# Narwee Housing Investigation Area

## Ethane Pipeline Risk Assessment

For Georges River Council

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# Summary

This report is a Preliminary Hazard Analysis (PHA) to determine if proposed zoning changes in the suburb of Narwee can be accommodated while satisfying the NSW Department of Planning, Industry and Environment's risk criteria as described in HIPAP 10.

Arriscar Pty Limited (Arriscar) has been requested by Georges River Council (Council) to prepare a PHA for the Narwee Precinct Housing Investigation Area (HIA). The Narwee Precinct Housing Investigation Area is located within the Notification Zone of the Moomba to Sydney Ethane (MSE) Pipeline that runs through the northern portion of the Georges River Local Government Area.

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

Based on generic failure rates for natural gas and liquefied flammable gas pipelines in the literature, the most appropriate data was used for the risk assessment. The 'long pipeline model' in DNVGL's SAFETI 8.23 software was used. The resulting risk values were compared with the risk criteria in HIPAP No.10 [1].

The following results were obtained from the risk assessment:

- Both the $1.0 \times 10^{-6}$ and $0.5 \times 10^{-6}$ risk contours encroach the eastern side of the HIA site. This precludes lots on the north eastern part of the HIA bordering Bryant Street from residential intensification and some lots on Berrille Road from sensitive land uses such as schools, aged care and childcare centres.
- No events with the potential to cause acute toxic injury or irritation were identified for inclusion in the risk analysis (Also refer to Section 4.4.6); therefore the proposed rezoning complies with the relevant DPI&E risk criteria (Refer to Section 3.4.2).
- The cumulative risk of property damage and accident propagation (Overpressure exceeding 14 kPa) does not reach $50 \times 10^{-6}$ per annum. This criterion does not apply to the proposed residential rezoning (Refer to Section 3.4.3).
- The cumulative risk of property damage and accident propagation (Heat radiation exceeding 23 $kW/m^2$) does not reach $50 \times 10^{-6}$ per annum. This criterion does not apply to the proposed residential rezoning (Refer to Section 3.4.3).
- The cumulative risk of injury (Overpressure exceeding 7 kPa) does not reach $50 \times 10^{-6}$ per annum; therefore the proposed rezoning complies with the relevant DPI&E risk criteria (Refer to Section 3.4.2).
- The cumulative risk of injury (Heat radiation exceeding 4.7 $kW/m^2$) does not reach $50 \times 10^{-6}$ per annum; therefore the proposed rezoning complies with the relevant DPI&E risk criteria (Refer to Section 3.4.2).
- The only noticeable increase in societal risk is between N = 30 and N = 300. At these points, the FN curve remains within the ALARP region. Such an insignificant change to the societal risk should not preclude the Narwee HIA from further development.

**Conclusions and Recommendations**

Rezoning of the Narwee Precinct Housing Investigation Area as described is compatible with the NSW DPIE risk criteria providing the following two recommendations are incorporated into the rezoning:

*Recommendation 1: Remove lots 407 and 432 of DP752056 from the HIA planned rezoning to ensure the criteria for residential development area complied with.*

*Recommendation 2: Ensure sensitive use development such as aged care facilities, childcare centres or schools is not approved for lots 1 through to 7 of DP16824 in the northeast corner of the HIA.*

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# Notation

| Abbreviation | Description |
|---|---|
| APD | Australian Pipeline Database |
| APGA | Australian Pipeline and Gas Association |
| Arriscar | Arriscar Pty Limited |
| BoM | Bureau of Meteorology |
| CIA | Chemical Industries Association |
| Council | Georges River Council |
| DBYD | Dial Before You Dig |
| DoT | United States Department of Transport |
| DPIE | Department of Planning Industry and Environment |
| FBR | Full Bore Rupture |
| HAZID | Hazard Identification |
| HDD | Horizontal Directional Drilling |
| HIA | Narwee Precinct Housing Investigation Area |
| km | Kilometre |
| kPa | Kilo Pascals |
| $kW/m^2$ | kiloWatts per square metre |
| LEP | Local Environmental Plan |
| LFL | Lower Flammable Limit |
| LGA | Local Government Area |
| LSIR | Location Specific Individual Risk |
| m | Metre |
| m/s | Metres per second |
| MAE | Major Accident Event |
| MAOP | Maximum Allowable Operating Pressure |
| $mg/m^3$ | Milligrams per cubic metre |
| mm | millimetres |
| MPa | Mega Pascals |
| MSE | Moomba-Sydney Ethane pipeline |
| NSW | New South Wales |
| OGP | Oil and Gas Producers Association |
| p.a. | Per annum |

| Abbreviation | Description |
|---|---|
| QRA | Quantitative Risk Assessment |
| TPA | Third Party Activity |
| UK HSE | United Kingdom health and Safety Executive |
| VCE | Vapour Cloud Explosion |

# 1 INTRODUCTION

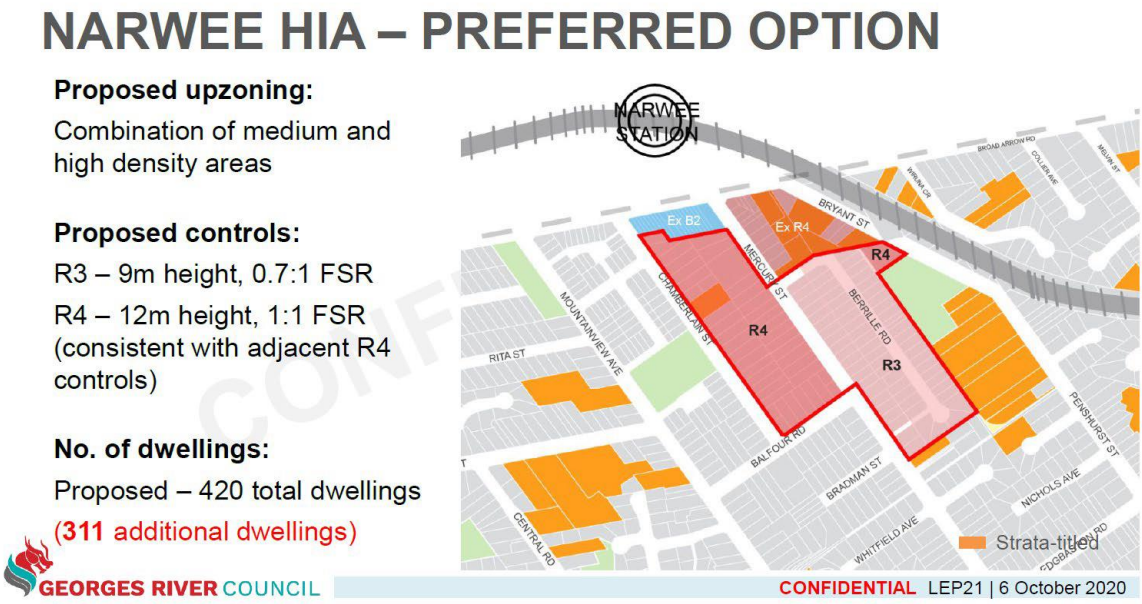
Arriscar Pty Limited (Arriscar) has been requested by Georges River Council (Council) to prepare a Hazard Analysis (Study) for the Narwee Precinct Housing Investigation Area (HIA). The Narwee Precinct Housing Investigation Area is located within the Notification Zone of the Moomba to Sydney Ethane (MSE) Pipeline that runs through the northern portion of the Georges River Local Government Area.

# 2 SITE DESCRIPTION

## 2.1 Narwee Precinct HIA

Council's Local Housing Strategy demonstrates that the local government area (LGA) will struggle to meet its 0-5 year target of 4,800 additional dwellings as specified by the South District Plan. The shortfall has been identified to be approximately 700 dwellings. Accordingly, additional housing capacity is required to be created in the LGA to address the known shortfall. The changes to zones and planning controls to create additional housing capacity will be incorporated into an amendment to the Georges River Local Environmental Plan (LEP) 2020. The area being investigated for the provision of additional housing is known as the Narwee Precinct Housing Investigation Area (HIA) (refer Figure 1 for location map). The HIA is located adjacent to the Narwee Local Centre. Council is proposing to change the zoning of the land within the HIA from R2 Low Density Residential to R3 Medium Density Residential and R4 – High Density Residential. The up zoning will increase the dwelling number from 109 to 420 in the study area.

**Figure 1 HIA Location and Description**




The average number of people per dwelling has been estimated as 2.8, based on the population projection for 2021[1]. Based on the additional 311 dwellings, this represents an increase in population of 871.

## 2.2 Ethane Pipeline

The Moomba Sydney Ethane pipeline (MSE) runs parallel to the T8 South Line railway. The location of the MSE in relation to the HIA is shown in Figure 2. The pipeline is owned by APA Group, which has been contacted by Arriscar for details of the MSE close to the HIA. Information obtained from APA is presented in Table 1.

[1] "Georges River Council 2019 NSW Population Projections", NSW Department of Planning, Industry and Environment.

**Figure 2 Location of the MSE in Relation to the HIA**

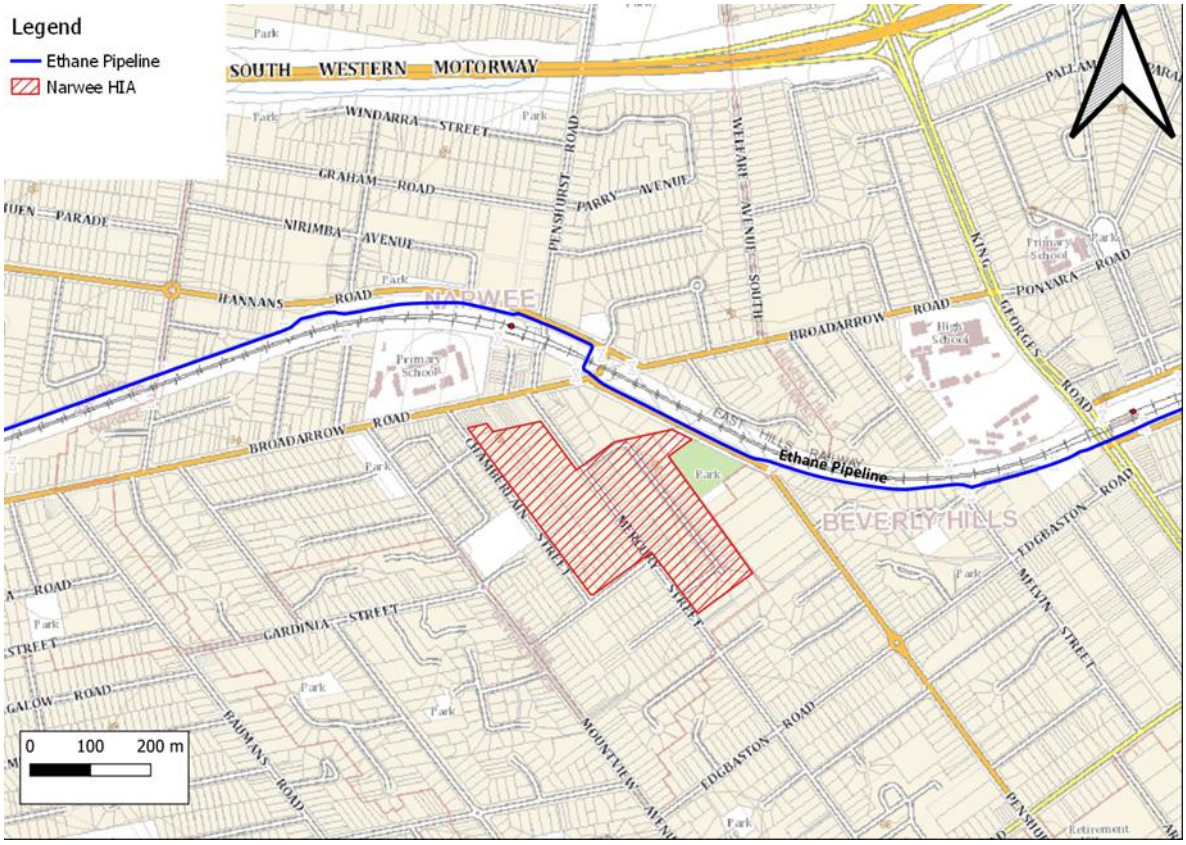



**Table 1 Data for the MSE Pipeline in Proximity to the HIA**

| Description | MSE Pipeline |
|---|---|
| Pipeline Owner | Gorodok Pty Ltd (part of APA Group) |
| Pipeline Name | Moomba to Sydney Ethane Pipeline |
| Product in pipeline | Ethane |
| Pipeline Licence (NSW) | New South Wales Licence No 15 |
| MAOP (Maximum allowable operating pressure) | 10,000kPa |
| Actual Operating Pressure | 8,200kPa |
| Operating Temperature | Typical 20°C |
| Material flow rate (pumping rate) | Typical 30 Tonne per hour |
| Pipeline Material | API -5L grade X60 |
| Pipeline Diameter | 200mm NB |
| Pipeline Wall Thickness | 11.9mm in area of concern |
| Design factor | |
| Critical defect length | 332mm |
| Minimum depth of cover | >1200mm – Varies between 1200 and 2500mm |
| Cathodic Protection for pipeline | Impressed Current Cathodic Protection applied. |
| External Coating on pipeline | HDPE (Yellowjacket) |

| Description | MSE Pipeline |
|---|---|
| | Joint Coating is 2 layer Tape Wrap system |
| Location of ALBVs from first ALBV upstream of HIA to first ALBV downstream of HIA | Upstream LV - Moorebank Ave kp1344<br>Downstream LV - Marsh Street kp1368 |
| Pressure set points for ALBVs and approximate closure time. | 4500kPa |
| Frequency of inspections and patrols undertaken | Ground Patrol Daily (Monday to Friday)<br>Aerial Patrol Fortnightly |
| Control measures for third party activity near pipeline | 11.9mm pipe wall thickness<br>>1.2m depth of cover<br>25mm Concrete Coating of pipeline (Rockjacket)<br>Either Top slabbing or top and side slabbing in all areas of concern apart from Rail Easements<br>Marker Posts<br>DBYD<br>Patrols Aerial patrol fortnightly.<br>Daily ground patrol<br>Liaison with Councils, telecommunications companies, Electricity companies, |
| Pigging done for pipeline? If so, how often? | Metal Loss intelligent pigging carried out on a risk basis program but is undertaken at 5 yearly presently. |
| Was intelligent pigging carried out to determine rate of loss of wall thickness? | Yes – no wall thickness loss has been found in this section of pipeline. |
| Location of nearest upstream pump / compressor station and pressure at this point. | Bulla Park |
| Are there non-return valves located in the pipeline downstream of and where? | Downstream NRV - Bexley Rd kp1363 |

## 2.3 Surrounding Suburbs and Populations

The suburbs surrounding the HIA and their populations as at the 2016 census are shown in Figure 3.

In addition to the population of surrounding suburbs, attention was placed on the daytime population of the following sensitive use locations:

- Narwee Public School
- Beverly Hills Girls High School and associated intensive English language centre.

