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Estimating failure frequencies for above-ground pipelines

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Executive Summary

GL was commissioned by RIVM to undertake a study to assist with a review being undertaken to derive gas release scenarios and frequencies for above-ground, high pressure, pipelines within the site boundary of a natural gas installation, for use in Quantified Risk Assessment (QRA) calculations for Land Use Planning purposes. Following meetings held with RIVM and other participants in the project, it was agreed that the focus of the study should be on those scenarios that determine the risk to the public well outside the site boundary; in particular full bore ruptures of, or releases from large holes in, above ground high pressure pipelines.

The study by GL was undertaken in two parts:

1. A survey of different databases and other possible sources of failure frequency information for the project, including an assessment of the suitability or otherwise of each.
2. Analysis of the possibility of adapting data and methodologies for buried cross-country natural gas transmission pipelines to above ground pipelines within an enclosed site.

The survey confirmed that the available sources of data for estimating leak frequencies of onshore gas storage sites are limited, largely because of the rarity of the events themselves. The UK HSE has, since 1992, collected detailed data on hydrocarbon releases on offshore platforms in the UK North Sea, in response to recommendations made following the Piper Alpha disaster in 1988. This HCR database provides a high quality, statistically significant, dataset for the derivation of leak frequencies for pipework and equipment on offshore installations. However, the focus of the present study is on the possibility of full bore ruptures or releases from very large holes in above-ground pipelines in particular, because it is these large releases that are most likely to give rise to consequences affecting the local population beyond the site boundary. It is these major events which will hence influence decisions on the extent and nature of developments permitted in the vicinity of natural gas installations. Values currently used by the regulatory authorities in The Netherlands and the UK are largely based on experience in other industries (e.g. chemical process industries) and judgement, and hence it is appropriate to consider alternative approaches to deriving suitable frequencies for these scenarios for natural gas installations.

Two possible approaches are described for estimating failure frequencies for above-ground pipelines; one a modified version of the methodology used by the UK HSE to derive failure frequencies for above-ground pipelines applied in risk calculations for land-use planning purposes; the other at RIVM's request using generic historical data for below-ground gas transmission pipelines in Europe (EGIG) complemented by a simple model (SPIDER) for the failure frequencies due to impacts.

Both methods result in failure frequencies being predicted for large gas releases from above-ground pipelines which are only weakly influenced by pipeline-specific or site-specific parameters due to the nature of the available historical data for failures due to material or construction faults, corrosion or other causes. Using EGIG historical data, averaged over the whole pipeline population, could lead to significant overestimates of the risk beyond the site boundaries in cases where large diameter pipelines are present. Ideally, in the future, sufficient data would be collected and shared between gas companies to allow statistics to be derived to validate failure frequency estimates for above-ground pipelines at gas installations.

Contents

1 Introduction

GL was commissioned by RIVM to undertake a study to assist with a review being undertaken to derive gas release scenarios and frequencies for above-ground, high pressure, pipelines within the site boundary of a natural gas installation, for use in Quantified Risk Assessment (QRA) calculations for Land Use Planning purposes. Following meetings held with RIVM and other participants in the project, it was agreed that the focus of the study should be on those scenarios that determine the risk to the public well outside the site boundary; in particular full bore ruptures of, or releases from large holes in, above-ground high pressure pipelines.

The study by GL was undertaken in two parts:

1. A survey of different databases and other possible sources of failure frequency information for the project, including an assessment of the suitability or otherwise of each.
2. Analysis of the possibility of adapting data and methodologies for buried cross-country natural gas transmission pipelines to above ground pipelines within an enclosed site.

The output from the survey of databases and other possible sources of data is summarised in Section 2, with further details in Appendix A. The analysis of the possibility of developing a suitable approach by analogy with methodologies applied to buried cross-country natural gas transmission pipelines is presented in the main body of the report, with recommendations on how existing approaches may be adapted and extended in order to be applicable to on-site situations.

2 Sources of Data for Failure Frequencies of Above-Ground Pipelines

2.1 Historical Data

The onshore gas industry worldwide has a good safety record, and accidents are rare. Accidents involving onshore gas installations (including underground gas storage sites) have occurred, but in the vast majority of cases, the consequences have been contained within the site boundary. There are a number of sources of incident data for cross-country pipelines, as a result of collaboration between pipeline companies in Europe [1] and the UK [2]. These provide statistical information to demonstrate that the level of risk to the public from high pressure gas pipelines is extremely low, and provide a valuable source of historical data in order to estimate failure frequencies for the purposes of risk assessment.

A review has been carried out of possible sources of historical data relevant to above-ground installations (AGIs), reported in Appendix A. However, the main conclusion was that there is no equivalent publicly-available source of historical failure statistics for onshore high pressure gas installations and above-ground pipelines in particular. Incidents involving such installations are very rare events and whereas cross-country pipelines cross land over which the operator has limited control (and hence are vulnerable to third party damage, with possible consequences for members of the public living nearby); an installation is contained within a controlled site, with access restricted to authorised personnel only. This means that failure frequency data for use in risk assessments is extremely limited, and risk assessments of onshore sites often make use of data derived from offshore operations involving comparable pipework and associated equipment, for example the HCR Database published by the UK HSE covering offshore installations in the North Sea [3]. A review and analysis of this data has been undertaken by DNV previously [4] and revisited as part of the current project for RIVM [5].

It should be borne in mind that offshore data, even for comparable pipework and associated equipment to an onshore AGI, encompasses a range of failure causes that may not all be applicable to an onshore site. However, regardless of the applicability of the offshore data to derive leak frequencies for onshore sites, it contains no data for full bore pipeline ruptures, and therefore is of limited value for determining the frequencies for the major events with the potential for significant off-site consequences, which is the key issue for Land Use Planning purposes and the focus of the present project for RIVM.

2.2 Generic Data

Possible sources of generic data for use in risk assessments for Land Use Planning purposes are considered in a European Commission publication [6]. Two main sources identified are the Dutch “Purple Book” [7] (since superseded by the Bevi Manual [8]) and failure frequencies used by the UK HSE [9]. Values given in the Purple Book were set by consensus following discussions between representatives from industry, the authorities and the government. Similarly, the values used by HSE also rely on expert judgement to some extent. The HSE values make an important distinction between “Pipework” (typically characterised by large numbers of flanged connections, instrumentation tappings with associated small bore pipework and/or significant pressure and temperature changes within the system) and “Above Ground Pipelines” (applicable only to natural gas installations and relating to pipelines which are essentially identical to buried gas transmission pipelines, but above-ground and within a controlled site). The generic values for process pipework were generally derived from data from the chemical process industries (for example chlorine, LPG and nuclear are cited as sources for the HSE values) and not natural gas operations. Furthermore, the HSE values for large diameter pipework were derived by extrapolation from data for small diameter pipework by applying expert judgement. The HSE values for above-ground pipelines were derived using a fault tree approach (see Appendix B) with judgement applied to a number of key inputs.

A summary of relevant generic failure frequency values that are used in risk assessments of natural gas installations is given in Table 1. These values are 'generic' in the sense that they refer to 'average of class' and do not take account of site-specific variations or any extra protective systems that a specific operator might install.

For a full QRA including an assessment of the risk on, or immediately surrounding, the site itself, additional values are required for lower consequence, higher frequency events such as small holes or leaks from flange connections, for example. As described in the previous section, offshore data is typically used to derive values for smaller leak frequencies, because it is well-documented and sufficiently extensive for statistical analysis.

Table 1: Generic Failure Frequencies for Above-Ground Pipework/Pipelines

Frequencies x 10^{-6} per m per year	TNO Purple Book[1] (Bevi Reference Manual [8])			HSE LUP[2]					
				Process Pipework					Above-ground Pipelines
Diameter (mm)	<75	75<150	>150	0-49	50-149	150-299	300-499	500-1000	**All**
Full Bore Rupture	1	0.3	0.1	1	0.5	0.2	0.07	0.04	0.0065
Leak from hole 10% of pipe diameter (maximum 50mm)	5	2	0.5						
3mm				10	2				
4mm						1	0.8	0.7	
25mm						0.7	0.5	0.4	
1/3 pipe diameter						0.4	0.2	0.1	
110mm									0.033
75mm									0.067
25mm									0.163

Note 1: Frequencies include flange leaks. Minimum length 10m. See Ref [7].

