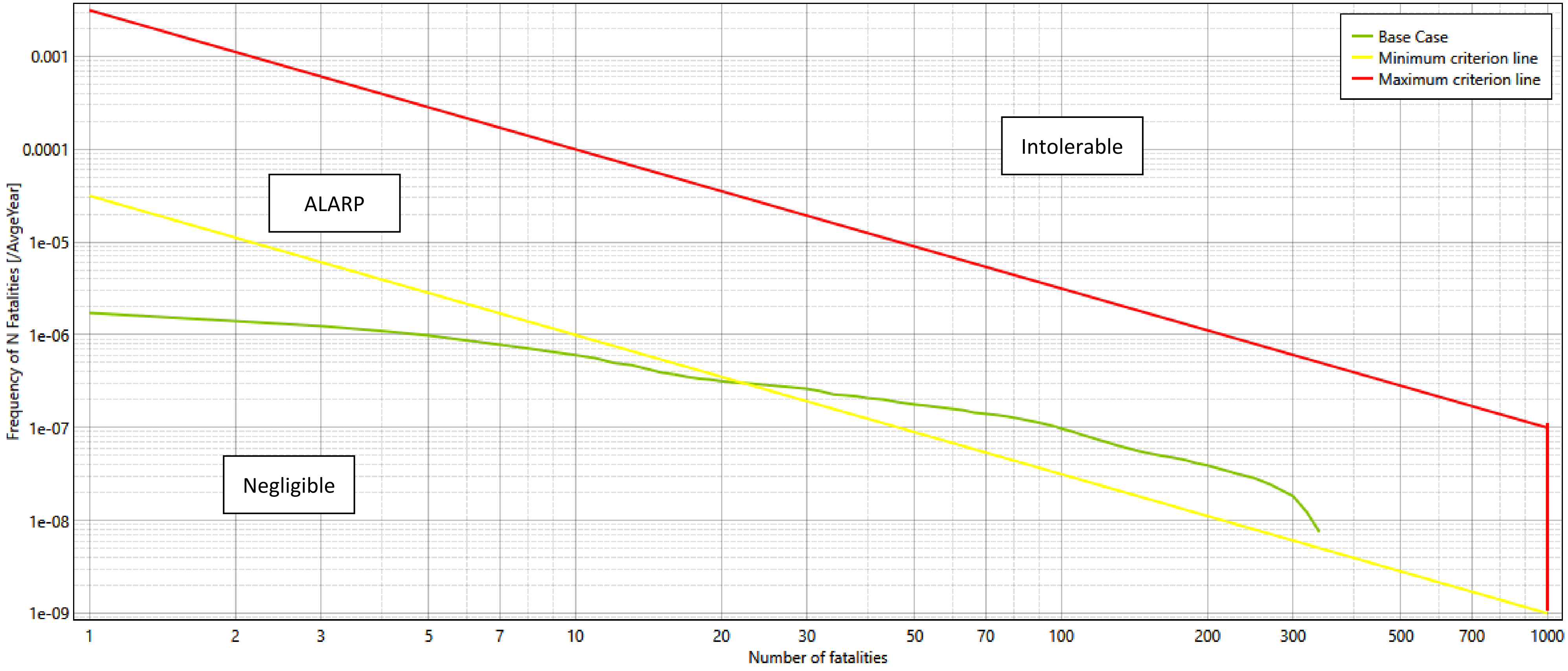
Two parameters are required to define societal risk: (a) Number of fatalities that may result from an incident; and (b) the frequency (likelihood) of occurrence of the incident.

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 F-N curve for the proposed development is shown in Figure 7. The entirety of this curve is in the 'Negligible' or 'ALARP' regions and complies with the DPIE's indicative societal risk criteria.

Figure 7 Societal Risk F-N Curve



9 FINDINGS AND RECOMMENDATIONS

9.1 Findings

Compliance with NSW DPIE Risk Criteria for Land Use Safety Planning

- The maximum individual fatality risk is 0.5 x 10^{-6} p.a. and this only occurs at one location where the Jet A1, and Jemena Pipelines are in close proximity to each other (Refer to Figure 6). This risk criterion level only applies to sensitive land uses (schools, hospitals, etc.), which are not proposed at this location. Therefore, the proposed development satisfies the individual fatality risk criteria in HIPAP No.10 [3].
- All other individual risk levels comply with the corresponding quantitative risk criteria in HIPAP No.10 [3] (Refer to Sections 8.2 to 8.6).
- The entirety of the F-N curve is in the 'Negligible' or 'ALARP' regions and complies with the DPIE's indicative societal risk criteria (Refer to Section 8.8).

9.2 Recommendations

The following recommendation is made:

If further population intensification is considered, i.e. a significantly larger number of apartments beyond the 109 contemplated in this report, additional risk analysis should be undertaken to ensure the societal risk criteria are still met.

10 REFERENCES

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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 Major Accident Events (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
- 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.*"

Table 14 List of Assumptions by Subject

Subject	No.	Assumption
Operational Data	1	Pipeline Operating Conditions
	2	Utilisation of Pipelines
Locational Data	3	Representative Wind Speeds, Wind Directions and Stability Classes
	4	Ambient Conditions
	5	Surface Roughness Length
	6	Total Population (Day and Night)
	7	Indoor / Outdoor Population Distribution (Day and Night)
Risk Analysis Methodology	8	Location and Segmentation of Pipelines
Consequence Analysis	9	Representative Materials
	10	Pressure / Pumping Rate for Release Modelling
	11	Representative Hole Diameters for Release Modelling
	12	Location of Release
	13	
	14	Maximum Extent of Flash Fire
	15	Isolation Time and Duration of Release
	16	
	17	3D Explosion Model Parameters
Likelihood Analysis	18	Likelihood of Release (Loss of Containment)
	19	Ignition Probability
	20	Probability of VCE or Flash Fire
Vulnerability Parameters	21	Exposure to Heat Radiation from a Fire (Indoor or Outdoor)
	22	Exposure to Flash Fire (Indoor or Outdoor)
	23	Exposure to Explosion Overpressure (Indoor or Outdoor)

A.1 Operational Data

Assumption No. 1: Pipeline Operating Conditions
Subject: Operational Data
Assumption/s: • All pipeline operating conditions (pressure, temperature, etc.) are as reported in Sections 4.3 and 4.4.
Justification and Impact/s of Assumption/s: • All operational data for the Jet A1 pipeline was supplied by Ampol Petroleum. • All operational data for the Jemena Primary and Secondary Natural Gas Mains was sourced from publicly available information, including the information provided in the DBYD response. • Operating conditions (particularly operating pressure) are required to undertake the release and dispersion modelling.
MAE/s Affected: • All.
Reference/s: • Email from Rob Moore Ampol Australia. • Jemena, *DBYD Response*, DBYD Sequence Number 101378280, 2 Sept. 2020. • Caltex Australia, *DBYD Response*, DBYD Sequence Number 101378283, 2 Sept. 2020.

Assumption No. 2: Utilisation of Pipelines
Subject: Operational Data
Assumption/s: • The Jet A1 Pipeline is utilised 100% of the time. • The Jemena Natural Gas Mains are 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: • Email from Rob Moore Ampol Australia. • Jemena, *DBYD Response*, DBYD Sequence Number 101378280, 2 Sept. 2020. • Caltex Australia, *DBYD Response*, DBYD Sequence Number 101378283, 2 Sept. 2020.