The student population has been extracted from the 2019 reports from both schools respectively, while the staff population has been based on Australian Bureau of Statistics data for teacher/student ratios, and teaching staff as a percentage of all school staff.

**Figure 3 Surrounding Suburbs and Populations**

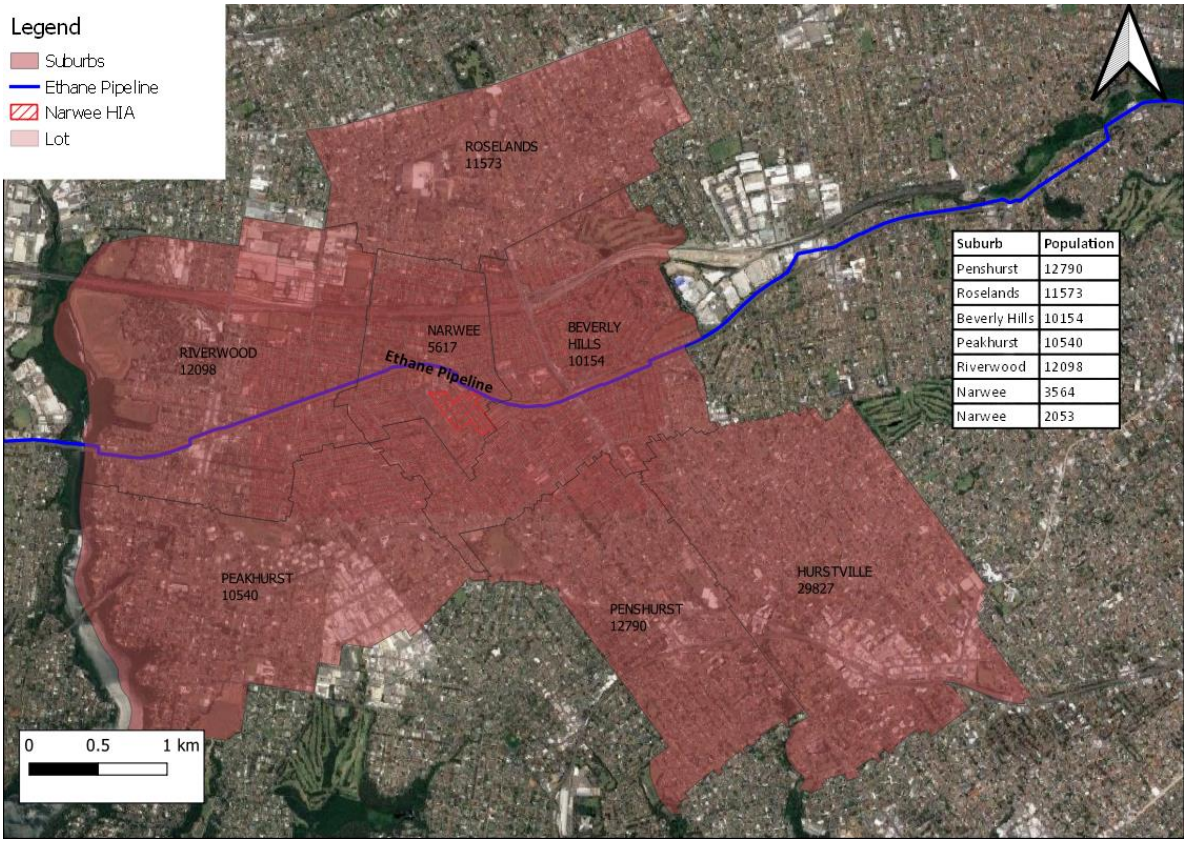



**Table 2 Nearby School Populations**

| School | Student Population | Staff[2] | Total |
|---|---|---|---|
| Narwee PS | 298[3] | 32 | 32 |
| BHGHS | 1160[4] | 124 | 124 |

[2] teachers made up 68.5% of in-school full-time equivalent staff, and the average student to teaching staff ratio for all schools was 13.7. (Australian Bureau of statistics, "Schools", https://www.abs.gov.au/statistics/people/education/schools/latest-release, accessed 15/12/2020.

[3] Narwee PS annual report

[4] Beverly Hills Girls High School annual report

# 3 RISK ASSESSMENT METHODOLOGY

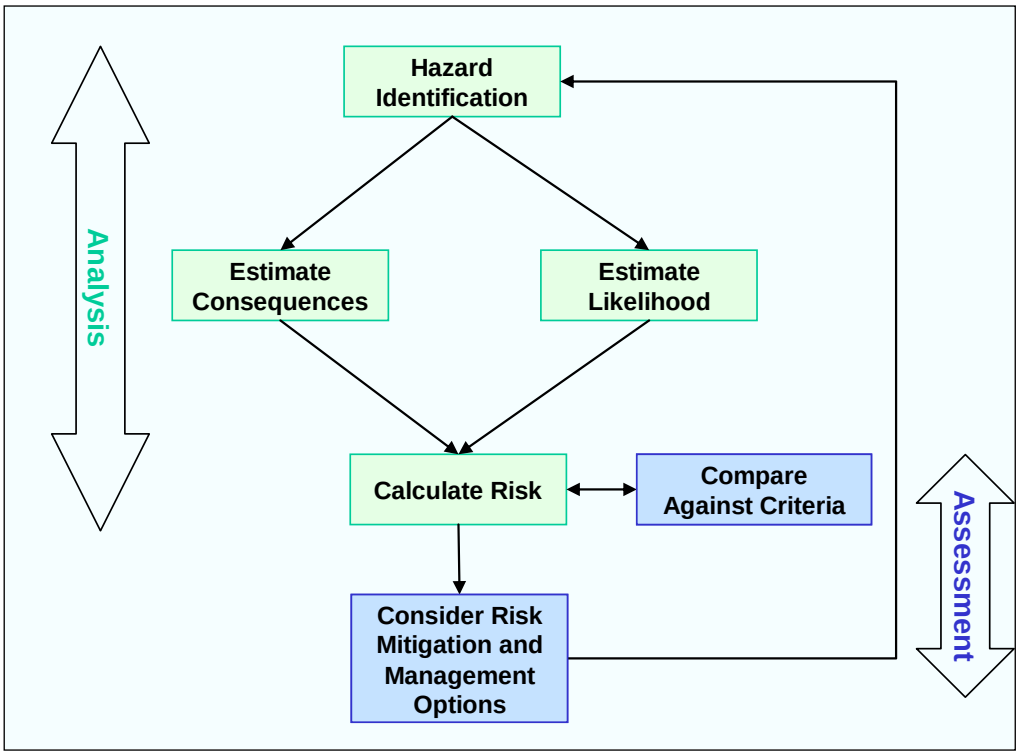
## 3.1 Introduction

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

In developing the estimates for use in a QRA, it is important to ensure that any estimates fall on the side of conservatism, particularly where there is uncertainty in the underlying data and assumptions. This precautionary approach uses 'cautious best estimate' values, which, whilst conservative, are still realistic. This approach is consistent with the DPI&E's guidelines for undertaking this type of assessment [2].

Diagrammatically, the QRA process is as follows:

**Figure 4 Overview of QRA Process [2]**




## 3.2 Methodology Overview

### 3.2.1 Hazard Identification and Register of Major Accident Events

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

For example, the Hazard identification (or HAZID) step for a QRA of a potentially hazardous pipeline would identify representative events that could result in a release of the material from the pipeline with the potential to cause harm (e.g. due to a subsequent ignition and fire/explosion). The representative potentially hazard events are commonly described as 'Major Accident Events' (or MAEs). In the context of the QRA, an MAE is an event with the potential to cause: off-site fatality

or injury; off-site property damage; or, long-term damage to the biophysical environment (i.e. any outcome for which DPI&E has defined an acceptable risk criterion – Refer to Section 3.4).

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

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

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

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

### 3.2.2 Hazard Consequence Analysis

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

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

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

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

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

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

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

### 3.2.3 Impairment Criteria

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

**Explosion**

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

The impact of explosion overpressure on humans takes two forms:

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

The effects of exposure to explosion overpressure are summarised in Table 3 [2].

**Table 3 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.<br>Minor injury from window breakage in building. |
| 7.0 | Glass fragments fly with enough force to cause injury.<br>Probability of injury is 10%. No fatality.<br>Damage to internal partitions and joinery of conventional buildings, but can be repaired. |
| 14.0 | 1% chance of ear drum rupture.<br>House uninhabitable and badly cracked. |
| 21.0 | 10% chance of ear drum rupture.<br>20% chance of fatality for a person within a conventional building.<br>Reinforced structures distort.<br>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.<br>House uninhabitable.<br>Heavy machinery damaged.<br>Significant damage to plant. |
| 70.0 | 100% chance of fatality for a person within a building or in the open.<br>100% loss of plant. |

**Fire**

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

The effects of exposure to thermal radiation are summarised in Table 4 [2]. The vulnerability criteria used in the risk analysis are included in Appendix A.6.

**Table 4 Effects of Thermal Radiation**

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

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

### 3.2.4 Frequency and Likelihood Analysis

Once the consequences of the various accident scenarios have been estimated, it is necessary to estimate the likelihood of each scenario. In a QRA, the likelihood must be estimated in quantitative terms (i.e. occurrences per year). Exponential notation (e.g. 5.0 x $10^{-6}$ per year or 5E-06 per year) is normally used because the likelihood of a MAE is usually a low number (i.e. less than 1 chance in 1000 to 10000 per year).

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

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

The frequency analysis data and results are summarised in Section 4.3 and Appendix C.

### 3.2.5 Risk Analysis and Assessment

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

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

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

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

The latest SAFETI 8.2.3 software package was used to generate the iso-risk contours / transects and societal risk results (Refer to Section 6).

## 3.3 Study Assumptions

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

To comply with the general principles outlined in Section 2.2 of HIPAP No. 6 [2], all steps taken in the risk analysis should be: "*traceable and the information gathered as part of the analysis should be well documented to permit an adequate technical review of the work to ensure reproducibility, understanding of the assumptions made and valid interpretation of the results*". Therefore, details of the key assumptions adopted for the risk analysis are provided in Appendix A.

## 3.4 Quantitative Risk Criteria

### 3.4.1 Individual Fatality Risk

The individual fatality risk imposed by a proposed (or existing) industrial activity should be low relative to the background risk. This forms the basis for the following individual fatality risk criteria adopted by the NSW DPI&E [1] and [3].

**Table 5 Individual Fatality Risk Criteria**

| Land Use | Risk Criterion [per million per year] |
|---|---|
| Hospitals, schools, childcare facilities and old age housing developments | 0.5 |
| Residential developments and places of continuous occupancy, such as hotels and tourist resorts | 1 |
| Commercial developments, including offices, retail centres, warehouses with showrooms, restaurants, and entertainment centres | 5 |
| Sporting complexes and active open space areas | 10 |
| Industrial sites | 50 * |

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

The DPI&E has adopted a fatality risk criterion of 1 x $10^{-6}$ per year (or 1 chance of fatality per million per year) for residential area exposure because this risk is very low in relation to typical background risks for individuals in NSW. For sensitive land uses such as schools, the criterion is one-half that for residential area, viz. 0.5 x $10^{-6}$ pe year.

### 3.4.2 Injury Risk

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

The DPI&E's suggested injury risk criterion for heat radiation is as follows:

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

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

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

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

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

### 3.4.3 Risk of Property Damage and Accident Propagation

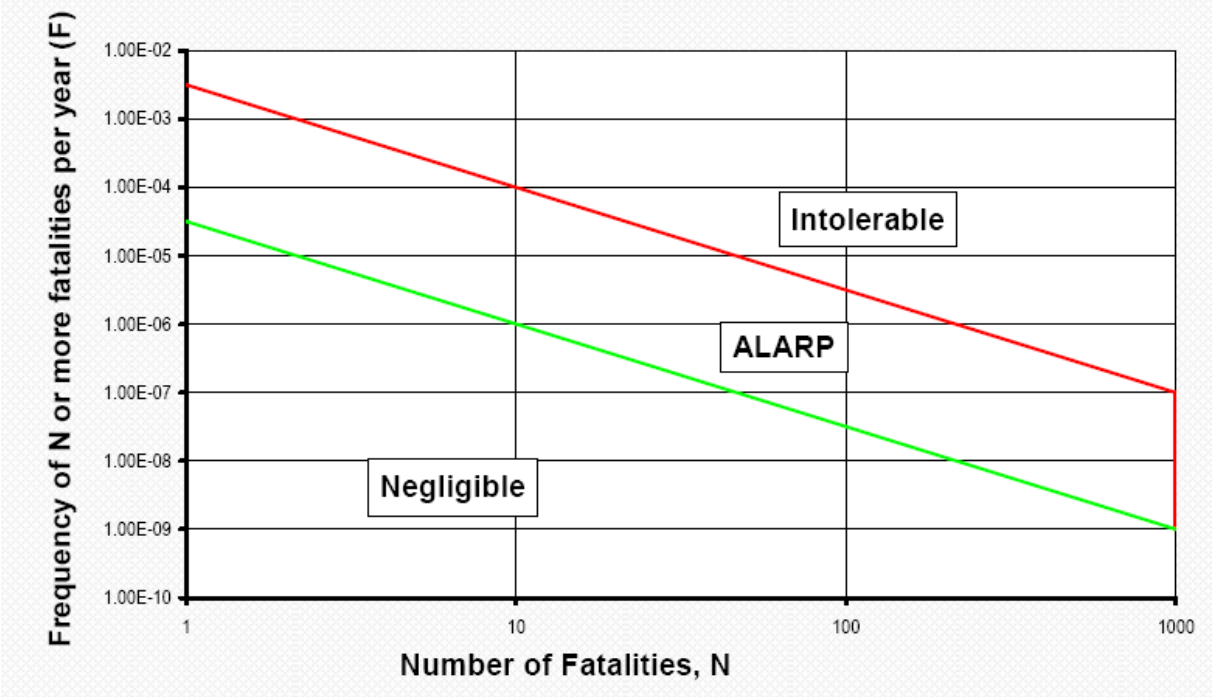
Heat radiation exceeding 23 kW/m$^2$ may cause unprotected steel to suffer thermal stress that may cause structural damage and an explosion overpressure of 14 kPa can cause damage to piping and low-pressure equipment. The DPI&E's criteria for risk of damage to property and accident propagation are as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

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

### 3.4.4 Societal Risk

The DPI&E's suggested societal risk criteria (Refer to Figure 5), recognise that society is particularly intolerant of accidents, which though infrequent, have a potential to create multiple fatalities. Below the negligible line, provided other individual criteria are met, societal risk is not considered significant. Above the intolerable level, an activity is considered undesirable, even if individual risk criteria are met. Within the 'As Low As Reasonably Practicable' (ALARP) region, the emphasis is on reducing risks as far as possible towards the negligible line. Provided other quantitative and qualitative criteria of HIPAP 4 [3] are met, the risks from the activity would be considered tolerable in the ALARP region.