Note 2: Frequencies understood to exclude flange leaks. See Ref [9].

2.3 Summary

The review of published data confirmed that the available sources of data for estimating leak frequencies of onshore gas storage sites are limited, largely because of the rarity of the events themselves. The UK HSE has, since 1992, collected detailed data on hydrocarbon releases on offshore platforms in the UK North Sea, in response to recommendations made following the Piper Alpha disaster in 1988. This HCR database provides a high quality, statistically significant, dataset for the derivation of leak frequencies for pipework and equipment on offshore installations.

However, the focus of the present study is on the possibility of full bore ruptures or releases from very large holes in above-ground pipelines in particular, because it is these large releases that are most likely to give rise to consequences affecting the local population beyond the site boundary. It is these major events which will hence influence decisions on the extent and nature of developments permitted in the vicinity of natural gas installations. Values currently used by the regulatory authorities in The Netherlands and the UK are largely based on experience in other industries (e.g. chemical process industries) and judgement, and hence it is appropriate to consider alternative approaches to deriving suitable frequencies for these scenarios for natural gas installations, as considered in the next section.

3 Derivation of Failure Frequencies by Analogy with Gas Transmission Pipelines

3.1 Threats to Onshore Pipelines

3.1.1 Buried Pipelines

There is considerable shared experience of the operation of high pressure natural gas transmission pipelines in Europe, recorded since 1970 by EGIG [1] which analyses statistics on gas loss incidents from buried steel transmission pipelines operated in fifteen different countries (including The Netherlands). Gas loss incidents are identified by EGIG as due to one of the following causes, with the percentage contribution to the total number of incidents (i.e. from small leaks to full bore ruptures) given in brackets:

- External interference (49.6%)
- Construction defect/material failure (16.5%)
- Corrosion (15.4%)
- Ground Movement (7.3%)
- Hot-tap made by error (4.6%)
- Other and unknown (6.7%)

In common with the experience of buried cross-countries pipelines operated by other industries, external interference is the most common cause of pipeline failures. Importantly, it is by far the most common cause of pipeline ruptures, and it is these events which dominate the risk, particularly at significant distances from a pipeline. The next most significant cause of pipelines ruptures is ground movement, which tends to be a localised threat in specific areas of land instability (for example, unstable slopes in mountainous areas or at river crossings or in areas of subsidence due to mining activities).

The experience captured in EGIG also demonstrates the importance of taking location-specific and pipeline-specific factors into account. For example, the location class of the pipeline (e.g. rural or suburban) influences the likelihood of third party activities taking place which may damage a pipeline. Similarly, the depth of cover will influence the likelihood of a pipeline being struck by such activities. The operating pressure, diameter, wall thickness and steel properties will influence the resistance of the pipeline to damage, whatever the cause.

In order to take these important factors into account, many companies and regulatory authorities now use predictive methods for estimating the failure frequencies used in risk assessments of pipelines, focussed on external interference as the dominant threat in terms of risk, which build on the historical experience captured in pipeline databases as described in Section 3.2.

3.1.2 Above-ground Pipelines

The threats to above-ground pipelines have similarities to those for buried pipelines; however, there are obvious differences due to their location within a controlled site, which would be expected to prevent accidental third party damage in all but the most extreme situations (e.g. aircraft crash). Also, because above-ground pipelines are clearly visible, any accidental damage would result from a failure of control over an operation within the site (e.g. vehicle movements or lifting operations), rather than an accidental impact due to a lack of awareness of the presence of the pipeline (as is often the case for buried pipelines).

In principle, the codes and standards followed in the design and maintenance of above-ground pipelines are similar to those applied to buried pipelines. For example, the quality of the steel, methods of welding and inspection and testing regimes will be similar and the threat from construction defects or material failures is similar to buried pipelines.

In terms of corrosion, there will be differences due to the exposure of the pipeline above ground and the absence of cathodic protection. The transition point where a buried pipeline comes above-ground is vulnerable to corrosion and must be monitored. Nevertheless, there are similarities with buried pipelines; for example, any corrosion is likely to develop as a small leak in the first instance, which should be detected before a major release of gas takes place, and the possibility of a rupture of an above-ground pipeline due to corrosion may be considered to be remote provided that appropriate precautions are taken.

The locations of above-ground installations are carefully chosen using a number of criteria and one of the main ones is the suitability and stability of the terrain. This means that it is unlikely that an above-ground installation would be constructed in an area of land instability (unlike buried pipelines, where it may be impractical to completely avoid areas with land stability issues in order to connect parts of a pipeline system). Hence, the threat from ground movement should be very much less for above-ground pipelines than buried pipelines, other than in unusual site-specific circumstances.

Above-ground pipelines may be exposed to additional threats, which are not normally relevant to buried pipelines. These include the threat from escalation (or “domino effects”) whereby a fire or explosion caused by a small leak (perhaps from an adjacent process area) results in a more severe failure of a large pipeline. (This threat is only relevant for buried pipelines where there is a parallel pipeline installation, with the possibility of interaction between two pipelines.) Another aspect to be considered is that above-ground pipelines may not be all-welded as is the case for buried pipelines, but may have flanged connections, which should be considered separately from the main body of the pipeline.

Finally, it is recognised that there is a possibility of failures due to deliberate attacks (terrorism), for which an above-ground installation is a more visible target than a buried pipeline, although it is also easier to protect and monitor an installation. However, this cause is not usually included in QRA’s of operational pipelines or installations, and is not considered further here.

3.2 Methodologies for Failure Frequencies of Buried Transmission Pipelines

The methodology for risk assessments of buried gas transmission pipelines used by Gasunie in The Netherlands and other companies, including National Grid in the UK, is based around the PIPESAFE package. PIPESAFE is a knowledge-based, integrated risk assessment package for gas transmission pipelines, developed by GL on behalf of a collaboration of gas transmission pipeline companies [10]. The approach followed by the UK gas industry in deriving failure frequencies is documented in guidance published by The Institution of Gas Engineers and Managers (IGEM/TD/2) [11]. [N.B. This was developed following work undertaken by the UK Onshore Pipeline operators Association (UKOPA) and the approach is not necessarily shared by HSE.].

The methodology combines historical incident data for gas transmission pipelines with a structural reliability model for external interference damage (FFREQ). FFREQ is a well-established mathematical model for the prediction of pipeline failure frequencies due to external interference originally developed in the 1980’s [12]. It combines historical data on the frequency and severity of damage (using Weibull distributions for the length and depth of gouges and gouges in dents) with a structural model that determines the severity of damage required to cause failure of the pipeline in question. This method allows the influence of the main pipeline-specific parameters (nominal pipeline diameter, pressure, wall thickness, material grade and toughness) on failure probability, given a hit, to be quantified. FFREQ divides damage into two types; gouges and dent/gouges, and calculates the failure frequency for each type independently, then combines them to give the overall failure frequency. The model uses separate damage distributions and incident rates for pipelines in Rural areas and Suburban areas. The distributions are constructed from records of damage that have occurred on the UK transmission system. Hit rates are higher in Suburban areas than Rural areas, reflecting the larger number of activities taking place. For application in The Netherlands, a modified version is used by Gasunie which takes account of the different historical experience of pipeline interference damage rates between the two countries.

Because the threat of pipeline rupture due to external interference dominates the risk from buried gas transmission pipelines, this is modelled in more detail than the failure frequencies for other causes, which are derived from the collective historical experience of the UKOPA companies, published annually [1]. It is also possible to apply an equivalent structural reliability approach to the prediction of failure frequencies due to corrosion (taking account of potential corrosion growth rates and the ability of an individual pipeline to withstand corrosion damage) where this is considered appropriate and the calculated values used in place of the historical values. A structural reliability model for corrosion is also included in PIPESAFE.

The UK HSE applies an equivalent approach to the derivation for failure frequencies for buried pipelines using a software package known as PIPIN (PIPeline INtegrity) [9]. PIPIN follows a similar approach to IGEM/TD/2, in that a structural reliability model, which takes account of the location and pipeline-specific properties, is used to predict the failure frequencies for external interference, whilst the failure frequencies for other causes are derived from UK historical experience.

3.3 Analogous Approaches for Above-Ground Pipelines

3.3.1 HSE LUP Methodology

The derivation of the HSE failure frequency values for above-ground natural gas pipelines described in Section 2.2 has been made available by HSE for this project, and is reproduced in Appendix B. This fault tree approach, documented in 2004, is based on consideration of the threats to above-ground pipelines by comparison with those for buried pipelines.

