Hunter Lateral Gas Pipeline
Preliminary Hazard Assessment

For MVC Services

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Summary

Jemena Gas Networks (NSW) Limited (Jemena) is proposing to modify the existing Infrastructure Approval for the Killingworth to Kooragang Island Pipeline (SSI-46360740). Jemena is proposing to construct and operate the Hunter Lateral, a 5.3 km underground pipeline which will allow gas supply between the proposed Santos Hunter Gas Pipeline to the existing Jemena-operated Killingworth to Kooragang Island Pipeline.

The following report details the methods and results of the Preliminary Hazard Analysis (PHA) conducted for the proposed pipeline on the request of MVC services on behalf of Jemena. The study was conducted in accordance with Hazardous Industry Planning Advisory Paper No. 6 – Guidelines for Hazard Analysis (HIPAP No. 6) [1] developed by the New South Wales Department of Planning, Housing and Infrastructure (DPHI). Risk results were assessed against the criteria outlined HIPAP No. 4 – Risk Criteria for Land Use Safety Planning [2] and HIPAP No. 10 - Land Use Safety Planning [3].

Following a comprehensive review of available leak frequency data, the failure rates reported by the United Kingdom Health and Safety Executive (UK HSE) [4] [5] were adopted for this study. A set of failure scenarios were selected for the pipeline which align with the leak frequency data, varying from a small hole of 10-25mm in diameter to a Full-Bore Rupture (FBR).

Following an analysis of available ignition data, the ignition probability adopted for this study was the Acton & Baldwin correlation, which relates ignition probability to pipeline pressure and breach size [6]. The total ignition probability was split 50:50 for immediate ignition and delayed ignition.

The consequence and risk modelling were performed in SAFETI 9.11 software package developed by DNV. The consequence analysis involved the estimation of the harmful effects of potential jet fires, flash fires and/or vapour cloud explosions.

Conclusions

1. The location specific individual risk of fatality due to the Hunter Lateral pipeline does not reach the lowest DPHI risk criteria threshold of 5E-07 per year.

2. The risk of injury, property damage and accident propagation due to the Hunter Lateral pipeline do not reach the relevant DPHI risk criteria thresholds.

3. The societal risk due to the Hunter Lateral pipeline is within the negligible region.

4. The overall risk generated by the pipeline is low.

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Notation

Abbreviation	Description
ABS	Australian Bureau of Statistics
AGL	Above Ground Level
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
Arriscar	Arriscar Pty Limited
AS / NZS	Australian and/or New Zealand Standard
BLEVE	Boiling Liquid Expanding Vapour Explosion
BoM	Bureau of Meteorology
BYDA	Before You Dig Australia
CFR	Code of Federal Regulations
CIA	Chemical Industries Association
CONCAWE	Conservation of Clean Air and Water in Europe
CPR	Committee for the Prevention of Disasters
DPHI	NSW Department of Planning, Housing and Infrastructure
DZN	Destination Zones
EGIG	European Gas Pipeline Incident Data Group
EP&A	Environmental Planning and Assessment
ERP	Emergency Response Plan
ESDV	Emergency Shutdown Valve
FBR	Full-Bore Rupture
FMECA	Failure Modes and Effects Criticality Analysis
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HDD	Horizontal Directional Drilling
HIPAP	Hazardous Industry Planning Advisory Paper
IOGP	Internation Association of Oil & Gas Producers
Jemena	Jemena Gas Networks (NSW) Limited
KP	Kilometre Point
LFL	Lower Flammable Limit
LGA	Local Government Area
LNG	Liquefied Natural Gas
LOC	Loss of Containment
LPG	Liquified Petroleum Gas

Abbreviation	Description
LSIR	Location Specific individual Risk
LUP	Land Use Planning
MAHP	Major Accident Hazard Pipeline
MAOP	Maximum Allowable Operating Pressure
MB	Mesh Blocks
ME	Multi-Energy
MISHAP	Model for the Estimation of Individual Societal Risk from the Hazards of Pipelines
MVC	MVC Services
NAP	Normal Atmospheric Pressure
NG	Natural Gas
NSW	New South Wales
OGP	International Association of Oil & Gas Producers
OSHA	Occupational Safety and Health Administration
PGS	Publication Series on Dangerous Substances (Dutch safety guidelines)
PHA	Preliminary Haard Analysis
PHMSA	Pipeline and Hazardous Materials Safety Administration
PSR	Pipelines Safety Regulations
QRA	Quantitative Risk Assessment
RAAF	Royal Australian Air Force
RDS	Rationalised Discharge Scenario
RIVM	National Institute for Public Health and the Environment (Netherlands)
RR	Research Report
SMS	Safety Management Study
SSI	State Significant Infrastructure
TNO	Netherlands Organisation for Applied Scientific Research
TNT	Trinitrotoluene
TPA	Third Party Activity
UDM	Unified Dispersion Model
UFL	Upper Flammability Limit
UK HSE / HSE	United Kingdom Health and Safety Executive
UKOPA	United Kingdom Pipeline Operators Association
VBR	Volume Blockage Ratio
VCE	Vapour Cloud Explosion
VROM	Ministry of Housing, Spatial Planning and the Environment (Netherlands)

1 INTRODUCTION

1.1 Background

Jemena Gas Networks (NSW) Limited (Jemena) is proposing to modify the existing Infrastructure Approval for the Killingworth to Kooragang Island Pipeline (SSI-46360740). Jemena is proposing to construct and operate the Hunter Lateral, a 5.3 km underground pipeline which will allow gas supply between the proposed Santos Hunter Gas Pipeline to the existing Jemena-operated Killingworth to Kooragang Island Pipeline.

This project plays a crucial role in providing a reliable and affordable gas supply for both urban and regional centres in the South of Australia. It also supports the transition to renewable energy by enabling gas-fired power generation to provide backup capacity and replace retiring coal-fired power stations.

MVC Services (MVC) has been tasked by Jemena to facilitate the modification process, in accordance with Section 5.25 of the Environmental Planning and Assessment Act 1979 (NSW).

MVC engaged Arriscar Pty Limited (Arriscar) to conduct a Preliminary Hazard Assessment (PHA) of the proposed pipeline and assess the risk against commonly used risk criteria. The following report details the analysis and findings of the PHA.

1.2 Scope

The scope of this study included undertaking a pipeline hazard analysis in accordance with Hazardous Industry Planning Advisory Paper No. 6 – Guidelines for Hazard Analysis (HIPAP No. 6) [1] developed by the NSW Department of Planning, Housing and Infrastructure (DPHI). The resulting risks are to be assessed against the criteria outlined HIPAP No. 4 – Risk Criteria for Land Use Safety Planning [2] and HIPAP No. 10 - Land Use Safety Planning [3].

The study area is to include the relevant lots and any relevant surrounding areas to ensure all potential impact areas are accounted for.

The following exclusions apply:

1. The PHA required by the NSW DPHI is not a Safety Management Study (SMS) as required under AS/NZS 2885.6. The work proposed excludes conducting an SMS. An allowance has been made for attendance (remotely) at any SMS workshop as part of the hazard identification process for the PHA.
2. The PHA is limited to the proposed 5.3 km Hunter Lateral Gas Pipeline. Assessment of the Hunter Gas Pipeline, and the Killingworth to Kooragang Island Pipeline are excluded.
3. Risk associated with the construction of the pipeline and cumulative risk from other hazardous industries or pipelines.
4. Risks associated with normal operations such as venting the pipeline are out of scope. It is anticipated that Jemena's normal procedures address these risks.
5. Environmental risks.
6. A geographical representation of societal risk.

1.3 Objectives

The PHA forms part of the Modification Report, which accompanies a modification application for the Killingworth to Kooragang Island Pipeline. The objectives of the PHA are to:

- Identify the inherent likelihood and consequence of risks arising from the project to life, property and the environment using a rigorous risk assessment process.
- Propose risk management measures to avoid or reduce the likelihood or consequence of the risk.
- Assess the residual risk arising from the project after all risk management measures have been implemented.

2 RISK ASSESSMENT METHODOLOGY

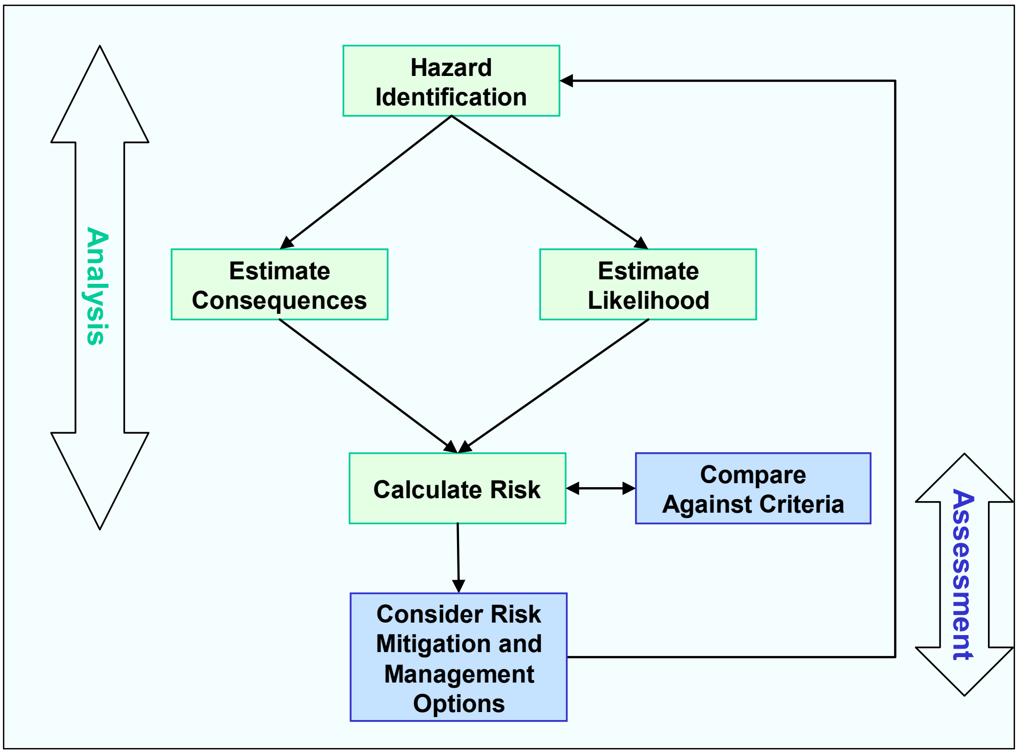
2.1 Introduction

A Quantitative Risk Assessment (QRA) involves the quantitative estimation of the consequences and likelihood of hazardous events to determine the risks generated by a facility. The risks of the facility are evaluated against risk criteria outlined regarding fatalities, injuries, and property damage, etc.

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 DPHI's guidelines for undertaking this type of assessment [1].

The QRA process is depicted diagrammatically in Figure 1:

Figure 1 Overview of QRA Process [1]



Source: NSW Department of Planning

2.2 Overview of Methodology

The methodology for a QRA involves the following main steps:

1. System definition, in which information on the facility is collected and assimilated.
2. Hazard identification, in which site events and external events are identified which may lead to potential adverse effects beyond the boundary of the site.
3. Consequence modelling, in which all the possible consequences of each event are estimated.
4. Frequency and likelihood estimation, in which the frequency (i.e. likelihood per year of occurrence) of each of the hazardous events is estimated, based on historical failure data.
5. Risk estimation, in which the frequencies and consequences of each event are combined to determine levels of risk.
6. Risk assessment, in which the calculated risks are assessed against relevant risk criteria.

2.3 Description of Facilities, Operation and Surroundings

The location of the proposed or existing facility and the surrounding areas are described to enable an appropriate consideration of the potential impacts.

2.4 Hazard Identification

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, or exposure to stored energy etc.). The basis for any risk study is the identification of hazards present within a facility. Hazard identification (or HAZID) is crucial, as a hazard that is not identified will not be modelled and assessed.

There is no single definitive method for HAZID; however, it should be comprehensive and systematic to ensure critical hazards are not excluded from further analysis. A desktop review of layout drawings, engineering documentation and a literature review provide useful inputs. Examples of hazard identification techniques include simple checklists based on historical incidents and earlier analyses, more detailed "what-if" style analyses and the most detailed structured techniques such as a Hazard and Operability (HAZOP) study and Failure Modes and Effects Criticality Analysis (FMECA).

As well as identifying the hazards that exist, it is also important to identify how these hazards could lead to a hazardous scenario/event. A hazardous scenario 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 an acceptable risk criterion has been defined by the DPHI– refer to Section 0).

As there is usually a large number of possible initiating events leading to a hazardous scenario, it would be impractical analyse all possibilities. Therefore, discrete initiating events are used to represent the range of possible hazardous scenarios that could occur. Generally, hazardous scenarios are represented by a limited number of leaks / hole sizes varying from small pin hole leaks to catastrophic ruptures.

When developing hazardous scenarios, the facility is first split into sections which are called isolatable sections. An isolatable section is a system of equipment and/or pipelines that contain similar materials under similar process conditions such as pressure and temperature. Preferably an isolatable section should be bounded by isolation points such as Emergency Shutdown Valves (ESDVs) or motorised 'fail close' valves but this may not be possible for all cases.

It is necessary to capture the following information, either during the hazard identification process, or as part of the preparation for hazard consequence modelling:

- Hazardous materials and materials properties;
- Inventory of hazardous materials that could contribute to the event;
- 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.

2.5 Consequence Analysis

The physical consequences of a hazardous scenario are generally dependent on the:

- State of the material (liquid or gas/vapour);
- Quantity released;
- Rate of release; and
- Ignition (for fire and explosion events).

The quantity released depends on the inventory, which is estimated from the isolatable sections, size of release (viz. assumed equivalent hole diameter) and duration of release (how soon can the release be detected and isolated).

The different types of consequences typically considered for a QRA are described below.

2.5.1 Discharge

The discharge from a hole is assumed to be from a circular orifice of equivalent diameter. This is the maximum flow rate for a given hole area and is used because it can be calculated readily and will produce the maximum release rate for a given hole area. The discharge behaviour is estimated from process conditions such as the pressure, temperature, and the state of the material (liquid or vapour).

The discharge from a pipeline leak is dependent on the pressure and also location along the pipeline. Releases from the pipeline were modelled using the 'long pipeline' model in SAFETI 9.11. The long pipeline discharge model involves time-varying modelling, which models the change in storage conditions to determine the release rate at different timesteps and locations.

However, small holes with a relative breach aperture (i.e. the area of the hole as a fraction of the total potential outflow area for the breach location) less than 0.01 were modelled utilising the steady state 'Orifice' model, which maintains a constant 'peak' release rate until the inventory is depleted. This implies a constant pressure at the release point. This is due to the time-consuming nature of time-varying discharge calculations, and the change in release rate for small holes is not significant [7].

There are two types of discharge scenarios that can be modelled for a pipeline in SAFETI 9.11.

1. **Location Specific Breach** – Determines the discharge scenario at a specific point along the pipeline.
2. **Section Breach** – Determines a Rationalised Discharge Scenario (RDS) for a section of the pipeline to be used as the representative discharge scenario for any point along the section (Refer to Section 2.5.1.1 for details regarding the segmentation pipelines).

The breach is considered to divide the pipeline into two independent sections: an upstream section A, and a downstream section B. The model performs discharge calculations for each section separately and combines the results to give the total mass released as a function of time [7].

Discharges from the Hunter Lateral pipeline were modelled using the section breach scenario. The average release rate over the first 30 seconds was used to determine the effects of jet fires, flash fires (i.e. dispersion) and explosions.

2.5.1.1 Segmentation of a Pipeline

During the discharge calculations, SAFETI 9.11 automatically divides the pipeline into sections. The program surveys the length of the pipeline, and identifies the points where the pipeline starts, where it ends, where valves are located, and where a user-defined section either starts or end. If the length between two adjacent points is greater than the value set for the Tolerance (distance) for a section boundary (default value is 0.1 m), then that length is defined as a section. This method for dividing the pipeline into Sections means that a given user-defined section will be divided into multiple Sections if there are valves inside it [7].

The discharge behaviour might vary significantly at different points along a given section, depending on the change in pressure along the section, and on the upstream and downstream distances to valves or the end of the pipeline. The program takes these variations into account by segmenting each section into sub-sections, using criteria for the maximum pressure-drop over a sub-section and the maximum length of a sub-section [7].

The primary criterion is the **maximum fractional pressure drop across a sub-section** (ΔP_{max}). This has a default value is 0.8, which means that if the pressure at the start of a given section is 10 bara, then the maximum length of the first sub-section will be the distance for the pressure to drop to 8 bara [7].

The secondary criterion is the **maximum fraction of pipe length for sub-sectioning** (L_{max}). The default value is 0.2, which means that if the total length of the pipeline is 10 km, the maximum length of a sub-section will be 2 km [7].

If the last sub-section length is less than the **minimum ideal sub-section piping length** (default value of 500 m), then the program adjusts the lengths for the last two sub-sections to make them equal. This is used to ensure that the final sub-section for a given section is not disproportionately short [7].

2.5.2 Dispersion

The dispersion rate of gas/vapour depends on meteorological conditions such as the wind speed, wind direction and atmospheric stability conditions. Location-specific meteorological data is required to perform a consequence analysis. The representative wind directions, wind speeds and wind stability classes are normally determined from annual average of weather data from the local weather station available through the Bureau of Meteorology (BoM).

The gas dispersions were modelled using the Unified Dispersion Model (UDM) in SAFETI 9.11. The flammable gas dispersions were modelled to the Lower Flammable Limit (LFL). Dispersion calculations are based on the total quantity released over one hour, assuming it is released at the average flowrate over the first 30 seconds. The dispersion results will determine the extent of flash fires, explosions and toxic effects.

2.5.3 Jet Fires

Jet fires are a potential consequence related to a hazardous scenario that continuously release flammable vapour or liquid with significant momentum. Ignition will produce a turbulent diffusion flame which emits heat radiation. The physical impacts of jet fires are modelled using the surface emissivity of the flame to produce contours of heat radiation levels. Fires impinging on adjacent equipment may cause structural failures and incident escalation.

Jet fires were modelled using the 'Cone' model of the single and two-phase Jet Fire (JFSH) model in SAFETI 9.11. The average release rate over the first 30 seconds was used to determine the effects of jet fires.

2.5.4 Pool Fires

Pool fires are a potential consequence related to a hazardous scenario that release flammable liquid onto the ground which may form an evaporating pool and/or accumulate in a bund/sump. Ignition will produce a turbulent diffusion flame that burns above the whole surface of the pool and emit heat radiation. The impacts of pool fires are modelled using the surface emissivity of the flame to produce contours of heat radiation levels. Fires impinging on adjacent equipment may cause structural failures and incident escalation.

Pool fires are not a credible consequence for the Hunter Lateral gas pipeline.

2.5.5 Flash Fires and Vapour Cloud Explosions

Volatile flammable liquid releases or flammable vapour/gas releases may form a cloud and disperse in the air. Ignition of the flammable gas-air mixture may result in a flash fire or vapour cloud explosion (VCE).

A flash fire is sudden, intense fire that lasts for a very short duration in which the flame propagation speed is less than the sonic velocity. 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.

It is possible for a VCE to occur instead of a flash fire if the cloud is within an area that is sufficiently congested due to buildings, vehicles, trees, or other obstacles. Flame acceleration increases due to the turbulence caused by the congested region and produces a blast wave. It is considered to be a deflagration if the flame speed is subsonic and a detonation if the flame speed is supersonic. These events are modelled to determine the overpressures generated by the explosion.

VCEs were modelled using the Multi-Energy (ME) model. An obstructed region was defined across the entire study area, characterised by a blast strength corresponding to TNO Multi-Energy curve number 4, a Volume Blockage Ratio (VBR) of 5%, and a height of 5 m. Unconfined explosions were modelled using a blast strength of 2 and an explosion efficiency of 100%.

2.5.6 Fireballs and BLEVE

A fireball is an intense spherical fire resulting from a sudden release of pressurized liquid or gas that is immediately ignited and emits heat radiation. Boiling Liquid Expanding Vapour Explosion (BLEVE) is an explosion caused by the sudden release of superheated liquid from a vessel in which its integrity has been compromised. The boiling liquid rapidly expands due to the pressure drop resulting in an explosion producing overpressures and heat radiation. BLEVEs involving flammable material will usually have an associated fireball.

Fireballs and BLEVE's were not considered in this study.

2.5.7 Toxic Effects

If a toxic, or an asphyxiant vapour/gas is released, then the potential may exist for injury or fatality if exposed (typically via inhalation). The dispersion of toxic gas/vapour is modelled to produce a concentration profile in three dimensions (downwind, crosswind and elevation). For releases that are constant over time, this can be represented by a set of contours of constant concentration (isopleths) on a plan drawing and/or summarised in a tabular format.

Toxic effects were not considered in this study.

2.6 Vulnerability Criteria

Vulnerability criteria have been developed by the DPHI for the effects of fires, explosions and toxic gas emissions which are listed below [2]. The vulnerability parameters used in this QRA are presented in the Assumptions Register (Refer to Appendix A).

2.6.1 Heat Radiation

The potential for injury or property damage from a fire is influenced by the intensity of the heat radiation emitted and the duration of exposure.

The effects of exposure to thermal radiation outlined in HIPAP No. 4 are presented in Table 1.