**Figure 5 Indicative Societal Risk Criteria**




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

HIPAP No.4 [3] also states that the criteria in Figure 5 are an indicative criteria and provisional only and do not represent a firm requirement in NSW.

## 3.5 Qualitative Risk Criteria

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

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

# 4 HAZARD IDENTIFICATION

## 4.1 Introduction

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

Section 4.2 - Properties of Ethane.

Section 4.3 - Pipeline Failure Modes.

Section 4.4 - Consequences.

Section 4.5 - Control Measures.

The representative MAEs carried forward to the consequence analysis are listed in Section 4.6.

## 4.2 Properties of Ethane

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

Physical properties are listed in Table 6.

**Table 6 Physical Properties of Ethane**

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

Ethane is:

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

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

## 4.3 Pipeline Failure Modes

Pipelines may leak due to various causes. The four principal failure modes that may result in a leak from an underground pipeline include [4]:

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

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

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

### 4.3.1 Mechanical Failure

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

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

### 4.3.2 Corrosion

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

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

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

### 4.3.3 Ground Movement and Other Failure Modes

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

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

This failure mode is credible for the MSE.

### 4.3.4 Third Party Activity

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

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

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

This failure mode is credible for the MSE.

## 4.4 Consequences of Gas Release

### 4.4.1 Asphyxiation

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

Methane and Ethane are simple asphyxiants 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 [5]) there is a rapid onset of impairment of mental activity.

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

The potential for unconsciousness and fatality is only significant at less than 10% oxygen. However, to reduce the oxygen concentration to 10% requires a relatively high concentration (viz. approximately 52% v/v, which equates to 641,000 mg/m$^3$ for Ethane and 342,000 mg/m$^3$ for Methane).

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

### 4.4.2 Jet Fire

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

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

### 4.4.3 Flash Fire

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

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

### 4.4.4 Vapour Cloud Explosion

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

In the case of a gas release from the gas pipelines in the vicinity of the school, a gas cloud explosion is less likely than a flash fire due to the relatively open areas and absence of congestion surrounding the MSE.

### 4.4.5 Gas Ingress into Buildings

The gas jet would disperse downwind, once the momentum effect is lost. If the wind direction were oriented towards the school buildings, there is potential for flammable gas to be drawn into the buildings through ventilation air intake, and through open windows. If the gas reaches lower flammability limit, an ignition within the building would result in a confined explosion with serious harm to occupants and structural damage.

### 4.4.6 Toxic Smoke

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

## 4.5 Control Measures

Under the NSW Pipelines Act (1967) and Pipeline Regulations (2013), a pipeline operator must ensure the design, construction, operation and maintenance of a licensed pipeline is in accordance with the relevant provisions of Australian Standard AS 2885 [6] for gas and liquid petroleum pipelines.

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

### 4.5.1 Prevention of Mechanical Failure

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

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

### 4.5.2 Corrosion Prevention

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

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

The Moomba to Sydney Ethane Pipeline is inspected using ‘intelligent pigging’ (Refer to Section 2.2) and has a significant wall thickness (11.9 mm). It is equipped with a cathodic protection system and a double layered HDPE coating (Refer to Section 2.2).

### 4.5.3 Prevention of Damage due to Ground Movement and Other Failures

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

### 4.5.4 Prevention of Damage due to Third Party Activity

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

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

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

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

### 4.5.5 Mitigation Control Measures

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

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

Leaks may be detected during visual inspections, incident notifications and/or by instrumented monitoring systems. If a leak is detected, then the HP pipelines can be isolated by closing automated and/or manual valves (Refer to Section 2.2 for locations of upstream and downstream isolation valves).

## 4.6 MAEs for Risk Analysis

The list of MAEs included in the risk analysis is provided in Table 7.

**Table 7 List of MAEs**

| MAE | Potential Consequences |
|---|---|
| Release of High Pressure Ethane from APA Moomba-Sydney Ethane Pipeline | Jet Fire, Flash Fire or Explosion |

# 5 CONSEQUENCE ANALYSIS

## 5.1 Release of Flammable Liquid / Gas

### 5.1.1 Representative Hole Diameter

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

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

**Table 8 Representative Hole Diameters Selected for Consequence Analysis**

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

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

### 5.1.2 Rate of Release

Release events were modelled using the 'Long Pipeline' model in SAFETI. The estimated release rates are tabulated below for each representative hole size.

**Table 9 Representative Hole Diameters Selected for Consequence Analysis**

| MAE | Hole Diameter (mm) | Release Rate [kg/s] |
|---|---|---|
| Release of High Pressure Ethane from APA Moomba-Sydney Ethane Pipeline | 10 | 3.5 |
| | 25 | 21.7 |
| | 75 | 195.4 |
| | 110 | 420.2 |
| | FBR | 317.8 * |

* Average release rate from 'Long Pipeline' model for t = 0 to 20 seconds.

### 5.1.3 Height and Orientation of Release

All releases were modelled as vertical releases at ground level. The Safeti GASPIPE module determines a creater size and air entrainment for a release from a buried pipeline.

The release of high pressure gas or liquefied gas from a buried pipeline would result a crater and gas would be released vertically from the crater [10].

### 5.1.4 Duration of Release

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

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

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

## 5.2 Fire Modelling

The latest SAFETI software package (Version 8.2.3) was used to model all the representative fire events included in the risk analysis.

The key data and assumptions used to model the representative fire events are included in Appendix A.4.

### 5.2.1 Jet Fire

Example distances to heat radiation levels of 4.7, 12.5, 23 and 35 kW/m$^2$ are tabulated in Appendix B.1.2 for representative jet fire events included in the risk analysis.

### 5.2.2 Flash Fire

Example distances to the lower flammability limit (LFL) concentration are tabulated in Appendix B.1.2 for representative flash fire events included in the risk analysis.

## 5.3 Vapour Cloud Explosion

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

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

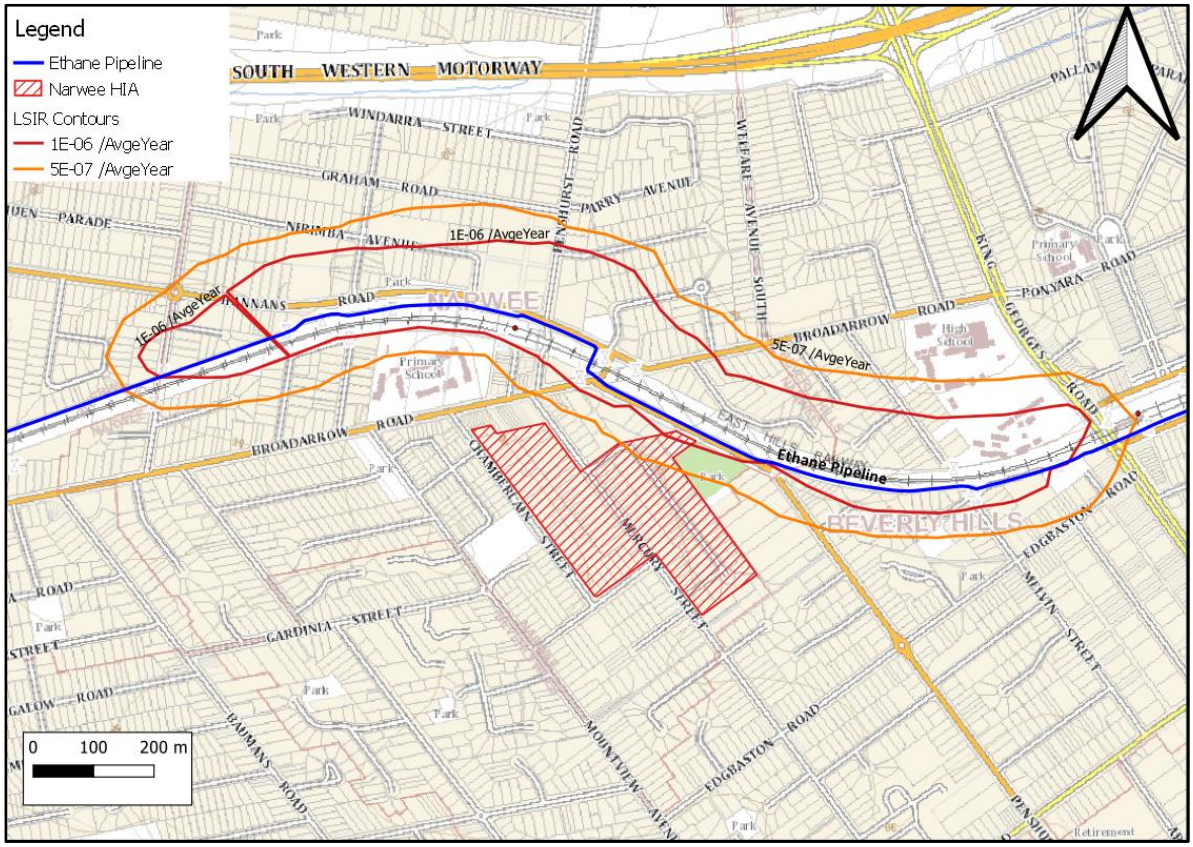
The Multi-Energy model in SAFETI was used to estimate the overpressure for a VCE. Results are provided in Appendix B.2.4.

# 6 RISK ANALYSIS

## 6.1 Individual Risk of Fatality

The risk contour for individual risk of fatality at 1.0 and 0.5 x $10^{-6}$ per annum (p.a.) for the three pipelines combined is shown in Figure 6. This value is the risk criterion for sensitive land uses in HIPAP No.10 [1].

**Figure 6 Location Specific Individual Risk Contours**




Both the 1.0 x $10^{-6}$ and 0.5 x $10^{-6}$ p.a. risk contours encroach the eastern side of the HIA site. This precludes lots on the north eastern part of the HIA bordering Bryant Street from residential purposes and some lots on Berrille Road from sensitive land uses such as schools, aged care and childcare centres. More detail on the lots where LSIR exceeds 1.0 x $10^{-6}$ is shown in Table 10 and Figure 7.

**Table 10 Lots where LSIR of Fatality Exceeds 0.5 per million per year.**

| Lot | Plan | Risk Exceeded (chance of fatality p.a.) |
|---|---|---|
| 1 | DP16824 | 0.5 x $10^{-6}$ |
| 2 | DP16824 | 0.5 x $10^{-6}$ |
| 3 | DP16824 | 0.5 x $10^{-6}$ |
| 4 | DP16824 | 0.5 x $10^{-6}$ |

| Lot | Plan | Risk Exceeded (chance of fatality p.a.) |
|---|---|---|
| 5 | DP16824 | $0.5 \times 10^{-6}$ |
| 6 | DP16824 | $0.5 \times 10^{-6}$ |
| 7 | DP16824 | $0.5 \times 10^{-6}$ |
| 407 | DP752056 | $1.0 \times 10^{-6}$ |
| 432 | DP752056 | $1.0 \times 10^{-6}$ |

### 6.2 Risk of Acute Toxic Injury or Irritation

No events with the potential to cause acute toxic injury or irritation were identified for inclusion in the risk analysis (Also refer to Section 4.4.6); therefore the proposed rezoning complies with the relevant DPI&E risk criteria (Refer to Section 3.4.2).

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

The cumulative risk of property damage and accident propagation (Overpressure exceeding 14 kPa) does not reach $50 \times 10^{-6}$ per annum. This criterion does not apply to the proposed residential rezoning (Refer to Section 3.4.3).

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

The cumulative risk of property damage and accident propagation (Heat radiation exceeding 23 kW/m$^2$) does not reach $50 \times 10^{-6}$ per annum. This criterion does not apply to the proposed residential rezoning (Refer to Section 3.4.3).

### 6.5 Risk of Injury (Exceeding 7 kPa)

The cumulative risk of injury (Overpressure exceeding 7 kPa) does not reach $50 \times 10^{-6}$ per annum; therefore the proposed rezoning complies with the relevant DPI&E risk criteria (Refer to Section 3.4.2).

### 6.6 Risk of Injury (Exceeding 4.7 kW/m$^2$)

The cumulative risk of injury (Heat radiation exceeding 4.7 kW/m$^2$) does not reach $50 \times 10^{-6}$ per annum; therefore the proposed rezoning complies with the relevant DPI&E risk criteria (Refer to Section 3.4.2).

### 6.7 Qualitative Risk Criteria

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

- Avoidance of all 'avoidable' risks – The pipelines are existing facilities and cannot be relocated to avoid risk exposure.

- Reduction, wherever practicable, of the risk from a major hazard, even where the likelihood of exposure is low – Some risk reduction measures are discussed in Section 8.9.
- Containment, wherever possible, within the site boundary of the effects (consequences) of the more likely hazardous events – The effects (consequences) of the more likely hazardous events (i.e. the smaller representative hole sizes) do not reach the proposed school development (Refer to Appendix B.1.2).
- Recognition that if the risk from an existing installation is already high, further development should not be permitted if it significantly increases that existing risk – The risk to the proposed development meets the individual risk criteria, and risk reduction measures are proposed to reduce the societal risk to meet the criteria.

## 6.8 Societal Risk

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

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

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

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

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

In HIPAP 10 [1], the following is reported in regard to the F-N criteria:

> *If a development proposal involves an intensification of population in the vicinity of a potential source of risk, then the incremental change in societal risk needs to be taken into account, even if individual risk criteria are met [Ref.2, Section 5.5.4]. The incremental societal risk should be compared against the indicative societal risk criteria in Section 5.4.2 of HIPAP No. 10 [Figure 4 below]. If the incremental societal risk lies within the 'Negligible' region, then the development should not be precluded and if it lies within the 'Tolerable if ALARP' region, then options should be considered to relocate people away from the affected areas [Ref.2, Section 5.5.4]. If, after taking this step, there is still a significant portion of the societal risk plot within the 'Tolerable if ALARP' region, the proposed development should only be approved if benefits clearly outweigh the risks [Ref.2, Section 5.5.4].*

An FN curve depicting the societal risk from the ethane pipeline in the area is shown in Figure 7. This shows the societal risk with both the HIA rezoned and fully developed, and also before the rezoning. The only noticeable increase in societal risk is between N = 30 and N = 300. At these points, the FN curve remains within the ALARP region. Such an insignificant change to the societal risk should not preclude the Narwee HIA from further development.