The same values are assumed for the failure frequencies due to material/construction (“mechanical”) faults and corrosion for above-ground pipelines as for buried pipelines, although it is noted that these assumptions should be reconsidered if the contributions from mechanical or corrosion become significant.

The dominant contribution to the failure frequencies is associated with an “External Event”, sub-divided as:

- Vehicle impact
- Lifting operation
- Natural events
- Aircraft crash

Of these, the dominant contributions to the failure frequencies are from vehicle impacts and impacts during lifting operations (dropped objects), analogous to the dominant contribution from impacts resulting from external interference in the case of buried pipelines. Impact during lifting operations is the main contributor to the predicted failure frequencies. Vehicle impacts are considered to arise either from internal vehicle movements within the site or from external vehicles which lose control and breach the site boundary at sufficient speed to cause a significant impact. Internal vehicles dominate the failure frequency values for vehicle movements.

Table 2 below summarises the contributions from each cause to the overall frequencies calculated by HSE. With the exception of pinholes, the failure frequencies for all release scenarios are essentially determined by the failure frequencies predicted for external events.

Table 2: Derived Failure Frequencies (from HSE document by S C Pointer, July 2004)

	Failure Frequencies per m per year			
	External events	Mechanical	Corrosion	Total
Rupture	6.5×10^{-9}	8×10^{-12}	1×10^{-11}	6.5×10^{-9}
Large Hole	3.3×10^{-8}	8×10^{-12}	1×10^{-11}	3.3×10^{-8}
Small Hole	6.7×10^{-8}	2×10^{-11}	1×10^{-11}	6.7×10^{-8}
Pin Hole	7.2×10^{-8}	9×10^{-8}	1×10^{-9}	16.3×10^{-8}

In addition, the document supplied by HSE and reproduced in Appendix B allows the contribution of each of the external events to be identified. [Note that in the HSE analysis, it is assumed that each installation includes a 20m length of above-ground pipeline in order to convert per installation event frequencies to per metre frequencies.] For example, the individual contributions from each of the external events considered in the fault tree analysis are presented in Table 3. There appears to be a minor calculation error in the HSE fault tree (Figure 1 in Appendix B) which leads to an incorrect overall total for ruptures, leading to the apparent discrepancy between Table 3 and Table 2.

Table 3: Contribution of External Events to Derived Failure Frequencies

	Failure Frequencies per m per year					
	Lifting	Vehicles (internal)	Vehicles (external)	Natural events	Aircraft crash	Total
Rupture	5×10^{-9}	1.5×10^{-9}	2.5×10^{-11}	4×10^{-10}	2.5×10^{-10}	7.175×10^{-9}
Large Hole	2.5×10^{-8}	7.5×10^{-9}	1.25×10^{-10}	1.8×10^{-10}	2.5×10^{-10}	3.3055×10^{-8}
Small Hole	5×10^{-8}	1.5×10^{-8}	2.5×10^{-10}	1.8×10^{-9}	0	6.705×10^{-8}
Pin Hole	5×10^{-8}	1.5×10^{-8}	2.5×10^{-10}	7.2×10^{-9}	0	7.245×10^{-8}
Total (all sizes)	1.3×10^{-7}	3.9×10^{-8}	6.5×10^{-10}	9.58×10^{-9}	5×10^{-10}	1.7973×10^{-7}

Note: No rounding has been applied to these values to facilitate consistency checks

As is apparent from Table 3, the overall failure frequencies for ruptures and large holes are essentially determined by the frequencies predicted for impacts during lifting and impacts from internal vehicle movements.

These in turn are strongly influenced by assumptions made in the analysis, based on a combination of limited evidence from related industries and judgement.

These include the assumption of 10 lifting operations in the vicinity of the above-ground pipeline per year and a 1 in 10 chance that the object is dropped directly onto the pipeline. Given an impact, the probability of a rupture is 1 in 1000 based on judgement. The probability that an object is dropped is 1 x 10^{-4} based on experience. Similarly, it is assumed that 500 vehicle movements take place within the site per year and the probabilities for a vehicle travelling at sufficient speed to break through barriers and cause a pipeline to fail is based on judgement. As noted above, the assumed length of above-ground pipeline is important because the main contributions are from events which are estimated per site per year, which are then converted to a frequency per metre per year using the assumed length of above-ground pipeline present (20m in the HSE analysis).

3.3.2 Possible Modifications to HSE Approach

The approach developed by HSE takes into account all of the main threats to above-ground (welded) pipelines, with the exception of escalation (domino effects). However, the assumptions used in the HSE analysis appear to be generally cautious.

The key disadvantage of the approach is that the output takes the form of single recommended values for above-ground pipelines:

The output takes no account of site-specific factors, e.g.

- The actual numbers of internal vehicle movements (which may not take place at all on some sites or at a much lower frequency than assumed).
- The layout of individual sites (which may be designed to avoid the need for lifting operations over an above-ground pipeline to take place at all).

Similarly, the output takes no account of pipeline-specific factors which govern the ability of a particular pipeline to withstand an impact, for example the pipeline wall thickness, diameter or the strength of the material.

3.3.2.1 External events

For buried pipelines, the dominant contribution to the risk (external interference) is modelled in a way that takes account of the frequency of impacts (e.g. the influence of location class, depth of cover, effectiveness of surveillance, etc.), the severity of impacts (from historical damage distributions) and the ability of the pipeline to withstand the damage (from a fracture mechanics treatment which takes account of the pipeline-specific properties).

By analogy with buried pipelines, it may be appropriate to adapt the HSE methodology to allow site-specific factors to be taken into account and to consider whether it may also be practical to take into account the ability of an above-ground pipeline to withstand damage.

As a minimum, it should be possible to make simple modifications to adapt the HSE approach for impacts due to internal vehicle movements and lifting in order to take account of the actual lengths of above-ground pipeline present, the number of vehicle movements within a site per year and the number of lifting operations taking place over the above-ground pipeline per year. This could be achieved by coding up the

HSE approach in a simple spreadsheet, as the key inputs to the model are simple multipliers of the frequencies, i.e.

- Length of above-ground pipeline (20m assumed)
- Number of internal vehicle movements per year (500 assumed)
- Number of lifting operations in the vicinity of the pipeline per year (10 assumed)

So, for example, if a site is unmanned and is visited only once per week by an inspection and maintenance team with a vehicle on site, then the number of internal vehicle movements per year will be 50 and the predicted frequencies due to an impact from an internal vehicle movement will be reduced by an order of magnitude. Similarly, if lifting operations in the vicinity of the above-ground pipeline take place annually, then the number of lifting operations will be one per year and the corresponding failure frequencies due to dropped objects from lifting would also be reduced by an order of magnitude.

The other external events included in the HSE methodology are external vehicle impacts, natural causes and aircraft crash. These all make a small contribution to the predicted frequencies for large releases as currently presented, but they may become important if the contributions from internal vehicles and lifting are reduced significantly. However, it could be argued that failures due to each of these other events require site-specific conditions to be present in order to be relevant:

- External vehicle impact – this assumes that the site is adjacent to a major road, with vehicles travelling at sufficient speed to breach the site boundary and cause an impact. Therefore, the contribution from this cause may only be appropriate if the site is adjacent to a major road.
- Aircraft crash – this is a possibility for any location, but it is more likely to occur where a site is located under a designated flight paths (for example the approaches to an airport). The contribution from this may be insignificant compared to other causes except for sites under a flightpath, and so it may be appropriate to include the contribution from this threat only in such cases.

3.3.2.2 Mechanical (material/construction)

The contributions from material and construction faults to the overall frequencies for large releases in Table 2 are several orders of magnitude less than those from external events. In fact, even though the values used by HSE are small, they are cautious compared with guidance for buried natural gas transmission pipelines published more recently in IGEM/TD/2 [20] based on extensive UK operational experience.

An alternative approach, suggested by RIVM, could be to derive appropriate values from historical data for incidents on below-ground transmission pipelines published by EGIG [1]. EGIG provides a breakdown of gas release incidents by cause, including “construction defects/material failure” and gives incident frequencies calculated for the whole dataset (from 1970) and a 5-year moving average. The more recent data should be a better reflection of the current position in terms of asset integrity management than including data from the whole period. By using the whole exposure, data would be included from a period that predates current asset integrity management practices and would be potentially misleading. It is clear from Figures 15 and 16 in the EGIG report that there have been significant improvements since the 1970s for all threats and therefore the 5-year moving average was used to derive frequencies in the following analysis.