A.2 Locational Data

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

Subject: Locational Data

Assumption/s:

- The probabilistic distribution of wind speed and wind direction for the representative stability classes is provided in Table 14 and Table 15, based on the Bureau of Meteorology (BoM) meteorological data for Mascot Airport.
- The data was split into daytime and night-time conditions.
- For the BoM meteorological data, night is defined as being the hour before dusk to the hour after sunrise. This varies depending on time of year; however, the average night time and day time duration were taken as 14 hours/day and 10 hours/day, respectively.

Justification and Impact/s of Assumption/s:

- The BoM meteorological data for Sydney Airport (Station ID: 94767) was processed in accordance with the methodology provided by the Victorian EPA
- Wind speed typically has minimal impact on jet fires due to momentum jet effects of a sonic release. However, higher wind speeds may cause the 'tilting' of the flame from a pool fire. An allowance for flame tilt is included in the SAFETI model.
- The downwind concentrations, and hence the hazard ranges for dispersion of flammable gas or vapour, vary with wind speed and Pasquil stability class. Therefore, multiple representative wind speed and stability class categories are included in accordance with standard practice for undertaking a quantified risk analysis (QRA).
- The day/night split of the weather data is required to allow for the fact that there is little or no occupancy of the school premises at night.
- The population data for Port Botany varies significantly for day time and night time. Therefore, the representative wind speed, stability class and wind direction data were determined for both daytime and night time (Refer to Table 14 and Table 15). This is to ensure that the corresponding conditions and populations are accounted for when estimating the societal risk.

MAE/s Affected:

- All.

Reference/s:

- Exemplary Energy manipulation of BoM data for Mascot Airport (Station ID: 94767) and World Met Station Number, WMO Index 94767. Used years 1989-2015.
- Stability categories calculated as per VIC EPA publication 1459. Sunrise and Sunset times obtained from NASA Jet Propulsion Laboratories' "Horizons" Ephemeris program.
- Bureau of Meteorology, http://www.bom.gov.au/climate/averages/tables/cw_94767.shtml.

Table 15 Probability of Representative Stability Classes and Wind Speeds (Day)

Stab. Class	Wind Speed (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
B	2.2	0.0100	0.0070	0.0060	0.0040	0.0090	0.0050	0.0060	0.0100	0.0060	0.0030	0.0030	0.0040	0.0080	0.0090	0.0120	0.0080	0.1104
D	8.5	0.0120	0.0382	0.0602	0.0291	0.0191	0.0131	0.0261	0.0341	0.1145	0.0321	0.0070	0.0171	0.0341	0.0171	0.0110	0.0080	0.4729
D	4.2	0.0030	0.0020	0.0010	0.0010	0.0020	0.0010	0.0020	0.0020	0.0020	0.0020	0.0020	0.0030	0.0050	0.0050	0.0050	0.0030	0.0412
D	1.6	0.0251	0.0161	0.0171	0.0141	0.0271	0.0201	0.0271	0.0231	0.0361	0.0131	0.0100	0.0131	0.0281	0.0361	0.0482	0.0211	0.3755
Total		0.0501	0.0633	0.0843	0.0482	0.0572	0.0392	0.0612	0.0692	0.1586	0.0502	0.0220	0.0372	0.0752	0.0672	0.0762	0.0401	1.0000

Table 16 Probability of Representative Stability Classes and Wind Speeds (Night)

Stab. Class	Wind Speed (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
D	8.3	0.0110	0.0301	0.0120	0.0030	0.0050	0.0070	0.0140	0.0251	0.0611	0.0271	0.0120	0.0170	0.0251	0.0080	0.0060	0.0040	0.2675
D	4.2	0.0060	0.0030	0.0020	0.0020	0.0020	0.0010	0.0020	0.0010	0.0020	0.0010	0.0020	0.0020	0.0040	0.0040	0.0060	0.0040	0.0441
D	1.0	0.0371	0.0281	0.0190	0.0090	0.0160	0.0130	0.0160	0.0140	0.0251	0.0150	0.0150	0.0210	0.0311	0.0220	0.0331	0.0291	0.3437
E	3.3	0.0230	0.0120	0.0080	0.0030	0.0040	0.0030	0.0030	0.0030	0.0050	0.0040	0.0060	0.0100	0.0160	0.0170	0.0240	0.0251	0.1663
F	1.0	0.0261	0.0130	0.0100	0.0060	0.0060	0.0050	0.0040	0.0040	0.0060	0.0040	0.0060	0.0100	0.0180	0.0170	0.0240	0.0190	0.1784
Total		0.1032	0.0862	0.0510	0.0230	0.0330	0.0290	0.0390	0.0471	0.0992	0.0511	0.0410	0.0600	0.0942	0.0680	0.0931	0.0812	1.0000

Assumption No. 4: Ambient Conditions
Subject: Locational Data

Assumption/s:

- The typical ambient conditions (temperature, atmospheric pressure, solar radiation and relative humidity) are based on the Bureau of Meteorology (BoM) meteorological data for Mascot Airport.
- The typical ambient conditions (temperature, atmospheric pressure, solar radiation and relative humidity) are listed in Table 16 and Table 17.

Table 17 Average Temperature, Relative Humidity and Solar Radiation (Day)

Stability Class	Wind Speed (m/s)	Average Temp (°C)	Average Solar Radiation (W/m²)	Average Relative Humidity (%)
B	2.2	21.9	640	0.57
D	8.5	21.0	470	0.59
D	4.2	19.5	390	0.63
D	1.6	18.4	270	0.71

Table 18 Average Temperature, Relative Humidity and Solar Radiation (Night)

Stability Class	Wind Speed (m/s)	Average Temp (°C)	Average Solar Radiation (W/m²)	Average Relative Humidity (%)
D	8.3	17.6	0	0.72
D	4.2	16.7	0	0.76
D	1.0	16.8	0	0.83
E	3.3	15.3	0	0.76
F	1.0	15.9	0	0.81

Justification and Impact/s of Assumption/s:

- The BoM meteorological data for Mascot Airport (Station ID: 94767) was processed in accordance with the methodology provided by the Victorian EPA.
- The average atmospheric pressure is a required input for the SAFETI model. Port Botany precinct is flat and essentially at sea level. Therefore, the average atmospheric pressure does not have a significant impact on the consequence calculations.
- The average solar radiation is a required input for the SAFETI model. More recent versions of the SAFETI software allow this to be entered for each representative stability class – wind speed rather than a single value for all conditions.

Assumption No. 4: Ambient Conditions
MAE/s Affected: • All.
Reference/s: • Exemplary Energy manipulation of BoM data for Mascot Airport (Station ID: 94767) and World Met Station Number, WMO Index 94767. Used years 2010 – 2014. • Stability categories calculated as per VIC EPA publication 1459. Sunrise and Sunset times obtained from NASA Jet Propulsion Laboratories' "Horizons" Ephemeris programme. • Bureau of Meteorology, http://www.bom.gov.au/climate/averages/tables/cw_94767.shtml.

Assumption No. 5: Surface Roughness Length

Subject: Locational Data

Assumption/s:

- The roughness length for different surface types, as listed in the SAFETI user manual, is shown below in Table 18.

Table 19 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 land either side of the proposed development is predominantly low-rise buildings and parklands. Therefore, a roughness length of 0.5 m is a representative value for this location.

Justification and Impact/s of Assumption/s:

- 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:

- Aerial photographs of study area.
- SAFETI software documentation.