**Figure 7 Societal Risk**

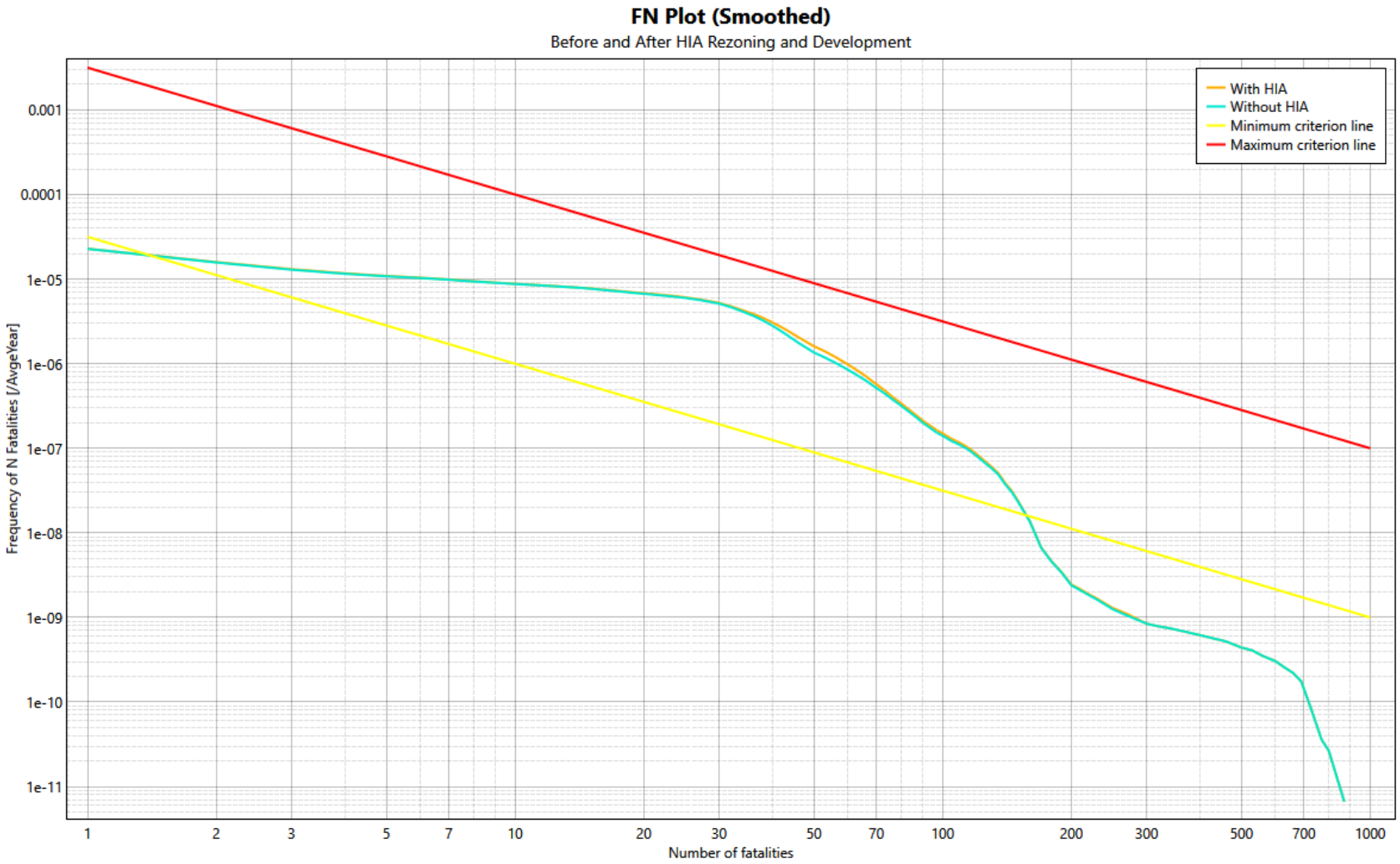


**Figure 8 Lots where LSIR of fatality exceeds 0.5 chances per million per year.**

# 7 FINDINGS AND RECOMMENDATIONS

## 7.1 Findings

The following findings were made from the risk assessment:

- The individual risk of fatality at north eastern corner of the HIA is 1.0 x $10^{-6}$ p.a. and at lots 407 and 432 of DP752056 exceeds the risk criterion for residential use in HIPAP No.10 [1].
- The individual risk of fatality at lots at the northern end of Berrille Road is 0.5 x $10^{-6}$ p.a. and at lots 1 through to 7 of DP16824 exceeds the risk criterion for sensitive use in HIPAP No.10 [1].
- The societal risk, represented as an F-N curve, is well below the upper limit of the risk tolerability band.
- Recommendations have been made to ensure compliance with HIPAP 10.

## 7.2 Recommendations

The following recommendations are mode to ensure compliance with the HIPAP 10 land use criteria:

*Recommendation 1: Remove lots 407 and 432 of DP752056 from the HIA planned rezoning to ensure the criteria for residential development area complied with.*

*Recommendation 2: Ensure sensitive use development such as aged care facilities, childcare centres or schools is not approved for lots 1 through to 7 of DP16824 in the northeast corner of the HIA.*

# 8 REFERENCES

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

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

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

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

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

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

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

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

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

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

[11] E. N. F. e. M. P. a. K. Silva, “Underground parallel pipelines domino effect: An analysis based on pipeline crater models and historical accidents,” vol. 43, no. June, 2016.

# Appendices

# Appendix A Assumptions

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

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

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

It is important that the assumptions be supported by:

- experimental data in the literature, where available;
- actual operating experience, where available;
- similar assumptions made by experts in the field and a general consensus among risk analysts; and
- 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 |
| **Assumption/s:**<br>• All pipeline operating conditions (pressure, temperature, etc.) are as reported in Section 2.2 |
| **Justification and Impact/s of Assumption/s:**<br>• All operational data for the pipelines was provided by the pipeline owner (APA Group).<br>• Operating conditions (particularly operating pressure) are required to undertake the release and dispersion modelling. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• Data provided by APA Group. |

| Assumption No. 2 Pipeline Utilisation |
|---|
| **Subject:** Operational Data |
| **Assumption/s:**<br>• Both pipelines are utilised 100% of the time. |
| **Justification and Impact/s of Assumption/s:**<br>• Utilisation data is required to undertake the release and dispersion modelling and to estimate the release frequency. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• Data provided by APA Group. |

## A.2 Locational Data

| Assumption No. 3: Representative Wind Speeds, Wind Directions and Stability Classes |
|---|
| **Subject:** Locational Data |
| **Assumption/s:**<br>• The probabilistic distribution of wind speed and wind direction for the representative stability classes is provided in Table 11 and Table 12.<br>• The data was split into daytime and night time conditions.<br>• Night-time is considered the period from 1 hour before sunset, to one hour after sunrise. This approximates to 10 hours daytime and 14 hours night-time. |
| **Justification and Impact/s of Assumption/s:**<br>• Meteorological data (mean cloud cover, temperature, wind speeds) is collected by the Bureau of Meteorology (BoM) for the Bankstown Airport weather station. This raw data was rationalised into a set of wind speed/weather stability classes for dispersion calculations. The Bankstown Airport weather station was selected as being the closest to the HIA with sufficient data and most representative.<br>• 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.<br>• The downwind gas concentrations, and hence the hazard ranges for dispersion of flammable gas or vapour, vary with wind speed and weather stability class. Therefore, multiple representative wind speed and stability class categories are included in accordance with standard practice for undertaking a quantitative risk assessment (QRA).<br>• The day/night split of the weather data is required to allow for the fact that residential, commercial and industrial occupancies change over a 24 hour period. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• BoM meteorological data for Bankstown AWS. |

**Table 11 Probability of Representative Stability Classes and Wind Speeds (Day)**

| Stab. Class | Wind Speed (m/s) | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW | SW | WSW | W | WNW | NW | NNW | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 3.0 | 0.025 | 0.012 | 0.011 | 0.011 | 0.014 | 0.009 | 0.008 | 0.006 | 0.010 | 0.008 | 0.011 | 0.013 | 0.023 | 0.022 | 0.020 | 0.020 | 0.222 |
| D | 7.4 | 0.006 | 0.001 | 0.008 | 0.020 | 0.018 | 0.029 | 0.038 | 0.036 | 0.027 | 0.005 | 0.007 | 0.015 | 0.022 | 0.015 | 0.006 | 0.006 | 0.259 |
| D | 4.4 | 0.026 | 0.011 | 0.020 | 0.031 | 0.038 | 0.031 | 0.028 | 0.022 | 0.030 | 0.014 | 0.027 | 0.028 | 0.032 | 0.025 | 0.027 | 0.022 | 0.414 |
| D | 1.8 | 0.008 | 0.003 | 0.002 | 0.002 | 0.003 | 0.002 | 0.003 | 0.003 | 0.006 | 0.006 | 0.008 | 0.009 | 0.014 | 0.015 | 0.014 | 0.008 | 0.105 |
| **Total** | | 0.064 | 0.026 | 0.042 | 0.064 | 0.073 | 0.072 | 0.076 | 0.067 | 0.073 | 0.033 | 0.053 | 0.065 | 0.092 | 0.076 | 0.068 | 0.056 | 1.000 |

**Table 12 Probability of Representative Stability Classes and Wind Speeds (Night)**

| Stab. Class | Wind Speed (m/s) | N | NNE | NE | ENE | E | ESE | SE | SSE | S | SSW | SW | WSW | W | WNW | NW | NNW | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D | 7.4 | 0.001 | 0.000 | 0.001 | 0.000 | 0.001 | 0.003 | 0.007 | 0.010 | 0.007 | 0.002 | 0.002 | 0.004 | 0.006 | 0.003 | 0.002 | 0.001 | 0.050 |
| D | 4.1 | 0.016 | 0.008 | 0.022 | 0.015 | 0.016 | 0.018 | 0.021 | 0.020 | 0.027 | 0.014 | 0.021 | 0.020 | 0.021 | 0.012 | 0.013 | 0.018 | 0.283 |
| D | 1.2 | 0.008 | 0.003 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.006 | 0.006 | 0.007 | 0.007 | 0.009 | 0.006 | 0.007 | 0.009 | 0.082 |
| E | 2.6 | 0.005 | 0.003 | 0.005 | 0.003 | 0.004 | 0.004 | 0.003 | 0.003 | 0.006 | 0.005 | 0.007 | 0.007 | 0.006 | 0.005 | 0.005 | 0.006 | 0.076 |
| F | 1.1 | 0.043 | 0.018 | 0.023 | 0.022 | 0.024 | 0.018 | 0.015 | 0.015 | 0.035 | 0.029 | 0.039 | 0.042 | 0.056 | 0.037 | 0.043 | 0.049 | 0.508 |
| **Total** | | 0.074 | 0.032 | 0.053 | 0.043 | 0.048 | 0.044 | 0.048 | 0.050 | 0.081 | 0.055 | 0.077 | 0.081 | 0.098 | 0.063 | 0.070 | 0.083 | 1.000 |

**Assumption No. 4: Ambient Conditions**

**Subject:** Locational Data

**Assumption/s:**

- The typical ambient conditions (temperature, atmospheric pressure, solar radiation and relative humidity) are listed in Table 13 and Table 14.

**Table 13 Average Temperature, Relative Humidity and Solar Radiation (Day)**

| Stability Class | Wind Speed (m/s) | Average Temp (°C) | Average Solar Radiation ($kW/m^2$) | Average Relative Humidity (fraction) |
|---|---|---|---|---|
| B | 3.0 | 23.7 | 0.8 | 0.42 |
| D | 7.4 | 22.7 | 0.5 | 0.47 |
| D | 4.4 | 20.6 | 0.4 | 0.52 |
| D | 1.8 | 16.8 | 0.3 | 0.69 |

**Table 14 Average Temperature, Relative Humidity and Solar Radiation (Night)**

| Stability Class | Wind Speed (m/s) | Average Temp (°C) | Average Solar Radiation ($kW/m^2$) | Average Relative Humidity (%) |
|---|---|---|---|---|
| D | 7.4 | 18.0 | 0.0 | 0.61 |
| D | 4.1 | 16.7 | 0.0 | 0.68 |
| D | 1.2 | 11.8 | 0.1 | 0.89 |
| E | 2.6 | 13.9 | 0.0 | 0.81 |
| F | 1.1 | 10.9 | 0.0 | 0.90 |

**Justification and Impact/s of Assumption/s:**

- The average ambient temperature is a required input for the SAFETI model. The temperature of the material in each pipeline is similar; therefore, the average ambient temperature does not have a significant impact on the consequence calculations.
- The average relative humidity is a required input for the SAFETI model. This is used in thermal radiation calculations to attenuate the heat radiation.
- The average solar radiation is a required input for the SAFETI model.

**MAE/s Affected:**

- All.

**Reference/s:**

- BoM meteorological data for Bankstown Airport.

**Assumption No. 5: Surface Roughness Length**

**Subject:** Locational Data

**Assumption/s:**

- The roughness length for different surface types, as listed in the SAFETI user manual, is shown below in Table 15.

**Table 15 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 |

- A conservative roughness length of 0.5 m is applicable for Narwee.

**Justification and Impact/s of Assumption/s:**

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

**MAE/s Affected:**

- Dispersion modelling for all relevant MAEs.

**Reference/s:**

- SAFETI software documentation.

| Assumption No. 6: Location of High Pressure Gas Pipelines |
|---|
| **Subject:** Locational Data |
| **Assumption/s:**<br>• The location of the pipelines is sourced from the Australian Pipeline and Gas Association's (APGA) Australian Pipeline Database |
| **Justification and Impact/s of Assumption/s:**<br>• The Australian Pipeline Database (APD) is made available to users to raise awareness of the location of high-pressure hydrocarbon pipelines and facilitate discussions between pipeline operators and stakeholders regarding the potential for planning and development decisions to trigger requirements in the Australian Standard, AS 2885, for pipeline Safety Management Studies.<br>• Use of the APD is conditional on several factors that are consistent with the objectives of this study, including:<br>  ◦ The APD is to be used solely for the purpose of facilitating discussion regarding planning activity and decisions in the vicinity of pipelines. **This is consistent with the objectives of this study**.<br>  ◦ The APD is not to be used for proving and construction activities. Dial Before You Dig enquiries must be made for these activities and any condition complied with. **It is not the intent of this study to provide detailed construction information**.<br>• When overlayed onto aerial photos, the APGA Pipeline database accuracy appears no less accurate than the accuracy expected of the consequence models and frequency estimates.<br>• |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• APGA Australian Pipeline Database |

| Assumption No. 7: Residential Population (Day and Night) |
|---|
| **Subject:** Locational Data |
| **Assumption/s:**<br>• The average number of residents per household used for the base case is 2.8 as per NSW DPIE projections.<br>• No allowance has been made for differences between night-time and daytime population. The study has used the ABS 2016 usual place of residence by state suburb to estimate the population surrounding the HIA at all times. |
| **Justification and Impact/s of Assumption/s:**<br>• The average number of residents per dwelling is based on NSW DPIE projections for Georges River Council.<br>• Keeping the daytime population the same as night-time population is conservative, as during week days there will be a migration from residential areas to commercial and industrial areas. |
| **MAE/s Affected:**<br>• All societal risk calculations. Population density, along with the area of consequence distances, determines the fN points of societal risk.<br>• Locational specific risk is not impacted by these assumptions. |
| **Reference/s:**<br>• Census of Population and Housing, 2016, TableBuilder<br>• "Georges River Council 2019 NSW Population Projections", NSW Department of Planning, Industry and Environment. |

**Assumption No. 8: Indoor / Outdoor distribution of people**

**Subject:** Locational Data

**Assumption/s:**

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

**Justification and Impact/s of Assumption/s:**

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

**Table 16 Proportion of Population Indoor and Outdoor During Day and Night [TNO]**

| Location | Day Time (8am to 6:00pm) | Night Time (6:00pm to 8am) |
|---|---|---|
| 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 DPI&E). It is reported in these analyses that the % of people indoors and outdoors is 90% indoors and 10% outdoors during the day, which differs slightly from the TNO data, but is typically justified as being more applicable for Australian environmental conditions. Similarly, it is reported in these analyses that the % of people indoors and outdoors is 95 to 99% indoors and 1 to 5% outdoors during the night.