From Figure 16 in the 7th EGIG report [1], the total failure frequency (all failure modes) in 2007 for material and construction faults expressed as a 5-year moving average is estimated to be approximately 1.6×10^{-8} per m.yr.

EGIG sub-divides gas release incidents into three hole sizes:

1. Pinhole/crack: The diameter of the hole is smaller than or equal to 2cm
2. Hole: The diameter of the hole is larger than 2cm and smaller than or equal to the diameter of the pipe.
3. Rupture: The diameter of the hole is larger than the pipeline diameter.

Examination of Figure 17 in the 7th EGIG report indicates that approximately 8% of all gas release incidents due to material and construction faults were ruptures, 24% large holes and the remainder (68%) pinholes or small cracks. Thus, the following failure frequencies for material and construction faults may be derived:

- Rupture: 1.3×10^{-9} per m.yr
- Large hole (>2cm in diameter): 3.8×10^{-9} per m.yr
- Pinhole/crack: 1.09×10^{-8} per m.yr

However, it should be noted that in the EGIG data, there is a strongly reducing trend for failures due to material and construction faults for newer pipelines, such that very few failures are recorded for any pipelines built after 1984 and none as ruptures. This is likely to be due to improved quality control of the steel manufacturing and of improved methods of welding, inspection and testing in the field, many of which would apply equally to above-ground pipelines.

3.3.2.3 Corrosion

Similarly, the contribution from corrosion to the overall frequencies for large releases in Table 2 is several orders of magnitude less than those from external events. Again, although the values used by HSE are small, they are cautious compared with the guidance for buried gas transmission pipelines in IGEM/TD/2.

A similar approach to that described in the previous section may be followed to derive corrosion failure frequencies based on analysis of EGIG data. From Figure 16 in the 7th EGIG report [1], the total failure frequency (all failure modes) in 2007 for corrosion expressed as a 5-year moving average is estimated to be approximately 2.2×10^{-8} per m.yr.

Examination of Figure 17 in the 7th EGIG report suggests that no gas release incidents due to corrosion occurred as ruptures; the text of the report explains that one rupture occurred due to corrosion (internal corrosion on a pipeline constructed before 1954 and previously used to transport coke oven gas) but this is excluded from the analysis. It is estimated that 4% of corrosion failures occurred as large holes and the remainder (96%) were pinholes or small cracks. Thus, the following failure frequencies for corrosion may be derived:

- Rupture: 0 per m.yr
- Large hole (>2cm in diameter): 8.8×10^{-10} per m.yr
- Pinhole/crack: 2.1×10^{-8} per m.yr

As observed for material and construction faults, there is a strongly reducing trend for failures due to corrosion for newer pipelines. In addition, increasing wall thickness of the pipeline leads to a strong reduction in the failure frequency due to corrosion, with no corrosion failures recorded for any pipelines with a wall thickness greater than 15mm.

Alternatively, pipeline-specific predictions for corrosion failure frequencies could be derived on a case-by-case basis using a structural reliability model (such as that included in PIPESAFE) and the results substituted for the historical values.

3.3.2.4 Natural events (and Other causes)

Failures due to ground movement are only likely at locations which are vulnerable to land stability issues, which are expected to be rare in The Netherlands, and it was initially considered that this threat should only be included at locations with known ground stability issues. However, HSE subsequently indicated that this threat in the fault tree methodology was also intended to include other causes, such as lightning or operator error (reduced by a factor of 5 from the frequencies for buried pipelines).

Following discussion with RIVM, it was accepted that the failure frequency for ground movement in The Netherlands should be negligible in comparison with other threats; however, a contribution for “Other” causes should be included. Therefore, a similar analysis was carried out of “Other and Unknown” causes as for material and construction faults and corrosion based on the information provided in the 7th EGIG report.

From Figure 16 in the 7th EGIG report [1], the total failure frequency (all failure modes) in 2007 for “Other and Unknown” failure causes expressed as a 5-year moving average is estimated to be approximately 1.3 x 10^{-8} per m.yr.

The limited resolution of Figure 17 in the 7th EGIG report prevents an accurate estimate being made of the proportion of pinhole/cracks, large holes and ruptures due to Other causes being made. According to the text of the report, a significant number (20) of “Other” incidents are due to lightning of which one led to a release from a large hole. Taking this information into account, it is estimated that 2% of Other failures were ruptures, 5% were large holes and the remainder (93%) were pinholes or small cracks. Thus, the following failure frequencies for Other causes may be derived:

- Rupture: 2.6 x 10^{-10} per m.yr
- Large hole (>2cm in diameter): 6.5 x 10^{-10} per m.yr
- Pinhole/crack: 1.2 x 10^{-8} per m.yr

3.3.3 Possible Extension to Address Pipeline Response to Impact

The above suggestions for refining the HSE approach would allow the site-specific factors that influence the main threats to be taken into account. However, by analogy with the methodologies applied to buried gas transmission pipelines, this only partially addresses the issue, because it ignores possible variations in the ability of above-ground pipelines to withstand an impact without giving rise to a major release of gas. If, in practice, there is limited variation in the diameter, wall thickness and material properties of the above-ground pipelines of interest, then this simplification may be reasonable. On the other hand, if there is a significant variation in the pipeline-specific parameters (as is the case for buried pipelines) then it may be appropriate to consider this aspect in more detail.

A full study of the possibility of applying sophisticated structural reliability techniques to above ground pipelines is beyond the scope of this report. An analogous approach to those used to predict failure frequencies of buried pipelines due to external interference would require as an input historical data on both the frequency of impacts on above-ground pipelines and a measure of the severity of the damage (possibly broken down by the function of each site), which is not available.

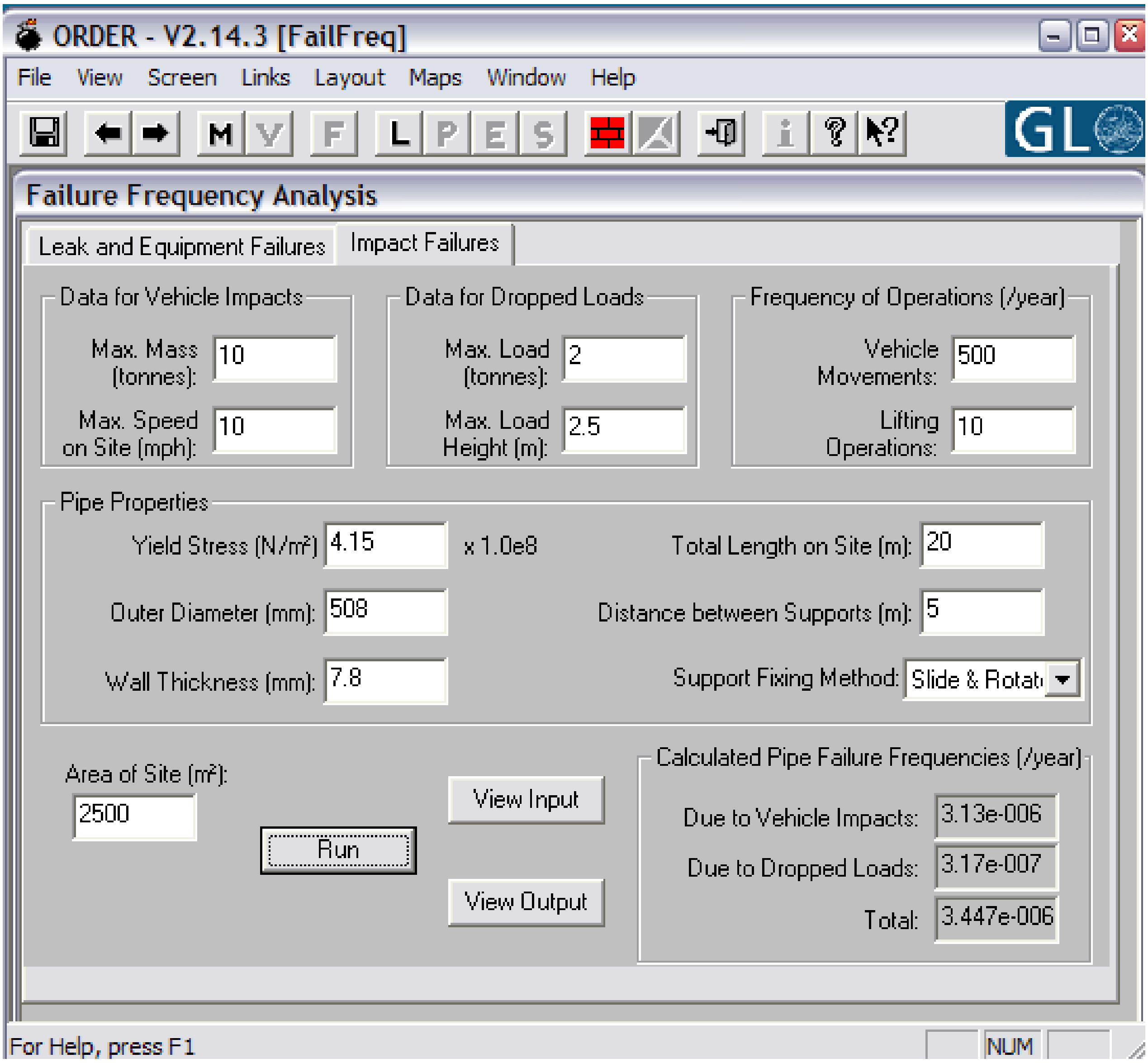
However, a simple model was developed and reported in 2003 by GL (then Advantica) on behalf of National Grid (then Transco), which aims to predict the total failure frequency of above-ground gas pipelines and pipework due to impact damage from both vehicles and lifting operations [13]. [The report is made available for the purpose of the current project by kind permission of National Grid.] This model (SPIDER: Software for Pipeline Impact Damage in Elevated Regions) has since been programmed and implemented in the GL software package for assessments of above-ground installations, ORDER [14]. However, it is stressed that the model has only been applied in rare instances by GL – for the purposes of QRAs of above-ground installations in the UK, the HSE failure frequency values for Land Use Planning are usually adopted for consistency with the regulatory framework.