Table 1 Effects of Thermal Radiation [2]

Heat Radiation (kW/m^2)	Effect/s
1.2	• Received from the sun at noon in summer
2.1	• Minimum to cause pain after 1 minute
4.7	• Will cause pain in 15-20 seconds and injury after 30 seconds exposure (at least second-degree burns will occur)
12.6	• Significant chance of fatality for extended exposure. High chance of injury • 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	• Likely fatality for extended exposure and chance of fatality for 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	• Cellulosic material will pilot ignite within one minute's exposure • Significant chance of fatality for people exposed instantaneously

2.6.2 Explosion Overpressure

The impact of explosion overpressure on humans takes two forms and can lead to serious injury or even fatality:

- Direct exposure could lead to organ damage (e.g. ear drum rupture or lung rupture), and/or knock a person over/into a hard object (e.g. ground or a wall).
- The person could be hit by a projectile, caused by the explosion, or from the collapse of buildings.

The effects of exposure to explosion overpressure outlined in HIPAP No. 4 are presented in Table 2.

Table 2 Effects of Vapour Cloud Explosions [2]

Overpressure (kPa)	Effect/s
3.5	• 90% glass breakage • No fatality and very low probability of injury
7.0	• Damage to internal partitions and joinery but can be repaired • Probability of injury is 10%. No fatality
14.0	• House uninhabitable and badly cracked.
21.0	• Reinforced structures distort • Storage tanks fail • 20% chance of fatality to a person in a building
35.0	• House uninhabitable • Wagons and plants items overturned • Threshold of eardrum damage • 50% chance of fatality for a person in a building and 15% chance of fatality for a person in the open
70.0	• Threshold of lung damage • 100% chance of fatality for a person in a building or in the open • Complete demolition of houses

2.6.3 Toxic Exposure

As there are no uniform specific criteria to cover all toxic effects, the vulnerability criteria selection for toxic exposure requires a literature review of the available toxicity data. As methane is non-toxic, toxic exposure is not examined in this study.

2.7 Frequency and Likelihood Analysis

Once the consequences of the various hazardous 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 hazardous scenario 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 frequency data for which a parts count of the failure items within an isolatable section may need to be conducted. Moreover, for fire and explosion scenarios ignition probabilities are taken into consideration when determining the likelihood. This is only possible because data on such incidents and failures has been collected by various organisations over several years. Various databases and reference documents are now available that provide this data.

When using historical data to forecast the likelihood of a future event, it is important to ensure any specific conditions that existed at the time of the historical event are considered. 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.

2.8 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 hazardous scenarios to generate a complete picture of the risk. The risk assessment step involves comparing the risk results against risk criteria.

Location-specific risk contours are usually used to represent off-site risk for a 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:

- 0.5×10^{-6} per year (5E-07 or 0.5 in a million per year);
- 1×10^{-6} per year (1E-06 or 1 in a million per year);
- 5×10^{-6} per year (5E-06 or 5 in a million per year);
- 10×10^{-6} per year (1E-05 or 10 in a million per year); and
- 50×10^{-6} per year (5E-05 or 0.1 in a million 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 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).

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.

2.9 Quantitative Risk Criteria

2.9.1 Location Specific Individual Fatality Risk

The maximum acceptable individual risk of fatality for off-site population types are presented in Table 3. These are location specific risk criteria and assumes 100% occupancy and no escape.

Table 3 DPHI Location Specific Individual Fatality Risk Criteria [2]

Maximum Individual Risk of Fatality (per year)	Limit of Exposure at the Following Locations
5E-07	Hospitals, child-care facilities, old age housing developments.
1E-06	Residential developments, places of continuous public occupancy.
5E-06	Commercial developments (offices, shops etc.)
1E-05	Sporting complexes and active open space areas.
5E-05	Limit of risk exposure for adjacent industrial land use. Preferably contained within facility boundary.

2.9.2 Injury Risk

Heat radiation of 4.7 kW/m^2 may cause pain in 20 seconds and injury after 30 seconds of exposure. The 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.*

Explosion overpressure of 7 kPa has a probability of 10% to cause injury. The injury 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 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.*

2.9.3 Risk of Property Damage and Accident Propagation

Heat radiation of 23 kW/m^2 may cause unprotected steel to suffer thermal stress that may cause structural damage. The property damage risk criterion for heat radiation is as follows:

> *Incident heat flux radiation at neighbouring potentially hazardous installations or at land zoned to accommodate such installations should not exceed a risk of 50 in a million per year for the 23 kW/m^2 heat flux level.*

Explosion overpressure of 14 kPa may cause significant damage to buildings making it unhabitable. The property damage risk criterion for explosion overpressure is as follows:

> *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.*

2.9.4 Societal Risk

It is possible that an incident at a hazardous facility may affect more than a single individual off-site, especially in the case of a full-bore rupture of a high-pressure gas pipeline, and the potential exists for multiple fatalities. The societal risk concept evolved from the concept of 'risk aversion', i.e. society is prepared to tolerate incidents that cause single fatalities at a more frequent interval (e.g. motor vehicle accidents) than for incidents causing multiple fatalities (e.g. an aircraft accident).

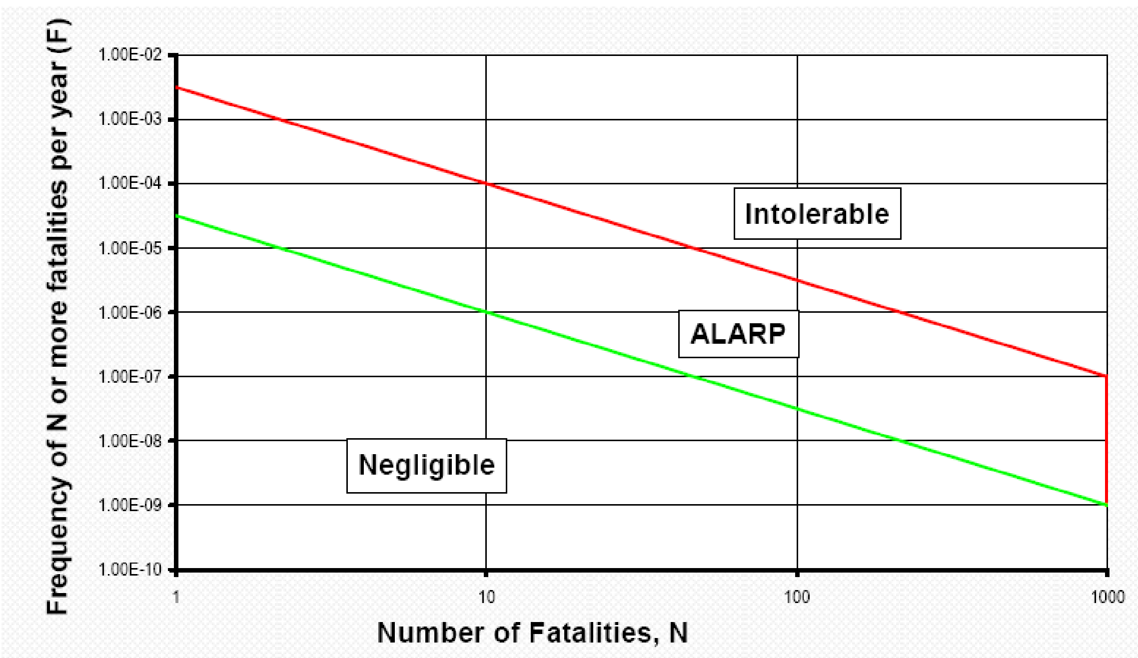
Two parameters are required to define societal risk:

a) Number of fatalities that may result from an incident; and

b) the frequency (likelihood) of occurrence of the incident.

Societal risk is commonly represented using F-N curves, which plot the cumulative frequency (F) of accident scenarios against the number of fatalities (N). Each point on the plot indicates the frequency with which N or more fatalities are expected to occur.

Figure 2 DPHI Societal Risk Criteria (F-N Plot) [2]



Source: NSW Department of Planning

The societal risk criteria incorporate an ALARP (As Low As Reasonably Practicable) approach. This is reflected as three societal risk bands: negligible, ALARP and intolerable, as shown in Figure 2.

- *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 No. 4* [2] *are met, the risks from the activity would be considered tolerable in the ALARP region.*

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.

2.10 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, vulnerability criteria, etc.).

To comply with the general principles outlined in Section 2.2 of HIPAP No. 6 [1], all steps taken in the risk analysis should be: "*traceable and the information gathered as part of the analysis should be well documented to permit an adequate technical review of the work to ensure reproducibility, understanding of the assumptions made and valid interpretation of the results*".

The key assumptions adopted for this QRA are listed in the Assumptions Register (Refer to Appendix A). Each assumption is numbered and detailed separately. The basis for each assumption is explained together with its potential impact on the results of the QRA and the hazardous scenarios potentially affected. Key references are also listed for each assumption, where relevant.

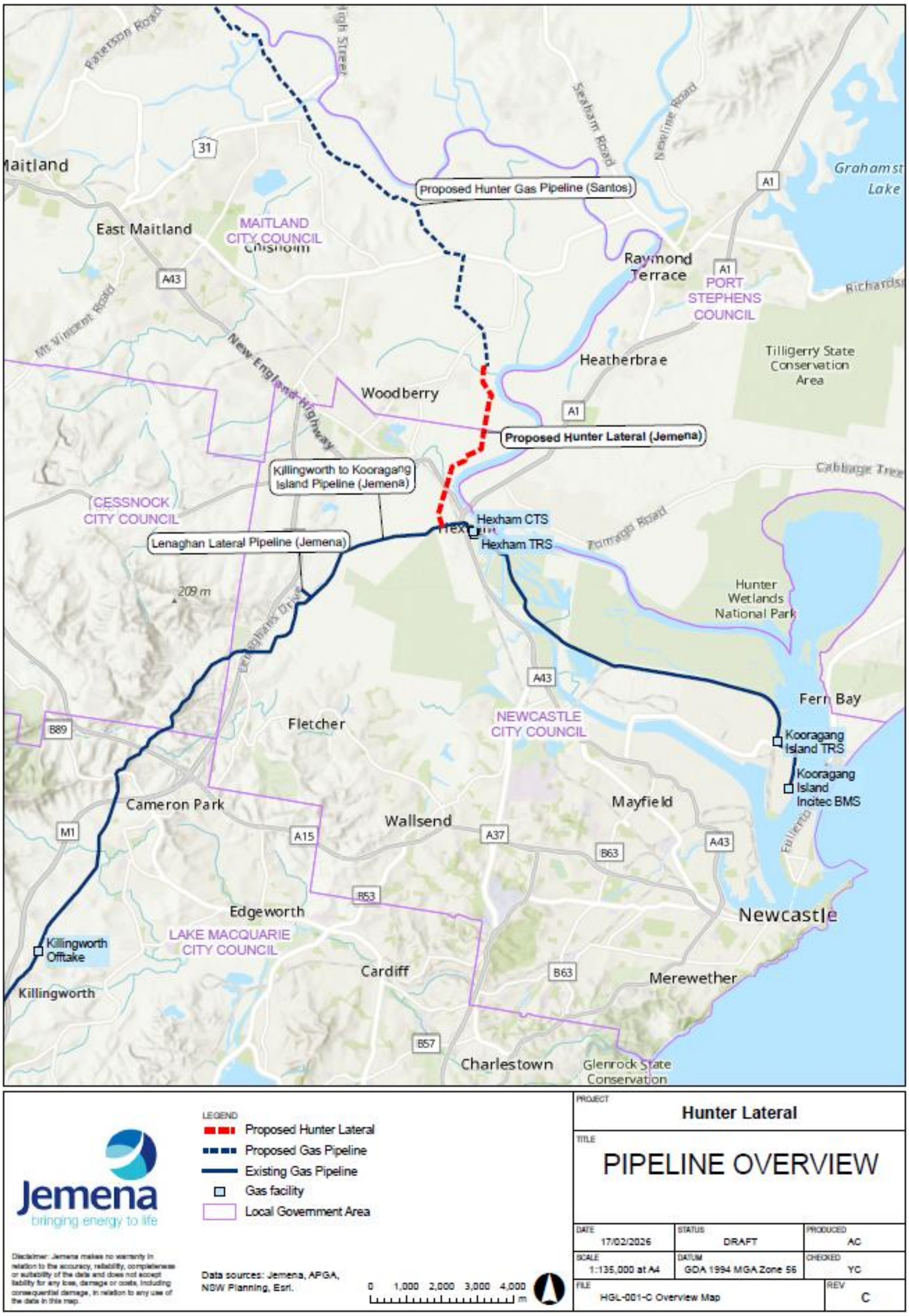
3 DESCRIPTION OF SITE, FACILITIES AND OPERATIONS

3.1 Site Location and Description

The proposed modification to the Infrastructure Approval seeks to construct and operate a new 5.3 km high-pressure gas pipeline (i.e. Hunter Lateral) and associated infrastructure at kilometre point (KP) 18.5 of the Killingworth to Hexham section of the Killingworth to Kooragang Island Pipeline [8].

The Hunter Lateral pipeline will connect the proposed Santos Hunter Gas Pipeline to the existing Jemena-operated Killingworth to Kooragang Island Pipeline through a new meter station at Millers Forest. The pipeline will be constructed underground between Millers Forest and Hexham, in the City of Newcastle and City of Maitland local government areas (LGA) [8]. The proposed and existing pipelines are presented in Figure 3.

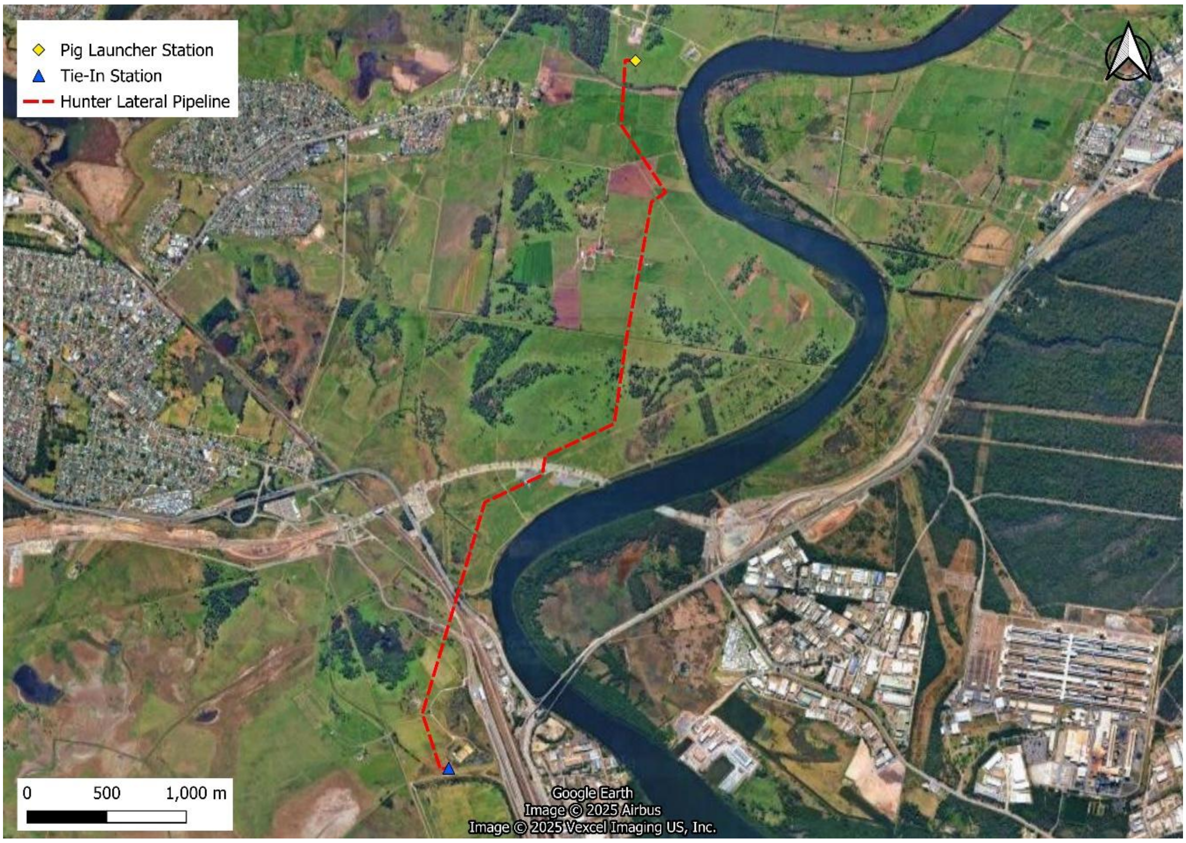
Figure 3 Lateral Location



Source: Jemena, APGA, NSW Department of Planning, Esri

The modification will include two aboveground stations as presented in Figure 4 but does not include any additional gas storage facilities.

Figure 4 Hunter Lateral Pipeline and Aboveground Stations

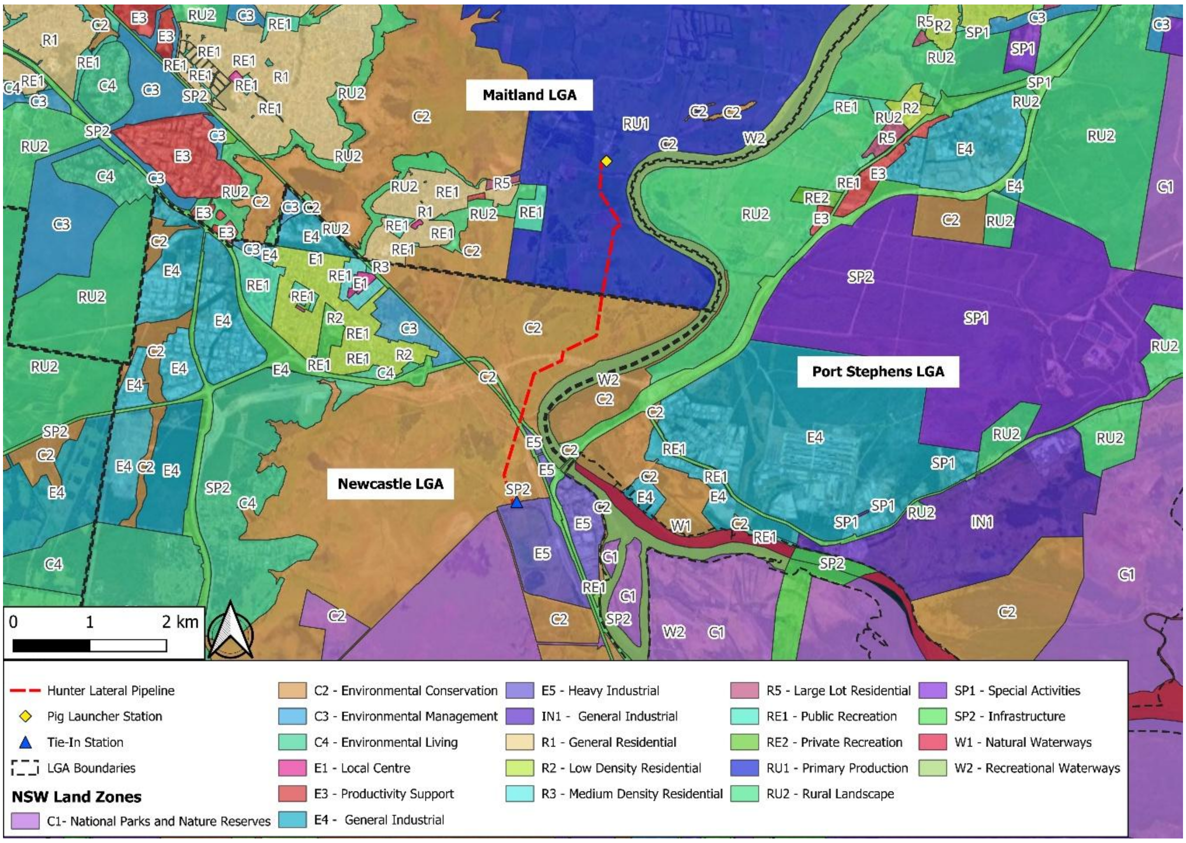


Source: Jemena, APGA

3.2 Surrounding Land Zones and Uses

The NSW planning zones surrounding the pipeline are presented in Figure 5. The pipeline will traverse through land zones classified as Environmental Conservation (C2), Primary Production (RU1) and Infrastructure (SP2).

Figure 5 Surrounding Land Zones



Source: NSW Department of Planning, Jemena, APGA

The surrounding land uses are presented in Figure 6. While the pipeline primarily crosses open farmland and parkland, other land use types such as residential areas, public parks, commercial and industrial operations are located at varying distances from the pipeline.

Figure 6 Surrounding Land Uses

Source: Jemena, APGA

3.3 Meteorology

The meteorological conditions such as windspeed, wind direction, stability class, temperature, solar radiation, and humidity are important in determining the extent of hazardous consequences. Meteorological data for the site is based upon 25 years of observations at Williamtown RAAF (Bureau of Meteorology Station ID 061078) which is one of the closest weather stations to the proposed development site.

Pasquil's stability classification scheme defines six wind stability classes (A to F). Class A refers to more turbulent, unstable conditions and Class F refers to more stable (inversion) conditions. Although the probability distribution of the 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 weather categories and their distribution considered in this analysis are presented in Table 4 - Table 7. Night-time is considered the period from one hour before sunset (5 pm), to one hour after sunrise (7 am); this approximates to 14 hours night-time (58%) and 10 hours daytime (42%).