**MAE/s Affected:**

- All societal risk calculations

**Reference/s:**

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

## A.3 Risk Analysis Methodology

| Assumption No. 9: Location and Segmentation of Pipelines |
|---|
| **Subject:** Risk Analysis Methodology |
| **Assumption/s:**<br>• Representative release events are modelled using the 'Long Pipeline' model in SAFETI, which distributes these events along the pipeline at set intervals. |
| **Justification and Impact/s of Assumption/s:**<br>• 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.<br>• The interval at which representative incidents are distributed along the pipeline is selected automatically by the 'Long Pipeline' model based on the incident consequence. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• SAFETI software documentation. |

## A.4 Consequence Analysis

| Assumption No. 10: Representative Materials |
|---|
| **Subject:** Consequence Analysis |
| **Assumption/s:**<br>• Ethane is modelled as 100% Ethane. |
| **Justification and Impact/s of Assumption/s:**<br>• 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.<br>• The ethane pipeline carries ethane which has been processed to serve as a petrochemical feed stock. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• Data provided by APA Group. |

| Assumption No. 11: Pressure and Flow for Release Modelling |
|---|
| **Subject:** Consequence Analysis |
| **Assumption/s:**<br>• A release of Ethane from the Moomba to Sydney Ethane Pipeline is modelled at 8.2 MPag (Operating pressure), compared to an MAOP of 10 MPag.<br>• Release events are modelled using the 'Long Pipeline' model in SAFETI and may be based on a time varying release rate (depending on hole size).<br>• 30 tonnes per hour flow is assumed |
| **Justification and Impact/s of Assumption/s:**<br>• The release rate is dependent on the pressure and the MAOP is the maximum pressure permitted under an existing licence.<br>• The pressure used to model the release rates was based on the pipeline pressure near the proposed development, as advised by the pipeline owner.<br>• 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 initial release rate.<br>• Providing a flow will slow the rate of pressure reduction calculated by the long pipeline model, but this is insignificant for the initial 30 second release, the basis of which the impact for jet fire has been assumed.<br>• A flow will increase the residual pressure the long pipeline model calculates, but as it will take much longer than 30 seconds to reach residual pressure, this is not relevant. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• Data provided by APA Group (TBA). |

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

**Subject:** Consequence Analysis

**Assumption/s:**

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

**Table 17 Representative Hole Diameters Selected for Consequence Analysis**

| Pipeline/s | 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) |
| APA Ethane Pipeline | Ethane | 202.9 | 10 or 25* | 75 | 110 | Full bore |

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

**Justification and Impact/s of Assumption/s:**

- The representative hole diameters were selected to align with the leak frequency data (Refer to C.1), which includes four hole size categories: Pinhole (≤ 25 mm); Small Hole (> 25 mm to ≤ 75 mm), Large Hole (> 75 mm to ≤ 110 mm); and, Rupture (> 110 mm). The representative hole diameter/s in each hole size category were selected based on a review of the available historical data (Refer to Appendix B.1):
  - Leaks from underground pipelines in the Pinhole size category tend to be larger for TPA incidents (i.e. typically c. 20 mm to 25 mm – Refer to Appendix D) than for the other failure modes (i.e. typically less than c. 10 mm). Therefore, two representative hole diameters were selected in this category: 25 mm for TPA and 10 mm for all other failure modes.
  - There is insufficient historical incident data for Ethane to determine the representative hole diameter/s in each hole size category. Therefore, the representative hole diameters were assumed to be the same as proposed by the UK HSE for LPG (Refer to C.1). Ethane is transported as a liquefied flammable gas.

**MAE/s Affected:**

- All.

**Reference/s:**

- Refer to Appendix B.1.

| Assumption No. 13: Location of Release for Transmission Pipelines |
|---|
| **Subject:** Consequence Analysis |
| **Assumption/s:**<br>• High pressure gas releases would create a crater on the ground. The direction of release for underground pipeline failures from the crater is always vertical.<br>• The location of failure on the pipe can be taken as:<br>- Top of the pipe (unobstructed releases); or<br>- Middle of the pipe (on the side – obstructed releases)<br>• The release frequency is distributed between the two locations (37% from middle of pipe and 63% from top of pipe for all release cases except non-TPA events with a hole size less than or equal to 25mm, which are modelled as 100% from middle of pipe). |
| **Justification and Impact/s of Assumption/s:**<br>• The crater size depends on the location of the hole on the pipe and hence all three locations (top, middle and bottom) may be modelled (DNVGL, 2020). Top releases are taken as non-obstructed releases and middle/ bottom releases are taken as obstructed releases.<br>• Impingement reduces the momentum of the release and the dispersion modelling is dominated by the representative wind conditions.<br>• The UK HSE [RR 1034] reports that some data from UKOPA includes the 'hole circumferential position' for releases from underground pipelines. Based on the 71 recorded incidents (All pipelines and materials) and average crater dimensions, an unobstructed release (c. ±71$^{o}$ from vertical) was estimated to occur for 63% of the releases and an obstructed release was estimated to occur for the balance (37% of releases). The distribution is not reported for different failure modes. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• SAFETI software documentation.<br>• UK HSE, 2015, *Review of the Event Tree Structure and Ignition Probabilities used in HSE's Pipeline Risk Assessment Code MISHAP*, Research Report (RR) 1034. |

## Assumption No. 14: Maximum Extent of Flash Fire

**Subject:** Consequence Analysis

**Assumption/s:**

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

**Justification and Impact/s of Assumption/s:**

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

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

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

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

  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

  $$t = 18.75 \text{ s.}$$

  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.

**MAE/s Affected:**

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

**Reference/s:**


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

| Assumption No. 15: Isolation Time and Duration of Release |
|---|
| **Subject:** Consequence Analysis |
| **Assumption/s:**<br>• Isolation time and duration of release is not specified as these will be significantly longer than the period of exposure required for an adverse effect to people (Refer to Section A.6) and time required for each representative release case to reach steady state. |
| **Justification and Impact/s of Assumption/s:**<br>• Ethane is flammable and any adverse impact will occur quickly (fire or explosion); therefore, the duration of exposure is not as critical as it would be if there were toxic materials in the pipeline (i.e. where the adverse impact can significantly increase for longer exposure durations).<br>• The assumption is justified from the consequence calculations of the Long Pipeline Model, using a 30 sec. exposure time (user specified), compared to isolation valve closure times which typically vary from minutes (full bore rupture case) to hours (small to medium leaks). |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• SAFETI software documentation. |

| Assumption No. 16: Shielding by Intervening Structures |
|---|
| **Subject:** Consequence Analysis |
| **Assumption/s:**<br>• The presence of intervening structures (e.g. buildings) does not shield other receptors from the heat radiation from a jet fire. |
| **Justification and Impact/s of Assumption/s:**<br>• In the SAFETI software, it is not possible to take account of the potential protection provided by intervening structures.<br>• 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.<br>• People located indoors are typically less vulnerable to fire, which is an relevant consideration for the societal risk assessment (Refer to Assumption No. 21). |
| **MAE/s Affected:**<br>• All MAEs with a pool fire or jet fire as a potential outcome. |
| **Reference/s:**<br>• SAFETI software documentation. |

| Assumption No. 17: 3D Explosion Model Parameters |
|---|
| **Subject:** Consequence Analysis |
| **Assumption/s:**<br>• 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.<br>• The peak side-on overpressure resulting from an explosion is estimated using the Extended Explosion Modelling option in the SAFETI software.<br>• The severity of the blast is based on an unconfined blast strength of 4, with no specified obstruction region.<br>• The blast strength is estimated based on the obstructed volume (%) and potential obstructions in each congested area. The following congested areas are included in the QRA:<br>  • **Buildings** - A medium obstructed volume (60% for a residential building) and level of congestion is assumed to simulate entry of the gas or vapour into the building and the subsequent confined explosion. This equates to TNO Model curve number 4.<br>• Only overpressure effects are included. Projectiles and whole-body displacement are not included. |
| **Justification and Impact/s of Assumption/s:**<br>• The explosive mass and blast strength are key parameters for modelling the overpressure from a VCE.<br>• There are no significantly congested locations in the study area; however, a confined explosion could occur if gas or vapour enters a building.<br>• The open space between the buildings in the study area is not strictly a congested area; however, the presence of vehicles, trees etc. at ground level may contribute to flame acceleration and the formation of an overpressure if ignition occurs. Therefore, TNO Model curve number 2 was assumed to apply, which is the default value in the SAFETI software.<br>• The 3D Obstructed Region Explosion Modelling option considers the interactions between the flammable cloud and obstructed regions that have been defined for the study area. This is more valid than simple models (e.g. TNT equivalence) which do not consider these interactions. |
| **MAE/s Affected:**<br>• All MAEs with a VCE as a potential outcome. |
| **Reference/s:**<br>• Centre for Chemical Process Safety, Estimating the flammable mass of vapour clouds", American Institute of Chemical Engineers, 1999.<br>• TNO, VROM, 'Yellow Book'.<br>• SAFETI software documentation. |

## A.5 Likelihood Analysis

| Assumption No. 18: Likelihood of Release (Loss of Containment) |
|---|
| **Subject:** Likelihood Analysis |
| **Assumption/s:**<br>• The likelihood of each representative release is provided in Appendix C.3.<br>• The UK HSE pipeline failure rate data is the primary data used for the risk assessment.<br>• The contribution to pipeline failure from ground movement has been adjusted down to allow for local conditions. |
| **Justification and Impact/s of Assumption/s:**<br>• 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.<br>• Generic failure rate data for cross-country pipelines from the UK, USA and Europe were reviewed. The UK data incorporates the European data. There are two sources of data from the UK: (a) HSE recommended data for land use safety planning (RR 1035); and (b) British Standards Institute PD 8010-3:2009+A1:2013. The HSE data is primarily used in this study, which is consistent with the NSW performance data.<br>• The HSE data identifies four contributors to pipeline failure: (a) mechanical failure; (b) corrosion; (c) ground movement/other; and (d) Third Party Activity (TPA). Of these, mechanical, corrosion and TPA are similar to conditions in Australia and hence no frequency adjustments due to local conditions are justified.<br>• The justification for the data used in this risk analysis is provided in Appendix C.1. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• Refer to Appendix C.1. |

| Assumption No. 19: Ignition Probability |
|---|
| **Subject:** Likelihood Analysis |
| **Assumption/s:**<br>• The probability of ignition for each representative release is provided in Appendix C.2. |
| **Justification and Impact/s of Assumption/s:**<br>• The estimated probability of ignition is a critical and significant input for the risk analysis. The risk results are directly proportional to this input.<br>• The justification for the data used in this risk analysis is provided in Appendix C.2. |
| **MAE/s Affected:**<br>• All. |
| **Reference/s:**<br>• Refer to Appendix C.2. |

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

## A.6 Vulnerability Parameters

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

**Subject:** Vulnerability Parameters

**Assumption/s:**

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

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

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

**Table 18 Probability of Fatality for Exposure to Heat Radiation (Outdoor)**

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

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

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

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

**Justification and Impact/s of Assumption/s:**

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

**Table 19 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.<br>30% chance of fatality for extended exposure.<br>Melting of plastics (cable insulation).<br>Causes the temperature of wood to rise to a point where it can be ignited by a naked flame after long exposure.<br>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.<br>10% chance of fatality on instantaneous exposure.<br>Spontaneous ignition of wood after long exposure.<br>Unprotected steel will reach thermal stress temperatures, which can cause failure.<br>Pressure vessel needs to be relieved or failure would occur. |
| 35.0 | 25% chance of fatality on instantaneous exposure. |
| 60.0 | Fatality on instantaneous exposure. |

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

**MAE/s Affected:**

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

**Reference/s:**

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

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

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

**Subject:** Vulnerability Parameters

**Assumption/s:**

- The probability of fatality from exposure to the peak side-on overpressure from an explosion is as shown in Table 20 (Person located outdoors) and Table 21 (Person located indoors).

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

| Overpressure (kPa) | Probability of Fatality | Source |
|---|---|---|
| 30 | 1.0 | SAFETI software (default value) |

**Table 21 Probability of Fatality from Exposure to Peak Side on-Overpressure (Indoor)**

| Overpressure (kPa) | Probability of Fatality | Source |
|---|---|---|
| 10 | 0.025 | SAFETI software (default value) |
| 30 | 1.0 | SAFETI software (default value) |

**Justification and Impact/s of Assumption/s:**

- When calculating location-specific individual injury or fatality risk contours (peak individual risk), all individuals must be considered to be located outdoors for 100% of the time since this is the underlying basis for the NSW DPI&E'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 DPI&E's injury/damage risk criterion for explosion overpressure is as follows: "Incident explosion overpressure at residential and sensitive use areas should not exceed 7 kPa at frequencies of more than 50 chances in a million per year".

**Incidents Affected:**

- All incidents with a VCE as a potential outcome.

**Reference/s:**

- NSW Department of Planning and Infrastructure, Jan 2011, Hazardous Industry Planning Advisory Paper (HIPAP) No. 4, *Risk Criteria for Land Use Safety Planning*.
- SAFETI software documentation.
- Oil & Gas Producers Association (OGP), Risk Assessment Data Directory, Report No. 434-14.1, *Vulnerability to Humans*, March 2010.
- Chemical Industries Association (CIA), 2003, *Guidance for the location and design of occupied buildings on chemical manufacturing sites*, 2nd. ed.