Assumption No. 6: Total Population (Day and Night)

Subject: Locational Data

Assumption/s:

- The risk analysis includes the estimated population within the Development. Surrounding residential populations located outside the Development (within the maximum estimated hazard range) are also included in the risk analysis.
- Populations are evenly distributed across each relevant area.
- **Proposed Residential Apartment Buildings** – The population in the apartment buildings of the Development is conservatively based on an occupancy rate of 2.2 persons per apartment, with 109 apartments. 20% of this population is assumed to be present during the day and 100% is present during the night.
- **Existing Residential Areas** – The population in the surrounding residential area has been based on occupancy rates from the 2016 Census (within the maximum estimated hazard range) is given in Table 19. The majority of these dwellings are residential houses.

Table 20 Surrounding Residential Population

Statistical Area 1 7-digit identifier	Population 2016	LGA			
1132001	15	Bayside	1135007	110	Randwick
1132002	9	Bayside	1135019	288	Randwick
1132003	0	Bayside	1135033	411	Randwick
1132113	418	Bayside	1135034	299	Randwick
1132114	485	Bayside	1135037	510	Randwick
1132115	437	Bayside	1135042	356	Randwick
1132116	472	Bayside	1135043	328	Randwick
1132121	0	Bayside	1135044	506	Randwick
1132123	8	Bayside	1135047	285	Randwick
1132401	11	Bayside	1135048	541	Randwick
1135056	405	Randwick	1135053	322	Randwick

Justification and Impact/s of Assumption/s:

- The occupancy rate and % of the total population present during the day and night was estimated from 2016 census data
- The total population and the % of the total population present during the day and night is required for estimation of the societal risk.

Assumption No. 6: Total Population (Day and Night)
MAE/s Affected: • All (Note: This assumption is only applicable to the calculation of societal risk).
Reference/s: • Australian Bureau of Statistics, 2016 census data

Assumption No. 7: Indoor / Outdoor Population Distribution (Day and Night)
Subject: Locational Data

Assumption/s:

- The % of people located indoors and outdoors during the day and night is dependent on the type of use, as follows:
  - **Proposed Residential Apartment Buildings** – 90% of the daytime population is indoors and 10% is outdoors. 99% of the night-time population is indoors and 1% is outdoors.
  - **Existing Residential Areas** – 90% of the daytime population is indoors and 10% is outdoors. 99% of the night-time population is indoors and 1% is outdoors.
- All population is located at ground level.

Justification and Impact/s of Assumption/s:

- The proportion of people located indoors and outdoors will affect the societal risk analysis, as the vulnerability to fire, explosion, etc. varies depending on location.
- The default values recommended by the TNO [‘Purple Book’] for residential and industrial areas are tabulated below.

Table 21 Proportion of Population Indoor and Outdoor During Day and Night [TNO]

Location	Day (8am to 6:30pm)	Night (6:30pm to 8am)
Indoor	93%	99%
Outdoor	7%	1%

- The % of the total population located indoors and outdoors was estimated from similar risk analyses. 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 (Note: This assumption is only applicable to the calculation of societal risk).

Reference/s:

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

A.3 Risk Analysis Methodology

Assumption No. 8: Location and Segmentation of Pipelines
Subject: Risk Analysis Methodology
Assumption/s: • All pipelines are physically located using the GIS functionality within SAFETI, based on the indicative locations provided by the DBYD information and the APGA Australian Pipeline Database. • Incidents were distributed along the pipeline at 25 m intervals.
Justification and Impact/s of Assumption/s: • Standard approach for linear sources.
MAE/s Affected: • All.
Reference/s: • SAFETI software documentation.

A.4 Consequence Analysis

Assumption No. 9: Representative Materials
Subject: Consequence Analysis
Assumption/s: • Jet Fuel is modelled as 100% Decane. • Natural gas is modelled as 100% Methane.
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. • Natural gas typically contains 85 to 95% methane.
MAE/s Affected: • All.
Reference/s: • https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas

Assumption No. 10: Pressure / Pumping Rate for Release Modelling
Subject: Consequence Analysis
Assumption/s: • A release of Jet Fuel from the Jet A1 Pipeline is modelled at 3,000 kPag (MAOP), with the maximum release rate limited to the pumping rate (c. 400 kl/hr). • A release of Natural Gas from the Jemena Secondary Mains is modelled at 1,050 kPag (MAOP). • A release of Natural Gas from the Jemena Primary Mains is modelled at 3,500 kPag (MAOP).
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. Therefore, use of the MAOP is a conservative, yet realistic, basis on which to model release rates; however, the rate of discharge from a liquid pipeline will be limited by the maximum capacity of the pump. • The pressure used to model the release rates was based on the pipeline pressure (Refer to Section 4).
MAE/s Affected: • All.
Reference/s: • Email from Rob Moore Ampol Australia. • Jemena, *DBYD Response*, DBYD Sequence Number 101378280, 2 Sept. 2020. • Caltex Australia, *DBYD Response*, DBYD Sequence Number 101378283, 2 Sept. 2020.

Assumption No. 11: Representative Hole Diameters for Release Modelling

Subject: Consequence Analysis

Assumption/s:

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

Table 22 Representative Hole Diameters Selected for Consequence Analysis

Pipeline/s	Material/s	Pipeline 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)
Jet A1 Pipeline	Jet Fuel	200	10 or 25*	75	110	Full bore
Jemena Primary Main	Natural Gas	150	10 or 25*	75	110	Full bore
Jemena Secondary Mains	Natural Gas	450	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 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) 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.

MAE/s Affected:

- All.

Reference/s:

- Refer to Appendix B.1.

Assumption No. 12: Location of Release from Underground Pipelines
Subject: Consequence Analysis
Assumption/s: • High pressure liquid or gas releases from an underground pipeline create a crater on the ground. The direction of release for underground pipeline failures from the crater is predominantly 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% horizontally impinged from the middle of the pipe and 63% vertically from the top of the pipe for all release cases except non-TPA events with a hole size less than or equal to 25mm, which are all modelled as horizontally impinged from the middle of the pipe). • All releases from underground (UG) pipelines are modelled at a release height of 0 m above ground level.
Justification and Impact/s of Assumption/s: • The position of the crater depends on the location of the hole on the pipe and three locations (top, middle and bottom) may be modelled using the 'Long Pipeline' Model in SAFETI (Note: This model cannot currently be used for liquid pipelines). 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. up to +/- 71^{o} 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. • The SAFETI software does not permit entry of a height of release below 0 m. • Modelling releases from underground (UG) pipelines at a release height of 0 m above ground level is generally conservative as the resultant point of release will be closer to the potential receptors. However, this is not a significant factor for the typical burial depths of the pipelines in the subject area (Refer to Section 4). • The default release height in the SAFETI software is 1 m.
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.

Assumption No. 13: Formation of Circular Pools
Subject: Consequence Analysis
Assumption/s: • All liquid releases (which rain out) form a circular pool.
Justification and Impact/s of Assumption/s: • The location is relatively flat
MAE/s Affected: • All MAEs where a liquid pool forms.
Reference/s: • Current topography in the vicinity of the Development.

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 50% of the lower flammability limit (LFL) concentration.
Justification and Impact/s of Assumption/s: • The peak to mean concentration within the gas cloud is approximately 2:1, and hence, while the average concentration is ½ LFL, there may be locations within the cloud where the concentration can be LFL, and hence ignition is possible. • The formation of localised higher concentrations is more applicable when the cloud passes around obstacles. This is particularly relevant where there are large obstacles (such as the multi-storey buildings in the proposed development).
MAE/s Affected: • All MAEs with a flash fire as a potential outcome.
Reference/s: • SAFETI software documentation.