Table 4 Daytime Weather Categories

Weather Category	Windspeed (m/s)	Stability Class	Temperature (°C)	Relative Humidity	Solar Radiation (kW/m^2)
1.9B	1.9	B	22.34	0.62	0.63
8.2D	8.2	D	21.25	0.56	0.49
4.2D	4.2	D	19.88	0.67	0.39
1.3D	1.3	D	17.96	0.81	0.22

Table 5 Daytime Weather Category Distribution

Direction	1.9B	8.2D	4.2D	1.3D	Total
N	1.65%	0.07%	1.54%	0.73%	**3.99%**
NNE	1.05%	0.16%	1.19%	0.35%	**2.76%**
NE	1.03%	1.11%	2.15%	0.40%	**4.69%**
ENE	0.69%	2.74%	1.97%	0.29%	**5.68%**
E	0.79%	2.98%	2.82%	0.35%	**6.94%**
ESE	0.87%	2.82%	2.99%	0.28%	**6.95%**
SE	1.35%	3.15%	3.04%	0.25%	**7.79%**
SSE	0.92%	3.98%	2.62%	0.26%	**7.77%**
S	0.57%	5.56%	2.83%	0.29%	**9.24%**
SSW	0.27%	1.62%	1.21%	0.19%	**3.30%**
SW	0.24%	0.84%	1.08%	0.22%	**2.38%**
WSW	0.37%	0.53%	1.18%	0.26%	**2.33%**
W	0.99%	2.79%	3.00%	0.64%	**7.43%**
WNW	1.64%	8.62%	5.28%	0.90%	**16.44%**
NW	1.94%	1.88%	3.70%	0.75%	**8.27%**
NNW	1.77%	0.22%	1.53%	0.52%	**4.05%**
TOTAL	**16.15%**	**39.07%**	**38.13%**	**6.65%**	**100.00%**

Table 6 Night-Time Weather Categories

Weather Category	Windspeed (m/s)	Stability Class	Temperature (°C)	Relative Humidity	Solar Radiation (kW/m^2)
8D	8.0	D	15.68	0.71	0.01
3.9D	3.9	D	16.20	0.81	0.01
1D	1	D	15.02	0.91	0.01
3.1E	3.1	E	14.29	0.83	0.00
1F	1	F	13.91	0.89	0.00

Table 7 Night-Time Weather Category Distribution

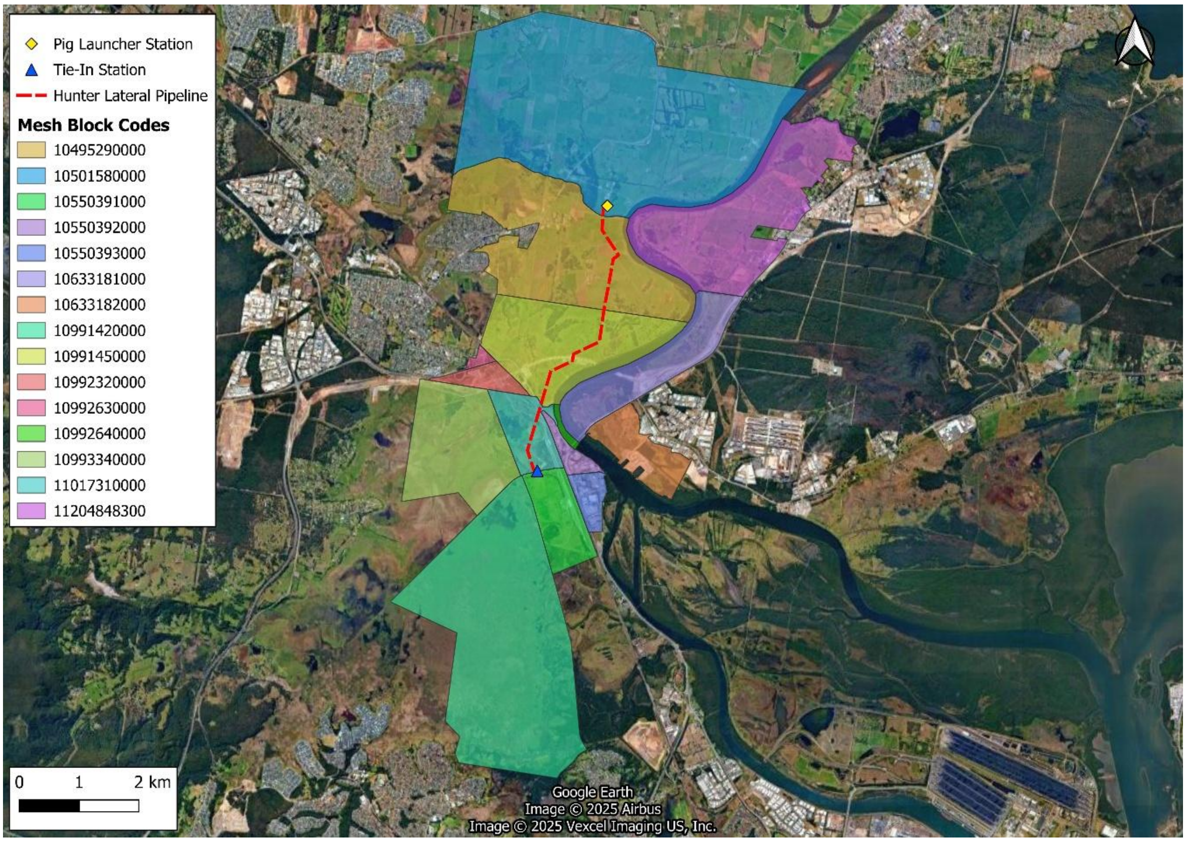
Direction	8D	3.9D	1D	3.1E	1F	Total
N	0.02%	1.12%	2.38%	0.39%	2.39%	**6.29%**
NNE	0.09%	1.84%	1.72%	0.50%	1.89%	**6.05%**
NE	0.50%	4.01%	1.80%	0.76%	1.93%	**9.01%**
ENE	0.41%	2.43%	1.61%	0.56%	1.67%	**6.68%**
E	0.23%	2.24%	1.60%	0.36%	1.51%	**5.93%**
ESE	0.29%	1.31%	0.68%	0.13%	0.59%	**3.00%**
SE	0.73%	1.53%	0.71%	0.14%	0.61%	**3.72%**
SSE	1.09%	1.51%	0.76%	0.11%	0.59%	**4.05%**
S	1.91%	2.41%	1.03%	0.21%	0.72%	**6.27%**
SSW	0.70%	1.13%	0.50%	0.09%	0.36%	**2.78%**
SW	0.42%	0.85%	0.47%	0.10%	0.42%	**2.25%**
WSW	0.39%	1.51%	0.73%	0.17%	0.74%	**3.53%**
W	1.35%	3.44%	1.71%	0.62%	2.07%	**9.20%**
WNW	4.05%	6.17%	2.74%	1.50%	3.27%	**17.73%**
NW	0.61%	3.28%	2.14%	1.07%	2.84%	**9.94%**
NNW	0.07%	0.81%	1.10%	0.28%	1.32%	**3.57%**
TOTAL	**12.85%**	**35.58%**	**21.66%**	**6.99%**	**22.92%**	**100.00%**

3.4 Surrounding Populations

The populations adopted for this study were based on the 2021 Census of Population and Housing conducted by the Australian Bureau of Statistics (ABS). Population data were extracted at the Mesh Block (MB) level for residential populations and at the destination zone (DZN) level for employment populations. These are illustrated in Figure 7 and Figure 8 respectively.

It was assumed that 100% of the residential population will be present during the night. Considering the population travelling outside their MB zone for work during the day, only 40% of the residential population was assumed to remain during the day. Furthermore, the populations were evenly distributed within each respective zone.

Figure 7 Residential Population

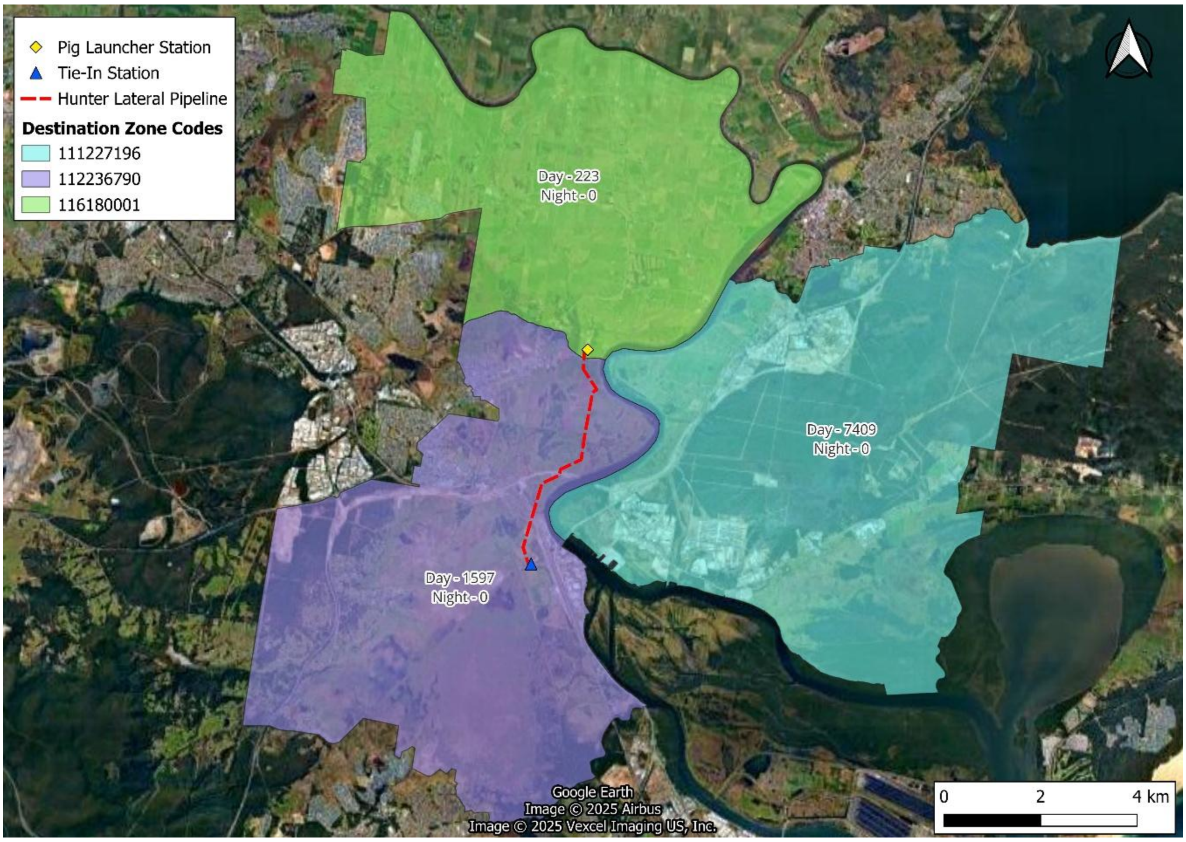


Source: Australian Bureau of Statistics, Jemena, APGA

Table 8 Mesh Block Populations

Mesh Block Code	Day Population	Night Population
10495290000	35	86
10501580000	39	96
10550391000	0	0
10550392000	5	11
10550393000	19	47
10633181000	0	0
10633182000	0	0
10991420000	0	0
10991450000	3	6
10992320000	0	0
10992630000	12	30
10992640000	0	0
10993340000	3	6
11017310000	2	4
11204848300	33	81

Figure 8 Employment Population



Source: Australian Bureau of Statistics, Jemena, APGA

4 HAZARD IDENTIFICATION

4.1 Introduction

The hazard identification was based on a review of the:

- Hunter Lateral pipeline details provided by MVC (Section 4.2)
- Properties of natural gas (Section 4.3)
- Pipeline failure modes (Section 4.4)
- Potential consequences of a release of natural gas (Section 4.5)
- Control Measures (Section 4.6)

The potential hazardous scenarios carried forward to the consequence, likelihood and risk analysis are listed in Section 4.7.

4.2 Hunter Lateral Pipeline Details

Details of the Hunter Lateral pipeline are presented in Table 9.

Table 9 Hunter Lateral Pipeline Details

<table>
<tr><th colspan="2">Pipeline Owner</th><td>Jemena</td></tr>
<tr><th colspan="2">Pipeline Name</th><td>Hunter Lateral</td></tr>
<tr><th colspan="2">Material/Product Transferred</th><td>Natural Gas - Sales</td></tr>
<tr><th colspan="2">Licence No.</th><td>Lic 8</td></tr>
<tr><th colspan="2">MAOP (& units)</th><td>6895kPa</td></tr>
<tr><th colspan="2">Normal Operating Pressure (& units)</th><td>5000kPa</td></tr>
<tr><th colspan="2">Operating Temperature (°C)</th><td>Inlet 15 – 20 °C</td></tr>
<tr><th colspan="2">Energy Throughput (TJ/day)</th><td>170 TJ/day</td></tr>
<tr><th colspan="2">Flowrate (kg/s)</th><td>47 kg/s</td></tr>
<tr><th colspan="2">Bi-directional ? (Yes / No)</th><td>Yes</td></tr>
<tr><th colspan="2">Pipeline Material</th><td>API 5L X60</td></tr>
<tr><th rowspan="3">Pipeline Outer Diameter (mm)</th><td>kp 1 to kp 2</td><td rowspan="3">508mm</td></tr>
<tr><td>kp 1 to kp 2</td></tr>
<tr><td>kp 1 to kp 2</td></tr>
<tr><th rowspan="3">Wall Thickness (mm)</th><td>kp 1 to kp 2</td><td rowspan="3">8.48mm</td></tr>
<tr><td>kp 1 to kp 2</td></tr>
<tr><td>kp 1 to kp 2</td></tr>
<tr><th rowspan="4">Depth of Cover (mm)</th><td>kp 0 to kp 2.95</td><td>Minimum 750mm in accordance with AS2885</td></tr>
<tr><td>kp 2.95 to kp3.1</td><td>Deeper than 1.2m (dependent on TfNSW future access across the pipeline) to be defined</td></tr>
<tr><td>kp 3.1 to kp 3.6</td><td>Minimum 750mm in accordance with AS2885</td></tr>
<tr><td>kp 3.6 to kp 4.4</td><td>HDD varied depths</td></tr>
</table>

	kp 4.4 to kp 5.2	Minimum 750mm in accordance with AS2885
Cathodic Protection		Impressed current
External Coating		2 layer FBE
Leak Detection		None
Locations of Nearest Isolation Valves	Upstream	At the custody transfer
	Downstream	At pig receiver
Leak Detection Time		Isolation plan development in Detailed Design phase
Leak Isolation Time		Isolation plan development in Detailed Design phase
Inspections		Buried pipeline inspected as part of pigging, above ground section has annual inspection
Control Measures for 3rd Party Interference		Marker posts , BYDA , pipeline patrol
Pigging		10 Yearly
Current Condition of Pipeline		New
Ancillary Facilities		None. The pipeline does not include any ancillary facilities such as compression or storage facilities.

4.3 Properties of Natural Gas

Natural Gas is principally used as a fuel. It typically contains 95 to 97% methane (CH_4) and is modelled as 100% methane in this QRA. Methane is:

- A gas at ambient conditions;
- Flammable;
- Lighter than air at ambient temperatures; and
- Colourless, odourless and non-toxic.

Physical properties of Methane are listed in Table 10.

Table 10 Physical Properties of Methane

Boiling Point (at 760 mmHg)	-162 °C
Flash Point	-188 °C
Autoignition Temperature	540 °C
Relative Density (Air =1)	0.55
Lower Flammability Limit (vol. %)	5%
Upper Flammability (vol. %)	15%

4.4 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 [4]:

- Mechanical failures
- Corrosion
- Ground movement and other failure modes,
- Third Party Activity (TPA)

It has been identified that acid sulphate soils may be present, and the area is subject to flooding. It is assumed given these have been identified, specific controls are in place to reduce the risk of these items to the baseline risk levels.

4.4.1 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 Hunter Lateral pipeline.

4.4.2 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 Hunter Lateral pipeline.

4.4.3 Ground Movement and Other Failure Modes

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

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

This failure mode is credible for the Hunter Lateral pipeline.

4.4.4 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. it may only weaken the pipeline such that it fails at a later time).

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

This failure mode is credible for the Hunter Lateral pipeline.

4.5 Potential Consequences

4.5.1 Ignition

If a release of Natural Gas ignites it could result in the following consequences as described in Section 2.5:

- **Jet Fire** – The potential for fatality due to exposure to heat radiation from a jet fire (including direct exposure to the jet) has been included in this QRA.
- **Flash Fire** – The potential for fatality due to direct exposure to a flash fire has been included in this QRA.
- **Vapour Cloud Explosion** – The potential for fatality due to exposure to overpressures from a vapour cloud explosion is included in this QRA. Fatalities due to secondary effects such as projectiles and whole-body displacement have not been included.

Other potential consequences that were considered are described below.

4.5.2 Asphyxiation

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

Natural Gas 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) 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).

Oxygen deficiency from exposure to Natural Gas 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, or 10%, 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 this QRA.

4.5.3 Toxic Smoke

Large quantities of smoke can be produced from hydrocarbon fires, especially flammable or combustible liquids such as gasoline (petrol) and diesel; 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. 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 this QRA.

4.6 Control Measures

Under the NSW Pipelines Act 1967 and Pipelines Regulation 2023, a pipeline operator must ensure the design, manufacture, construction, operation, maintenance, testing and decommissioning of pipelines must be carried out in accordance with the relevant requirements of AS(/NZS) 2885 Pipelines—Gas and Liquid Petroleum as in force from time-to-time. The following sections briefly discuss control measures referred to in AS(/NZS) 2885.

4.6.1 Prevention of Mechanical Failure and Corrosion

Section 6 of AS 2885.3:2022 [9] requires operators of licensed pipelines to develop and implement systems and processes to ensure the pipeline structural integrity for the design life of the pipeline is in accordance with as part of the pipeline management system.

Continual monitoring is required while the pipeline is in operation to ensure that pipeline structural integrity is maintained, any anomalies or defects should be assessed and repaired. They shall not be operated above the Maximum Allowable Operating Pressure (MAOP).

Pipelines are generally inspected via pigging to observe any mechanical defects; and cathodic protection systems and external pipe coatings are implemented to minimise the likelihood of failure due to corrosion. The 2024 NSW Pipelines Performance Report indicates that the 98.8% of pipelines in NSW are cathodically protected with an effectiveness of 99.3% [10].

4.6.2 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 [11].

To comply with AS/NZS 2885.1:2018 [11], 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). The minimum depth of cover of the Hunter Lateral pipeline is 750 mm.

4.6.3 Prevention of Damage due to Third Party Activity

Section 7 of AS2885.3:2022 addresses pipeline corridor management including external interference (Section 7.2). Section 7.2 discusses controls, including:

- Liaison with One Call Services, such as Before You Dig Australia (BYDA). The 2024 NSW Pipelines Performance Report indicates that over 99.8% of parties contacted BYDA before any excavation work [10].
- Protective slabbing
- Pipeline marking, such as above ground markers and buried marker tape
- Agreements with other entities, such as other users of common infrastructure corridors
- Pipeline patrols / surveillance
- Remote intrusion monitoring

A Safety Management Study (as per AS/NZS 2885.6:2018 [12]) is used to assess the risks associated with threats to the pipeline and to instigate appropriate measures to manage the identified threats. The probability of leak on impact depends on the pipeline wall thickness. The depth of cover may also reduce the likelihood of impact.

4.6.4 Mitigation Control Measures

An Emergency Response Plan (ERP) shall be developed and implemented to address all pipeline related emergency events (AS 2885.3 [9], Section 11). The Emergency Response Plan should detail the response and recovery strategies and procedures to address all pipeline related emergency events including:

- Loss of containment
- Full-bore ruptures
- Fires
- Natural events

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

4.7 Hazardous Scenarios Carried Forward to the Risk Analysis

The hazardous scenarios carried forward to the consequence, likelihood and risk estimation steps of this QRA are provided in Table 11.

Table 11 List of Hazardous Scenarios

Hazardous Scenarios	Potential Consequences
Release of High-Pressure Natural Gas from Hunter Lateral Pipeline	Jet Fire, Flash Fire, and/or VCE

5 CONSEQUENCE ANALYSIS

5.1.1 Representative Hole Diameters

The representative hole diameters adopted for the consequence analysis are presented in Table 12. The hole diameters were selected based on a review of the available historical incident data (Refer to Appendix C). The selection was intended to align with the hole size categories of the leak frequency data adopted for this study (Refer to Section 6). The hole size categories applicable for the Hunter Lateral pipeline are as follows:

- Pinhole (≤ 25 mm);
- Small Hole (> 25 mm to ≤ 75 mm);
- Large Hole (> 75 mm to ≤ 110 mm); and
- Full-Bore Rupture (> 110 mm).

The conservative upper limit of the hole size categories was selected as the representative hole diameter for each category except for the Full-Bore Rupture (FBR) category. In the case of a FBR, flow can occur from both upstream and downstream towards the rupture. The total maximum flow area is therefore twice the cross-sectional area of the pipe. An equivalent hole diameter (D_E) for this scenario is $\sqrt{2} \times D$ as shown below, where D is the diameter of the pipeline:

$$Total\ Flow\ Area = 2 \times \frac{\pi D^2}{4} = 2 \times \frac{\pi \times 491^2}{4} = 378689.1\ mm^2$$

Where D is the internal diameter of the pipeline. Then,

$$\frac{\pi D_E^2}{4} = 378689.1\ mm^2$$

$$D_E = \sqrt{\frac{4 \times 378689.1}{\pi}} = 694.4\ mm$$

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 for the pinhole category: 25 mm for TPA and 10 mm for all other failure modes.

Table 12 Representative Hole Diameters

Pipeline	Internal Diameter (mm)	Representative Hole Diameter (d)			
		Pinhole (≤ 25 mm)	Small Hole (25 mm < d ≤ 75 mm)	Large Hole (75 mm < d ≤ 110 mm)	FBR (> 110 mm)
Hunter Lateral	491	10 / 25	75	110	694.4

5.1.2 Release Rates

A release of natural gas from the Hunter Lateral pipeline was modelled at the MAOP of 6.895 MPa. The proposed Hunter Lateral pipeline will offtake natural gas from the proposed Hunter gas pipeline and supply the Killingworth to Kooragang Island Pipeline, both of which have an internal diameter of 494.8 mm.