The SPIDER model takes into account:

- The diameter, wall thickness and yield stress of the pipeline
- The method of support and the spacing between supports
- The area of the site and the length of above-ground pipeline present
- The frequency of vehicle movements and the size and speed of vehicles
- The frequency of lifting operations, the lifting height and mass of loads

Note that the model makes no allowance for the presence of protective barriers (although this could be addressed in an ad hoc way by reducing the frequency of vehicle movements, for example).

A screenshot of the model in use within ORDER is shown in Figure 1. Note that the model output provides overall failure frequencies for the site due to accidental impacts (divided between vehicle impacts and dropped load impacts) and does not predict the frequencies by failure mode (e.g. rupture, hole or pinhole).



Failure Frequency Analysis

Data for Vehicle Impacts
Max. Mass (tonnes): 10
Max. Speed on Site (mph): 10

Data for Dropped Loads
Max. Load (tonnes): 2
Max. Load Height (m): 2.5

Frequency of Operations (/year)
Vehicle Movements: 500
Lifting Operations: 10

Pipe Properties
Yield Stress (N/m²) 4.15 x 1.0e8
Total Length on Site (m): 20
Outer Diameter (mm): 508
Distance between Supports (m): 5
Wall Thickness (mm): 7.8
Support Fixing Method: Slide & Rotat

Area of Site (m²): 2500

Calculated Pipe Failure Frequencies (/year)
Due to Vehicle Impacts: 3.13e-006
Due to Dropped Loads: 3.17e-007
Total: 3.447e-006

Figure 1: Screenshot of SPIDER Model in ORDER

For the example in the screenshot, a pipeline of 508mm diameter and 7.8mm wall thickness has been chosen. The size of the site, the length of above-ground pipeline, the frequency of vehicle movements and the frequency of lifting operations have been selected to be the same as assumed in the HSE approach. Other inputs were chosen as possible values in order to generate non-zero failure frequencies. In this example, the predicted frequency of 3.4 x 10^{-6} per year for all releases due to impacts from vehicles or lifting operations on the site can be compared with the equivalent total of 3.4 x 10^{-6} for the same site from the HSE values in Table 3 (i.e. the sum of the total frequencies for internal vehicles and lifting multiplied by a 20m length of above-ground pipeline).

Changing the inputs to the model in terms of the frequency of operations of the properties of the pipeline has a corresponding effect on the results. The model considers a range of loads up to the specified maximum weight and height and for vehicles up to the maximum weight and speed. Because the model calculates whether the worst case dropped load or vehicle impact would exceed the ability of the pipeline to withstand the impact, the model will calculate a total failure frequency of zero if the pipeline is predicted to be able to withstand the worst case events.

For example, taking the same case as above, but replacing the pipeline with a smaller pipeline, 610mm diameter and with a wall thickness of 11.9mm, results in a predicted failure frequency of zero, because the specified values for vehicles and dropped loads are insufficient to cause the pipeline to fail. Therefore, it is important when using this model, that appropriate inputs are applied to ensure that the worst case impact scenarios are captured.

3.4 Escalation

A limitation of the analogy with buried gas transmission pipelines is that the possibility of escalation (e.g. a small release of gas from one component is ignited, resulting in a fire or explosion which in turn causes a more serious failure of another component) is not taken into account in the historical statistics. Incidents involving interaction between buried pipelines are unusual, both because buried pipelines are rarely in close proximity to each other but also because of the protection afforded by the soil above the pipelines. In contrast, above-ground pipelines within a gas installation may be in close proximity to each other and with other components and may be vulnerable to escalation as a result.

The possibility of escalation resulting from fires or explosions from small leaks in adjacent pipelines, pipework or equipment may be considered as an additional contribution to the frequencies above, but will be heavily dependent on site-specific details; for example, the extent of pipelines and other components above-ground, the site layout and the mitigations measures in place including the ability to detect gas releases and shut-down the plant safely and quickly in the event of an emergency. A separate study has been conducted by Gasunie as part of this project, which assesses the potential for gas releases from flanges (which could arise from a failure of a gasket over a limited portion of the pipeline circumference) and also the possibility that such a gas release from a flange could cause escalation to a full bore rupture of another pipeline nearby, estimated to be 7.4 x 10^{-10} per flange, per year [15].

GL has also performed safety studies for several gas installations, both in the UK and elsewhere, taking account of the potential for escalation on a site-specific basis. In cases where the space available for the above-ground infrastructure is strictly limited, this can result in a more densely packed site than normal, with the possibility of a “domino effect” resulting in escalation of a minor event to one with more serious consequences. Details of the studies are confidential, but in the most congested case, involving gas compression and process equipment, metering facilities and pipelines in close proximity, it was shown that the frequency of escalation to major pipework ruptures or vessel failures was up to 50% of the failure frequency determined from generic failure data before the implementation of additional mitigation measures.

4 Discussion

The fault tree approach developed by HSE provides a sound basis for deriving suitable failure frequencies for above-ground pipelines and is partly based on the approach adopted for equivalent buried pipelines. However, the assumptions underlying the analysis are site-specific and the values are unlikely to be appropriate for all sites. The frequencies for large releases, which determine the risk to the public at distances far beyond the site boundary, are dominated by failures resulting from accidental impacts either from vehicles or lifting operations, which in turn are a function of the numbers of vehicle movements or lifting operations taking place. The approach suggested in this report is intended to allow site-specific factors to be taken into account for these threats, which dominate the failure frequencies. However, all relevant threats should be considered and additional contributions included (e.g. for external vehicle impact or aircraft crash) where these are relevant.

Because the dominant threats are a function of activities with a frequency per site (and not per metre of pipeline) it may be more convenient to consider the HSE values in terms of a failure frequency per site per year. An interpretation of the HSE methodology is presented in Table 4, which is intended to allow actual values to be used for the numbers of operations taking place per year as well as the actual lengths of above-ground pipeline present. In this way, site-specific estimates of the failure frequencies may be made, and where the risk levels are of concern, provides a simple means of estimating the effect of possible risk reduction measures which either prevent or minimise the possibility of impacts taking place (such as avoiding the need for any lifting operations over pipelines or reducing the number of vehicle movements).