Assumption No. 15: Isolation Time and Duration of Release
Subject: Consequence Analysis
Assumption/s: • Isolation time and duration of release is not specified as these will be 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: • Jet Fuel and natural gas are 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, using a 30 second exposure time (user specified) 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.

Assumption No. 16: Shielding 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.
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. • People located indoors are typically less vulnerable to fire, which is a relevant consideration for the societal risk assessment (Refer to Assumption No. 21).
MAE/s Affected: • All MAEs with a pool fire or jet fire as a potential outcome.
Reference/s: • SAFETI software documentation.

Assumption No. 17: 3D 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 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 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.
  • **Open Spaces** - A relatively low level of congestion is assumed for the open spaces. This equates to TNO Model curve number 2.
• 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 2 was assumed to apply, which is the default value in the SAFETI software. • 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

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.3. • 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 slightly more conservative than the NSW performance data for licenced pipelines. • The HSE data identifies four contributors to pipeline failure: (a) mechanical failure; (b) corrosion; (c) ground movement/other; and (d) Third Party Activity (TPA). • The justification for the data used in this risk analysis is provided in Appendix C.1.
MAE/s Affected: • All.
Reference/s: • Refer to Appendix C.1.

Assumption No. 19: Ignition Probability
Subject: Likelihood Analysis
Assumption/s: • The probability of ignition for each representative release is provided in Appendix C.2.
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.2.
MAE/s Affected: • All.
Reference/s: • Refer to Appendix C.2.

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 an explosion (Probability = 0.4) or a flash fire (Probability = 0.6).
Justification and Impact/s of Assumption/s: • Ignition of a free gas cloud may demonstrate characteristics of a flash fire and/or an explosion. This is modelled as two separate events: as a pure flash fire and a pure explosion. • The assumed probabilities are consistent with the guidance in the TNO 'Purple Book' and are the default values in the SAFETI software.
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

Assumption No. 21: Exposure 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.
- The probability of fatality for an individual located outdoors (30 seconds exposure), as calculated using the above probit equation, is as follows:

Table 23 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

- 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.

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

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 24 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.

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.

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 24 (Person located outdoors) and Table 25 (Person located indoors).

Table 25 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 26 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)

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 DPIE'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 DPIE'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 Consequence Analysis – Example Data and Results

B.1 Representative Hole Diameters

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 following available historical data.

B.1.1 Leak 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 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 27 Dimensions of Rupture Events for Onshore Underground Steel Pipelines for Refined and/or Petroleum Products (NON-HVL) (Reported Values Only)

MAOP		Pipe Diameter (in)	Rupture Width (in)	Rupture Length (in)	Approx. Rupture Area (sq.in)	% of Cross-Section Area	Equiv. Hole Diameter (mm)	Cause
(psig)	(kPag)							
400	2859	6.625	1.5	17	20.0	58.1	128.3	Material Failure of Pipe or Weld - Manufacturing
1200	8375	6.625	1	9	7.1	20.5	76.2	Material Failure of Pipe or Weld - Manufacturing
1440	10030	8	2.1	4.9	8.1	16.1	81.5	Natural Force - Heavy Rains / Floods
1200	8375	8.625	0.5	30	11.8	20.2	98.4	Excavation Damage
1865	12960	8.625	3.1	14.3	34.8	59.6	169.1	Corrosion - External
1142	7975	10	0.5	34	13.4	17.0	104.7	Corrosion - External
1342	9354	10	0.7	107.2	58.9	75.0	220.0	Material Failure of Pipe or Weld - Manufacturing
1097	7665	12	1	17	13.4	11.8	104.7	Excavation Damage
983	6879	12.75	1.7	26.2	35.0	27.4	169.5	Incorrect Operation - Overpressure
1440	10030	12.75	3	38.4	90.5	70.9	272.6	Material Failure of Pipe or Weld - Manufacturing
840	5893	18	3.5	35.7	98.1	38.6	283.9	Material Failure of Pipe or Weld - Manufacturing

Table 28 Dimensions of Puncture Events for Onshore Underground Steel Pipelines for Refined and/or Petroleum Products (NON-HVL) (US DoT - Reported Values Only)

MAOP		Pipe Diameter (in)	Puncture Axial Length (in)	Puncture Circum-ferential Length (in)	Approx. Puncture Area (sq.in)	% of Cross-Section Area	Equiv. Hole Diameter (mm)	Cause
(psig)	(kPag)							
250	1825	4	0.1	0.1	0.0	0.1	2.5	Excavation Damage
720	5066	6	5	4.5	17.7	62.5	120.5	Excavation Damage
1440	10030	6	3	2	4.7	16.7	62.2	Excavation Damage
1200	8375	6.625	6	3	14.1	41.0	107.8	Excavation Damage
615	4342	8	4.5	4.5	15.9	31.6	114.3	Excavation Damage
1291	9002	8	2.5	2	3.9	7.8	56.8	Other Outside Force - Other Vehicle
570	4031	8.625	6	3	14.1	24.2	107.8	Other Outside Force - Other Fire/Explosion
960	6720	8.625	0.5	0.1	0.0	0.1	5.7	Excavation Damage
1135	7927	8.625	7	9	49.5	84.7	201.6	Excavation Damage
753	5293	10	2	2	3.1	4.0	50.8	Excavation Damage
1296	9037	10	10	3	23.6	30.0	139.1	Excavation Damage
720	5066	10.75	8	3	18.8	20.8	124.4	Excavation Damage
753	5293	10.75	3	8	18.8	20.8	124.4	Excavation Damage
1150	8030	10.75	3.5	2	5.5	6.1	67.2	Excavation Damage
1194	8334	12.75	1	0.2	0.2	0.1	11.4	Excavation Damage
1226	8554	12.75	2.5	1	2.0	1.5	40.2	Excavation Damage
1298	9051	12.75	7	4.5	24.7	19.4	142.6	Excavation Damage
1440	10030	12.75	2	0.1	0.2	0.1	11.4	Excavation Damage
175	1308	16	1	8	6.3	3.1	71.8	Material Failure of Pipe or Weld - Construction, Installation or Fabrication

B.1.2 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 29 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

Fault ID	Discovery Date	Product	Wall Thickness (mm)	Diameter (in)	Diameter (mm)	Equivalent Hole Diameter (mm)	Cause
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.1.3 Leak Data for Underground Cross-Country Pipelines – Natural Gas Distribution

US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Reported Data for Underground Steel Natural Gas Distribution 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 30 Dimensions of Rupture Events for Underground Steel Natural Gas Distribution 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

MAOP (psig)	MAOP (kPag)	Pipe Diameter (in)	Rupture Length (in)	Rupture Width (in)	Approx. Rupture Area (sq.in)	% of Cross-Section Area	Equiv. Hole Diameter (mm)	Cause
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 31 Dimensions of Puncture Events for Underground Steel Natural Gas Distribution Pipelines (US DoT - Reported Values Only)

MAOP (psig)	MAOP (kPag)	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
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

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)							
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

B.2 Example Consequence Analysis Results for Representative Release Scenarios

Example hazard ranges for the modelled release cases are tabulated in Appendix B.2.1 to B.2.3.