To take into account inflow from both above-mentioned pipelines during a breach, the upstream and downstream ends of the Hunter Lateral were modelled as 5 km long pipelines with a representative diameter of 700 mm. Sensitivity testing has shown that increasing the pipeline length to account for the full length did not materially change the calculated release rates.

The pipeline was modelled with a flowrate of 47 kg/s. This will influence the dynamics within the pipeline during a breach and affect the calculated release rates. The average rate over the first 30 seconds was chosen as the representative release rate. The discharge model and calculated release rates for each representative scenario are presented in Table 13.

Table 13 Representative Release Rates

Section	Hole Diameter (mm)	Discharge Model	Release Rate (kg/s)
Underground	10	Steady State / Peak	0.9
	25	Steady State / Peak	5.6
	75	Steady State / Peak	50.6
	110	Time-Varying / Average	171
	694.4 (FBR)	Time-Varying / Average	2790
Pig Launcher Station	10	Steady State / Peak	0.9
	25	Steady State / Peak	5.6
	75	Steady State / Peak	50.6
	110	Time-Varying / Average	171
	694.4 (FBR)	Time-Varying / Average	2790
Tie-In Station	10	Steady State / Peak	0.9
	25	Steady State / Peak	5.6
	75	Steady State / Peak	50.6
	110	Time-Varying / Average	171
	694.4 (FBR)	Time-Varying / Average	2780

5.1.3 Location and Direction Release

High pressure gas releases from an underground pipeline would create a crater on the ground. The direction of release from the crater is always vertical. This assumption is part of the modelling approach in Safeti and cannot be modified.

Three locations of failure were considered for all hole sizes except the FBR scenario:

- Top of the pipe (unobstructed release); or
- Middle of the pipe (on the side - obstructed release)

The release frequencies were distributed between the three locations as follows:

- Top of the pipe – 63%
- Middle of the pipe – 37%

5.1.4 Duration of Release

Any adverse impact due to the ignition of natural gas will occur quickly; therefore, the duration of release is not as critical as it would be if there were a toxic material in the pipeline (i.e. where the adverse impact can significantly increase for longer release durations).

5.1.5 Consequences of Hazardous Scenarios

The consequence analysis was conducted using SAFETI 9.11 software package at a height of interest of 1 m Above Ground Level (AGL). The consequences of the hazardous scenarios identified were modelled to estimate the potential impacts with respect to heat radiation and overpressures. Toxic effects were not carried forward to the consequence analysis (Refer to Section 4.5.2). The consequence analysis results are presented in Appendix B.

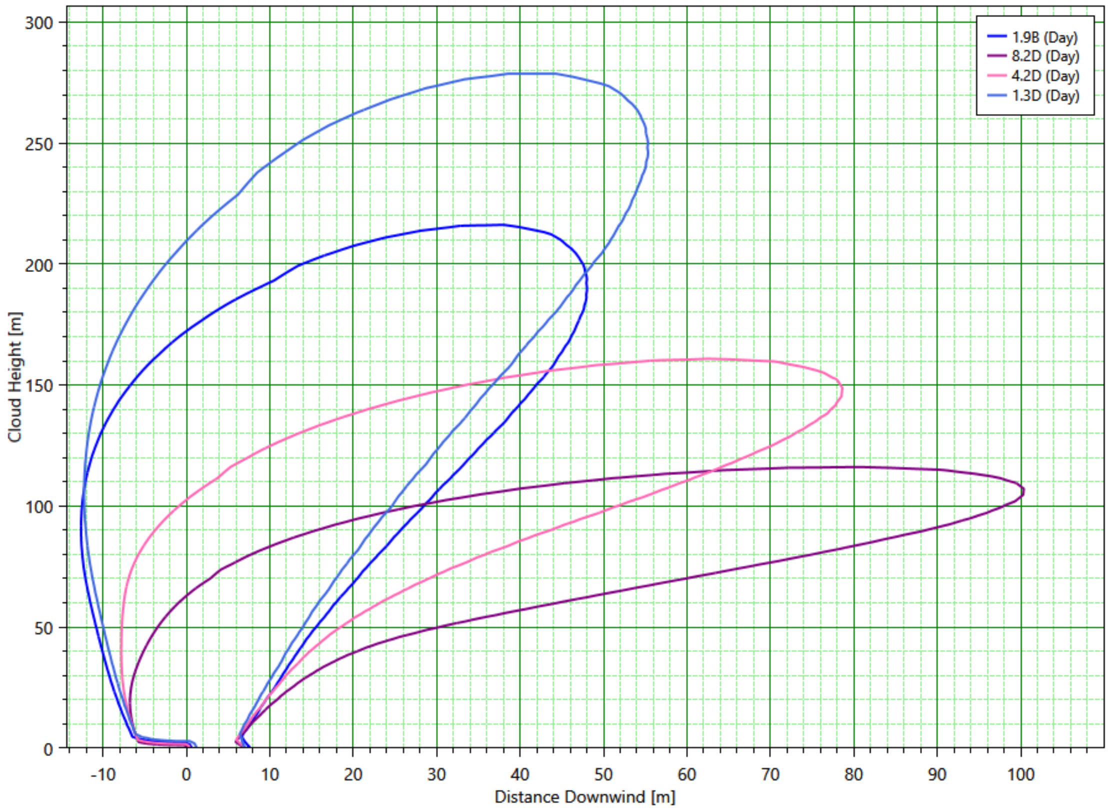
The underground sections were modelled at a depth of 750 mm, and the aboveground stations were modelled at 1 m AGL. A summary of the potential worst-case consequence distances for selected parameters have been tabulated in Table 14.

Table 14 Worst-Case Consequence Distances at 1 m AGL

Consequence	Parameter	Release Location / Section		
		Underground	Pig Launcher Station	Tie-In Station
Flash Fire	Maximum Extent to LFL	6.3 m	693 m	691 m
Jet Fire	Maximum Extent to 4.7 kW/m^2 Heat Flux	608 m	689 m	688 m
	Maximum Extent to 12.6 kW/m^2 Heat Flux	376 m	527 m	526 m
	Maximum Extent to 23.0 kW/m^2 Heat Flux	276 m	455 m	454 m
VCE	Maximum Extent to 7 kPa Overpressure	49.3 m	639 m	637 m
	Maximum Extent to 10 kPa Overpressure	32.8 m	596 m	594 m

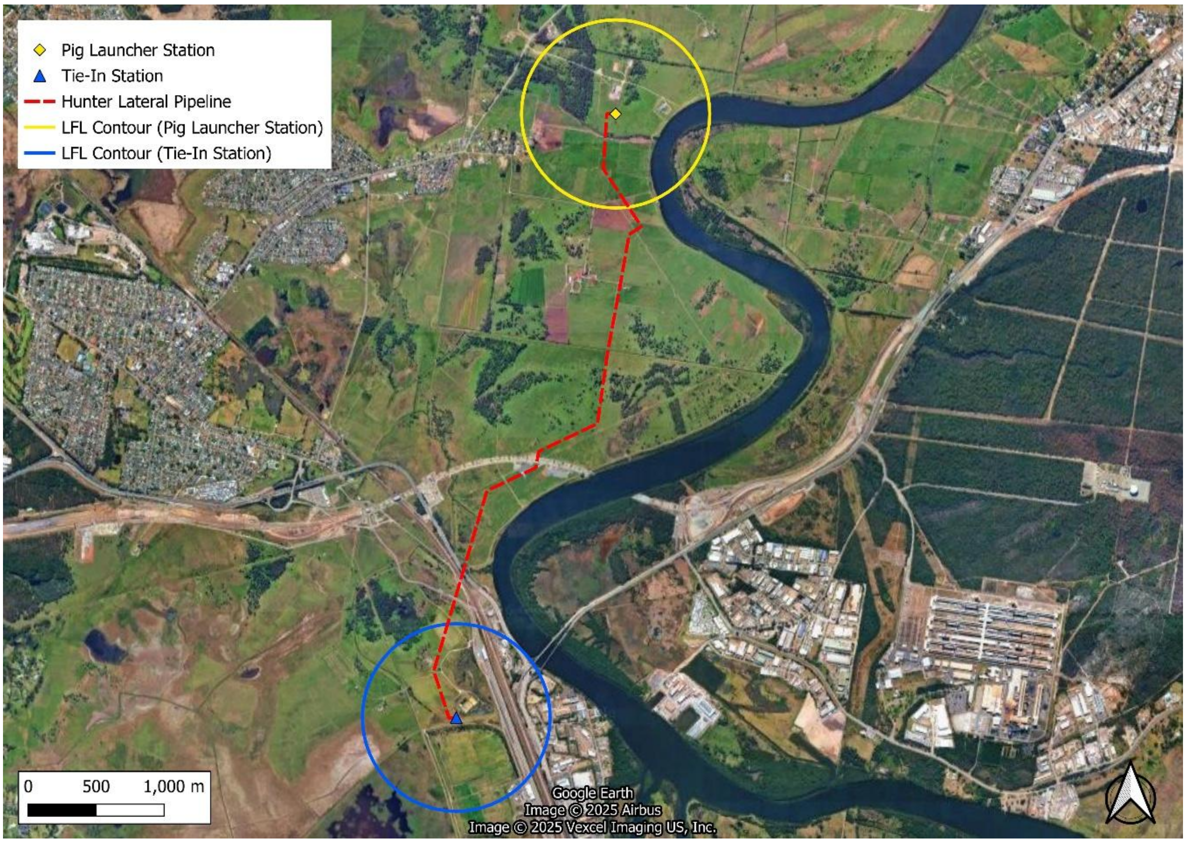
A side view dispersion profile of a FBR is presented in Figure 9. This figure shows the extent of a flammable cloud may be significant (approximately 100 m), but at elevations greater than 30 m. At less than 10 m height, the extent of a flash fire is less than 10 m.

Figure 9 Dispersion to LFL (Side View) [RDS 1_694.4 mm (FBR)]



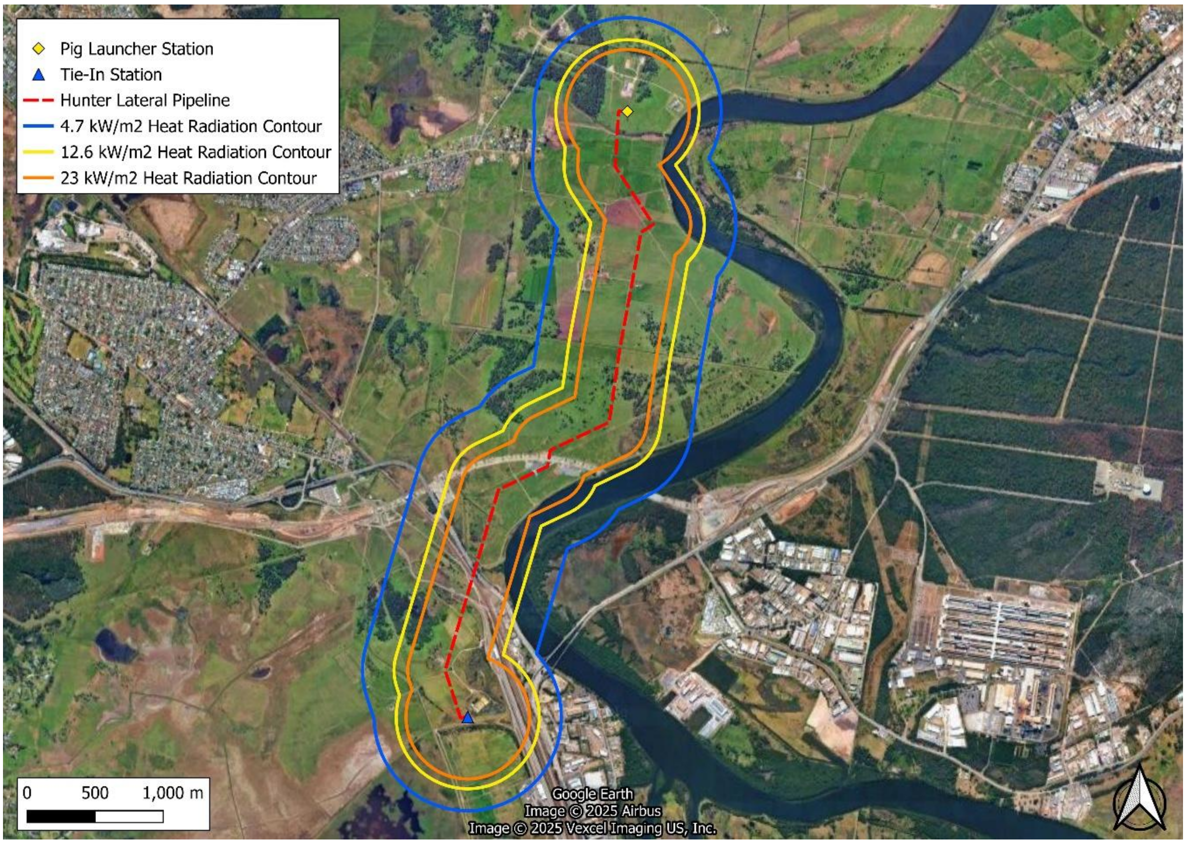
The maximum extent of the flammable cloud to LFL for a release from the pig launcher and tie-in stations are presented in Figure 10.

Figure 10 Maximum Extent to LFL for Aboveground Stations



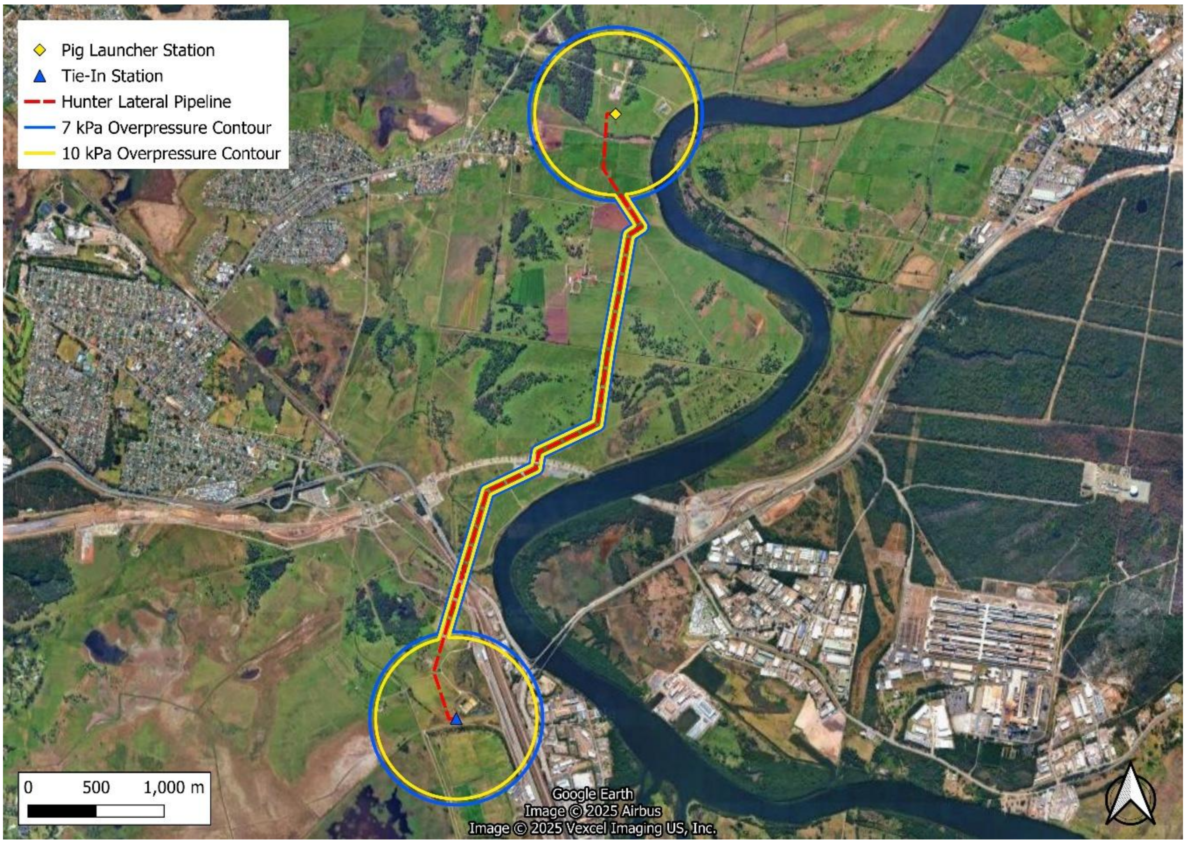
The maximum extent to heat radiation levels of 4.7, 12.6 and 23 kW/m^2 are presented in Figure 11, indicating the potential for injuries and property damage due to a jet fire. Note that these represent worst case consequences distances presented in Table 14 and are not associated with a frequency of occurrence.

Figure 11 Maximum Extent to 4.7, 12.6 and 23 kW/m2 Heat Radiation Levels



Explosion overpressures can reach up to 10 kPa but do not reach 14 kPa for any release scenarios, indicating that injuries and minor property damages may occur due to a VCE. The maximum extent to 7 kPa and 10 kPa explosion overpressures are illustrated in Figure 12. These represent worst case consequences distances presented in Table 14 and are not associated with a frequency of occurrence.

Figure 12 Maximum Extent to 7 kPa and 10 kPa VCE Overpressures



6 FREQUENCY AND LIKELIHOOD ANALYSIS

6.1 Likelihood of Release

A review of the likelihood of a release (i.e. leak) from underground natural gas pipelines is presented in the Appendix D. The leak frequency data reported in RR1035 developed for the UK HSE [4] was deemed the most appropriate for this study.

Leak frequency data in RR1035 has been reported for four hole size categories (pinhole, small hole, large hole and rupture), four failure mode categories (mechanical failure, corrosion, ground movement / other and TPA), and in some cases for varying pipe diameters and / or wall thicknesses. The leak frequencies for each failure mode and hole size are presented in Table 15.

Table 15 Underground Natural Gas Pipeline Leak Frequencies [4]

Failure Mode	Pipeline Diameter (mm)	Wall Thickness (mm)	Leak Frequency (per km per year)				
			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	≥ 305	All	8.70E-06	1.00E-08	1.00E-08	1.00E-08	8.73E-06
Corrosion	All	5 to < 10	3.30E-05	1.00E-08	1.00E-08	1.00E-08	3.30E-05
Ground Movement / Other	All	All	1.20E-05	2.50E-06	1.50E-07	2.50E-06	1.72E-05
TPA	All	All	2.20E-05	2.40E-06	1.00E-07	1.00E-07	2.46E-05
Hunter Lateral Pipeline Total	**≥ 305**	**5 to < 10**	**7.57E-05**	**4.92E-06**	**2.70E-07**	**2.62E-06**	**8.35E-05**
%			**90.6%**	**5.9%**	**0.3%**	**3.1%**	**100%**

The likelihood of a release from the aboveground stations are presented in Table 16 and were based on the following data source:

- UK Health and Safety Executive (HSE), 2019, Failure Rate and Event Data for use within Risk Assessments (02/02/19), Item FR 3.1.2 Above Ground Pipelines in a Gas Installation [5].

Table 16 Failure Rates for Aboveground Stations [5]

Failure Category	Failure Rate (per m per year)
Pinhole (≤ 25 mm)	1.60E-07
Small Hole (> 25 mm to ≤ 75 mm)	6.70E-08
Large Hole (> 75 mm to ≤ 110 mm)	3.30E-08
Rupture (> 110 mm)	6.50E-09

6.2 Likelihood of Representative Release Scenarios

The likelihood of each representative release scenario for the Hunter Lateral pipeline are presented in Table 17. The 10 mm scenario was assigned the total frequency of non-TPA pinhole failures, while the 25 mm scenario was assigned the total frequency of TPA-related pinhole failures.

Furthermore, the underground release frequencies were distributed between two puncture locations; 37% for middle of the pipe and 63% for top of the pipe. Refer to Appendix A for more details regarding the distribution of the release frequency data.

Table 17 Representative Release Frequencies — Underground Sections

Release Scenario	Release Frequency (per km per year)		Total Release Frequencies	Probability of Scenario Compared to Total
	TPA	All Other Failure Modes		
10 mm (Top)		3.38E-05	3.38E-05	40.5%
10 mm (Mid)		1.99E-05	1.99E-05	23.8%
25 mm (Top)	1.39E-05		1.39E-05	16.6%
25 mm (Mid)	8.14E-06		8.14E-06	9.7%
75 mm (Top)	1.51E-06	1.59E-06	3.10E-06	3.7%
75 mm (Mid)	8.88E-07	9.32E-07	1.82E-06	2.2%
110 mm (Top)	6.30E-08	1.07E-07	1.70E-07	0.2%
110 mm (Mid)	3.70E-08	6.29E-08	9.99E-08	0.1%
FBR	1.00E-07	2.52E-06	2.62E-06	3.1%
Total	**2.46E-05**	**5.89E-05**	**8.35E-05**	**100%**

The likelihood of each representative release scenario for the aboveground stations of the pipeline are presented in Table 18. In the absence of specific data, the length of piping at the aboveground stations were assumed to be 50 m based on a comparable installation.