Table 4: Generic Failure Frequencies for Above-Ground Pipelines derived from Modified HSE LUP Methodology

	Lifting Impacts	Vehicle Impacts	Mechanical	Corrosion	Natural and Other
	Per lifting operation near pipeline per year	Per on site vehicle movement per year	Per m per year	Per m per year	Per m per year
Rupture	1×10^{-8}	6×10^{-11}	8×10^{-12}	1×10^{-11}	4×10^{-10}
Large Hole	5×10^{-8}	3×10^{-10}	8×10^{-12}	1×10^{-11}	1.8×10^{-10}
Small Hole	1×10^{-7}	6×10^{-10}	2×10^{-11}	1×10^{-11}	1.8×10^{-9}
Pin Hole	1×10^{-7}	6×10^{-10}	9×10^{-8}	1×10^{-9}	7.2×10^{-9}
Total	2.6×10^{-7}	1.56×10^{-9}	9×10^{-8}	1×10^{-9}	9.58×10^{-9}

However, by analogy with the methodology for buried pipelines, this simple approach ignores another important factor, which is the ability of the pipeline to resist an impact. GL has proposed a simple model [13] to allow the influence of site-specific and pipeline-specific factors to be taken into account in evaluating the failure frequencies for impacts, which would in turn allow the values for both Lifting Impacts and Vehicle Impacts in Table 4 to be modified as appropriate. As discussed in the previous section, the model calculates whether or not the worst case impacts result in a failure of the pipeline, and hence will calculate zero frequencies if the specified scenarios do not include any impacts of sufficient magnitude to cause a gas release from a particular pipeline. It is therefore important, when using the model, that appropriate inputs are defined in order to capture the worst case impact scenarios. Because the model predicts only whether an impact results in a gas release, and not the size of the release, it is proposed that the total frequencies predicted using the model would be apportioned across the rupture failure mode and different hole sizes in the same ratios as in Table 4 (i.e. rupture 4%, large hole 20%, small hole 38%, pin hole 38% for both lifting impacts and vehicle impacts).

The frequencies assigned to Mechanical, Corrosion and Natural and Other failures, although very small, are non-zero. Following discussion with RIVM, it was proposed to update these with new values derived from analysis of most recent data from the 7th EGIG report [1]. It was agreed that the failure frequency for ground movement in The Netherlands should be negligible in comparison with other threats; however, a contribution for "Other" causes (including lightning) would be retained.

EGIG sub-divides gas release incidents into three hole sizes:

1. Pinhole/crack: The diameter of the hole is smaller than or equal to 2cm
2. Hole: The diameter of the hole is larger than 2cm and smaller than or equal to the diameter of the pipe.
3. Rupture: The diameter of the hole is larger than the pipeline diameter.

A modified version of Table 4 applying the values derived from the EGIG report and showing the contribution to the failure frequencies for lifting and vehicle impacts proposed to be determined using SPIDER, is summarised in Table 5.

Table 5: Failure Frequencies for Above-Ground Pipelines derived from EGIG [1]

	Lifting Impacts	Vehicle Impacts	Mechanical	Corrosion	Other
	Per year	Per year	Per m per year	Per m per year	Per m per year
Rupture	4% of total		1.3×10^{-9}	0	2.6×10^{-10}
Large Hole (>2cm diameter)	58% of total		3.8×10^{-9}	8.8×10^{-10}	6.5×10^{-10}
Pin Hole	38% of total		1.09×10^{-8}	2.1×10^{-8}	1.2×10^{-8}
Total	Determined using SPIDER		1.6×10^{-8}	2.2×10^{-8}	1.3×10^{-8}

In order to demonstrate the application of the proposed approach to site-specific cases, two worked examples are presented in Appendix C, comparing the results from the modified HSE approach and the results obtained by applying the EGIG analysis and SPIDER model to (ignoring any contribution from escalation). In Case 1, based on an above-ground pipeline at a compressor station, the failure frequencies predicted for lifting impacts are all zero, because no lifting operations take place in the vicinity of the pipeline. The failure frequencies predicted for large releases due to vehicle impacts are similar for the two approaches in this particular example. However, in both approaches, the contribution from impacts is negligible compared with the values derived from historical data for mechanical, corrosion and other causes. Case 2 is based on an above-ground pipeline at an export station, but applying artificially severe parameters for lifting and vehicle movements (including the fictional assumption of 10 lifting operations per year, with an greater lifting height and load than would be used in practice) to represent an unusually busy site. With these factors applied, lifting dominates the failure frequencies for large releases according to the modified HSE methodology, whereas the results from the EGIG/SPIDER methodology are still dominated by mechanical, corrosion and other causes.

The cases studies illustrate that both approaches result in very significant frequencies being predicted for large releases from above-ground pipelines. In the case of the modified HSE methodology, with no contribution from lifting or vehicles and no additional contribution from escalation, the failure frequency for ruptures will be at least 4×10^{-7} per km.year. From the analysis of the EGIG data, the minimum frequency for ruptures will be predicted to be at least 1.5×10^{-6} per km.year. The generic frequencies estimated from the EGIG data in particular will be higher in many cases than would be predicted for the equivalent below-ground pipelines using structural reliability analysis techniques (which take into account the individual pipeline properties). The general application of averaged EGIG historical data raises concerns due to the inability to take into account the pipeline-specific properties such as diameter, pressure and wall thickness in particular (and hence design factor, which is widely recognised in pipeline standards as a key measure to control the likelihood of a pipeline rupture occurring). For land use planning purposes, the critical scenarios are ruptures or releases in the above-ground pipelines, because these will give hazard ranges well outside the site boundary which may influence planning decisions. Smaller pipelines will have correspondingly smaller hazard ranges and they may be less important than larger diameter pipelines in this context. The pipeline population in EGIG includes a high proportion of smaller diameter pipelines (more than 50% are less than 17” diameter) and these pipelines will tend to have thinner walls than the larger pipelines. The implication of this is that the use of average values from EGIG will lead to failure frequencies that are dominated by incidents on small diameter, thin wall pipelines, being applied to large diameter, thick wall pipelines. Because the larger pipelines will have greater hazard ranges, by coupling the consequence predictions for large diameter pipelines with failure frequencies derived from the average for the whole pipeline population, the method could lead to significant overestimates of the risk beyond the site boundaries and may be excessively cautious.

Alternatively, an equivalent approach could be adopted for above-ground pipelines to that used for below-ground pipelines (see Section 3.2). This would ensure consistency with risk assessments undertaken of below-ground pipelines in The Netherlands and would allow the influence of pipeline-specific and site-specific factors to be taken into account. Because the failure frequencies of the above-ground pipelines are contained within a controlled environment, it might be expected that their failure frequencies should be less than the failure frequencies calculated for equivalent cross-country pipelines below-ground. To address the key difference between the threats to below-ground and above-ground pipelines (i.e. accidental interference damage), the failure frequencies predicted for external interference to buried pipelines (predicted for buried pipelines using structural reliability models) would be replaced with those predicted for lifting and vehicle impacts within a controlled site; for example, using SPIDER or a structural reliability model similar to that employed in PIPESAFE.

It should be noted that the methods described in the report are intended to be applied above-ground pipelines which are essentially similar to buried gas transmission pipelines in their design, construction, operation and maintenance. They are not intended to be applied to process pipework, characterised by more complex piping and instrumentation arrangements or changes in process fluid compositions and temperatures, for example. If the above-ground pipeline contains a flange connection or connections, then the flange should be considered as an additional source of gas release. In addition, the possibility of escalation resulting from fires or explosions from small leaks in adjacent pipelines, pipework or equipment should also be considered as an additional contribution. Previous work by GL suggests that the contribution from escalation could increase the generic failure frequencies by a maximum of 50% even for a congested site, and so in most realistic situations the contribution from escalation would be expected to be smaller.

5 Conclusions and Recommendations

Two possible approaches are described for estimating failure frequencies for above-ground pipelines; one a modified version of the methodology used by the UK HSE to derive failure frequencies for above-ground pipelines applied in risk calculations for land-use planning purposes; the other at RIVM's request using generic historical data for below-ground gas transmission pipelines in Europe (EGIG) complemented by a simple model (SPIDER) for the failure frequencies due to impacts.