B.2.1 Pool Fire Consequence Analysis Results

Table 32 Example Pool Fire Consequence Analysis Results

Release Scenario	Time	Weather	Height of Interest (m)	Equilibrium Pool Diameter (m)	Downwind Distance to 4.7 kW/m² at Height of Interest (m)	Downwind Distance to 12.5 kW/m² at Height of Interest (m)	Downwind Distance to 23 kW/m² at Height of Interest (m)	Downwind Distance to 35 kW/m² at Height of Interest (m)
Release of High-Pressure Jet Fuel from Ampol Jet A1 Pipeline								
10 mm (MID)	Day	B2.2	0	8.5	26.5	17.6	12.2	9.0
		D8.5		8.5	28.0	21.3	16.7	11.3
		D1.6		8.5	25.5	16.5	11.4	8.5
		D4.2		8.5	27.5	19.6	14.1	9.9
25 mm (MID)	Day	B2.2	0	21	38.7	24.2	18.4	16.0
		D8.5		21	42.5	25.7	19.1	16.8
		D1.6		21	37.3	23.5	17.9	15.7
		D4.2		21	40.8	25.1	18.8	16.5
75 mm (MID)	Day	B2.2	0	43	59.6	39.3	32.1	29.2
		D8.5		43	64.3	40.0	33.1	30.3
		D1.6		43	57.9	38.5	31.7	28.7
		D4.2		43	62.1	39.9	32.7	29.8
110 mm (MID)	Day	B2.2	0	43	59.6	39.3	32.1	29.2
		D8.5		43	64.3	40.0	33.1	30.3
		D1.6		43	57.9	38.5	31.7	28.7
		D4.2		43	62.1	39.9	32.7	29.8
FBR (MID)	Day	B2.2	0	61*	78.7	52.4	43.5	39.6
		D8.5		61*	85.7	53.7	44.5	40.9
		D1.6		61*	76.5	51.5	42.7	39.1

Release Scenario	Time	Weather	Height of Interest (m)	Equilibrium Pool Diameter (m)	Downwind Distance to 4.7 kW/m^2 at Height of Interest (m)	Downwind Distance to 12.5 kW/m^2 at Height of Interest (m)	Downwind Distance to 23 kW/m^2 at Height of Interest (m)	Downwind Distance to 35 kW/m^2 at Height of Interest (m)
		D4.2		61*	82.3	53.4	44.0	10.1

Note: * FBR case pool size increased from the equilibrium pool size to the maximum credible unignited pool spread of 3000m^2 for the Sydney Water Easement.

B.2.2 Example Jet Fire Consequence Analysis Results

Table 33 Example Jet Fire Consequence Analysis Results

Release Scenario	Time	Weather	Height of Interest (m)	Flame Length (m)	Downwind Distance to 4.7 kW/m^2 at Height of Interest (m)	Downwind Distance to 12.5 kW/m^2 at Height of Interest (m)	Downwind Distance to 23 kW/m^2 at Height of Interest (m)	Downwind Distance to 35 kW/m^2 at Height of Interest (m)
Release of High-Pressure Jet Fuel from Ampol Jet A1 Pipeline								
25 mm (TOP)	Day	B2.2	0	28.6	54.7	32.8	19.6	8.3
		D8.5		20.7	53.1	20.8	12.1	7.0
		D4.2		23.9	52.8	34.1	26.1	20.1
		D1.6		31.0	55.6	31.0	15.0	4.0
75 mm (TOP)	Day	B2.2	0	52.4	96.6	56.4	31.5	12.2
		D8.5		37.9	93.8	62.8	48.0	41.6
		D4.2		43.7	91.8	60.1	44.3	32.1
		D1.6		56.7	97.7	52.8	23.1	6.5
110 mm (TOP)	Day	B2.2	0	52.4	96.6	56.4	31.5	12.2
		D8.5		37.9	93.8	62.8	48.0	41.6
		D4.2		43.7	91.8	60.1	44.3	32.1
		D1.6		56.7	97.7	52.8	23.1	6.5
FBR (TOP)	Day	B2.2	0	52.4	96.6	56.4	31.5	12.2

Release Scenario	Time	Weather	Height of Interest (m)	Flame Length (m)	Downwind Distance to 4.7 kW/m^2 at Height of Interest (m)	Downwind Distance to 12.5 kW/m^2 at Height of Interest (m)	Downwind Distance to 23 kW/m^2 at Height of Interest (m)	Downwind Distance to 35 kW/m^2 at Height of Interest (m)
		D8.5		37.9	93.8	62.8	48.0	41.6
		D4.2		43.7	91.8	60.1	44.3	32.1
		D1.6		56.7	97.7	52.8	23.1	6.5
Release of Natural Gas (Methane) from Jemena Secondary Main								
10 mm (MID)	Day	B2.2	0	5.3	3.0	2.6	2.5	1.4
		D8.5		5.5	2.9	2.7	2.6	1.6
		D4.2		5.4	3.0	2.7	2.5	1.5
		D1.6		5.3	3.0	2.6	2.4	1.4
25 mm (MID)	Day	B2.2	0	12.1	8.1	6.0	5.2	5.0
		D8.5		13.7	7.4	6.6	6.3	5.9
		D4.2		12.5	6.0	2.6	2.3	2.3
		D1.6		11.8	8.1	5.9	5.1	4.8
25 mm (TOP)	Day	B2.2	0	10.3	8.0	n/a	n/a	n/a
		D8.5		7.4	11.7	7.4	4.1	n/a
		D4.2		8.6	10.5	2.9	n/a	n/a
		D1.6		11.1	6.4	n/a	n/a	n/a
75 mm (MID)	Day	B2.2	0	30.9	31.2	18.6	14.8	12.9
		D8.5		36.5	30.6	19.8	17.8	16.7
		D4.2		32.5	31.1	18.5	15.9	14.1
		D1.6		30.3	31.2	18.6	14.5	12.5
75 mm (TOP)	Day	B2.2	0	27.1	24.5	n/a	n/a	n/a
		D8.5		19.6	32.5	20.1	11.5	n/a

Release Scenario	Time	Weather	Height of Interest (m)	Flame Length (m)	Downwind Distance to 4.7 kW/m^2 at Height of Interest (m)	Downwind Distance to 12.5 kW/m^2 at Height of Interest (m)	Downwind Distance to 23 kW/m^2 at Height of Interest (m)	Downwind Distance to 35 kW/m^2 at Height of Interest (m)
		D4.2		22.5	30.0	11.9	n/a	n/a
		D1.6		29.2	21.3	n/a	n/a	n/a
110 mm (MID)	Day	B2.2	0	41.5	46.7	28.1	20.8	17.4
		D8.5		49.0	46.4	27.9	24.8	22.9
		D4.2		43.6	46.7	28.1	22.1	19.3
		D1.6		40.7	46.6	28.1	20.3	17.2
110 mm (TOP)	Day	B2.2	0	37.9	36.1	n/a	n/a	n/a
		D8.5		27.3	46.6	28.6	16.6	3.8
		D4.2		31.5	43.2	18.3	n/a	n/a
		D1.6		40.7	31.9	n/a	n/a	n/a
FBR (MID) – 450 mm	Day	B2.2	0	123.0	180.1	110.6	78.9	61.3
		D8.5		137.4	178.9	111.1	80.8	71.2
		D4.2		125.9	178.8	110.7	80.0	62.4
		D1.6		121.7	179.5	109.9	78.0	60.9
FBR (TOP) – 450 mm	Day	B2.2	0	128.1	145.2	50.7	n/a	n/a
		D8.5		92.5	172.8	104.9	65.2	30.2
		D4.2		106.4	164.0	80.8	34.1	n/a
		D1.6		137.9	134.7	35.5	n/a	n/a