The aboveground pinhole failure rate was split between the 10 and 25 mm hole sizes, based on the ratio between the frequency of TPA and all other failure modes for underground pinhole releases (Refer to Section 6.1, Table 15)

Table 18 Representative Release Frequencies — Aboveground Stations

Station	Length of Piping (m)	Hole Size	Failure Frequency (per year)
Pig Launcher / Tie-In Stations	50	10 mm	5.7E-06
		25 mm	2.3E-06
		75 mm	3.4E-06
		110 mm	1.7E-06
		FBR	3.3E-07
		Total	**1.3E-05**

6.3 Probability of Ignition

A review of relevant ignition probability data and ignition probability correlations was conducted (Refer to Appendix D.2). The ignition probabilities adopted for this study are as follows:

- **Underground Sections**: The total ignition probability was based on the Acton & Baldwin correlation [6], which relates ignition probability to pipeline pressure and breach size (Refer to Table 19).
- **Aboveground Stations:** The total ignition probability was based on the International Association of Oil & Gas Producers (IOGP) Scenario 3 – Pipe Gas LPG Industrial [13], which is release rate dependent (Refer to Table 20).
- The total ignition probability was split 50:50 for immediate ignition and delayed ignition.

Table 19 Ignition Probabilities — Underground Sections

Pipeline Diameter (mm)	Operating Pressure (barg)	Equivalent Hole Diameter (mm)	pd^2	Total Ignition Probability	Probability of Immediate Ignition	Probability of Delayed Ignition
491	68.95	10	0.01	0.056	0.0278	0.0278
		25	0.04	0.056	0.0279	0.0279
		75	0.39	0.058	0.0291	0.0291
		110	0.83	0.061	0.0306	0.0306
		FBR	16.62	0.283	0.142	0.142

Table 20 Ignition Probabilities — Aboveground Stations

Station	Representative Hole Diameter (mm)	Release Rate (kg/s)	Total Ignition Probability	Probability of Immediate Ignition	Probability of Delayed Ignition
Pig Launcher Station	10	0.9	0.006	0.003	0.003
	25	5.6	0.022	0.011	0.011
	75	50.6	0.110	0.055	0.055
	110	171	0.271	0.136	0.136
	FBR	2790	1	0.5	0.5
Tie-In Station	10	0.9	0.006	0.003	0.003
	25	5.6	0.022	0.011	0.011
	75	50.6	0.110	0.055	0.055
	110	171	0.271	0.136	0.136
	FBR	2780	1	0.5	0.5

7 Risk Analysis and Assessment

7.1 Location Specific Individual Fatality Risk

The location specific individual risk (LSIR) of fatality due to the Hunter Lateral pipeline does not reach the DPHI's lowest risk criteria threshold of 5E-07 per year.

7.2 Injury Risk

The risk of injury due to the Hunter Lateral pipeline does not reach the DPHI's risk criteria threshold of 4.7 kW/m^2 heat radiation and 7 kPa overpressure at a frequency of 5E-05 per year.

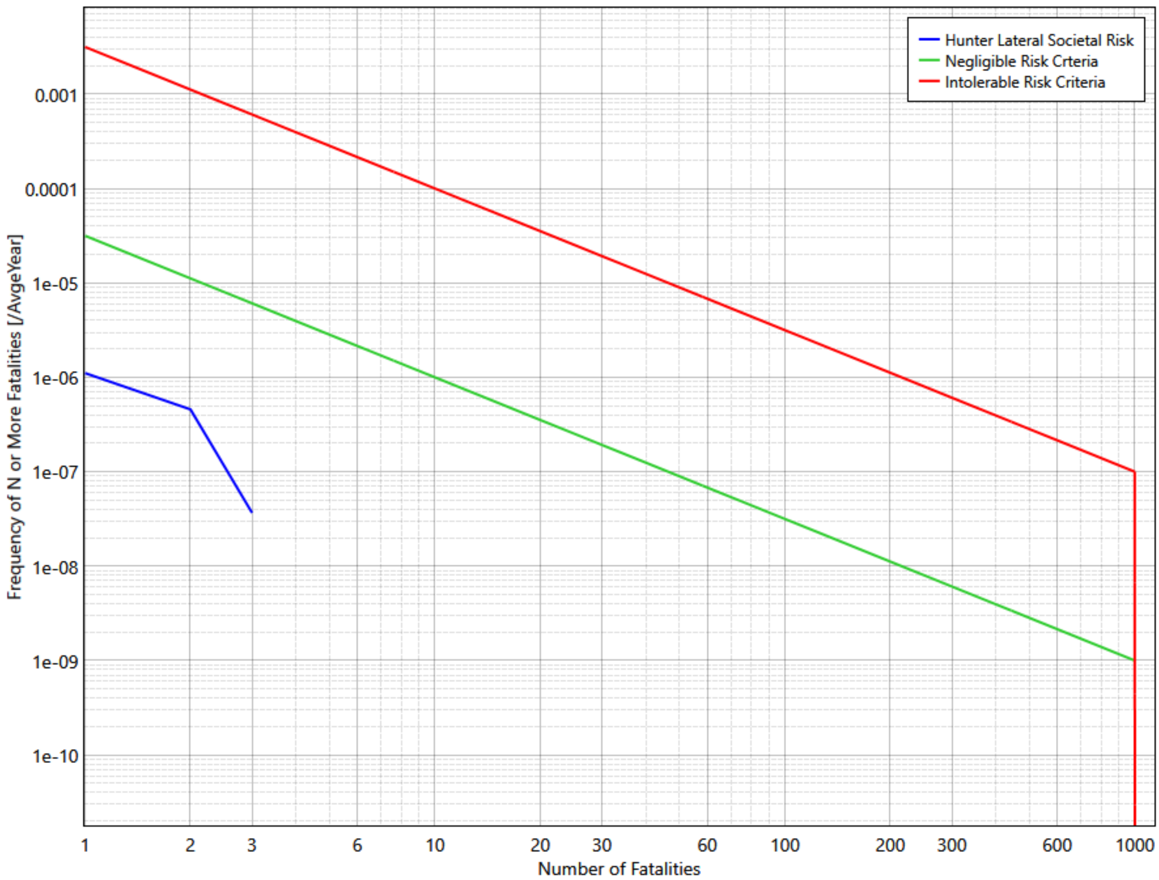
7.3 Risk of Property Damage and Accident Propagation

The risk of property damage and accident propagation due to the Hunter Lateral pipeline does not reach the DPHI's risk criteria threshold of 23 kW/m^2 heat radiation and 14 kPa overpressure at a frequency of 5E-05 per year.

7.4 Societal Risk

The societal risk due to the Hunter Lateral pipeline is presented in Figure 13 as an F-N curve. The societal risk is negligible.

Figure 13 Societal Risk of the Hunter Lateral Pipeline (F-N Curve)



7.5 Qualitative Risk Criteria

- *All 'avoidable' risks should be avoided* — The proposed pipeline will be located underground and predominantly travel through open land classified as conservation or primary production zones with low population densities.
- *The risk from a major hazard should be reduced wherever practicable* — The pipeline will be designed, constructed and operated in compliance with AS 2885 series of standards and other regulatory requirements. General pipeline safety measures including corrosion resistance, patrols, marker posts and routine inspections will be implemented.
- *The consequences (effects) of the more likely hazardous events (i.e. those of high probability of occurrence) should, wherever possible, be contained within the boundaries of the installation* — This is not applicable for a pipeline as there is no boundary.
- *Where there is an existing high risk from a hazardous installation, additional hazardous developments should not be allowed if they add significantly to that existing risk* — The pipeline does not add any significant risk to any hazardous installations.

8 CONCLUSIONS AND RECOMMENDATIONS

The risk generated by the proposed Hunter Lateral pipeline is low. The LSIR of fatality, injury, property damage and accident propagation risks were determined to below the thresholds of the relevant DPHI risk criteria. The societal risk due to the pipeline was determined to be negligible.

The proposed route of the pipeline satisfies existing DPHI risk criteria.

9 REFERENCES

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Appendices

Appendix A Assumption Register

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 section.

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 hazardous scenarios 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.*"

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A.1 Operational Data

Assumption No. 1 Pipeline Operating Conditions
Subject: Operational Data
Assumptions: • The operating pressure and temperature of the pipeline were assumed to be 6.895 MPa and 15°C respectively. • The mass flowrate of Natural Gas through the pipeline was assumed to be 47 kg/s.
Justification and Impacts of Assumptions: • Operational data for the pipeline was provided by MVC. • Operating conditions (particularly operating pressure) are required to undertake the release and dispersion modelling. • Providing a flow will influence the dynamics within the pipeline during a release event, altering the discharge rate and subsequent dispersion.
Hazardous Scenarios Affected: • All.
References: • Email correspondence with MVC Services.

Assumption No. 2 Pipeline Utilisation
Subject: Operational Data
Assumptions: • The pipeline is utilised 100% of the time.
Justification and Impacts of Assumptions: • Utilisation data is required to estimate the release frequency. • The pipeline will always contain natural gas at pressure to provide energy to industries and communities.
Hazardous Scenarios Affected: • All.
References: •

A.2 Locational Data

Assumption No. 3: Representative Wind Speeds, Wind Directions and Stability Classes
Subject: Locational Data
Assumptions: • Representative weather data is based upon 25 years of observations at Williamtown RAAF (Station ID 061078), operated by the Australian Bureau of Meteorology (BoM). • The average ambient conditions (temperature, solar radiation and relative humidity), and the probabilistic distribution of wind speed and wind direction for the representative stability classes were determined using BoM data. • The data was split into daytime and night-time conditions. • Night-time is considered the period from 1 hour before sunset, to one hour after sunrise. This approximates to 10 hours daytime and 14 hours night-time.
Justification and Impacts of Assumptions: • Williamtown RAAF is the closest BoM station approximately 14 km from the area of the study. • Raw data from Williamtown RAAF observations have been rationalised into a set of wind speed/weather stability classes for dispersion calculations. • Wind will cause flames to tilt downwind. The higher the wind speed, the greater the tilt. The net effect of the tilt is to increase the heat radiation in the downwind direction. This is much more pronounced for pool fires than jet fires because jet fires have much greater momentum. An allowance for flame tilt is included in the SAFETI models for pool fires and vertical jet fires. The SAFETI model assumes horizontal jet fires are directed in the same direction as the wind. • Downwind gas concentrations, and hence the hazard ranges for dispersion of flammable gas or vapour, vary with wind speed and weather stability class. Therefore, multiple representative wind speed and stability class categories are included in accordance with standard practice for undertaking a quantitative risk assessment (QRA). • The day/night split of the weather data is required to allow for the fact that residential, commercial and industrial occupancies change over a 24-hour period.
Hazardous Scenarios Affected: • All.
References: • BoM meteorological data for Williamtown RAAF obtained through Exemplar Energy.

Assumption No. 4: Surface Roughness Length

Subject: Locational Data

Assumptions:

- A roughness length of 0.5 m is applicable for the study area.

Justification and Impacts of Assumptions:

- The roughness length for different surface types, as listed in the SAFETI user manual, is shown below in Table 21. The Hunter lateral will be located predominantly within land that can be characterised as open farmland and/or parkland with scattered trees.

Table 21 Surface Roughness Length

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

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

Hazardous Scenarios Affected:

- Dispersion modelling for all relevant hazardous scenarios.

References:

- SAFETI software documentation.

Assumption No. 5: Location of High-Pressure Gas Pipeline
Subject: Locational Data
Assumptions: • The location of the pipeline is based upon electronic drawings provided by MVC Services.
Justification and Impacts of Assumptions: • The drawings received represents the most accurate information available at the time of the study.
Hazardous Scenarios Affected: • All.
References: • Email correspondence with MVC Services.

Assumption No. 6: Population (Day and Night)
Subject: Locational Data
Assumptions: • Residential and employment populations are based upon the Census of Population and Housing, 2021, obtained from the Australian Bureau of Statistics TableBuilder service. • The residential population is based upon mesh blocks, while the employment population is based upon destination zones. • The populations are distributed evenly.
Justification and Impacts of Assumptions: • The 2021 Census data is the most recent census data available. • Mesh blocks and destination zones are the smallest geographic areas for which relevant data is available.
Hazardous Scenarios Affected: • All societal risk calculations. Population density, along with the area of consequence distances, determines the F-N points of societal risk. • Locational specific risk is not impacted by these assumptions.
References: • Census of Population and Housing, 2021, TableBuilder.

Assumption No. 7: Indoor / Outdoor Distribution of People

Subject: Locational Data

Assumptions:

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

Justification and Impacts of Assumptions:

- The default values recommended by the TNO 'Purple Book' for residential and industrial areas are tabulated below.

Table 22 Proportion of Population Indoor and Outdoor During Day and Night [TNO]

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

- The % of the total population located indoors and outdoors was estimated from similar risk analyses (Including some data provided by NSW DPHI). 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 that the % of people indoors and outdoors is 95 to 99% indoors and 1 to 5% outdoors during the night.

Hazardous Scenarios Affected:

- All societal risk calculations.

References:

- RIVM, Guidelines for Quantitative Risk Assessment (Purple Book), CPR 18E, 3rd edition, VROM, 2005

A.3 Consequence Analysis

Assumption No. 8: Representative Materials
Subject: Consequence Analysis
Assumptions: • Natural gas is modelled as 100% methane.
Justification and Impacts of Assumptions: • 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 consists mainly of methane (CH_4), with varying levels of heavier hydrocarbons and other gases such as carbon dioxide.
Hazardous Scenarios Affected: • All.
Reference/s: • Geoscience Australia, https://www.ga.gov.au/scientific-topics/energy/resources/petroleum-resources/gas accessed 15/11/2024

Assumption No. 9: Representative Release Rates
Subject: Consequence Analysis
Assumptions: • A release of natural gas from the Hunter lateral pipeline is modelled at the MAOP of 6.895 MPag. • Upstream and downstream ends of the Hunter Lateral pipeline were modelled as 5 km long pipelines with a diameter of 700 mm. • The average release rate over the first 30 seconds was used to determine the effects of jet fires, flash fires, and explosions. • Dispersion calculations are based on the total quantity released over one hour, assuming it is released at the average flowrate over the first 30 seconds. • For hole sizes with a relative aperture ratio below of 0.01, the model maintains a constant pressure at the release point (i.e. steady state discharge model), which implies a constant release rate at the point of release.
Justification and Impacts of Assumptions: • The release rate is dependent on the operating pressure. • The diameter at the upstream and downstream ends was increased to account for inflow from both ends of the proposed Hunter gas pipeline and the Killingworth to Kooragang Island Pipeline. • The long pipeline model assumes the input pressure is reduced by frictional losses along the pipeline length until the breach point. This results in a lower pressure at the release point than the operating pressure and hence also a lower release rate.
Hazardous Scenarios Affected: • All.
References: • Data provided by MVC Services

Assumption No. 10: Representative Hole Diameters for Release Modelling

Subject: Consequence Analysis

Assumptions:

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

Table 23 Representative Hole Diameters Selected for Consequence Analysis

Pipeline	Material	Internal 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)
Hunter Lateral	Methane	491	10 / 25*	75	110	694.4**

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

**Full bore rupture flow area is set at twice the pipe cross sectional area, to account for inflow from both ends of the pipeline either side of the rupture.

Justification and Impacts of Assumptions:

- The representative hole diameters were selected based on a review of the available historical incident data (Refer to Appendix C), and the leak frequency data (Refer to Appendix D) adopted for this study which included four hole size categories:
  - Pinhole (≤ 25 mm);
  - Small Hole (> 25 mm to ≤ 75 mm);
  - Large Hole (> 75 mm to ≤ 110 mm);
  - Rupture (> 110 mm).
- Leaks from underground pipelines in the Pinhole size category tend to be larger for TPA incidents (i.e. typically c. 20 mm to 25 mm – Refer to Appendix C.1) 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.
  - This is also consistent with the predicted hole sizes in this size category reported in Table E5 of AS/NZS 2885.1:2018, which are based on excavator weight and tooth dimensions (i.e. 15 mm for 5 tonne excavators, 20 mm for 10-15 tonne excavators and 25 mm for 20-25 tonne excavators).

Hazardous Scenarios Affected:

- All.

References:

- Refer to Appendix C and Appendix D.

Assumption No. 11: Location and Direction of Release
Subject: Consequence Analysis
Assumptions: • The underground sections of the pipeline are modelled as buried sections with a depth of cover of 750 mm as advised by MVC. • High pressure gas releases from an underground pipeline would create a crater on the ground. The direction of release for underground pipeline failures from the crater is always vertical. This assumption is part of the modelling approach in Safeti and cannot be modified. • The location of failure on the underground 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 for all hole sizes as follows: - 37% from middle of pipe - 63% from top of pipe • The aboveground stations are modelled in the horizontal direction at 1 m above ground level.
Justification and Impacts of Assumptions: • The crater size depends on the location of the hole on the pipe. • Impingement reduces the momentum of the release, and the dispersion modelling is dominated by the representative wind conditions. • RR1034 published by the UK HSE reports that some data from UKOPA includes the ‘hole circumferential position’ for releases from underground pipelines. Based on the 71 recorded incidents (All pipelines and materials) and average crater dimensions, an unobstructed release (c. ±71° from vertical) was estimated to occur for 63% of the releases and an obstructed release was estimated to occur for the balance (37% of releases). The distribution is not reported for different failure modes.
Hazardous Scenarios Affected: • All.
References: • SAFETI software documentation. • UK HSE, Review of the Event Tree Structure and Ignition Probabilities used in HSE’s Pipeline Risk Assessment Code MISHAP, Research Report (RR) 1034, 2015.

Assumption No. 12: Maximum Extent of Flash Fire

Subject: Consequence Analysis

Assumptions:

- The maximum extent of a flash fire is defined by the downwind and crosswind distances from the release location to a concentration equal to 100% of the lower flammability limit (LFL) concentration calculated using an 18.75 s averaging time.

Justification and Impacts of Assumptions:

- Justification is provided in (Benintendi, 20171031, p. 341):

  For passive dispersion models, the shorter the averaging time, the higher the centreline concentration, and there is concern that flammable concentrations may exist beyond the 100% LFL contour determined for a specific averaging time.

  To take into account the different averaging times, the following empirical formula is recommended for converting concentrations from 10 minute averaging time to another (Hanna et al., 1993):

  $$\frac{C_t}{C_{600}} = \left(\frac{600}{t}\right)^{0.2} \text{...(1)}$$

  where time is in seconds. C_t denotes time averaged concentration at the new averaging time of t seconds

  Hanna claims that experimentally:

  $$C_{max} = 2 \times C_{600} \text{...(2)}$$

  where C_{max} is the maximum peak concentration in the plume.

  Substituting C_{max} from (2) with $C_{600}\left(\frac{600}{t}\right)^{0.2}$ from (1) and solving for t, it is yields

  t = 18.75 s.

  This time should be adopted to carry out worst case predictions for the extent of 100% LFL. It is the core averaging time for flammable dispersion in Safeti.

- For the materials under consideration, flash fires are not expected to be a major contributor because the gases involved are either buoyant, or have a neutral buoyancy, and should ignition occur, effects from jet fires are expected to dominate.

Hazardous Scenarios Affected:

- All hazardous scenarios with a flash fire as a potential outcome.

References:

- SAFETI software documentation.
- Benintendi, R. (20171031). Process Safety Calculations. [[VitalSource Bookshelf version]]. Retrieved from vbk://9780081012291.
- Hanna, S.R., Strimaitus, D.G., Chang, J., 1993. Hazard Response Modeling Uncertainty (A Quantitative Method) Vol 11 - Evaluation of Commonly Used Hazardous Gas Dispersion Models, Environics Division Air Force Engineering & Services Center, Engineering & Services Laboratory.

Assumption No. 13: Isolation Time and Duration of Release
Subject: Consequence Analysis
Assumptions: • Isolation time and duration of release is not specified as these will be significantly longer than the period of exposure required for an adverse effect to people and the time required for each representative release case to reach steady state.
Justification and Impacts of Assumptions: • Methane (natural gas) is flammable, and any adverse impact will occur quickly (fire or explosion); therefore, the duration of exposure is not as critical as it would be if there were toxic materials in the pipeline (i.e. where the adverse impact can significantly increase for longer exposure durations). • The consequence calculations of the Long Pipeline Model, uses the average releases rate over the first 30 seconds and an exposure time of 30 seconds (user specified), compared to isolation valve closure times which typically vary from minutes (full bore rupture case) to hours (small to medium leaks).
Hazardous Scenarios Affected: • All.
References: • SAFETI software documentation.

Assumption No. 14: Shielding by Intervening Structures
Subject: Consequence Analysis
Assumptions: • The presence of intervening structures (e.g. buildings) does not shield other receptors from the heat radiation from a jet fire.
Justification and Impacts of Assumptions: • In the SAFETI software, it is not possible to take account of the potential protection provided by intervening structures. • This analysis is taking place during the concept stage of development of a large growth area. There is insufficient information available to determine the location of large structures that could offer protection against radiant heat. • People located indoors are typically less vulnerable to fire, which is a relevant consideration for the societal risk assessment (Refer to Assumption No. 20).
Hazardous Scenarios Affected: • Scenarios with a pool fire or jet fire as a potential outcome.
References: • SAFETI software documentation.

Assumption No. 15: 3D Explosion Model Parameters
Subject: Consequence Analysis
Assumptions: • 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. • An obstruction region was defined to cover the entire study area with a height of 5m. • The severity of the blast was based on a blast strength of 4 (i.e. TNO multi energy curve number 4). • Unconfined explosions were modelled using a blast strength of 2 and an explosion efficiency of 100%. • Only overpressure effects are included. Projectiles and whole-body displacement are not included.
Justification and Impacts of Assumptions: • 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, congested area was included as a conservative approach. • The blast strength is estimated based on the obstructed volume (%) and potential obstructions in each congested area. A medium obstructed volume (60% for a residential building) and level of congestion is assumed to simulate entry of the gas or vapour into the building and the subsequent confined explosion. This equates to TNO Model curve number 4. • 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.
Hazardous Scenarios Affected: • All hazardous scenarios with a VCE as a potential outcome.
References: • Centre for Chemical Process Safety, Estimating the flammable mass of vapour clouds”, American Institute of Chemical Engineers, 1999. • TNO, Methods for the Calculation of Physical Effects, ‘Yellow Book’, CPR 14E, 3rd Edition, VROM PGS 2, 2005. • SAFETI software documentation.