Both methods result in failure frequencies being predicted for large gas releases from above-ground pipelines which are only weakly influenced by pipeline-specific or site-specific parameters due to the nature of the available historical data for failures due to material or construction faults, corrosion or other causes. Using EGIG historical data, averaged over the whole pipeline population, could lead to significant overestimates of the risk beyond the site boundaries in cases where large diameter pipelines are present. Ideally, in the future, sufficient data would be collected and shared between gas companies to allow statistics to be derived to validate failure frequency estimates for above-ground pipelines at gas installations.

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Appendix A Review of Sources of Data for Estimating Failure Frequencies for Above-ground Natural Gas Installations

A.1 Approach

To support the project, GL was requested to undertake a review of available historical data that could be relevant to above-ground natural gas installations and above-ground high pressure gas pipelines in particular.

The review drew on a recent previous survey by GL of possible sources of failure frequencies for components on high pressure natural gas installations. The historical data available fell into one of three different categories:

- Databases recording incidents only
- Databases recording incidents and corresponding population/exposure for statistical analysis
- Published recommendations for failure frequency values

The sources identified were then reviewed and sources of incident data only, without corresponding exposure data to allow failure frequencies to be calculated, were excluded. Fifteen sources remained, as follows:

- HCR Database (UK HSE) [1]
- Land Use Planning Guidelines (UK HSE) [2]
- Incident Identification Study (International LNG Importer's Group - GIIGNL) [3]
- New Generic Leak Frequencies for Process Equipment (DNV) [4]
- Gas Pipeline Incident reports (European Gas Incident Group - EGIG) [5]
- Cross-country Oil Pipelines Performance reports (CONCAWE oil pipelines management group) [6]
- Pipeline Performance in Alberta (Alberta Energy and Utilities Board - EUB) [7]
- Analysis of Incidents for Gas Transmission and Gathering System Pipelines – DoT US data (Pipeline Research Council International - PRCI) [8]
- PIPESAFE (predictive structural reliability models) [9]
- Handbook Failure Frequencies 2009 for drawing up a Safety Report (Flemish Government) [10]
- Purple Book [11]
- BEVI reference manual (RIVM, Netherlands) [12]
- Lees' Loss Prevention in the Process Industry (textbook) [13]
- Ility Engineering failure rate database (internet site) [14]
- OREDA 2009 (Offshore Reliability Data 5th Edition) [15]

Each of these was then considered in more detail in order to identify which components, of interest for assessment of onshore gas installations, were covered by each source of information and the output is summarised in Table 6, with the components of particular interest in this project (i.e. connections, pipework and pipelines) highlighted. In this table, the green shaded cells indicate which components are addressed in each data source.

Table 6: Summary of Output from Review of Data Sources

	UK HSE		3. GIIGNL	4. DNV	5. EGIG	6. CONCAWE	7. EUB	8. PRCI	9. PIPESAFE	10. FF Handbook	11. Purple Book	12. BEVI Manual	13. Lees	14. Ility Database	15. OREDA
	1. HCR	2. LUP													
Installations			🟩												
Boiler															🟩
Compressor	🟩			🟩								🟩			🟩
Connection	🟩	🟩		🟩									🟩		
Cooler	🟩			🟩											🟩
Demister															
Filter	🟩			🟩											
Flare															
Heater	🟩			🟩						🟩	🟩	🟩		🟩	🟩
Instrumentation	🟩			🟩											

	UK HSE														
	1. HCR	2. LUP	3. GIIGNL	4. DNV	5. EGIG	6. CONCAWE	7. EUB	8. PRCI	9. PIPESAFE	10. FF Handbook	11. Purple Book	12. BEVI Manual	13. Lees	14. Ility Database	15. OREDA
Metering															
Pig Trap	🟩														
Pipework	🟩	🟩		🟩						🟩	🟩	🟩		🟩	
Pipeline		🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
Pressure Vessel	🟩	🟩		🟩						🟩	🟩	🟩			🟩
Pump	🟩	🟩		🟩						🟩	🟩	🟩			
Tank	🟩									🟩	🟩	🟩			
Tubing/Impulse Pipe															
Valve	🟩			🟩									🟩	🟩	🟩
Venting											🟩				
Wellhead															🟩

A.2 Sources with Information on Connections, Pipework and Pipelines

A.2.1 Historical data from offshore installations

The HCR Database maintained by UK HSE provides good quality data allowing release frequencies to be calculated for a wide range of components and leak sizes. Experience has shown that the derived frequencies can vary depending on the assumptions and method of analysis used. This aspect is being considered in detail on behalf of RIVM by DNV in order to propose leak frequency values for onshore installations based on the offshore data [16]. However, although the offshore data may be used to derive leak frequencies (possibly adapted to take account of the different circumstances onshore and offshore), the offshore data cannot be used reliably to determine the frequencies for large releases, in particular ruptures, of above-ground pipelines due to the lack of experience of such large events in the offshore data.

A.2.2 Generic values for onshore installations

The UK HSE has published the failure frequencies used as part of their own methodology applied in advising on Land Use Planning decisions. These include “generic” values used in Land Use Planning assessments for onshore gas installations, which distinguish between process pipework and above-ground natural gas pipelines. The values for process pipework and flanges are mainly derived from older data for the chlorine process industry. As part of the current project for RIVM, HSE supplied the methodology used to derive the failure frequencies for above-ground pipelines (reproduced in this report as Appendix B). This applies a fault tree approach, developed by analogy with buried pipelines, and takes into account the threat of damage due to impacts from lifting operations and vehicles in addition to other threats in common with buried pipelines.

Generic values are also published in the Purple Book, BEVI reference manual, and the Flemish Handbook of Failure Frequencies 2009, which give identical values. These are comparable to the UK HSE values, but include flange leaks in pipework leak frequencies. Their applicability to onshore high pressure gas installations is currently under review by RIVM as part of this project.

A.2.3 Historical data from onshore pipelines

There are several established databases for buried pipelines, where pipeline companies have co-operated over many years to share data on failures (and in some cases, damage) to buried pipelines and published summary reports.

The EGIG database provides good quality data for below-ground, high pressure (>16 bar) onshore natural gas pipelines and includes information on both gas release incidents and the corresponding pipeline population to allow historical failure frequencies to be estimated. However, fenced installations are excluded from the scope.

The UKOPA database covers UK major hazards pipeline (including gas and liquid pipelines), and provide data on incidents and on the corresponding pipeline population. In contrast to EGIG, UKOPA collects detailed information on pipeline damage incidents in addition to product loss incidents. However, fenced installations are again excluded from the scope of the database.

The CONCAWE database covers liquid pipelines only and so is less relevant for the purpose of this report. It has not been considered further.

A.2.4 Historical data from onshore pipelines and installations

The Canadian NEB (and Alberta EUB) pipeline performance safety reports cover liquid and gas pipelines including installations since 2000. All unintended or uncontrolled releases of natural gas should be reported and the data distinguishes “Pipe body failures” and “Operational gas leaks” (e.g. venting from valves and seepage from gaskets). The pipeline population is given by total length only, but details of the population of installations (or the components within them) are not supplied.

Information on US pipeline data is published online by PHMSA which covers both liquid and gas pipelines including installations. Data has been collected over many years (from 1970, with refinements in 1985 and 1997) and a substantial volume of data is available for analysis. Pipelines are classified as “Gathering”, “Transmission” or “Distribution” and incidents are reportable above a threshold cost of $50,000 (at 1984 prices). However, as with the Canadian data, information is only available on the pipeline population (by total length only), not numbers of installations or components.

In order to identify incidents that may have occurred at installations, spreadsheets were downloaded from the NEB (Canada) and PKMSA (US) internet sites and then sorted and filtered to identify incidents that occurred on above-ground natural gas pipelines.

Just one incident was identified in the NEB database which may be relevant. This was an ignited incident, which occurred at a meter station in 2009. However, because the incident was reported as still under investigation, no further details were available.

The data from the PHMSA website was filtered further to identify reported ruptures of above-ground steel pipelines, which suggested 12 possible incidents in 1985-1997 and 6 in 1998-2009. No fatalities were reported in connection with any of the incidents. However, there is uncertainty about the definition of a rupture in these incidents and the locations of the above-ground pipelines (in particular whether the pipelines are within fenced installations). Further information would be required in order to determine the relevance of these incidents to the current study, which was not available from the databases. An internet search was carried out to try and identify additional information on the largest reported incident (by cost). This was identified as fire damage to a compressor station caused by a rupture at an adjacent plant.