Release Scenario	Time	Weather	Height of Interest (m)	Flame Length (m)	Downwind Distance to 4.7 kW/m^2 at Height of Interest (m)	Downwind Distance to 12.5 kW/m^2 at Height of Interest (m)	Downwind Distance to 23 kW/m^2 at Height of Interest (m)	Downwind Distance to 35 kW/m^2 at Height of Interest (m)
Release of Natural Gas (Methane) from Jemena Primary Main								
10 mm (MID)	Day	B1.9	0	9.1	5.2	4.5	4.0	3.8
		D7.5		10.1	5.4	4.9	4.7	4.5
		B2.2		9.4	5.3	4.6	4.2	4.0
		D8.5		8.9	5.2	4.4	3.9	3.7
25 mm (MID)	Day	D4.2	0	20.3	17.5	10.9	9.2	8.2
		D1.6		23.8	16.5	12.2	11.1	10.5
		B2.2		21.3	17.3	11.3	9.9	8.8
		D8.5		19.8	17.5	10.7	9.0	8.0
25 mm (TOP)	Day	D4.2	0	17.4	14.7	n/a	n/a	n/a
		D1.6		12.6	20.3	12.7	7.2	n/a
		B2.2		14.5	18.6	6.7	n/a	n/a
		D8.5		18.7	12.4	n/a	n/a	n/a
75 mm (MID)	Day	D4.2	0	48.3	57.6	34.8	24.8	20.9
		D1.6		56.9	57.7	33.5	29.4	27.1
		B2.2		50.6	57.7	35.0	26.4	22.9
		D8.5		47.4	57.6	34.8	24.3	20.4
75 mm (TOP)	Day	D4.2	0	45.5	44.6	8.2	n/a	n/a
		D1.6		32.8	56.8	34.9	20.7	5.6
		B2.2		37.8	52.9	23.2	n/a	n/a
		D8.5		48.9	39.9	n/a	n/a	n/a

Release Scenario	Time	Weather	Height of Interest (m)	Flame Length (m)	Downwind Distance to 4.7 kW/m^2 at Height of Interest (m)	Downwind Distance to 12.5 kW/m^2 at Height of Interest (m)	Downwind Distance to 23 kW/m^2 at Height of Interest (m)	Downwind Distance to 35 kW/m^2 at Height of Interest (m)
110 mm (MID)	Day	D4.2	0	64.1	83.6	50.9	35.9	28.8
		D1.6		74.5	84.6	51.3	40.2	36.6
		B2.2		66.8	84.1	51.4	36.6	31.0
		D8.5		63.0	83.5	50.7	35.7	28.5
110 mm (TOP)	Day	D4.2	0	63.4	65.4	16.7	n/a	n/a
		D1.6		45.7	81.4	49.8	30.2	9.8
		B2.2		52.7	76.1	34.9	10.9	n/a
		D8.5		68.2	59.2	n/a	n/a	n/a
FBR (MID) – 150 mm	Day	D4.2	0	81.3	112.2	68.6	48.7	38.1
		D1.6		93.3	114.3	70.0	52.1	47.0
		B2.2		84.2	113.1	69.5	49.9	39.7
		D8.5		80.1	112.0	53.8	34.8	24.6
FBR (TOP) – 450 mm	Day	D4.2	0	82.9	88.8	27.2	n/a	n/a
		D1.6		59.8	108.8	66.5	40.9	15.6
		B2.2		68.9	102.0	48.3	17.6	n/a
		D8.5		89.2	81.2	n/a	n/a	n/a

B.2.3 Example Flash Fire Consequence Analysis Results

Table 34 Example Flash Fire Consequence Analysis Results

Release Scenario	Time	Weather	Height of Interest (m)	Mass Flow Rate (kg/s)	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Distance to ½ LFL at Height of Interest (m)
Release of High-Pressure Gasoline from Ampol Jet A1 Pipeline							
25 mm (TOP)	Day	B1.8	0	21.5	Not Reached	Not Reached	Not Reached
		D7.5			Not Reached	Not Reached	Not Reached
		D1.6			Not Reached	Not Reached	Not Reached
		D4.1			Not Reached	Not Reached	Not Reached
75 mm (TOP)	Day	B1.8	0	89.6 *	Not Reached	Not Reached	Not Reached
		D7.5			Not Reached	Not Reached	Not Reached
		D1.6			Not Reached	Not Reached	Not Reached
		D4.1			Not Reached	Not Reached	Not Reached
110 mm (TOP)	Day	B1.8	0	89.6 *	Not Reached	Not Reached	Not Reached
		D7.5			Not Reached	Not Reached	Not Reached
		D1.6			Not Reached	Not Reached	Not Reached
		D4.1			Not Reached	Not Reached	Not Reached
FBR (TOP)	Day	B1.8	0	89.6 *	Not Reached	Not Reached	Not Reached
		D7.5			Not Reached	Not Reached	Not Reached
		D1.6			Not Reached	Not Reached	Not Reached
		D4.1			Not Reached	Not Reached	Not Reached

Release Scenario	Time	Weather	Height of Interest (m)	Mass Flow Rate (kg/s)	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Distance to ½ LFL at Height of Interest (m)
Release of Natural Gas (Methane) from Jemena Secondary Main							
10 mm (MID)	Day	B1.8	0	0.14	1.5	4.5	6.7
		D7.5			1.3	3.2	4.6
		D1.6			1.4	4.0	5.9
		D4.1			1.6	5.2	8.2
25 mm (MID)	Day	B1.8	0	0.86	3.5	11.1	20.0
		D7.5			2.8	7.0	14.7
		D1.6			3.3	9.8	20.0
		D4.1			3.8	12.9	21.3
25 mm (TOP)	Day	B1.8	0	0.86	0.0	0.1	0.1
		D7.5			0.0	0.1	0.1
		D1.6			0.0	0.1	0.1
		D4.1			0.0	0.1	0.1
75 mm (MID)	Day	B1.8	0	7.7	10.6	34.5	46.9
		D7.5			7.9	38.2	60.4
		D1.6			9.8	36.7	52.0
		D4.1			11.5	35.1	46.1
75 mm (TOP)	Day	B1.8	0	7.7	0.1	0.2	0.2
		D7.5			0.1	0.2	0.2
		D1.6			0.1	0.2	0.2
		D4.1			0.1	0.2	0.2

Release Scenario	Time	Weather	Height of Interest (m)	Mass Flow Rate (kg/s)	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Distance to ½ LFL at Height of Interest (m)
110 mm (MID)	Day	B1.8	0	16.6	17.2	45.4	59.6
		D7.5			14.7	53.4	77.9
		D1.6			16.8	48.7	65.7
		D4.1			18.1	45.2	57.3
110 mm (TOP)	Day	B1.8	0	16.6	0.2	0.2	0.3
		D7.5			0.2	0.3	0.3
		D1.6			0.2	0.3	0.3
		D4.1			0.2	0.2	0.3
FBR (MID) – 450 mm	Day	B1.8	0	227	61.4	102.8	128.1
		D7.5			68.7	125.4	167.7
		D1.6			65.1	110.0	139.3
		D4.1			62.3	96.2	111.7
FBR (TOP) – 450 mm	Day	B1.8	0	227	0.7	1.1	1.2
		D7.5			0.8	1.3	1.4
		D1.6			0.8	0.9	1.2
		D4.1			0.7	1.1	1.2
Release of Natural Gas (Methane) from Jemena Primary Main							
10 mm (MID)	Day	B1.8	0	0.44	2.6	7.6	14.2
		D7.5			2.1	5.2	8.1
		D1.6			2.5	6.7	12.6
		D4.1			2.8	9.0	16.3
25 mm (MID)	Day	B1.8	0	2.78	6.2	23.2	35.1