# Appendix B Consequence Analysis – Example Data and Results

## B.1 Representative Hole Diameters

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

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

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

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

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

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

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

| Fault ID | Discovery Date | Product | Wall Thickness (mm) | Diameter (in) | Diameter (mm) | Equivalent Hole Diameter (mm) | Cause |
|---|---|---|---|---|---|---|---|
| 1950 | 1998 | NG | 4.4 | 3.9 | 100 | 1.1 | Corrosion |
| 1948 | 1997 | NG | 4.4 | 3.9 | 100 | 11.3 | Corrosion |
| 400 | 1998 | NG | Not Recorded | 4 | 102 | 2.8 | Corrosion |
| 3112 | 2010 | NG | 4.4 | 4.5 | 114 | 1.1 | Corrosion |
| 1424 | 1990 | NG | 4.5 | 4.5 | 114 | 3.6 | Corrosion |
| 1998 | 2001 | NG | 4.8 | 5.9 | 150 | 24.5 | Corrosion |
| 2569 | 2005 | NG | 4.7 | 6.4 | 163 | 1.1 | Corrosion |
| 2979 | 2009 | NG | 4.3 | 6.4 | 163 | 17.8 | Corrosion |
| 728 | 1990 | NG | 6 | 6.6 | 168 | 1.1 | Corrosion |
| 425 | 2000 | NG | 6.6 | 8.6 | 218 | 1.1 | Corrosion |
| 417 | 1998 | NG | 5.2 | 8.6 | 218 | 3.2 | Corrosion |
| 402 | 1999 | NG | 5.2 | 8.6 | 218 | 3.6 | Corrosion |
| 422 | 1999 | NG | 6.6 | 8.6 | 218 | 3.6 | Corrosion |
| 1934 | 1993 | NG | 6.4 | 14 | 356 | 1.1 | Corrosion |
| 730 | 1994 | NG | 6.4 | 18 | 457 | 1.1 | Corrosion |
| 1460 | 2001 | NG | 6.35 | 12.7 | 323 | 3.6 | Ground movement/Other |
| 1490 | 1989 | NG | 6.4 | 12.8 | 325 | 1.1 | Ground movement/Other |
| 1489 | 1989 | NG | 6.4 | 12.8 | 325 | 3.6 | Ground movement/Other |
| 1388 | 1998 | NG | 8 | 18 | 457 | 2.3 | Ground movement/Other |

| Fault ID | Discovery Date | Product | Wall Thickness (mm) | Diameter (in) | Diameter (mm) | Equivalent Hole Diameter (mm) | Cause |
|---|---|---|---|---|---|---|---|
| 2923 | 2008 | NG | 9.52 | 18 | 457 | 3.4 | Ground movement/Other |
| 2872 | 2000 | NG | 9.52 | 18 | 457 | 27.8 | Ground movement/Other |
| 1972 | 1990 | NG | 4.5 | 3.5 | 89 | 3.6 | Mechanical |
| 1949 | 1997 | NG | 4.4 | 3.9 | 100 | 3.6 | Mechanical |
| 1947 | 1990 | NG | 4.4 | 4 | 102 | 3.6 | Mechanical |
| 1909 | 1989 | NG | 4.4 | 4 | 102 | 11.3 | Mechanical |
| 1913 | 1990 | NG | 4.4 | 4 | 102 | 11.3 | Mechanical |
| 1914 | 1990 | NG | 4.4 | 4 | 102 | 11.3 | Mechanical |
| 1916 | 1990 | NG | 4.4 | 4 | 102 | 11.3 | Mechanical |
| 1917 | 1990 | NG | 4.4 | 4 | 102 | 11.3 | Mechanical |
| 1919 | 1990 | NG | 4.4 | 4 | 102 | 11.3 | Mechanical |
| 363 | 1997 | NG | Not recorded | 5.9 | 150 | 1.1 | Mechanical |
| 1928 | 1990 | NG | 4.5 | 5.9 | 150 | 11.3 | Mechanical |
| 1973 | 1990 | NG | 4.5 | 5.9 | 150 | 11.3 | Mechanical |
| 2028 | 1990 | NG | 4.8 | 5.9 | 150 | 11.3 | Mechanical |
| 2078 | 1989 | NG | 5.6 | 5.9 | 150 | 11.3 | Mechanical |
| 1996 | 1993 | NG | 4.8 | 6.6 | 168 | 1.1 | Mechanical |
| 1875 | 1989 | NG | 5.2 | 6.6 | 168 | 11.3 | Mechanical |
| 1886 | 1990 | NG | 4.4 | 6.6 | 168 | 11.3 | Mechanical |
| 1887 | 1990 | NG | 4.4 | 6.6 | 168 | 11.3 | Mechanical |
| 1925 | 1989 | NG | 4.4 | 6.6 | 168 | 11.3 | Mechanical |
| 1926 | 1989 | NG | 4.4 | 6.6 | 168 | 11.3 | Mechanical |
| 1940 | 1990 | NG | 4.4 | 6.6 | 168 | 11.3 | Mechanical |
| 2069 | 1990 | NG | 6.4 | 8.6 | 218 | 3.6 | Mechanical |
| 1876 | 1989 | NG | 6.4 | 8.6 | 218 | 11.3 | Mechanical |
| 2055 | 1989 | NG | 6.4 | 8.6 | 218 | 11.3 | Mechanical |
| 1710 | 1989 | NG | 7.9 | 14 | 356 | 3.6 | Mechanical |
| 1842 | 1992 | NG | 9.5 | 17.7 | 450 | 1.1 | Mechanical |
| 1361 | 1994 | NG | 9.5 | 24 | 610 | 1.1 | Mechanical |
| 1117 | 1993 | NG | 12.7 | 36 | 914 | 160.1 | Mechanical |
| 1918 | 1990 | NG | 4.4 | 4 | 102 | 22.6 | TPA |
| 1987 | 1990 | NG | 4.8 | 6.6 | 168 | 23.9 | TPA |
| 2980 | 2009 | NG | 5.56 | 6.6 | 168 | 25 | TPA |
| 1645 | 1992 | NG | 7.1 | 8.6 | 218 | 5.5 | TPA |
| 366 | 1991 | NG | 4.8 | 8.6 | 218 | 24 | TPA |
| 2783 | 2006 | NG | 4.5 | 8.6 | 219 | 25 | TPA |
| 1560 | 1989 | NG | 6.4 | 12.8 | 325 | 56.2 | TPA |
| 1185 | 1998 | NG | 10.4 | 15.7 | 400 | 20 | TPA |
| 1193 | 1990 | NG | 9.5 | 16 | 406 | 25 | TPA |
| 3109 | 2009 | Propylene | 7.1 | 6.6 | 168 | 6.8 | TPA |

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

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

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

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

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

| MAOP | | Pipe Diameter (in) | Rupture Length (in) | Rupture Width (in) | Approx. Rupture Area (sq.in) | % of Cross-Section Area | Equiv. Hole Diameter (mm) | Cause |
|---|---|---|---|---|---|---|---|---|
| (psig) | (kPag) | | | | | | | |
| 15 | 205 | 1.66 | 1.5 | 1.5 | 1.8 | 81.7 | 38.1 | Natural Force - High Winds |
| 95 | 756 | 20 | 16 | 1 | 12.6 | 4.0 | 101.6 | Corrosion - External |
| 15 | 205 | 1 | 3.3 | 1 | 2.6 | 330.0 | 46.1 | Excavation Damage |
| 60 | 515 | 1.25 | 2 | 0.1 | 0.2 | 12.8 | 11.4 | Excavation Damage |
| 60 | 515 | 2 | 7.5 | 0.5 | 2.9 | 93.8 | 49.2 | Material Failure of Pipe or Weld - Butt Weld |
| 60 | 515 | 2.375 | 6.5 | 2.1 | 10.7 | 242.0 | 93.8 | Material Failure of Pipe or Weld - Butt Weld |
| 60 | 515 | 2.375 | 2 | 2 | 3.1 | 70.9 | 50.8 | Excavation Damage |
| 433 | 3087 | 4 | 10 | 0.2 | 1.6 | 12.5 | 35.9 | Excavation Damage |
| 60 | 515 | 6.625 | 12.5 | 0.5 | 4.9 | 14.2 | 63.5 | Material Failure of Pipe or Weld - Pipe |
| 78 | 639 | 16 | 16 | 16 | 201.1 | 100.0 | 406.4 | Other Cause - Unknown |

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

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

| MAOP (psig) | MAOP (kPag) | Pipe Diameter (in) | Puncture Axial Length (in) | Puncture Circumferential Length (in) | Approx. Puncture Area (sq.in) | % of Cross-Section Area | Equiv. Hole Diameter (mm) | Cause |
|---|---|---|---|---|---|---|---|---|
| 60 | 515 | 4 | 24 | 2 | 37.7 | 300.0 | 176.0 | Excavation Damage |
| 60 | 515 | 4 | 9 | 3 | 21.2 | 168.8 | 132.0 | Excavation Damage |
| 60 | 515 | 4 | 0.8 | 0.8 | 0.5 | 4.0 | 20.3 | Excavation Damage |
| 250 | 1825 | 4 | 5 | 3 | 11.8 | 93.8 | 98.4 | Excavation Damage |
| 285 | 2066 | 4 | 0.6 | 1.3 | 0.6 | 4.9 | 22.4 | Excavation Damage |
| 300 | 2170 | 4.5 | 1 | 12.6 | 9.9 | 62.2 | 90.2 | Excavation Damage |
| 10 | 170 | 6 | 6 | 6 | 28.3 | 100.0 | 152.4 | Excavation Damage |
| 35 | 343 | 6 | 3 | 3 | 7.1 | 25.0 | 76.2 | Excavation Damage |
| 60 | 515 | 6 | 6 | 6 | 28.3 | 100.0 | 152.4 | Excavation Damage |
| 60 | 515 | 6 | 6 | 6 | 28.3 | 100.0 | 152.4 | Excavation Damage |
| 60 | 515 | 6 | 6 | 6 | 28.3 | 100.0 | 152.4 | Excavation Damage |
| 60 | 515 | 6 | 0.5 | 0.5 | 0.2 | 0.7 | 12.7 | Other Outside Force - Electrical arcing |
| 150 | 1136 | 6 | 1.5 | 0.5 | 0.6 | 2.1 | 22.0 | Excavation Damage |
| 200 | 1480 | 6 | 1.2 | 1 | 0.9 | 3.3 | 27.8 | Excavation Damage |
| 200 | 1480 | 6 | 2 | 2 | 3.1 | 11.1 | 50.8 | Excavation Damage |
| 300 | 2170 | 6 | 0.5 | 0.5 | 0.2 | 0.7 | 12.7 | Excavation Damage |
| 400 | 2859 | 6 | 4 | 1 | 3.1 | 11.1 | 50.8 | Excavation Damage |
| 500 | 3549 | 6 | 1 | 0.5 | 0.4 | 1.4 | 18.0 | Other Outside Force - Other Vehicle |
| 60 | 515 | 6.58 | 1 | 1 | 0.8 | 2.3 | 25.4 | Other Outside Force - Other Vehicle |
| 300 | 2170 | 6.625 | 3 | 4 | 9.4 | 27.3 | 88.0 | Excavation Damage |
| 50 | 446 | 8 | 2.1 | 2.1 | 3.5 | 6.9 | 53.3 | Excavation Damage |
| 50 | 446 | 8 | 11 | 4 | 34.6 | 68.8 | 168.5 | Excavation Damage |
| 60 | 515 | 8 | 0.1 | 0.1 | 0.0 | 0.0 | 2.5 | Excavation Damage |
| 80 | 653 | 8 | 12 | 8 | 75.4 | 150.0 | 248.9 | Excavation Damage |
| 120 | 929 | 8 | 6.5 | 2.5 | 12.8 | 25.4 | 102.4 | Excavation Damage |
| 157 | 1184 | 8 | 3.9 | 3.2 | 9.8 | 19.5 | 89.7 | Excavation Damage |
| 300 | 2170 | 8 | 4 | 2 | 6.3 | 12.5 | 71.8 | Excavation Damage |
| 400 | 2859 | 8 | 2 | 6 | 9.4 | 18.8 | 88.0 | Excavation Damage |
| 870 | 6100 | 8 | 25.1 | 25.1 | 494.8 | 984.4 | 637.5 | Excavation Damage |
| 0.43 | 104 | 8.625 | 6 | 6 | 28.3 | 48.4 | 152.4 | Excavation Damage |
| 60 | 515 | 8.625 | 1 | 1 | 0.8 | 1.3 | 25.4 | Other Outside Force - Not Specified |
| 250 | 1825 | 8.625 | 1 | 5 | 3.9 | 6.7 | 56.8 | Excavation Damage |
| 15 | 205 | 10 | 5 | 5 | 19.6 | 25.0 | 127.0 | Excavation Damage |
| 50 | 446 | 10 | 1.5 | 0.5 | 0.6 | 0.8 | 22.0 | Excavation Damage |
| 60 | 515 | 10 | 0.3 | 13 | 3.1 | 3.9 | 50.2 | Excavation Damage |
| 60 | 515 | 10 | 1 | 3 | 2.4 | 3.0 | 44.0 | Excavation Damage |
| 150 | 1136 | 10 | 7.5 | 1.1 | 6.5 | 8.3 | 73.0 | Excavation Damage |
| 240 | 1756 | 10 | 2 | 2 | 3.1 | 4.0 | 50.8 | Excavation Damage |
| 82 | 667 | 10.75 | 3 | 2 | 4.7 | 5.2 | 62.2 | Excavation Damage |
| 33 | 329 | 12 | 11 | 4 | 34.6 | 30.6 | 168.5 | Excavation Damage |
| 60 | 515 | 12 | 3 | 3 | 7.1 | 6.3 | 76.2 | Excavation Damage |
| 100 | 791 | 12 | 2.3 | 2.5 | 4.5 | 4.0 | 60.9 | Excavation Damage |
| 100 | 791 | 12 | 3 | 3 | 7.1 | 6.3 | 76.2 | Excavation Damage |
| 225 | 1653 | 12 | 7 | 6.3 | 34.6 | 30.6 | 168.7 | Excavation Damage |

| MAOP | | Pipe Diameter (in) | Puncture Axial Length (in) | Puncture Circumferential Length (in) | Approx. Puncture Area (sq.in) | % of Cross-Section Area | Equiv. Hole Diameter (mm) | Cause |
|---|---|---|---|---|---|---|---|---|
| (psig) | (kPag) | | | | | | | |
| 0.64 | 106 | 12.75 | 2.5 | 2.5 | 4.9 | 3.8 | 63.5 | Other Outside Force - Not Specified |
| 15 | 205 | 12.75 | 6 | 6 | 28.3 | 22.1 | 152.4 | Excavation Damage |
| 170 | 1273 | 14 | 6 | 3 | 14.1 | 9.2 | 107.8 | Other Outside Force - Other Vehicle |
| 58 | 501 | 16 | 2.5 | 5 | 9.8 | 4.9 | 89.8 | Excavation Damage |
| 188 | 1398 | 16 | 4 | 4 | 12.6 | 6.3 | 101.6 | Excavation Damage |
| 300 | 2170 | 16 | 1.1 | 3.5 | 3.0 | 1.5 | 49.8 | Excavation Damage |
| 150 | 1136 | 20 | 5 | 1 | 3.9 | 1.3 | 56.8 | Excavation Damage |
| 400 | 2859 | 26 | 0.2 | 0.2 | 0.0 | 0.0 | 5.1 | Excavation Damage |

## B.2 Consequence Analysis Results for Representative Release Scenarios

Hazard ranges for the modelled release cases are tabulated in Sections B.2.1 to B.2.4

### B.2.1 Discharge Results

**Table 25 Discharge Results**

| Hole Size | Release rate [kg/s] | Release duration [s] | Release velocity [m/s] | Droplet diameter [um] | Release temperature [°C] | Liquid fraction | Release phase |
|---|---|---|---|---|---|---|---|
| 10mm MID | 3.36283 | 3600 | 27.8388 | 12.2374 | -88.572 | 0.526525 | Two phase |
| 25mm MID | 21.0177 | 3600 | 27.896 | 12.2374 | -88.572 | 0.526525 | Two phase |
| 75mm MID | 189.159 | 3600 | 77.104 | 12.2374 | -88.572 | 0.526525 | Two phase |
| 75mm TOP | 189.159 | 3600 | 223.95 | 12.2374 | -88.572 | 0.526525 | Two phase |
| 110mm MID | 406.902 | 2191.2 | 108.958 | 12.2374 | -88.572 | 0.526525 | Two phase |
| 110mm TOP | 406.902 | 2191.2 | 242.953 | 12.2374 | -88.572 | 0.526525 | Two phase |
| FBR | 262.322 | 833.634 | 18.3191 | 170.88 | -88.572 | 0.431467 | Two phase |

### B.2.2 Flash Fire Consequence Analysis Results

Flash fire consequences are summarised in Table 26 and Table 27.