A.4 Likelihood Analysis

Assumption No. 16: Likelihood of Release (Loss of Containment)
Subject: Likelihood Analysis
Assumptions: • The UK HSE pipeline failure rate data is the primary data used for the PHA.
Justification and Impacts of Assumptions: • 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 underground cross-country pipelines from the UK, USA and Europe were reviewed (Refer to Appendix D). The UK data incorporates the European data. There are two sources of data from the UK: (a) HSE recommended data for land use safety planning (RR 1035); and (b) British Standards Institute PD 8010-3:2009+A1:2013. The HSE data is primarily used in this study, which is consistent with the NSW performance data. • The UK HSE data identifies four contributors to underground pipeline failure: (a) mechanical failure; (b) corrosion; (c) ground movement/other; and (d) Third Party Activity (TPA).
Hazardous Scenarios Affected: • All.
References: • Refer to Appendix D. • UK Health and Safety Executive (HSE), 2019, Failure Rate and Event Data for use within Risk Assessments (02/02/19), Item FR 3.1.2 Above Ground Pipelines in a Gas Installation.

Assumption No. 17: Ignition Probability
Subject: Likelihood Analysis
Assumptions: • The probability of ignition for underground releases is based on the correlation of Acton and Baldwin as advised in the IOGP Risk Assessment Data Directory 434-06 "Ignition Probabilities", being $$P_{(ign)} = Min(0.0137 \times pd^2 + 0.0555, 1),$$ where p is the pipeline operating pressure (bar, gauge pressure) and d is the pipeline diameter (m). • For underground puncture releases (all causes), the same ignition probability relationship may be applied, with d equal to the release hole diameter and with the coefficient of the pd^2 value halved. $$P_{(ign)} = Min(0.00654 \times pd^2 + 0.0555, 1)$$ • For aboveground stations releases, the ignition probability was based on ignition data published by IOGP.
Justification and Impacts of Assumptions: • The estimated probability of ignition is a critical and significant input for the risk analysis. The risk results are directly proportional to this input. • Relevant ignition data for cross-country pipelines were reviewed (Refer to Appendix D.2).
Hazardous Scenarios Affected: • All.
References: • Refer to Appendix D.2. • International Association of Oil & Gas Producers, "Ignition Probabilities (Report 434-06)," 2019.

Assumption No. 18: Probability of VCE or Flash Fire
Subject: Likelihood Analysis
Assumptions: • The conditional probability of a flash fire only, given delayed ignition is 0.6. • The conditional probability of a VCE with a flash fire is 0.4.
Justification and Impacts of Assumptions: • Ignition of a vapour cloud may demonstrate characteristics of a flash fire and/or an explosion. SAFETI uses the delayed ignition probability in conjunction with the conditional probabilities.
Hazardous Scenarios Affected: • All scenarios with clouds in an obstructed region.
References: • SAFETI software documentation. • TNO, VROM, *Guidelines for Quantitative Risk Assessment*, 'Purple Book', CPR18E, 3rd Edition.

A.5 Risk Analysis Methodology

Assumption No. 19: Location and Segmentation of Pipelines
Subject: Risk Analysis Methodology
Assumptions: • Representative release events are modelled using the 'Long Pipeline' model in SAFETI, which distributes release events along the pipeline at appropriate intervals.
Justification and Impacts of Assumptions: • The 'Long Pipeline' model in SAFETI is used to estimate the time-dependent release from a long pipeline. The 'Long Pipeline' model includes inputs for use in the risk calculations, such as pipeline burial depth, leak frequency, etc. • The interval at which representative incidents are distributed along the pipeline is selected automatically by the 'Long Pipeline' model based on the incident consequence.
Hazardous Scenarios Affected: • All.
Reference/s: • SAFETI software documentation.

A.6 Vulnerability Parameters

Assumption No. 20: Exposure to Heat Radiation from a Fire (Indoor or Outdoor)
Subject: Vulnerability Parameters

Assumptions:

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

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

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

Table 24 Probability of Fatality for Exposure to Heat Radiation (Outdoor)

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

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

Table 25 Probability of Fatality Inside Buildings Exposed to Heat Radiation

Radiant Heat Flux (kW/m^2)	Probability of Fatality
≥35	1.0
<35	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/m2, and 1 at 35 kW/m2 or greater.

Assumption No. 20: Exposure to Heat Radiation from a Fire (Indoor or Outdoor)

Justification and Impacts of Assumptions:

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

Table 26 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).

Hazardous Scenarios Affected:

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

Assumption No. 20: Exposure to Heat Radiation from a Fire (Indoor or Outdoor)

References:

- TNO, Methods for the Determination of Possible Damage, 'Green Book', CPR 16E, 1st Edition, VROM, 1992.
- RIVM, Guidelines for Quantitative Risk Assessment, 'Purple Book', CPR 18E, 3rd Edition, VROM PGS 3, 2005.

Assumption No. 21: Exposure to Flash Fire (Indoor or Outdoor)

Subject: Vulnerability Parameters

Assumptions:

- 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 Impacts of Assumptions:

- 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.

Hazardous Scenarios Affected:

- All scenarios with a flash fire as a potential outcome.

References:

- SAFETI software documentation.
- RIVM, Guidelines for Quantitative Risk Assessment, 'Purple Book', CPR 18E, 3rd Edition, VROM PGS 3, 2005.

Assumption No. 22: Exposure to Explosion Overpressure (Indoor or Outdoor)

Subject: Vulnerability Parameters

Assumptions:

The probability of fatality from exposure to the peak side-on overpressure from an explosion is as shown in Table 27 (person located outdoors) and Table 28 (person located indoors).

Table 27 Probability of Fatality from Exposure to Peak Side on-Overpressure (Outdoor)

Overpressure (kPa)	Probability of Fatality	Source
21	0	HIPAP No. 4

Assumption No. 22: Exposure to Explosion Overpressure (Indoor or Outdoor)

35	0.15	HIPAP No. 4
70	1	HIPAP No. 4

Table 28 Probability of Fatality from Exposure to Peak Side on-Overpressure (Indoor)

Overpressure (kPa)	Probability of Fatality	Source
21	0.2	HIPAP No. 4
35	0.5	HIPAP No. 4
70	1	HIPAP No. 4

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

Table 29 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.

Assumption No. 22: Exposure to Explosion Overpressure (Indoor or Outdoor)
Justification and Impacts of Assumptions: • 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 DPHI'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 DPHI'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".
Hazardous Scenarios Affected: • All incidents with a VCE as a potential outcome.
References: • NSW Department of Planning, Jan 2011, Hazardous Industry Planning Advisory Paper (HIPAP) No. 4, *Risk Criteria for Land Use Safety Planning*. • SAFETI software documentation. • International Association of Oil & Gas Producers (IOGP), 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 Results

B.1 Discharge Results

The discharge results for each representative release scenario are presented in Table 30.

Table 30 Discharge Results

Section	Scenario	Representative Release Rate (kg/s)	Temperature (°C)	Liquid Mass Fraction	Velocity (m/s)	Release Duration (s)
Underground	RDS 1_10 mm (Top)	0.9	-125	0	57.6	3600
	RDS 1_10 mm (Mid)	0.9	-125	0	44.7	3600
	RDS 1_25 mm (Top)	5.6	-125	0	162	3600
	RDS 1_25 mm (Mid)	5.6	-125	0	44.7	3600
	RDS 1_75 mm (Top)	50.6	-125	0	373	3600
	RDS 1_75 mm (Mid)	50.6	-125	0	103	3600
	RDS 1_110 mm (Top)	171	-114	0	425	3600
	RDS 1_110 mm (Mid)	171	-114	0	194	3600
	RDS 1_694.4 mm (FBR)	2790	-96.5	0	132	3600
Pig Launcher Station	10 mm	0.9	-125	0	663	3600
	25 mm	5.6	-125	0	663	3600
	75 mm	50.6	-125	0	663	3600
	110 mm	171	-114	0	708	3600
	694.4 mm (FBR)	2790	-95	0	733	3600
Tie-In Station	10 mm	0.9	-125	0	663	3600
	25 mm	5.6	-125	0	663	3600
	75 mm	50.6	-125	0	663	3600
	110 mm	171	-114	0	708	3600
	694.4 mm (FBR)	2780	-94.9	0	733	3600

B.2 Flash Fire Results

The extent of flammable cloud dispersions for each representative release scenario are presented in Table 31.

Table 31 Flash Fire Results

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
Underground	RDS 1_10 mm (Top)	1.9B (Day)	0.208	0.311	0.565	1.16	4.8
		8.2D (Day)	0.263	0.404	0.646	1.33	2.6
		4.2D (Day)	0.223	0.333	0.587	1.32	3.67
		1.3D (Day)	0.201	0.298	0.55	1.16	6.18
		8D (Night)	0.261	0.4	0.64	1.32	2.61
		3.9D (Night)	0.22	0.329	0.582	1.32	3.76
		1D (Night)	0.198	0.294	0.545	1.12	6.77
		3.1E (Night)	0.214	0.306	0.567	1.27	4.26
		1F (Night)	0.2	0.275	0.541	1.06	6.87
	RDS 1_10 mm (Mid)	1.9B (Day)	0.229	0.339	0.615	1.33	4.72
		8.2D (Day)	0.304	0.463	0.72	1.47	2.47
		4.2D (Day)	0.249	0.367	0.643	1.43	3.53
		1.3D (Day)	0.22	0.322	0.596	1.3	6.11
		8D (Night)	0.301	0.457	0.714	1.46	2.48
		3.9D (Night)	0.245	0.362	0.636	1.42	3.6
		1D (Night)	0.217	0.317	0.59	1.26	6.71
		3.1E (Night)	0.237	0.334	0.619	1.44	4.14
		1F (Night)	0.218	0.296	0.585	1.21	7
	RDS 1_25 mm (Top)	1.9B (Day)	0.259	0.352	0.656	1.97	11.3
		8.2D (Day)	0.274	0.37	0.679	2.47	6.31
		4.2D (Day)	0.263	0.355	0.664	2.28	8.55

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
		1.3D (Day)	0.256	0.346	0.652	1.92	13.7
		8D (Night)	0.273	0.368	0.676	2.43	6.33
		3.9D (Night)	0.262	0.354	0.66	2.24	8.98
		1D (Night)	0.255	0.344	0.648	1.83	14.6
		3.1E (Night)	0.257	0.335	0.656	2.14	9.85
		1F (Night)	0.249	0.318	0.645	1.64	14.1
	RDS 1_25 mm (Mid)	1.9B (Day)	0.428	0.601	1.14	3.5	10.7
		8.2D (Day)	0.477	0.671	1.23	4.49	5.57
		4.2D (Day)	0.441	0.614	1.17	4.3	7.98
		1.3D (Day)	0.419	0.581	1.12	3.67	14.3
		8D (Night)	0.473	0.665	1.22	4.44	5.6
		3.9D (Night)	0.437	0.609	1.16	4.22	8.41
		1D (Night)	0.415	0.576	1.11	3.5	16
		3.1E (Night)	0.426	0.572	1.14	3.95	9.14
		1F (Night)	0.408	0.533	1.1	2.9	15.2
	RDS 1_75 mm (Top)	1.9B (Day)	0.388	0.497	0.929	4.49	30.7
		8.2D (Day)	0.397	0.505	0.943	6.2	17.7
		4.2D (Day)	0.39	0.496	0.934	5.67	24.1
		1.3D (Day)	0.385	0.49	0.93	4.61	35.9
		8D (Night)	0.397	0.504	0.946	6.12	17.7
		3.9D (Night)	0.389	0.495	0.932	5.55	24.8
		1D (Night)	0.384	0.489	0.927	4.39	38.6
		3.1E (Night)	0.377	0.468	0.93	5.1	26.6
		1F (Night)	0.366	0.445	0.93	3.7	35.4
	RDS 1_75 mm (Mid)	1.9B (Day)	0.713	0.964	1.85	7.28	30.4
		8.2D (Day)	0.727	1.03	1.89	10.9	16.5

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
		4.2D (Day)	0.713	0.953	1.85	9.51	23
		1.3D (Day)	0.704	0.939	1.84	7.66	38.2
		8D (Night)	0.723	0.967	1.88	10.8	16.5
		3.9D (Night)	0.71	0.949	1.85	9.32	23.4
		1D (Night)	0.701	0.934	1.83	7.26	42.6
		3.1E (Night)	0.694	0.9	1.84	8.53	25.1
		1F (Night)	0.68	1.18	1.82	6.14	37.9
	RDS 1_110 mm (Top)	1.9B (Day)	0.585	0.745	1.42	7.94	53.3
		8.2D (Day)	0.59	0.745	1.43	11.6	30.7
		4.2D (Day)	0.584	0.737	1.41	10.3	42
		1.3D (Day)	0.579	0.732	1.41	8.33	62.7
		8D (Night)	0.59	0.745	1.43	11.4	30.8
		3.9D (Night)	0.583	0.737	1.43	10.2	42.4
		1D (Night)	0.579	0.732	1.42	7.91	67.4
		3.1E (Night)	0.565	0.696	1.43	9.33	45.1
		1F (Night)	0.549	0.665	1.41	6.86	57.7
	RDS 1_110 mm (Mid)	1.9B (Day)	0.882	1.19	2.22	10.4	54.1
		8.2D (Day)	0.883	1.19	2.24	16.1	29.6
		4.2D (Day)	0.875	1.18	2.22	13.9	40.6
		1.3D (Day)	0.87	1.17	2.22	11.1	66.5
		8D (Night)	0.879	1.19	2.22	15.8	29.7
		3.9D (Night)	0.873	1.18	2.22	13.6	41.5
		1D (Night)	0.867	1.17	2.21	10.4	70.7
		3.1E (Night)	0.851	1.19	2.21	12.4	43.6
		1F (Night)	0.834	1.34	2.21	9.14	61.6
	RDS 1_694.4 mm (FBR)	1.9B (Day)	4.52	6.27	11.8	48	189

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
		8.2D (Day)	4.36	5.85	11.8	100	105
		4.2D (Day)	4.37	5.86	11.8	78.6	149
		1.3D (Day)	4.37	5.87	11.8	55.3	249
		8D (Night)	4.34	5.82	11.7	97.1	106
		3.9D (Night)	4.36	5.85	11.8	75.1	149
		1D (Night)	4.36	5.86	11.8	51	276
		3.1E (Night)	4.25	5.77	11.8	71	150
		1F (Night)	4.15	5.95	11.8	53.7	192
Pig Launcher Station	10 mm	1.9B (Day)	1.95	5.87	0.556	5.88	1.01
		8.2D (Day)	1.84	4.77	0.532	4.77	1.01
		4.2D (Day)	1.91	5.44	0.547	5.45	1.01
		1.3D (Day)	1.97	6.18	0.559	6.2	1.01
		8D (Night)	1.82	4.74	0.529	4.75	1.01
		3.9D (Night)	1.9	5.46	0.546	5.47	1.01
		1D (Night)	1.96	6.24	0.558	6.26	1.01
		3.1E (Night)	1.94	5.59	0.544	5.59	1
		1F (Night)	2.04	5.97	0.534	5.97	0.994
	25 mm	1.9B (Day)	4.82	16.7	1.52	16.7	0.974
		8.2D (Day)	4.4	13.6	1.42	13.6	0.983
		4.2D (Day)	4.67	15.5	1.47	15.5	1.02
		1.3D (Day)	4.89	17.2	1.52	17.2	1.02
		8D (Night)	4.37	13.5	1.41	13.5	0.985
		3.9D (Night)	4.65	15.5	1.47	15.5	1.02
		1D (Night)	4.89	17.3	1.52	17.3	1.02
		3.1E (Night)	4.71	15.9	1.48	15.9	1.01
		1F (Night)	4.84	16.4	1.46	16.4	0.995

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
	75 mm	1.9B (Day)	16.1	87.5	7.99	87.6	0.914
		8.2D (Day)	14.8	89.7	6.62	89.8	0.972
		4.2D (Day)	15.5	83	7	83	1.01
		1.3D (Day)	16.1	77.3	7.26	77.3	1.39
		8D (Night)	14.6	87.1	6.6	87.7	1.08
		3.9D (Night)	15.4	80.1	6.96	80.3	1.35
		1D (Night)	16	75.7	7.25	75.8	1.51
		3.1E (Night)	15.8	77.3	7.08	77.4	1.37
		1F (Night)	16.3	68.2	6.82	68.3	1.38
	110 mm	1.9B (Day)	36.4	192	16.3	192	1.18
		8.2D (Day)	34.5	211	13.2	211	0.882
		4.2D (Day)	34.6	178	13.9	179	1.68
		1.3D (Day)	34.5	154	14.3	156	3.37
		8D (Night)	34	190	13	192	2.31
		3.9D (Night)	34.2	162	13.7	165	3.03
		1D (Night)	34.2	147	14.3	151	4.01
		3.1E (Night)	34.5	154	13.8	157	3.04
		1F (Night)	33.8	132	13.2	133	2.66
	694.4 mm (FBR)	1.9B (Day)	214	462	54.3	588	38.5
		8.2D (Day)	217	693	48.4	791	18.8
		4.2D (Day)	205	540	50.6	649	27.6
		1.3D (Day)	196	449	51.9	550	37.2
		8D (Night)	211	547	46.8	644	23.5
		3.9D (Night)	201	473	49.4	565	30.2
		1D (Night)	194	424	51.3	517	38.1
		3.1E (Night)	194	458	48.5	537	25.6

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
		1F (Night)	171	423	45.4	461	16.5
Tie-In Station	10 mm	1.9B (Day)	1.95	5.86	0.556	5.87	1.01
		8.2D (Day)	1.84	4.77	0.532	4.77	1.01
		4.2D (Day)	1.91	5.44	0.547	5.45	1.01
		1.3D (Day)	1.97	6.18	0.559	6.2	1.01
		8D (Night)	1.82	4.74	0.529	4.75	1.01
		3.9D (Night)	1.9	5.46	0.546	5.47	1.01
		1D (Night)	1.96	6.24	0.558	6.26	1.01
		3.1E (Night)	1.94	5.59	0.544	5.59	1
		1F (Night)	2.04	5.97	0.534	5.97	0.995
	25 mm	1.9B (Day)	4.82	16.6	1.52	16.6	0.975
		8.2D (Day)	4.4	13.6	1.42	13.6	0.984
		4.2D (Day)	4.66	15.5	1.47	15.5	1.02
		1.3D (Day)	4.88	17.2	1.52	17.2	1.02
		8D (Night)	4.36	13.4	1.41	13.5	0.985
		3.9D (Night)	4.65	15.5	1.47	15.5	1.02
		1D (Night)	4.88	17.2	1.51	17.2	1.02
		3.1E (Night)	4.71	15.9	1.48	15.9	1.01
		1F (Night)	4.84	16.4	1.45	16.4	0.995
	75 mm	1.9B (Day)	16.1	87.4	7.98	87.5	0.914
		8.2D (Day)	14.8	89.6	6.62	89.8	0.972
		4.2D (Day)	15.5	82.9	7	82.9	1.01
		1.3D (Day)	16	77.2	7.26	77.3	1.39
		8D (Night)	14.6	87.1	6.6	87.6	1.08
		3.9D (Night)	15.4	80	6.96	80.3	1.35
		1D (Night)	16	75.6	7.25	75.8	1.51

Section	Scenario	Weather	Distance to UFL at Height of Interest (m)	Distance to LFL at Height of Interest (m)	Width to LFL at Height of Interest (m)	Max Flash Fire Distance for All Heights (m)	Height at Max Flash Fire Distance for All Heights (m)
		3.1E (Night)	15.8	77.3	7.08	77.3	1.37
		1F (Night)	16.3	68.2	6.81	68.2	1.38
	110 mm	1.9B (Day)	36.5	192	16.3	193	1.18
		8.2D (Day)	34.6	211	13.2	211	0.883
		4.2D (Day)	34.7	179	13.9	180	1.68
		1.3D (Day)	34.6	154	14.4	158	3.37
		8D (Night)	34.1	191	13	192	2.13
		3.9D (Night)	34.3	162	13.7	166	3.03
		1D (Night)	34.3	147	14.3	151	4.02
		3.1E (Night)	34.6	154	13.9	157	3.04
		1F (Night)	33.9	132	13.2	133	2.67
	694.4 mm (FBR)	1.9B (Day)	214	461	54.2	586	38.4
		8.2D (Day)	216	691	48.3	789	18.7
		4.2D (Day)	204	538	50.5	646	27.5
		1.3D (Day)	196	448	51.8	549	37.1
		8D (Night)	211	546	46.7	642	23.4
		3.9D (Night)	201	472	49.3	564	30.1
		1D (Night)	193	423	51.2	516	37.9
		3.1E (Night)	193	457	48.4	536	25.6
		1F (Night)	170	422	45.3	460	16.5

B.3 Jet Fire Results

The downwind distances to radiated heat flux levels for each representative release scenario are presented in Table 32.