Release Scenario	Time	Weather	Height of Interest (m)	Mass Flow Rate (kg/s)	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Distance to ½ LFL at Height of Interest (m)
		D7.5			4.7	19.9	40.6
		D1.6			5.7	23.4	38.6
		D4.1			6.7	24.6	35.2
25 mm (TOP)	Day	B1.8	0	2.78	0.1	0.1	0.1
		D7.5			0.1	0.1	0.1
		D1.6			0.1	0.1	0.1
		D4.1			0.1	0.1	0.1
75 mm (MID)	Day	B1.8	0	25.0	22.4	54.6	71.3
		D7.5			20.8	65.7	94.5
		D1.6			22.4	58.6	78.4
		D4.1			23.4	52.9	66.7
75 mm (TOP)	Day	B1.8	0	25.0	0.2	0.3	0.3
		D7.5			0.2	0.3	0.4
		D1.6			0.2	0.3	0.3
		D4.1			0.2	0.3	0.4
110 mm (MID)	Day	B1.8	0	53.8	33.4	68.7	88.2
		D7.5			34.4	83.7	116.8
		D1.6			34.4	73.6	96.2
		D4.1			34.2	65.5	80.4
110 mm (TOP)	Day	B1.8	0	53.8	0.4	0.4	0.5
		D7.5			0.4	0.4	0.5
		D1.6			0.4	0.5	0.5

Release Scenario	Time	Weather	Height of Interest (m)	Mass Flow Rate (kg/s)	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Distance to ½ LFL at Height of Interest (m)
		D4.1			0.4	0.4	0.5
FBR (MID) – 150 mm	Day	B1.8	0	100	43.6	81.6	104.1
		D7.5			47.2	99.9	137.1
		D1.6			45.7	87.4	113.0
		D4.1			44.4	77.0	92.4
FBR (TOP) – 150 mm	Day	B1.8	0	100	0.5	0.6	0.7
		D7.5			0.4	0.7	0.8
		D1.6			0.5	0.7	0.7
		D4.1			0.5	0.7	0.7

* Limited to process flow rate

Appendix C Likelihood Analysis - Data and Results

C.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, *2018-19 Licensed Pipelines Performance Report*. This includes data for all licensed pipelines in NSW for the 5-year period: 2014/15 to 2018/19; 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.

The leak frequency data reported in RR1035 was adopted for the QRA as it is slightly more conservative than the NSW performance data for licenced pipelines 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.

Leak frequency data could not be derived for the Jet A1 Pipeline using the approach in the British Standards Institute PD 8010-3:2009+A1:2013 since some of required input data (e.g. pipe wall thickness) was not available for the risk analysis. Similarly, this approach could not be fully applied to the Natural Gas Secondary Mains since it cannot be used for pipelines with a diameter less than c. 200 mm and the rupture and leak frequencies due to 'TPA' cannot be estimated for pipelines with a design factor less than 0.3.

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).

C.1.1 Liquid Fuel Pipelines

NSW Performance Report

The average leak frequency from the 2019 NSW Performance Report for all licensed pipelines in NSW for the 5-year period 2014/15 to 2018/19 is 8.2E-05 per km per year.

The NSW Performance Report includes pipelines regulated under the Pipelines Act 1967 and the Pipelines Regulation 2013. The Jet A1 Pipeline is not regulated under this Act and Regulation and therefore its data is not included in the NSW Performance Report.

Other similar liquid fuel pipelines are included in NSW Performance Report and AS 2885 is the primary standard applied to these pipelines. Therefore, a similar level of performance might be applicable for the Jet A1 Pipeline.

UK HSE (RR1035)

The total leak frequency data reported in Section 7.5 of RR1035 for underground gasoline pipelines is marginally higher than the average leak frequency from the 2019 NSW Performance Report.

The UK HSE (RR1035) data (Refer to Table 34) was adopted in the risk analysis for the Jet A1 pipeline.

Table 35 Leak Frequencies for Underground Gasoline Pipelines (adopted for Jet Fuel)

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	8.2E-06	1.0E-05	1.0E-05	4.1E-06	3.2E-05
Corrosion	All	All	1.2E-05	1.2E-05	1.2E-05	2.1E-06	3.8E-05
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 Frequency =	5.4E-05	2.7E-05	2.2E-05	8.8E-06	**1.1E-04**
		% =	48.3	24.0	19.8	7.8	

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

The approach included in Annex B of PD 8010-3:2009+A1:2013 could not be used to estimate the leak frequencies for the Jet A1 Pipeline since some of required input data (e.g. pipe wall thickness) was not available for the risk analysis.

C.1.2 Natural Gas Mains

NSW Performance Report

The average leak frequency from the 2019 NSW Performance Report for all licensed pipelines in NSW for the 5-year period 2014/15 to 2018/19 is 8.2E-05 per km per year. The NSW Performance Report includes pipelines regulated under the Pipelines Act 1967 and the Pipelines Regulation 2013. This includes some high-pressure Natural Gas pipelines.

Jemena's Primary and Secondary Natural Gas Mains are not licensed high-pressure pipelines in NSW and typically operate at lower pressures than the Natural Gas pipelines included in the NSW Performance Report.

UK HSE (RR1035)

The leak frequencies reported by the UK HSE in RR1035 are based on an analysis of the UKOPA incident data. The UKOPA data applies for natural gas pipelines operating at above 800 kPa (absolute) and is therefore applicable for Jemena's higher pressure Natural Gas Mains in the vicinity of the Tupia Street development (i.e. primary and secondary mains operating at up to 3500kPag and 1050 kPag respectively).

The total leak frequency data reported in Section 7.1 of RR1035 for 100 to 350 mm diameter pipelines with wall thickness < 5 mm (Refer to Table 35) is approximately 4 to 10 times greater than the average leak frequency from the 2019 NSW Performance Report. This difference appears to be reasonable as the NSW Performance Report data only applies to licensed high-pressure pipelines and Jemena's Primary and Secondary Natural Gas Mains are not licensed pipelines in NSW.

The UK HSE (RR1035) data (Refer to Table 35) was adopted in the risk analysis for the higher pressure Primary and Secondary Natural Gas Mains in the study area.

Table 36 Leak Frequencies for Underground Natural Gas 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	< 115	All	4.5E-04	1.0E-08	1.0E-08	1.0E-08	4.5E-04
	127 to < 273		1.5E-04	1.0E-08	1.0E-08	1.0E-08	1.5E-04
	≥ 305		8.7E-06	1.0E-08	1.0E-08	1.0E-08	8.7E-06
Corrosion	All	< 5	3.1E-04	1.0E-08	1.0E-08	1.0E-08	3.1E-04
		5 to < 10	3.3E-05	1.0E-08	1.0E-08	1.0E-08	3.3E-05
		≥ 10	1.0E-07	1.0E-08	1.0E-08	1.0E-08	1.3E-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 Freq. =	100	< 5	7.9E-04	4.9E-06	2.7E-07	2.6E-06	**8.0E-04**
% =			99.0	0.6	0.0	0.3	
Total Freq. =	150	< 5	4.9E-04	4.9E-06	2.7E-07	2.6E-06	**5.0E-04**
% =			98.4	1.0	0.1	0.5	

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
Total Freq. =	350	< 5	3.5E-04	4.9E-06	2.7E-07	2.6E-06	**3.6E-04**
% =			97.8	1.4	0.1	0.7	

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 some of the leak frequencies for the Primary and Secondary Natural Gas Mains (Refer to Table 36). This approach could only be used to estimate some of the leak frequencies for the 450 mm secondary main since it cannot be used for pipelines with a diameter less than c. 200 mm and the rupture and leak frequencies due to 'TPA' cannot be estimated for pipelines with a design factor less than 0.3.