**Table 26 Night Conditions Flash Fire Consequence Results @ 1.5m**

| Scenario | Weather | Distance to UFL [m] | Distance to LFL [m] |
|---|---|---|---|
| 10mm MID | Night 7.4D | 0.301073 | 0.494594 |
| | Night 4.1D | 0.262295 | 0.415784 |
| | Night 1.2D | 0.23986 | 0.37244 |
| | Night 2.6E | 0.245089 | 0.372118 |
| | Night 1.1F | 0.238525 | 0.360591 |
| 25mm MID | Night 7.4D | 0.605001 | 0.93528 |
| | Night 4.1D | 0.57235 | 0.928429 |
| | Night 1.2D | n/a | n/a |
| | Night 2.6E | 0.556368 | 0.8455 |
| | Night 1.1F | 0.73762 | 1.25107 |
| 75mm MID | Night 7.4D | 0.968616 | 1.40848 |
| | Night 4.1D | 0.899169 | 1.3634 |
| | Night 1.2D | n/a | n/a |
| | Night 2.6E | 0.987639 | 1.46125 |
| | Night 1.1F | 1.12651 | 1.65385 |
| 75mm TOP | Night 7.4D | 0.454121 | 0.669037 |
| | Night 4.1D | 0.483847 | 0.642223 |
| | Night 1.2D | 0.435344 | 0.57378 |
| | Night 2.6E | 0.402065 | 0.676163 |
| | Night 1.1F | 0.524944 | 0.681131 |
| 110mm MID | Night 7.4D | 1.09626 | 1.63582 |
| | Night 4.1D | 1.1312 | 1.60342 |
| | Night 1.2D | n/a | n/a |
| | Night 2.6E | 1.11351 | 1.66095 |
| | Night 1.1F | 1.17966 | 2.15482 |

| Scenario | Weather | Distance to UFL [m] | Distance to LFL [m] |
|---|---|---|---|
| 110mm TOP | Night 7.4D | 0.579839 | 0.880726 |
| | Night 4.1D | 0.636101 | 0.891684 |
| | Night 1.2D | 0.545465 | 0.737539 |
| | Night 2.6E | 0.648917 | 0.726443 |
| | Night 1.1F | 2.13096 | 2.4035 |
| FBR | Night 7.4D | 2.51792 | 4.00571 |
| | Night 4.1D | 2.47882 | 63.9235 |
| | Night 1.2D | n/a | 563.376 |
| | Night 2.6E | 5.44559 | 240.704 |
| | Night 1.1F | n/a | 760.342 |

**Table 27 Day Conditions Flash Fire Consequence Results @ 1.5m**

| Scenario | Weather | Distance to UFL [m] | Distance to LFL [m] |
|---|---|---|---|
| 10mm MID | Day 3.0B | 0.259096 | 0.40971 |
| | Day 7.4D | 0.302804 | 0.495874 |
| | Day 4.4D | 0.268108 | 0.422162 |
| | Day 1.8D | 0.244603 | 0.382835 |
| 25mm MID | Day 3.0B | 0.577187 | 0.905592 |
| | Day 7.4D | 0.605228 | 0.944331 |
| | Day 4.4D | 0.585518 | 0.903947 |
| | Day 1.8D | 0.565012 | 0.880377 |
| 75mm MID | Day 3.0B | 0.95049 | 1.39284 |
| | Day 7.4D | 0.971771 | 1.41828 |
| | Day 4.4D | 0.979143 | 1.40506 |
| | Day 1.8D | 0.955827 | 1.42497 |
| 75mm TOP | Day 3.0B | 0.436497 | 0.606146 |

| Scenario | Weather | Distance to UFL [m] | Distance to LFL [m] |
|---|---|---|---|
| | Day 7.4D | 0.450618 | 0.671614 |
| | Day 4.4D | 0.474869 | 0.583237 |
| | Day 1.8D | 0.459707 | 0.581716 |
| 110mm MID | Day 3.0B | 1.09541 | 1.58889 |
| | Day 7.4D | 1.09234 | 1.636 |
| | Day 4.4D | 1.05192 | 1.6399 |
| | Day 1.8D | 1.15754 | 1.45789 |
| 110mm TOP | Day 3.0B | 0.609834 | 0.725001 |
| | Day 7.4D | 0.574682 | 0.88837 |
| | Day 4.4D | 0.60875 | 0.758772 |
| | Day 1.8D | 0.606049 | 0.819511 |
| FBR | Day 3.0B | 2.63131 | 72.2279 |
| | Day 7.4D | 2.52719 | 4.00309 |
| | Day 4.4D | 2.5427 | 3.97845 |
| | Day 1.8D | n/a | 369.767 |

### B.2.3 Jet Fire Consequence Results

**Table 28 Night conditions downwind distance (m) to varying heat radiation levels @1.5m height**

| Scenario | Weather | Flame length [m] | 4.7 kW/m² | 12.5 kW/m² | 23 kW/m² | 35 kW/m² |
|---|---|---|---|---|---|---|
| 10mm MID | Night 7.4D | 15.4137 | 36.2344 | 25.7318 | 20.7212 | 17.3124 |
| | Night 4.1D | 17.5777 | 35.2043 | 22.905 | 18.3773 | 14.9506 |
| | Night 1.2D | 24.0439 | 31.4725 | 15.2168 | 5.16234 | 2.6527 |
| | Night 2.6E | 20.0051 | 33.0635 | 22.1309 | 15.2742 | 8.72711 |
| | Night 1.1F | 24.4283 | 30.9909 | 13.9378 | 4.52177 | 2.38346 |
| 25mm MID | Night 7.4D | 33.0057 | 82.8305 | 56.4073 | 43.2919 | 37.1495 |
| | Night 4.1D | 37.6394 | 80.3777 | 51.9729 | 40.7744 | 32.5507 |
| | Night 1.2D | 51.4859 | 74.1326 | 38.5215 | 15.1818 | 7.17755 |
| | Night 2.6E | 42.8375 | 76.9789 | 50.549 | 35.1405 | 21.9833 |
| | Night 1.1F | 52.309 | 73.3382 | 36.3914 | 7.80717 | 6.39315 |
| 75mm MID | Night 7.4D | 75.751 | 178.05 | 114.441 | 90.3438 | 75.0872 |
| | Night 4.1D | 86.3858 | 179.552 | 118.081 | 86.4133 | 62.5533 |
| | Night 1.2D | 118.165 | 188.858 | 95.5009 | 36.4659 | 10.3794 |
| | Night 2.6E | 98.3158 | 187.996 | 114.783 | 72.1621 | 39.3073 |
| | Night 1.1F | 120.054 | 187.668 | 92.3495 | 31.7884 | 11.1151 |
| 75mm TOP | Night 7.4D | 67.3769 | 134.771 | 88.2091 | 63.2512 | 43.1545 |
| | Night 4.1D | 76.836 | 137.002 | 79.182 | 42.6218 | 16.3195 |
| | Night 1.2D | 105.102 | 148.441 | 62.1582 | 9.32861 | 3.09274 |
| | Night 2.6E | 87.4472 | 141.502 | 72.6663 | 26.4795 | 7.7403 |
| | Night 1.1F | 106.782 | 149.42 | 60.2394 | 8.48664 | n/a |
| 110mm MID | Night 7.4D | 100.735 | 222.986 | 144.57 | 112.38 | 89.2663 |
| | Night 4.1D | 114.877 | 223.129 | 141.185 | 94.238 | 58.0945 |
| | Night 1.2D | 157.137 | 235.818 | 110.135 | 31.6694 | 10.3344 |

| Scenario | Weather | Flame length [m] | 4.7 kW/m² | 12.5 kW/m² | 23 kW/m² | 35 kW/m² |
|---|---|---|---|---|---|---|
| | Night 2.6E | 130.742 | 231.467 | 132.26 | 72.3049 | 30.331 |
| | Night 1.1F | 159.65 | 236.372 | 107.933 | 21.4508 | 9.24072 |
| 110mm TOP | Night 7.4D | 92.0788 | 178.495 | 114.712 | 78.5117 | 48.3914 |
| | Night 4.1D | 105.006 | 180.592 | 101.059 | 49.3176 | 17.4803 |
| | Night 1.2D | 143.634 | 195.571 | 75.8767 | 10.0053 | n/a |
| | Night 2.6E | 119.507 | 186.125 | 91.7839 | 28.4011 | 8.28061 |
| | Night 1.1F | 145.931 | 196.976 | 74.6552 | 8.96141 | 3.55963 |
| FBR | Night 7.4D | 95.025 | 216.794 | 141.098 | 111.62 | 93.9591 |
| | Night 4.1D | 108.366 | 244.581 | 158.814 | 122.425 | 97.0024 |
| | Night 1.2D | 148.23 | 243.251 | 140.582 | 77.666 | 42.1375 |
| | Night 2.6E | 123.331 | 246.722 | 161.296 | 115.688 | 82.0804 |
| | Night 1.1F | 150.6 | 242.675 | 137.609 | 73.2436 | 39.0828 |

**Table 29 Day conditions downwind distance (m) to varying heat radiation levels @1.5m height**

| Scenario | Weather | Flame length [m] | 4.7 kW/m² | 12.5 kW/m² | 23 kW/m² | 35 kW/m² |
|---|---|---|---|---|---|---|
| 10mm MID | Day 3.0B | 19.2096 | 33.8811 | 22.5711 | 16.7715 | 11.0687 |
| | Day 7.4D | 15.4137 | 36.2258 | 25.7269 | 20.7174 | 17.3105 |
| | Day 4.4D | 17.2438 | 35.4707 | 22.996 | 18.5843 | 15.5168 |
| | Day 1.8D | 22.0342 | 32.7303 | 19.9703 | 10.1044 | 4.67641 |
| 25mm MID | Day 3.0B | 41.1341 | 77.6455 | 51.4682 | 37.6553 | 26.1303 |
| | Day 7.4D | 33.0057 | 82.8017 | 56.3901 | 43.2775 | 37.1428 |
| | Day 4.4D | 36.9245 | 81.0255 | 52.2558 | 41.244 | 33.6189 |
| | Day 1.8D | 47.1823 | 76.3817 | 46.638 | 26.3797 | 12.8607 |
| 75mm MID | Day 3.0B | 94.4063 | 185.947 | 117.038 | 77.9057 | 48.3125 |
| | Day 7.4D | 75.751 | 177.96 | 114.396 | 90.3111 | 75.0537 |
| | Day 4.4D | 84.7449 | 179.156 | 117.818 | 87.5264 | 64.9061 |

| Scenario | Weather | Flame length [m] | 4.7 kW/m² | 12.5 kW/m² | 23 kW/m² | 35 kW/m² |
|---|---|---|---|---|---|---|
| | Day 1.8D | 108.288 | 191.596 | 107.961 | 56.3172 | 23.5816 |
| 75mm TOP | Day 3.0B | 83.9699 | 140.626 | 75.1901 | 31.4588 | 9.70718 |
| | Day 7.4D | 67.3769 | 134.706 | 88.1677 | 63.2112 | 43.1052 |
| | Day 4.4D | 75.3765 | 136.628 | 80.3778 | 45.3869 | 18.63 |
| | Day 1.8D | 96.3166 | 144.915 | 67.0353 | 16.006 | 4.1992 |
| 110mm MID | Day 3.0B | 125.543 | 230.34 | 136.198 | 79.4108 | 37.8202 |
| | Day 7.4D | 100.735 | 222.857 | 144.502 | 112.327 | 89.2086 |
| | Day 4.4D | 112.695 | 222.563 | 142.471 | 97.6457 | 62.3301 |
| | Day 1.8D | 144.003 | 234.49 | 122.192 | 49.8887 | 17.892 |
| 110mm TOP | Day 3.0B | 114.755 | 185.101 | 95.3717 | 34.971 | 10.643 |
| | Day 7.4D | 92.0788 | 178.397 | 114.648 | 78.4468 | 48.311 |
| | Day 4.4D | 103.011 | 180.272 | 102.8 | 54.6322 | 19.8216 |
| | Day 1.8D | 131.628 | 190.614 | 83.9181 | 17.0719 | 5.05714 |
| FBR | Day 3.0B | 118.427 | 247.658 | 163.523 | 120.893 | 90.122 |
| | Day 7.4D | 95.025 | 216.687 | 141.028 | 111.583 | 93.92 |
| | Day 4.4D | 106.307 | 241.124 | 156.029 | 121.05 | 96.6181 |
| | Day 1.8D | 135.84 | 245.53 | 153.517 | 99.4098 | 60.9654 |

### B.2.4 Explosion Consequence Analysis Results

**Table 30 Night conditions distance (m) to varying overpressures**

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| 25mm MID | Night 4.1D | 0.07<br>0.1379<br>0.2068 | 22.3334<br>Not reachable<br>Not reachable | 36.8812<br>0<br>0 |

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| | Night 1.2D | 0.07<br>0.1379<br>0.2068 | 29.8931<br>Not reachable<br>Not reachable | 49.9448<br>0<br>0 |
| | Night 2.6E | 0.07<br>0.1379<br>0.2068 | 23.8805<br>Not reachable<br>Not reachable | 39.7018<br>0<br>0 |
| | Night 1.1F | 0.07<br>0.1379<br>0.2068 | 29.4919<br>Not reachable<br>Not reachable | 49.0793<br>0<br>0 |
| 75mm MID | Night 7.4D | 0.07<br>0.1379<br>0.2068 | 45.3671<br>Not reachable<br>Not reachable | 74.056<br>0<br>0 |
| | Night 4.1D | 0.07<br>0.1379<br>0.2068 | 47.4054<br>Not reachable<br>Not reachable | 78.5124<br>0<br>0 |
| | Night 1.2D | 0.07<br>0.1379<br>0.2068 | 52.3269<br>Not reachable<br>Not reachable | 88.8059<br>0<br>0 |
| | Night 2.6E | 0.07<br>0.1379<br>0.2068 | 50.0521<br>Not reachable<br>Not reachable | 82.8301<br>0<br>0 |
| | Night 1.1F | 0.07<br>0.1379<br>0.2068 | 54.0368<br>Not reachable<br>Not reachable | 89.9293<br>0<br>0 |
| 75mm TOP | Night 7.4D | 0.07<br>0.1379<br>0.2068 | 34.6262<br>Not reachable<br>Not reachable | 56.8297<br>0<br>0 |
| | Night 4.1D | 0.07<br>0.1379<br>0.2068 | 32.9483<br>Not reachable<br>Not reachable | 55.6096<br>0<br>0 |