Table 32 Jet Fire Results

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
Underground	RDS 1_10 mm (Top)	1.9B (Day)	14.9	14.3	4.75	1.25	0.515
		8.2D (Day)	10.4	19.4	14.2	11.3	10.4
		4.2D (Day)	12	17.1	11.7	7.82	3.56
		1.3D (Day)	16.2	11.9	2.25	Not reached at height of interest	Not reached at height of interest
		8D (Night)	10.4	19.3	14.1	11.2	10.3
		3.9D (Night)	12.1	16.7	11.4	6.96	3.1
		1D (Night)	16.9	10.2	1.66	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	12.9	16.4	9.98	4.54	2.29
		1F (Night)	16.9	10.3	1.7	Not reached at height of interest	Not reached at height of interest
	RDS 1_10 mm (Mid)	1.9B (Day)	15.4	15.2	5.53	2.11	0.852
		8.2D (Day)	10.7	19.8	14.6	11.7	10.7
		4.2D (Day)	12.3	17.6	12.2	8.37	4.01
		1.3D (Day)	16.6	12.6	2.35	0.556	Not reached at height of interest
		8D (Night)	10.7	19.7	14.5	11.6	10.6
		3.9D (Night)	12.5	17.2	11.9	7.49	3.39
		1D (Night)	17.4	10.8	1.99	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	13.3	16.8	10.6	4.61	2.24
		1F (Night)	17.3	10.9	2	Not reached at height of interest	Not reached at height of interest

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
	RDS 1_25 mm (Top)	1.9B (Day)	28.6	27	6.46	Not reached at height of interest	Not reached at height of interest
		8.2D (Day)	19.9	37.2	24.1	19.2	15
		4.2D (Day)	22.9	32.9	18.4	8.34	2.57
		1.3D (Day)	30.9	23.1	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
		8D (Night)	19.8	37	23.9	19	14.6
		3.9D (Night)	23.2	32.7	17.6	7	2.3
		1D (Night)	32.3	20.6	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	24.7	31.5	14.3	3.92	Not reached at height of interest
		1F (Night)	32.2	20.8	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
	RDS 1_25 mm (Mid)	1.9B (Day)	33.1	35.2	13.3	3.69	1.11
		8.2D (Day)	23.1	44	29.6	24.2	21
		4.2D (Day)	26.5	39.3	26.2	16.4	7.35
		1.3D (Day)	35.8	30.3	6.91	0.533	Not reached at height of interest
		8D (Night)	23	44	29.5	24.1	20.8
		3.9D (Night)	26.9	39.2	25.6	14.8	6.37
		1D (Night)	37.4	26.9	5.76	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	28.6	38.7	23	10.1	4.54
		1F (Night)	37.3	27.1	5.85	Not reached at height of interest	Not reached at height of interest
	RDS 1_75 mm (Top)	1.9B (Day)	64.9	62.5	15.6	Not reached at height of interest	Not reached at height of interest
		8.2D (Day)	45.3	80.5	49.6	31.5	15.7

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
		4.2D (Day)	51.9	75.5	36.2	12.8	Not reached at height of interest
		1.3D (Day)	70.2	55.8	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
		8D (Night)	45	80.7	49.6	31.4	15.7
		3.9D (Night)	52.7	74.8	34.4	12	Not reached at height of interest
		1D (Night)	73.3	52.4	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	56.1	72.2	27.9	Not reached at height of interest	Not reached at height of interest
		1F (Night)	73.1	53	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
	RDS 1_75 mm (Mid)	1.9B (Day)	76.8	85.6	28.7	2.53	Not reached at height of interest
		8.2D (Day)	53.6	107	69.3	54.5	42.5
		4.2D (Day)	61.4	98.6	59.5	35.2	17.1
		1.3D (Day)	83.1	76.8	22	Not reached at height of interest	Not reached at height of interest
		8D (Night)	53.3	107	69.2	54.3	42.3
		3.9D (Night)	62.4	98.2	57.6	31.9	13
		1D (Night)	86.8	71.4	17.3	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	66.4	96.1	50.6	20.4	9.14
		1F (Night)	86.6	72.1	17.7	Not reached at height of interest	Not reached at height of interest
	RDS 1_110 mm (Top)	1.9B (Day)	107	109	31.9	Not reached at height of interest	Not reached at height of interest
		8.2D (Day)	75	138	83.1	51.5	23.8

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
		4.2D (Day)	86	129	62.4	25.5	Not reached at height of interest
		1.3D (Day)	116	99.6	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
		8D (Night)	74.6	138	83.2	51.7	24.1
		3.9D (Night)	87.3	128	59.9	23.2	Not reached at height of interest
		1D (Night)	121	94.7	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	92.9	124	51.4	13.7	Not reached at height of interest
		1F (Night)	121	95.7	Not reached at height of interest	Not reached at height of interest	Not reached at height of interest
	RDS 1_110 mm (Mid)	1.9B (Day)	120	135	48.7	Not reached at height of interest	Not reached at height of interest
		8.2D (Day)	83.4	164	106	77.3	54.7
		4.2D (Day)	95.7	156	86.1	42.4	19.7
		1.3D (Day)	129	124	36.3	Not reached at height of interest	Not reached at height of interest
		8D (Night)	83	164	106	77.1	54.4
		3.9D (Night)	97.1	155	83.5	38.1	17.9
		1D (Night)	135	118	28.7	Not reached at height of interest	Not reached at height of interest
		3.1E (Night)	103	151	73.3	30.3	Not reached at height of interest
		1F (Night)	135	119	29.9	Not reached at height of interest	Not reached at height of interest
	RDS 1_694.4 mm (FBR)	1.9B (Day)	404	552	259	130	57.9
		8.2D (Day)	282	571	376	276	203

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
		4.2D (Day)	323	608	365	235	143
		1.3D (Day)	437	522	227	98.1	Not reached at height of interest
		8D (Night)	280	572	376	276	203
		3.9D (Night)	328	607	359	225	130
		1D (Night)	456	506	211	68.2	Not reached at height of interest
		3.1E (Night)	349	599	336	187	108
		1F (Night)	456	511	214	72.8	Not reached at height of interest
Pig Launcher Station	10 mm	1.9B (Day)	10.9	14.2	12.5	11.7	11
		8.2D (Day)	10.9	13.4	12.1	11.5	10.9
		4.2D (Day)	10.9	13.9	12.4	11.6	11
		1.3D (Day)	10.8	14.2	12.5	11.7	10.9
		8D (Night)	10.8	13.3	12	11.4	10.9
		3.9D (Night)	10.8	13.9	12.3	11.6	10.9
		1D (Night)	10.8	14.2	12.5	11.7	10.9
		3.1E (Night)	10.8	13.9	12.4	11.6	10.9
		1F (Night)	10.8	14.2	12.5	11.6	10.9
	25 mm	1.9B (Day)	24.6	37.9	31.7	28.8	27
		8.2D (Day)	26.3	37.3	32.3	30	28.7
		4.2D (Day)	25.1	37.6	31.8	29.2	27.6
		1.3D (Day)	24.2	37.8	31.5	28.6	26.7
		8D (Night)	26	37.1	32.1	29.8	28.4
		3.9D (Night)	24.9	37.5	31.7	29.1	27.4
		1D (Night)	24.1	37.7	31.4	28.4	26.6
		3.1E (Night)	24.6	37.6	31.6	28.9	27.2

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
		1F (Night)	24	37.7	31.3	28.4	26.6
	75 mm	1.9B (Day)	63.6	114	90.1	79.4	72.4
		8.2D (Day)	70.4	113	93.9	85.5	80.4
		4.2D (Day)	65.8	113	91.5	81.6	75.4
		1.3D (Day)	62.6	113	89.5	78.6	71.4
		8D (Night)	69.6	113	93.5	84.9	79.9
		3.9D (Night)	65.2	113	91.2	81.2	74.9
		1D (Night)	62	113	89.3	78.3	70.6
		3.1E (Night)	64.1	114	90.7	80.4	73.9
		1F (Night)	61.9	114	89.4	78.3	70.8
	110 mm	1.9B (Day)	104	197	153	133	119
		8.2D (Day)	114	198	160	144	134
		4.2D (Day)	107	198	156	137	124
		1.3D (Day)	102	196	152	131	118
		8D (Night)	113	197	159	143	133
		3.9D (Night)	106	197	155	136	123
		1D (Night)	101	196	151	130	117
		3.1E (Night)	104	197	154	134	122
		1F (Night)	101	196	151	130	117
	694.4 mm (FBR)	1.9B (Day)	303	675	517	448	407
		8.2D (Day)	320	688	527	455	411
		4.2D (Day)	307	679	511	449	412
		1.3D (Day)	300	675	518	447	405
		8D (Night)	317	689	526	453	410
		3.9D (Night)	305	678	513	449	412
		1D (Night)	298	678	519	447	404

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
		3.1E (Night)	302	678	517	450	411
		1F (Night)	298	681	520	448	405
Tie-In Station	10 mm	1.9B (Day)	10.9	14.2	12.5	11.7	11
		8.2D (Day)	10.9	13.4	12.1	11.5	10.9
		4.2D (Day)	10.9	13.9	12.4	11.6	11
		1.3D (Day)	10.8	14.2	12.5	11.7	10.9
		8D (Night)	10.8	13.3	12	11.4	10.8
		3.9D (Night)	10.8	13.9	12.3	11.6	10.9
		1D (Night)	10.8	14.2	12.5	11.7	10.9
		3.1E (Night)	10.8	13.9	12.3	11.6	10.9
		1F (Night)	10.8	14.2	12.5	11.6	10.9
	25 mm	1.9B (Day)	24.6	37.9	31.6	28.8	27
		8.2D (Day)	26.3	37.3	32.3	30	28.7
		4.2D (Day)	25.1	37.6	31.8	29.2	27.6
		1.3D (Day)	24.2	37.8	31.4	28.6	26.7
		8D (Night)	26	37.1	32	29.8	28.4
		3.9D (Night)	24.9	37.5	31.6	28.6	26.4
		1D (Night)	24	37.7	31.3	28.4	26.6
		3.1E (Night)	24.6	37.6	31.6	28.8	27.1
		1F (Night)	24	37.7	31.3	28.4	26.5
	75 mm	1.9B (Day)	63.6	113	90.1	79.4	72.3
		8.2D (Day)	70.3	113	93.9	85.4	80.4
		4.2D (Day)	65.8	113	91.4	81.6	75.4
		1.3D (Day)	62.6	113	89.5	78.6	71.4
		8D (Night)	69.5	113	93.5	84.9	79.8
		3.9D (Night)	65.1	113	91.1	81.1	74.9

Section	Scenario	Weather	Flame Length (m)	Distance Downwind to 4.7 kW/m2 (m)	Distance Downwind to 12.6 kW/m2 (m)	Distance Downwind to 23 kW/m2 (m)	Distance Downwind to 35 kW/m2 (m)
		1D (Night)	62	113	89.2	78.2	70.6
		3.1E (Night)	64.1	114	90.7	80.4	73.9
		1F (Night)	61.9	114	89.3	78.3	70.7
	110 mm	1.9B (Day)	104	198	153	133	119
		8.2D (Day)	114	198	161	144	134
		4.2D (Day)	107	198	156	137	125
		1.3D (Day)	102	196	152	131	118
		8D (Night)	113	198	160	143	133
		3.9D (Night)	106	197	155	136	124
		1D (Night)	101	196	151	130	117
		3.1E (Night)	105	197	154	134	122
		1F (Night)	101	196	151	130	117
	694.4 mm (FBR)	1.9B (Day)	302	674	516	447	406
		8.2D (Day)	319	687	526	454	410
		4.2D (Day)	307	678	510	448	411
		1.3D (Day)	299	673	516	446	404
		8D (Night)	316	687	525	453	409
		3.9D (Night)	304	676	511	448	411
		1D (Night)	298	677	517	446	403
		3.1E (Night)	302	677	516	449	410
		1F (Night)	297	679	519	447	404

B.4 Explosion Overpressure Results

The worst case exploded mass, peak overpressure and distance to 7 kPa and 10 kPa overpressures are presented in Table 33.

Table 33 Worst Case Explosion Overpressure Results

Section	Scenario	Weather Period	Exploded Mass (kg)	Peak Overpressure (kPa)	Distance to 7 kPa Overpressure (m)	Distance to 10 kPa Overpressure (m)
Underground	10 mm (Top)	Day	0.1	10.1	4.5	3.0
		Night	0.1	10.1	4.3	3.0
	10 mm (Mid)	Day	0.2	10.1	5.0	3.3
		Night	0.2	10.1	5.0	3.4
	25 mm (Top)	Day	0.4	10.1	6.9	4.5
		Night	0.4	10.1	6.9	4.5
	25 mm (Mid)	Day	1.0	10.1	9.7	6.5
		Night	1.0	10.1	9.7	6.4
	75 mm (Top)	Day	1.6	10.1	10.4	6.7
		Night	1.6	10.1	10.5	6.7
	75 mm (Mid)	Day	2.9	10.1	12.8	8.2
		Night	3.2	10.1	13.2	8.4
	110 mm (Top)	Day	4.6	10.1	15.2	9.8
		Night	4.9	10.1	15.5	9.9
	110 mm (Mid)	Day	6.9	10.1	17.2	11.0
		Night	7.2	10.1	17.5	11.2
	694.4 mm (FBR)	Day	124.9	10.1	47.4	31.6
		Night	130.7	10.1	49.3	32.8
Pig Launcher Station	10 mm	Day	0.04	10.1	6.6	5.4
		Night	0.05	10.1	6.7	5.5
	25 mm	Day	0.9	10.1	17.3	14.2
		Night	0.9	10.1	17.3	14.3

Section	Scenario	Weather Period	Exploded Mass (kg)	Peak Overpressure (kPa)	Distance to 7 kPa Overpressure (m)	Distance to 10 kPa Overpressure (m)
	75 mm	Day	70.5	10.1	78.6	65.2
		Night	61.2	10.1	75.1	62.6
	110 mm	Day	464.9	10.1	162.1	137.9
		Night	384.7	10.1	153.5	129.9
	694.4 mm (FBR)	Day	6437.2	10.1	639.2	595.6
		Night	5187.2	10.1	530.7	489.8
Tie-In Station	10 mm	Day	0.04	10.1	6.6	5.4
		Night	0.05	10.1	6.6	5.4
	25 mm	Day	0.9	10.1	17.2	14.2
		Night	0.9	10.1	17.3	14.2
	75 mm	Day	70.4	10.1	78.4	65.0
		Night	61.1	10.1	75.0	62.5
	110 mm	Day	466.6	10.1	162.5	138.3
		Night	385.8	10.1	153.6	130.0
	694.4 mm (FBR)	Day	6383.7	10.1	637.3	593.7
		Night	5156.2	10.1	529.2	488.3

Appendix C Historical Accident Data

C.1 Aboveground 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.

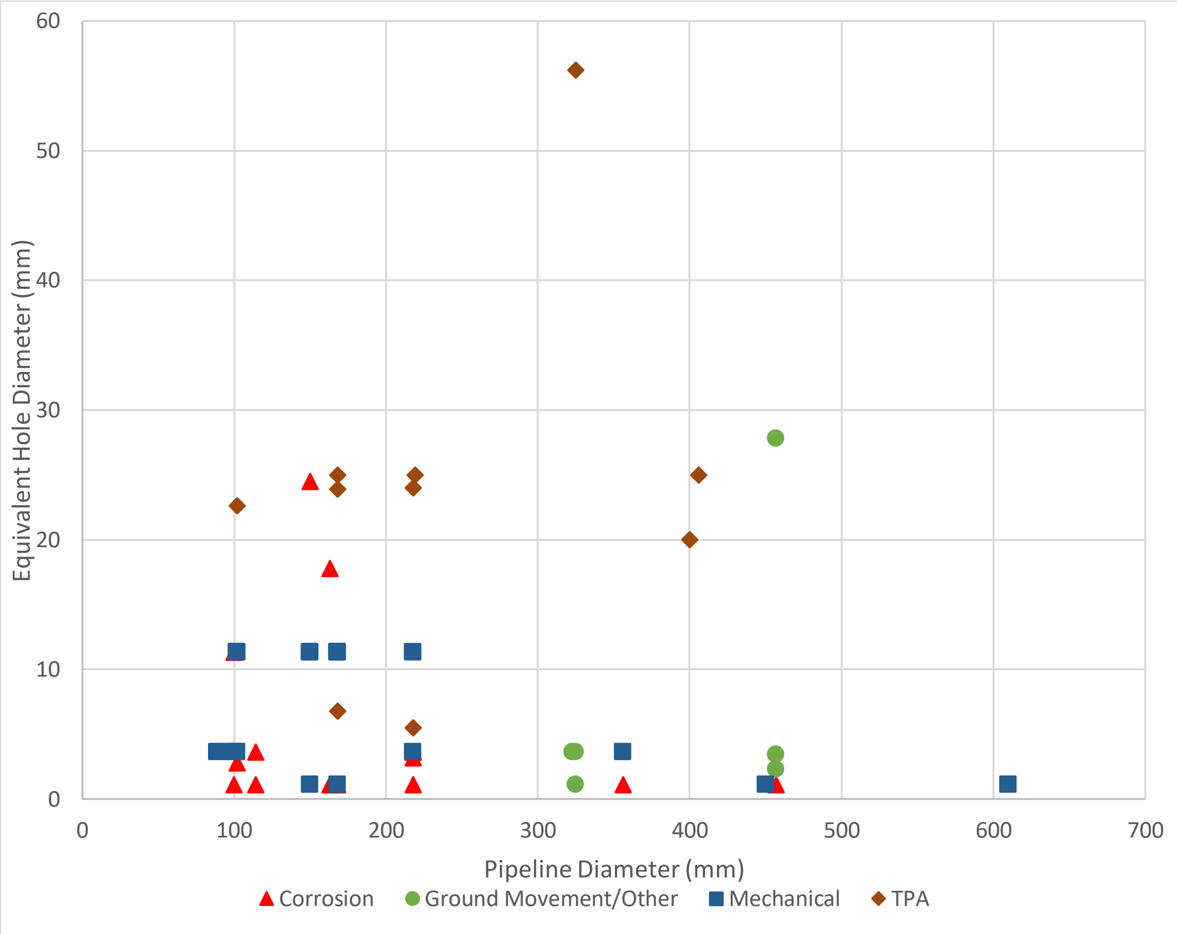
Failure reports in the UKOPA database include details such as the length and width of each failure. Table 34 presents incidents where the hole size was reported, as cited by the UK HSE in RR1035 [4]. This dataset is almost entirely composed of Natural Gas (NG) leaks, with only one incident involving another material (propylene).

Table 34 Dimensions of Leaks for Aboveground or Underground Cross-Country 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

Fault ID	Discovery Date	Product	Wall Thickness (mm)	Diameter (in)	Diameter (mm)	Equivalent Hole Diameter (mm)	Cause
363	1997	NG	Not recorded	5.9	150	1.1	Mechanical
1928	1990	NG	4.5	5.9	150	11.3	Mechanical
1973	1990	NG	4.5	5.9	150	11.3	Mechanical
2028	1990	NG	4.8	5.9	150	11.3	Mechanical
2078	1989	NG	5.6	5.9	150	11.3	Mechanical
1996	1993	NG	4.8	6.6	168	1.1	Mechanical
1875	1989	NG	5.2	6.6	168	11.3	Mechanical
1886	1990	NG	4.4	6.6	168	11.3	Mechanical
1887	1990	NG	4.4	6.6	168	11.3	Mechanical
1925	1989	NG	4.4	6.6	168	11.3	Mechanical
1926	1989	NG	4.4	6.6	168	11.3	Mechanical
1940	1990	NG	4.4	6.6	168	11.3	Mechanical
2069	1990	NG	6.4	8.6	218	3.6	Mechanical
1876	1989	NG	6.4	8.6	218	11.3	Mechanical
2055	1989	NG	6.4	8.6	218	11.3	Mechanical
1710	1989	NG	7.9	14	356	3.6	Mechanical
1842	1992	NG	9.5	17.7	450	1.1	Mechanical
1361	1994	NG	9.5	24	610	1.1	Mechanical
1117	1993	NG	12.7	36	914	160.1	Mechanical
1918	1990	NG	4.4	4	102	22.6	TPA
1987	1990	NG	4.8	6.6	168	23.9	TPA
2980	2009	NG	5.56	6.6	168	25	TPA
1645	1992	NG	7.1	8.6	218	5.5	TPA
366	1991	NG	4.8	8.6	218	24	TPA
2783	2006	NG	4.5	8.6	219	25	TPA
1560	1989	NG	6.4	12.8	325	56.2	TPA
1185	1998	NG	10.4	15.7	400	20	TPA
1193	1990	NG	9.5	16	406	25	TPA
3109	2009	Propylene	7.1	6.6	168	6.8	TPA

Figure 14 Equivalent Hole Diameter for Leaks from Above Ground or Underground Cross-Country Pipelines (UKOPA - Reported Values Only)



C.2 Underground Cross-Country Pipelines – Natural Gas

US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Reported Data for Underground Natural Gas Steel Pipelines (January 2010 to December 2024)

Hole dimensions are not consistently reported in the US DoT database. The following tables include all recorded incidents where hole size information was available. For these cases, the reported length and width were used to calculate the equivalent diameter of a circular opening with the same cross-sectional area.