The data applicable for pipelines with a wall thickness ≤ 5 mm was used.

The 450 mm secondary main was conservatively assumed to be constructed prior to 1980, so the leak frequencies due to material and construction defects (mechanical failures) were not reduced by a factor of 5 for this pipeline (as per Section B.7 of PD 8010-3:2009+A1:2013).

Leak frequency data is not reported for internal corrosion; therefore, the total leak frequencies reported in Table 36 may be underestimated.

For leaks or ruptures due to 'Ground Movement / Other', the landslide potential in the study area was assumed to be "low to nil" in accordance with the description in Table B.15 of PD 8010-3:2009+A1:2013.

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).

Due to limitations in applying the approach included in Annex B of PD 8010-3:2009+A1:2013 to the Secondary Natural Gas Mains in the study area, it is not possible to draw a meaningful conclusion from the data presented in Table 36 (other than to note that the total leak frequency is a similar order of magnitude to the data presented in Table 35).

Table 37 Approx. Leak Frequencies for Natural Gas Main (350 mm Diameter)

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	4.2E-04	1.9E-05	0.0E+00	0.0E+00	4.4E-04
Corrosion	3.0E-04	7.6E-05	0.0E+00	0.0E+00	3.8E-04
Ground Movement / Other	8.0E-07	8.0E-07	8.0E-07	3.1E-07	2.7E-06
TPA	No Data	No Data	No Data	No Data	No Data
Total Leak Freq. =	≥ 7.2E-04	≥ 9.6E-05	≥ 8.0E-07	≥ 3.1E-07	≥ **8.20E-04**
% =	88.2	11.7	0.10	0.04	

C.2 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.2.1 - C.2.3).

Gasoline

1. The total ignition probability was based on OGP Scenario 1, which is release rate dependent (Refer to Section C.2.1).

   The US DoT data (Refer to Section C.2.2) is exclusively for underground cross-country pipelines carrying flammable or combustible liquids. Some data is also reported by UKOPA; (Refer to Section C.2.1); however, this includes liquids and gases.

   OGP Scenario 1 was adopted for the risk analysis since the maximum total ignition probability (0.07) is more conservative than the UKOPA data (total ignition = 0.047) and the US DoT data for gasoline (viz. total ignition prob. = 0.03 (all releases)).

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 risk analysis.

Natural Gas

1. The total ignition probability was based on OGP Scenario 3, which is release rate dependent (Refer to Section C.2.1).

   The correlation proposed by Acton & Baldwin (Refer to Section C.2.3) is more conservative for smaller leaks; however, the OGP data is more conservative for ruptures and is more consistent with the EGIG and UK HSE data (Refer to Section C.2.3) for the calculated full bore rupture release rates.

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 appears to be more consistent with other data sources (e.g. Acton & Baldwin, UK HSE – Refer to Section C.2.3).

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.2.1 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 38 Ignition Probability - UKOPA

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

OGP, Ignition Probabilities for Pipe-Liquid-Industrial (Scenario 1: Liquid Releases from onshore pipeline in industrial area)

The following data applies for releases of flammable liquids that do not have any significant flash fraction (10% or less) if released 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 39 Ignition Probability – OGP Scenario 1

Release Rate (kg/s)	Total Ignition Probability
0.1	0.0010
0.2	0.0016
0.5	0.0028
1	0.0045
2	0.0070
5	0.0126
10	0.0198
20	0.0311
50	0.0563
100	0.0700
200	0.0700
500	0.0700
1000	0.0700

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 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

C.2.2 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 2017)

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 41 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
Diesel, Fuel Oil, Kerosene or Jet Fuel	0	101	0.0	0	13	0.0	1	10	0.1	0	7	0	1	131	0.01
Gasoline (Non-Ethanol)	0	96	0.0	1	8	0.1	2	5	0.4	0	6	0	3	115	0.03

C.2.3 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 42 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
450	10.5	FBR	2.13	0.042	0.042	0.085
		110	0.13	0.028	0.028	0.056
		75	0.06	0.028	0.028	0.056
		25	0.01	0.028	0.028	0.056
		10	0.00	0.028	0.028	0.056
150	35	FBR	0.79	0.033	0.033	0.066
		110	2.48	0.029	0.029	0.058
		75	1.69	0.028	0.028	0.057
		25	0.02	0.028	0.028	0.056
		10	0.00	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 43 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 44 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 45 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.3 Likelihood of Representative Release Scenarios

The estimated likelihood of each representative release scenario is listed in Table 45, Table 46, Table 47 and.

Table 46 Release Frequency – Jet A1 Pipeline

Leak Scenario	Release Frequency (per km per year)		
	TPA	All Other Failure Modes	Total Release Frequency
10mm MID	-	3.22E-05	3.22E-05
25mm MID	8.14E-06	-	8.14E-06
25mm TOP	1.39E-05	-	1.39E-05
75mm MID	8.88E-07	9.07E-06	9.95E-06
75mm TOP	1.51E-06	1.54E-05	1.69E-05
110mm MID	3.70E-08	8.20E-06	8.23E-06
110mm TOP	6.30E-08	1.40E-05	1.40E-05
FBR MID	3.70E-08	3.22E-06	3.26E-06
FBR TOP	6.30E-08	5.48E-06	5.54E-06
Total	2.46E-05	8.76E-05	**1.12E-04**

Table 47 Release Frequency – Jemena Secondary Natural Gas Main (450 mm Diameter)

Leak Scenario	Release Frequency (per km per year)		
	TPA	All Other Failure Modes	Total Release Frequency
10mm MID	-	3.31E-04	3.31E-04
25mm MID	8.14E-06	-	8.14E-06
25mm TOP	1.39E-05	-	1.39E-05
75mm MID	8.88E-07	9.32E-07	1.82E-06
75mm TOP	1.51E-06	1.59E-06	3.10E-06
110mm MID	3.70E-08	6.29E-08	9.99E-08
110mm TOP	6.30E-08	1.07E-07	1.70E-07
FBR MID	3.70E-08	9.32E-07	9.69E-07
FBR TOP	6.30E-08	1.59E-06	1.65E-06
Total	2.46E-05	3.36E-04	**3.60E-04**

Table 48 Release Frequency – Jemena Primary Natural Gas Main (150 mm Diameter)

Leak Scenario	Release Frequency (per km per year)		
	TPA	All Other Failure Modes	Total Release Frequency
10mm MID	-	4.72E-04	4.72E-04
25mm MID	8.14E-06	-	8.14E-06
25mm TOP	1.39E-05	-	1.39E-05
75mm MID	8.88E-07	9.32E-07	1.82E-06
75mm TOP	1.51E-06	1.59E-06	3.10E-06
110mm MID	3.70E-08	6.29E-08	9.99E-08
110mm TOP	6.30E-08	1.07E-07	1.70E-07
FBR MID	3.70E-08	9.32E-07	9.69E-07
FBR TOP	6.30E-08	1.59E-06	1.65E-06
Total	2.46E-05	4.77E-04	**5.02E-04**