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| | Night 1.2D | 0.07<br>0.1379<br>0.2068 | 25.1721<br>Not reachable<br>Not reachable | 45.1571<br>0<br>0 |
| | Night 2.6E | 0.07<br>0.1379<br>0.2068 | 29.7696<br>Not reachable<br>Not reachable | 51.534<br>0<br>0 |
| | Night 1.1F | 0.07<br>0.1379<br>0.2068 | 30.1444<br>Not reachable<br>Not reachable | 52.6069<br>0<br>0 |
| 110mm MID | Night 7.4D | 0.07<br>0.1379<br>0.2068 | 63.2709<br>Not reachable<br>Not reachable | 102.074<br>0<br>0 |
| | Night 4.1D | 0.07<br>0.1379<br>0.2068 | 52.8512<br>Not reachable<br>Not reachable | 90.4023<br>0<br>0 |
| | Night 1.2D | 0.07<br>0.1379<br>0.2068 | 76.4359<br>Not reachable<br>Not reachable | 126.985<br>0<br>0 |
| | Night 2.6E | 0.07<br>0.1379<br>0.2068 | 56.5272<br>Not reachable<br>Not reachable | 96.4783<br>0<br>0 |
| | Night 1.1F | 0.07<br>0.1379<br>0.2068 | 72.9959<br>Not reachable<br>Not reachable | 120.38<br>0<br>0 |
| 110mm TOP | Night 7.4D | 0.07<br>0.1379<br>0.2068 | 50.1102<br>Not reachable<br>Not reachable | 82.1738<br>0<br>0 |
| | Night 4.1D | 0.07<br>0.1379<br>0.2068 | 49.2169<br>Not reachable<br>Not reachable | 82.3242<br>0<br>0 |

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| | Night 1.2D | 0.07<br>0.1379<br>0.2068 | 24.0175<br>Not reachable<br>Not reachable | 44.6749<br>0<br>0 |
| | Night 2.6E | 0.07<br>0.1379<br>0.2068 | 36.2312<br>Not reachable<br>Not reachable | 64.0848<br>0<br>0 |
| | Night 1.1F | 0.07<br>0.1379<br>0.2068 | 83.33<br>Not reachable<br>Not reachable | 121.526<br>0<br>0 |
| FBR | Night 7.4D | 0.07<br>0.1379<br>0.2068 | 85.7746<br>Not reachable<br>Not reachable | 135.304<br>0<br>0 |
| | Night 4.1D | 0.07<br>0.1379<br>0.2068 | 107.345<br>Not reachable<br>Not reachable | 170.756<br>0<br>0 |
| | Night 1.2D | 0.07<br>0.1379<br>0.2068 | 489.242<br>Not reachable<br>Not reachable | 452.409<br>0<br>0 |
| | Night 2.6E | 0.07<br>0.1379<br>0.2068 | 208.581<br>Not reachable<br>Not reachable | 249.833<br>0<br>0 |
| | Night 1.1F | 0.07<br>0.1379<br>0.2068 | 742.752<br>Not reachable<br>Not reachable | 488.282<br>0<br>0 |

**Table 31 Night conditions distance (m) to varying overpressures**

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| 25mm MID | Day 4.4D | 0.07<br>0.1379<br>0.2068 | 22.1318<br>Not reachable<br>Not reachable | 36.5145<br>0<br>0 |

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| | Day 1.8D | 0.07<br>0.1379<br>0.2068 | 25.9887<br>Not reachable<br>Not reachable | 43.3296<br>0<br>0 |
| 75mm MID | Day 3.0B | 0.07<br>0.1379<br>0.2068 | 31.4981<br>Not reachable<br>Not reachable | 56.1914<br>0<br>0 |
| | Day 7.4D | 0.07<br>0.1379<br>0.2068 | 45.5259<br>Not reachable<br>Not reachable | 74.2695<br>0<br>0 |
| | Day 4.4D | 0.07<br>0.1379<br>0.2068 | 47.1803<br>Not reachable<br>Not reachable | 78.0525<br>0<br>0 |
| | Day 1.8D | 0.07<br>0.1379<br>0.2068 | 53.479<br>Not reachable<br>Not reachable | 89.0413<br>0<br>0 |
| 75mm TOP | Day 3.0B | 0.07<br>0.1379<br>0.2068 | 26.9986<br>Not reachable<br>Not reachable | 47.3026<br>0<br>0 |
| | Day 7.4D | 0.07<br>0.1379<br>0.2068 | 34.8208<br>Not reachable<br>Not reachable | 57.0774<br>0<br>0 |
| | Day 4.4D | 0.07<br>0.1379<br>0.2068 | 33.8316<br>Not reachable<br>Not reachable | 56.6709<br>0<br>0 |
| | Day 1.8D | 0.07<br>0.1379<br>0.2068 | 24.2555<br>Not reachable<br>Not reachable | 43.4842<br>0<br>0 |
| 110mm MID | Day 3.0B | 0.07<br>0.1379<br>0.2068 | 55.9749<br>Not reachable<br>Not reachable | 95.4165<br>0<br>0 |

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| | Day 7.4D | 0.07<br>0.1379<br>0.2068 | 63.3773<br>Not reachable<br>Not reachable | 102.206<br>0<br>0 |
| | Day 4.4D | 0.07<br>0.1379<br>0.2068 | 67.17<br>Not reachable<br>Not reachable | 109.363<br>0<br>0 |
| | Day 1.8D | 0.07<br>0.1379<br>0.2068 | 72.5086<br>Not reachable<br>Not reachable | 119.854<br>0<br>0 |
| 110mm TOP | Day 3.0B | 0.07<br>0.1379<br>0.2068 | 32.4059<br>Not reachable<br>Not reachable | 58.0102<br>0<br>0 |
| | Day 7.4D | 0.07<br>0.1379<br>0.2068 | 50.2588<br>Not reachable<br>Not reachable | 82.3678<br>0<br>0 |
| | Day 4.4D | 0.07<br>0.1379<br>0.2068 | 49.0142<br>Not reachable<br>Not reachable | 81.924<br>0<br>0 |
| | Day 1.8D | 0.07<br>0.1379<br>0.2068 | 28.153<br>Not reachable<br>Not reachable | 51.4747<br>0<br>0 |
| FBR | Day 3.0B | 0.07<br>0.1379<br>0.2068 | 96.6122<br>Not reachable<br>Not reachable | 162.778<br>0<br>0 |
| | Day 7.4D | 0.07<br>0.1379<br>0.2068 | 86.2348<br>Not reachable<br>Not reachable | 135.932<br>0<br>0 |
| | Day 4.4D | 0.07<br>0.1379<br>0.2068 | 105.4<br>Not reachable<br>Not reachable | 167.14<br>0<br>0 |

| Scenario | Weather | Overpressure level [bar] | Maximum distance [m] | Diameter [m] |
|---|---|---|---|---|
| | Day 1.8D | 0.07 | 324.741 | 335.912 |
| | | 0.1379 | Not reachable | 0 |
| | | 0.2068 | Not reachable | 0 |

# Appendix C Likelihood Analysis - Data and Results

## C.1 Likelihood of Release from Underground Pipelines

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

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

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

Contribution from ground movement for local conditions are expected to be lower than reported in RR1035 since the local terrain is flat, with minimal slopes and significant water crossings. Therefore, the HSE data for ground movement was reduced to ¼ of its value, which is consistent with the data included in BSI PD 8010-3:2009+A1:2013.

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

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

- An analysis of pipeline failure data from multiple organisations, including:
  - CONCAWE (CONservation of Clean Air and Water in Europe);
  - UKOPA (United Kingdom Onshore Pipeline Operators' Association); and
  - EGIG (European Gas pipeline Incident Group).
- A conservative, yet realistic, analysis of the available data. For example:
  - For failure mode categories where zero failures have occurred, assumptions have been made to estimate the chance of a failure, even if not seen historically (over the observation period).

- Only the most recent 22 years of historical incident data was analysed to ensure a consistent pipeline population and to remove the older incident data, which may not be as representative of current practice.
- Incident data for pipelines carrying products at elevated temperatures was excluded from the analysis.
- Although the location of failures (e.g. rural or urban) may be recorded in the various databases, it is recognised that there is insufficient data to estimate the leak frequency for different locations.
- The recommended failure rates for specific materials have been derived from the most appropriate dataset (e.g. for a specific substance the failure rates for corrosion may derived from the CONCAWE products dataset, whilst the mechanical failure rates may be derived from the UKOPA dataset).

**NSW Performance Report**

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

**UK HSE (RR1035)**

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

The total leak frequency data reported in Section 7.6 of RR1035 for underground LPG pipelines is slightly more conservative (e.g. 2.1E-04 per km per year for a pipeline with wall thickness ≥ 5 mm to < 10 mm) and was adopted in the QRA for the underground HP Ethane pipeline (Refer to Table 32).

**Table 32 Leak Frequencies for Underground LPG Pipelines**

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

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

The data and approach included in Annex B of PD 8010-3:2009+A1:2013 was used to estimate the leak frequencies for the Moomba to Sydney Ethane Pipeline (Refer to Table 33). The data applicable for a pipeline with a wall thickness of 8.1 mm, manufactured after 1980, was used.

Leak frequency data is not reported for internal corrosion; therefore, the total leak frequencies reported in Table 33 may be underestimated.

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

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

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

The rupture frequency due to 'TPA' was derived from the generic pipeline failure frequency, which was modified in accordance with the relevant parameters for the Moomba to Sydney Ethane Pipeline (i.e. location, design factor, wall thickness and depth of cover). As this pipeline has concrete slab protection and marker tapes, the base rupture frequency was reduced by a factor of 0.125 (Table A.0, p.31).

**Table 33 Approx. Leak Frequencies for Underground Ethane Pipeline**

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

**US Department of Transportation (DoT)**

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

To enable a comparison with the UK data, the data for all Highly Volatile Liquids (Except Ammonia) was analysed and the leaks categorised using the same representative hole sizes as reported in the UK (i.e. RR1035 and PD8010). The results are reported in Table 34.

.

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

**Table 34 Leak Frequencies for Underground HVL Pipelines (Excluding Ammonia)**

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

## C.2 Ignition Probability

The ignition probabilities adopted in the risk analysis are listed below. This was based on a review of relevant ignition probability data and ignition probability correlations (Refer to Sections C.2.1 - C.2.3).

**Ethane**

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

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

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

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

**Natural Gas**

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

   The correlation proposed by Acton & Baldwin (Refer to Section C.2.4) is more conservative for smaller leaks; however, the OGP data is more conservative for ruptures and is more consistent with the EGIG and UK HSE data (Refer to Section C.2.4) for the calculated full bore rupture release rates.

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

The OGP data assumes an immediate ignition probability of 0.001. A 50:50 split appears to be more consistent with other data sources (e.g. Acton & Baldwin, UK HSE – Refer to Section C.2.4).

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

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

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

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

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

**Table 35 Ignition Probability - UKOPA**

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

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

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

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

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

**Table 36 Ignition Probability – OGP Scenario 3**

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

### C.2.2 Ignition Probability Data for Underground Cross-Country Pipelines – Flammable or Combustible Liquids

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

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

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

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

(1) Not otherwise reportable under this section;

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

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

(4) Cleaned up promptly;

(c) Death of any person;

(d) Personal injury necessitating hospitalisation;

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

**Table 37 Ignition Probability – US DoT**

| Liquid | Leak | Mechanical Puncture | Other | Rupture | Total |
|---|---|---|---|---|---|

| | # with Ignition | # with no ignition | Prob. of Ignition | # with Ignition | # with no ignition | Prob. of Ignition | # with Ignition | # with no ignition | Prob. of Ignition | # with Ignition | # with no ignition | Prob. of Ignition | # with Ignition | # with no ignition | Prob. of Ignition |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HVLs * | 0 | 46 | 0.0 | 0 | 7 | 0.0 | 4 | 2 | 0.7 | 5 | 5 | 0.5 | 9 | 60 | 0.13 |

* Highly Volatile Liquids (Includes Ethane).

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

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

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

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

**Table 38 Ignition Probability – UK HSE (RR 1034)**

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

(1) For example: ethylene

(2) For example: butane, ethane and propane

(3) For example: ammonia, carbon monoxide

### C.2.4 Ignition Probability Data for Underground Cross-Country Pipelines – Natural Gas

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

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

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

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

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

$P_{ign}$ = probability of ignition

p = pipeline operating pressure (bar)

d = pipeline diameter for ruptures (m)

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

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

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

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

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

**Table 39 Ignition Probability – Acton & Baldwin**

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

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

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

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

**Table 40 Ignition Probability – EGIG**

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

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

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

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

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

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

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

**Table 41 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 42 Ignition Probability – Data Cited by UK HSE (RR 1034)**

| Data source | Ignition probability | |
|---|---|---|
| World-wide, Townsend & Fearnehough (1986) | Leaks | 0.1 |
| | Ruptures | 0.5 |

| | | |
|---|---|---|
| US Gas, Jones (1986) | Ruptures | 0.26 |
| | All sizes | 0.16 |
| European Gas, European Gas Pipeline Incident Data Group (1988) | Pinholes / cracks | 0.02 |
| | Holes | 0.03 |
| | Ruptures < 16” | 0.05 |
| | Ruptures ≥ 16” | 0.35 |
| | All sizes | 0.03 |

## C.3 Likelihood of Representative Release Scenarios

The estimated likelihood of each representative release scenario is listed in Table 43.

**Table 43 Release Frequency – Ethane Pipeline (MSE)**

| Leak Scenario | Release Frequency (per km per year) | | | Probability of scenario compared to total |
|---|---|---|---|---|
| | TPA | All Other Failure Modes | Total Release Frequency | |
| 10mm MID | | 1.53E-04 | 1.53E-04 | 0.7200 |
| 10mm TOP | | 0.00E+00 | 0.00E+00 | 0.0000 |
| 25mm MID | 2.20E-05 | | 2.20E-05 | 0.1036 |
| 25mm TOP | 0.00E+00 | | 0.00E+00 | 0.0000 |
| 75mm MID | 2.40E-06 | 5.94E-06 | 8.34E-06 | 0.0393 |
| 75mm TOP | 0.00E+00 | 1.01E-05 | 1.01E-05 | 0.0476 |
| 110mm MID | 1.00E-07 | 2.70E-06 | 2.80E-06 | 0.0132 |
| 110mm TOP | 0.00E+00 | 4.60E-06 | 4.60E-06 | 0.0217 |
| FBR | 1.00E-07 | 1.15E-05 | 1.16E-05 | 0.0547 |
| Total | 2.46E-05 | 1.88E-04 | **2.124E-04** | 1.0000 |