Table 35 Dimensions of Rupture Events for Underground Natural Gas Steel Pipelines (US DoT - Reported Values Only)

Failure Mode	Pipeline Diameter (mm)	Wall Thickness (mm)	Rupture Length (m)	Rupture Width (m)	Approx. Rupture Area (m^2)	Equiv. Hole Diameter (mm)
Corrosion	114.3	3.2	0.61	0.10	0.05	161.6
Corrosion	219.075	4.8	0.20	0.81	0.13	309.8
Corrosion	219.075	4.8	0.20	0.20	0.03	203.2
Corrosion	762	10.3	30.81	2.39	57.78	1077.6
Corrosion	508	7.9	10.97	1.60	13.75	718.4
Ground Movement / Other	304.8	6.4	0.84	0.03	0.02	145.9
Ground Movement / Other	508	9.5	2.44	4.57	8.76	718.4
Ground Movement / Other	609.6	8.7	0.61	0.61	0.29	609.6
Ground Movement / Other	914.4	13.1	2.87	0.91	2.06	1293.2
Ground Movement / Other	304.8	7.9	0.30	0.09	0.02	166.9
Ground Movement / Other	254	9.3	0.25	0.25	0.05	254.0
Mechanical Failure	323.85	6.4	0.76	0.32	0.19	458.0
Mechanical Failure	323.85	5.6	5.94	0.91	4.27	458.0
Mechanical Failure	1066.8	12.3	3.09	0.04	0.09	343.3
Mechanical Failure	508	10.3	3.68	1.60	4.61	718.4

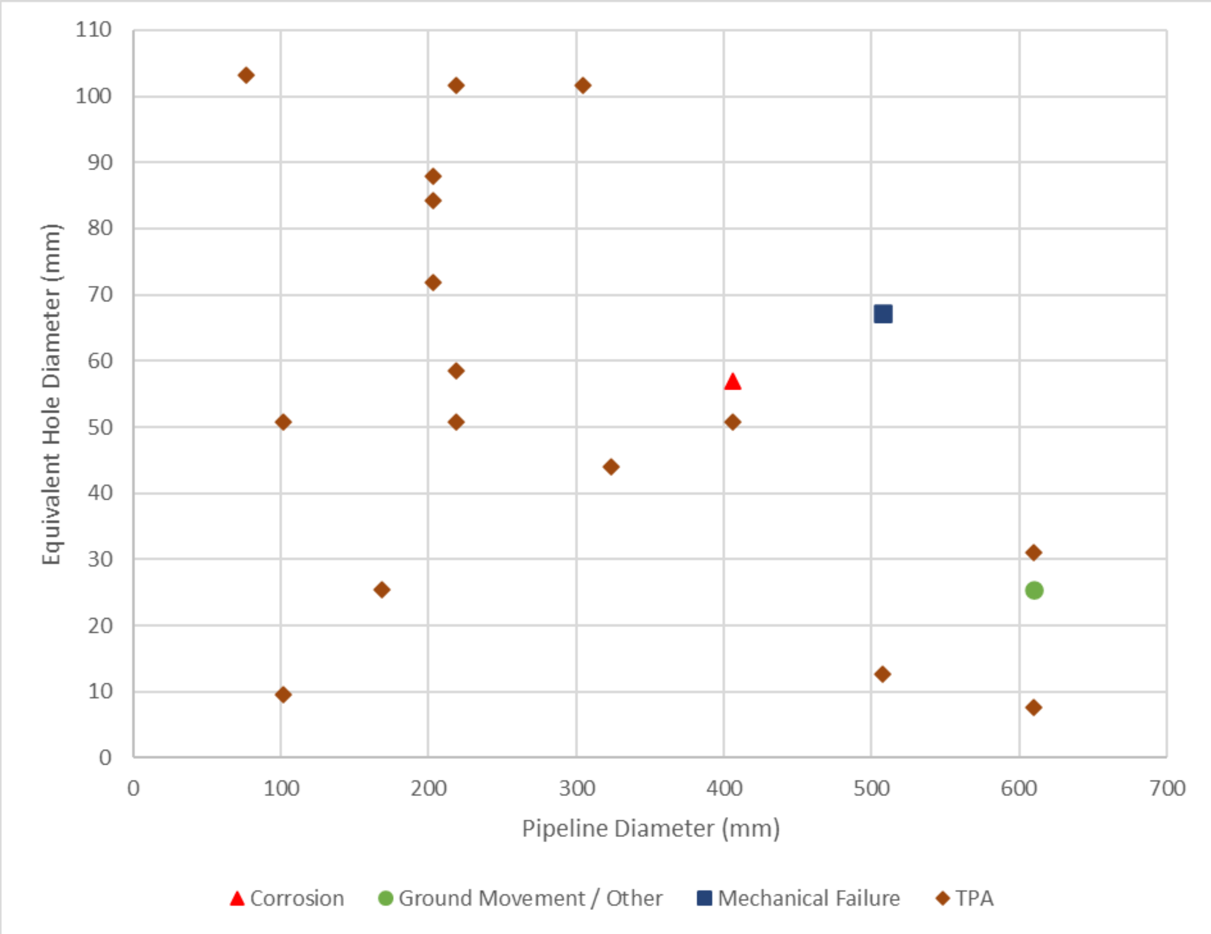
Failure Mode	Pipeline Diameter (mm)	Wall Thickness (mm)	Rupture Length (m)	Rupture Width (m)	Approx. Rupture Area (m²)	Equiv. Hole Diameter (mm)
Mechanical Failure	762	8.3	3.05	1.52	3.65	1077.6
Mechanical Failure	762	7.1	14.33	2.39	26.86	1077.6
Mechanical Failure	762	9.5	2.39	0.05	0.10	348.6
TPA	406.4	5.6	1.28	0.91	0.92	574.7
TPA	152.4	4.8	0.1	0.2	0.01	125.1
TPA	304.8	5.6	0.91	0.30	0.22	431.1
TPA	508	6.8	3.05	0.38	0.91	718.4
TPA	114.3	4.8	0.2	0.1	0.01	124.4
TPA	323.85	5.2	0.30	0.91	0.22	458.0
TPA	406.4	7.1	3.23	0.41	1.03	574.7

Table 36 Dimensions of Puncture Events for Underground Natural Gas Steel Pipelines (US DoT - Reported Values Only)

Failure Mode	Pipeline Diameter (mm)	Wall Thickness (mm)	Puncture Length (mm)	Puncture Width (mm)	Approx. Puncture Area (mm²)	Equiv. Hole Diameter (mm)
Corrosion	406.4	6.4	1277.6	2.5	2548.7	57.0
Ground Movement / Other	609.6	12.3	25.4	25.4	506.7	25.4
Mechanical Failure	508.0	6.5	355.6	12.7	3547.0	67.2
TPA	219.1	4.8	50.8	203.2	8107.3	101.6
TPA	219.1	4.8	50.8	50.8	2026.8	50.8
TPA	304.8	5.2	50.8	203.2	8107.3	101.6
TPA	508.0	6.0	12.7	12.7	126.7	12.7
TPA	323.9	5.6	25.4	76.2	1520.1	44.0
TPA	609.6	6.8	38.1	25.4	760.1	31.1

Failure Mode	Pipeline Diameter (mm)	Wall Thickness (mm)	Puncture Length (mm)	Puncture Width (mm)	Approx. Puncture Area (mm^2)	Equiv. Hole Diameter (mm)
TPA	76.2	4.0	38.1	279.4	8360.7	103.2
TPA	609.6	7.1	7.6	7.6	45.6	7.6
TPA	203.2	6.4	152.4	50.8	6080.5	88.0
TPA	203.2	4.8	50.8	101.6	4053.7	71.8
TPA	219.1	6.4	58.4	58.4	2680.5	58.4
TPA	406.4	5.6	50.8	50.8	2026.8	50.8
TPA	101.6	8.6	50.8	50.8	2026.8	50.8
TPA	101.6	4.0	5.1	17.8	70.9	9.5
TPA	203.2	4.8	279.4	25.4	5573.8	84.2
TPA	168.3	6.4	25.4	25.4	506.7	25.4

Figure 15 Equivalent Hole Diameter for Leaks from Underground Natural Gas Steel Pipelines (US DoT - Reported Values Only)



Appendix D Likelihood Analysis

D.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 Climate Change, Energy, the Environment and Water, New South Wales, Licensed Pipelines Performance Reports [14]. These reports includes data for all licensed pipelines in NSW covering a 5-year period;
- UK HSE, Health and Safety Laboratory, "Research Report RR1035 - Update of pipeline failure rates for land use planning assessments," HSE Books, London, 2015;
- British Standards Institute, 2013, Pipeline Systems – Part 3: Steel Pipelines on Land – Guide to the Application of Pipeline Risk Assessment to Proposed Developments in the Vicinity of Major Accident Hazard Pipelines Containing Flammables – Supplement to PD 8010-1:2004, PD 8010-3:2009+A1:2013;
- US Department of Transportation (DoT), Pipeline and Hazardous Materials Safety Administration (PHMSA), Accident Reports - Reported Data for Underground Natural Gas Steel Pipelines (January 2010 to December 2024) [15]; and
- Australia/New Zealand Pipeline Incident Database

A comparison of failure frequency databases was conducted by determining the total generic failure frequencies from each source, with the NSW Pipeline Performance Report serving as the baseline. However, it was not possible to calculate the generic failure frequency from the data reported in PD 8010 due to the absence of exposure data. A summary of the generic failure frequencies is provided Table 37 below.

Table 37 Generic Pipeline Failure Frequencies

Database	Failure Rate (per km per yr)					% Difference
	Pinhole (≤ 25 mm)	Small Hole (> 25 mm to ≤ 75 mm)	Large Hole (> 75 mm to ≤ 110 mm)	Rupture (> 110 mm)	Total Failure Frequency	
NSW	-	-	-	-	1.4E-04	Baseline
UK HSE	1.2E-04	4.9E-06	2.7E-07	2.6E-06	1.3E-04	-4%
US DoT	6.9E-06	1.5E-06	7.0E-07	3.9E-06	1.3E-05	-91%
PD 8010	9.9E-05	5.4E-05	3.0E-05	1.3E-04	3.1E-04	+128%
AS/NZ Pipeline Incident Database	-	-	-	-	3.0E-05	-78%

The leak frequency data reported in RR1035 (refer to Appendix D.1.2) was adopted for this analysis, as it is the most comparable to the NSW pipeline performance data. RR1035 includes leak frequencies categorized by four-hole sizes (pinhole, small hole, large hole, and rupture), four failure modes (mechanical failure, corrosion, ground movement/other, and third-party activity), and in some cases, by pipe diameter and/or wall thickness.

In contrast, the NSW performance data presents incident frequencies without categorizing them by failure mechanism, pipeline diameter, or wall thickness, which limits the potential for detailed analysis.

The leak frequency data from British Standards Institute PD 8010-3:2009+A1:2013 (refer to Appendix D.1.3) was not used, as the failure frequencies are not clearly defined for all failure modes. In the absence of historical failure data, the UK HSE adopts a probabilistic approach to estimate incident frequency, whereas PD 8010 does not provide any guidance on such an approach. Additionally, the rupture frequency due to third-party activity (TPA), estimated using the methodology in Annex B of PD 8010-3:2009+A1:2013, is inconsistent with data from the UK HSE and US DoT.

The leak frequency data derived from the US DoT data (Refer to Appendix D.1.4) was not used since the total leak frequency is lower than reported in RR1035 and the NSW performance data.

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).

D.1.1 NSW Performance Reports

The average leak frequency from the NSW Performance Reports for all licensed pipelines in NSW for the 12-year period from 2011-12 to 2022-23 is **1.4E-04 per km per year**. The loss of containment data presented in these reports are tabulated in Table 38.

Table 38 NSW Licenced Pipelines LOC Data

Year	LOC Events per 1,000 km
2011/12	0
2012/13	0.41
2013/14	0
2015/16	0
2016/17	0
2017/18	0.41
2018/19	0
2019/20	0.21
2020/21	0
2021/22	0
2022/23	0.62
Average	0.14

D.1.2 UK HSE (RR1035)

The leak frequency data reported in Section 7.1 of RR1035 for underground natural gas pipelines are presented in Table 39. Pipeline exposure data based on pipeline diameter and wall thickness obtained from RR1035 are presented in Table 40 and Table 41 respectively.

Utilizing the pipeline exposure data, the total generic pipeline failure frequency was determined to be **1.3E-04 per km per year** as presented in Table 42.

Table 39 Leak Frequencies for Underground Natural Gas Pipelines Reported in RR1035

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

Table 40 Pipeline Exposure by Diameter

Pipeline Diameter	Exposure (km.yr)
<115	19798
127 to 273	93913
>305	342909

Table 41 Pipeline Exposure by Wall Thickness

Wall Thickness	Exposure (km.yr)
< 5	25681
5 to 10	213527
>= 10	217413

Table 42 Generic Leak Frequencies for Underground Natural Gas Pipelines

Failure Mode	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	5.7E-05	1.0E-08	1.0E-08	1.0E-08	5.7E-05
Corrosion	3.3E-05	1.0E-08	1.0E-08	1.0E-08	3.3E-05
Ground Movement / Other	1.2E-05	2.5E-06	1.5E-07	2.5E-06	1.7E-05
TPA	2.2E-05	2.4E-06	1.0E-07	1.0E-07	2.5E-05
Total Leak Frequency	1.2E-04	4.9E-06	2.7E-07	2.6E-06	**1.3E-04**
%	94.1%	3.7%	0.2%	2.0%	100%

D.1.3 British Standards Institute (PD 8010-3:2009+A1:2013)

The data and approach included in Annex B of PD 8010-3:2009+A1:2013 was used to estimate the leak frequencies for the pipelines (Refer to Table 43). It was not possible to estimate a generic average failure frequency in the absence of pipeline exposure data. This data is applicable for a pipeline with a wall thickness of 8.5 mm.

The rupture frequency due to 'TPA' was derived from the generic pipeline failure frequency. For leaks (other than ruptures) due to 'Ground Movement / Other' or 'TPA', 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).

Table 43 Leak Frequencies for Hunter Lateral Pipeline based on PD 8010

Failure Mode	Approx. Leak Frequency (per km per yr)					Comments (Refer to Annex B of PD 8010-3:2009+A1:2013)
	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	4.0E-05	1.6E-05	0.0E+00	0.0E+00	5.6E-05	Only the pinhole leak frequency was reported.
Corrosion	3.2E-05	1.1E-05	3.0E-06	0.0E+00	4.6E-05	No data reported for internal corrosion. These frequencies represent external corrosion.
Ground Movement / Other	1.9E-06	1.9E-06	1.9E-06	6.5E-07	6.2E-06	Based on average incident rate (0.02 per 1000 km.yr) and survival values of 0.032 (Rupture) and 0.28 (Leaks).
TPA	2.5E-05	2.5E-05	2.5E-05	1.3E-04	2.1E-04	Proportion of ruptures = 0.63
Total Leak Freq. =	9.9E-05	5.4E-05	3.0E-05	1.3E-04	**3.1E-04**	
% =	32%	17%	10%	41%	100%	

D.1.4 US Department of Transportation (DoT)

The Pipeline and Hazardous Materials Safety Administration (PHMSA) Accident Reports contain data on incidents involving various pipelines. To enable comparison with UK data, the subset of incidents involving underground natural gas transmission pipelines was analysed. Leaks were categorised using the same failure modes and representative hole sizes as defined in UK sources (i.e., RR1035 and PD8010).

Incidents involving pipes or valves manufactured prior to 1970 were excluded from the analysis. Pipeline safety has improved significantly since the 1970 and inclusion of these events lead to incorrect conclusions regarding the failure frequency. All leaks with no reported hole size were allocated to the 'Pinhole' category. These are typically described as cracks or pinholes and may include leaks from smaller fittings. The results are summarised in Table 44.

Period of Recorded Incident Data =	15	yrs	(Jan 2010 to Dec 2024)
Total Length of Natural Gas Pipelines =	7127667	km.yrs	(Jan 2010 to Dec 2024)

Table 44 Leak Frequencies for Underground Natural Gas Transmission Pipelines

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	2.5E-06	1.4E-07	0.0E+00	1.1E-06	3.8E-06
Corrosion	1.3E-06	1.4E-07	0.0E+00	7.0E-07	2.1E-06
Ground Movement / Other	1.8E-06	1.4E-07	0.0E+00	9.8E-07	2.9E-06
TPA	1.3E-06	1.1E-06	7.0E-07	1.1E-06	4.2E-06
Total Leak Frequency	6.9E-06	1.5E-06	7.0E-07	3.9E-06	**1.3E-05**
%	52.7%	11.8%	5.4%	30.1%	100%

D.1.5 Australia/New Zealand Pipeline Incident Database

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

- Total km of pipelines within a given interval (refer to Table 45); and
- Total number of leaks and ruptures in the period 2000 to 2018. A total of 17 are reported in the database.

Table 45 Australian Pipeline Population by Half Decade

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

The expected total release frequency is:

$$f = \frac{N}{km.y} = \frac{17}{568,000} = 3 \times 10^{-5}\ \mathrm{km^{-1}y^{-1}}$$

D.2 Ignition Probability

A review of relevant ignition probability data and ignition probability correlations was conducted using the following sources:

- United Kingdom Pipeline Operators Association (UKOPA), UKOPA Pipeline Product Loss Incidents and Faults Report (1962-2014), 2015;
- UK Health and Safety Executive (HSE), Review of the Event Tree Structure and Ignition Probabilities used in HSE's Pipeline Risk Assessment Code MISHAP, Research Report (RR) 1034, 2015;
- European Gas Pipeline Incident Data Group, Gas Pipeline Incidents, 9th Report of the European Gas Pipeline Incident Data Group (Period 1970 – 2013), 2015;
- International Association of Oil & Gas Producers, Ignition Probabilities (Report 434-06), 2019; and
- Acton, M.R., Acton, O.J. and Robinson. C., A Review of Natural Gas Transmission Pipeline Incidents to Derive Ignition Probabilities for Risk Assessment, Hazards 26.

For this analysis:

- The total ignition probability was based on the Acton & Baldwin correlation (Refer to Appendix D.2.2).
    a. The Acton & Baldwin correlation is recommended by the IOGP.
    b. The data in UK HSE's RR 1034 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).
    c. The total ignition probability for rupture scenarios reported in the UKOPA database is lower compared to the correlation.
    d. The correlation probabilities are comparable to the EGIG data.
- The total ignition probability was split 50:50 for immediate ignition and delayed ignition.

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.

D.2.1 Ignition Probability Data for Above Ground or Underground Cross-Country Pipelines – Various Materials

United Kingdom Pipeline Operators Association (UKOPA), UKOPA Pipeline Product Loss Incidents and Faults Report (1962-2014), 2015)

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. Hence, this data is not exclusive to underground natural gas pipelines.

The number of Incidents reported in the UKOPA database are presented in Table 46. There were 9 out of 192 (4.7%) product loss incidents that resulted in ignition.

Table 46 Ignition Probability - UKOPA

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

International Association of Oil & Gas Producers, Ignition Probabilities (Report 434-06), 2019 - Scenario 3: Gas or LPG Release from Onshore Pipeline in an Industrial or Urban Area)

The ignition data presented for Scenario 3 in the IOGP directory is applicable for releases of flammable gases (other than buried natural gas pipelines), vapours or liquids significantly above their normal (Normal Atmospheric Pressure (NAP)) boiling point from onshore cross-country pipelines running through industrial or urban areas.

For buried natural gas pipelines, IOGP recommends using the Acton & Baldwin correlation described in Appendix D.2.2.

D.2.2 Ignition Probability Data for Underground Cross-Country Pipelines – Natural Gas

Acton, M.R., Acton, O.J. and Robinson. C., A Review of Natural Gas Transmission Pipeline Incidents to Derive Ignition Probabilities for Risk Assessment, Hazards 26

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:

$$P_{ign} = 0.0555 + 0.0137pd^2, 0 \leq pd^2 \leq 69$$

$$P_{ign} = 1\ , pd^2 > 69$$

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 by PIPESAFE group between 1970 and 2004; and
- PMSHA incident 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 coefficient of the pd^2 value halved. This reflects the difference between the two sources contributing to the gas release following a rupture and the single source contributing to a puncture release.

Table 47 Ignition Probability – Acton & Baldwin

Pipeline Diameter (mm)	Operating Pressure (bar)	Equivalent Hole Diameter (mm)	pd^2	Total Ignition Probability	Probability of Immediate Ignition	Probability of Delayed Ignition
195.2	100	10	0.01	0.056	0.0278	0.0278
		25	0.06	0.056	0.0280	0.0280
		75	0.56	0.059	0.0297	0.0297
		110	1.21	0.064	0.0319	0.0319
		FBR	3.81	0.108	0.0539	0.0539

European Gas Pipeline Incident Data Group, Gas Pipeline Incidents, 9th Report of the European Gas Pipeline Incident Data Group (Period 1970 – 2013), 2015

Although the pipeline definition does not exclude 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 48 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 Health and Safety Executive (HSE), Review of the Event Tree Structure and Ignition Probabilities used in HSE's Pipeline Risk Assessment Code MISHAP, Research Report (RR) 1034, 2015 - 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 RR 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 49 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 50 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

D.2.3 Ignition Probability Data for Underground Cross-Country Pipelines – Gases Other Than Natural Gas

UK Health and Safety Executive (HSE), Review of the Event Tree Structure and Ignition Probabilities used in HSE's Pipeline Risk Assessment Code MISHAP, Research Report (RR) 1034, 2015 - Typical Event Tree Probabilities for Flammable Gas other than Natural Gas

The following data is proposed in RR 1034 for the UK HSE's computer program MISHAP to calculate the level of risk around Major Accident Hazard Pipelines (MAHPs), particularly in land use planning (LUP) assessments (Refer to Table 51). A MAHP may be above or below ground; however, the MISHAP model appears to be primarily for underground pipelines. The probabilities are not reported for varying hole sizes and appear to be only applicable for larger release events.

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

Table 51 Ignition Probability – UK HSE (RR 1034)

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

(1) For example: ethylene

(2) For example: butane, ethane and propane

(3) For example: ammonia, carbon monoxide