The US incident data could be investigated further, possibly requesting PHMSA for more details, but because the value of this is limited for statistical purposes without the corresponding population information, it was not pursued further for this report.

A.2.5 Predictive models for onshore pipelines

Predictive structural reliability analysis (SRA) models have been developed for buried pipelines, in order to take account of pipeline-specific and location-specific factors such as the pipeline design factor and whether the pipeline is in a rural or suburban location. Models developed for external interference (generally the dominant threat for buried pipelines) and corrosion are included in the PIPESAFE package.

The models use a combination of historical data (e.g. pipeline hit rates and damage distributions in the case of external interference) with a theoretical fracture mechanics treatment.

Because the models were developed for buried cross-country pipelines, the basis of the external inference models reflect that experience, in particular hit rates for external interference to pipelines outside a boundary fence and with damage distributions reflecting the type of machinery in general use. This may not be appropriate for an above-ground pipeline within a site, where the most likely impacts will be from operational activities (e.g. lifting operations or vehicle movements on site). SRA models for external interference could be adapted for use at above-ground installations, provided that estimates can be made of the hit rate and the appropriate damage distributions.

Corrosion, on the other hand, will not be influenced by whether the pipeline is inside or outside a boundary fence and therefore it may be possible to apply the predictive corrosion models such as that in PIPESAFE, although it is noted that there will be differences in the methods of preventing corrosion and inspecting the pipelines if they are above-ground or below-ground. Particular care needs to be take to avoid corrosion at the interface between above-ground and below-ground.

A.2.6 Other references

These (Lees' textbook and the Ility Engineering database) are based on information obtained elsewhere, and did not appear to add to the information already obtained, so they were not considered further.

A.3 Industry-specific data

Individual companies do record gas release incidents at their own installations but it has been difficult for companies to co-operate in sharing this information largely partly because companies have different criteria for reporting and recording incidents and have different definitions of installations and the components within them. As a result, it has been difficult to agree a common format and definitions in order to collect data alongside that for buried pipelines (e.g. EGIG).

For the purpose of this project, an exercise is being carried out by RIVM with assistance from the Dutch companies to estimate the numbers of incidents that have occurred at installations in The Netherlands retrospectively, which is being reported separately.

In the UK, gas release incidents are reportable to the UK HSE under RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations), introduced in 1995. This requires reports to be made of all natural gas releases greater than 500kg in open air (or >10kg within buildings) and/or death or major injury. It may be possible to obtain retrospective reports of gas release incidents under RIDDOR. No very large releases have occurred; however, it may be possible to use this information coupled with estimates of the numbers of installations to make upper bound estimates of historical gas release frequencies in a future study.

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Appendix B UK HSE Methodology for Failure Frequencies of Above-Ground Pipelines

Failure Frequencies for Above Ground Natural Gas Pipelines

Panel Chairman

Background

1. This paper concerns Panel Action 2000/02, which notes a need for a methodology for the assessment of risks associated with above ground pipelines. The paper deals with the establishment of failure frequencies for use in an appropriate consequence model.

2. MSDU has an established tool, PIPIN, for the determination of failure frequencies for buried gas pipelines. Whilst this tool is suitable for the vast majority of pipeline LUP cases there are a small number in which the failure of above ground sections of pipeline might be significant. Consequently, a methodology is required for the determination of failure frequencies for above ground pipelines.

3. This paper describes the work carried out to derive suitable frequencies for use in Land Use Planning work involving above ground natural gas pipelines. The work has assumed the pipelines are part of an Above Ground Installation and, as such, contained within a secure compound. The frequencies derived may require modification in the event that a case involving an above ground pipeline that is not within a secure compound is encountered.

Existing Pipeline/Pipework Data and Methodologies

Buried Pipelines

4. Failure frequencies for HP natural gas transmission buried pipelines are determined using PIPIN. The total frequency is made up of 4 separate elements;

   - Mechanical – failures due to inherent defects in welds or parent materials.
   - Corrosion – failure due to corrosion of the pipe, predominantly from the outside.
   - Natural – failures due to natural events such as loss of support to the pipeline following a landslip.
   - Third Party – failures due to intervention from a third party, such as being struck by an excavator bucket.

5. Of the four elements, the first three; mechanical, corrosion and natural, are established from historical data for buried pipelines (predominantly gas) in the UK whilst the fourth, third party, is assessed theoretically using a structural reliability model together with statistical distributions of damage severity obtained from historical data.

Applicability to Above Ground Pipelines

6. Are failure frequencies obtained from PIPIN applicable to above ground pipelines?

   - Mechanical – these failures are determined predominantly by the code(s) used for design and construction of the pipeline. These should be the same for the above and below ground sections of a pipeline. Consequently the mechanical frequency obtained from PIPIN is considered to be applicable to above ground pipelines.
   - Corrosion – Although the corrosion protection arrangements are likely to be similar, the local conditions will be different for above ground and buried pipelines. However, the contribution of the corrosion element to the total failure frequency is small (for buried pipelines), particularly for the Large Hole and Rupture cases that tend to dominate Risk Assessments. At this stage the PIPIN data will be considered valid, although this position will be revisited if, ultimately, the corrosion element becomes significant in the total failure frequency.
   - Natural – This main failure mode for a buried pipe due to natural causes is through the loss of support along a significant length of the pipeline. Considering the situation for above ground pipelines, the lengths exposed to this risk will be significantly shorter and therefore the likelihood of failure should be lower. A reduction of a half an order of magnitude on the PIPIN frequencies is proposed.
   - Third Party Activity – The potential causes of TPA damage to above ground pipelines are completely different for above ground and buried pipelines. Consequently there is considered to be no justification for using PIPIN generated frequencies for above ground pipelines.

FRED Data for Pipework

7. The data currently used for process pipework in MSDU LUP work originates from 1985, and is based on a review of 22 separate references. In addition, the failure frequencies for large diameter pipes, of a size normally relevant for pipelines are derived mainly from that for pipes below 100mm diameter, reducing by about a half an order of magnitude from one diameter range to the next. Because of this, and the absence of information on the contribution of the various causes to the total for large diameter pipes, it is not considered appropriate to recommend use of this data to above ground pipelines without further validation.

Derivation of Failure Frequencies

8. Given the above, there would be value in attempting to derive Third Party Activity failure frequencies for above ground pipelines. These could then be combined with PIPIN values (or modified PIPIN values) for the remaining three failure causes to give a total frequency. As a check they can be compared to the values currently used by MSDU for general pipework.

Fault Tree Structure

9. The top-level structure of the fault-tree is shown in Figure 1. This identifies the key ways in which the pipeline might fail as a result of an 'external event'.

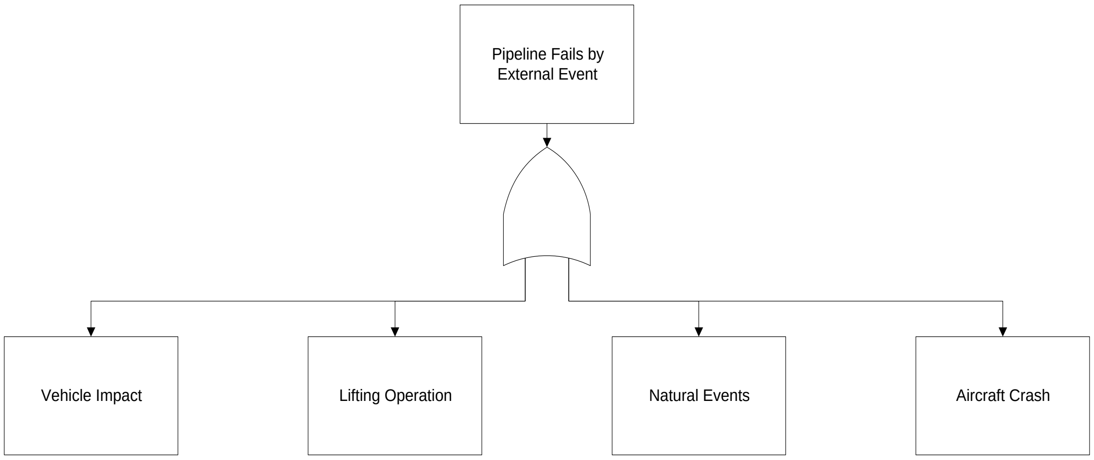

Figure 1 Top Level Fault Tree

10. The two key events in the Fault Tree above that require further detailed analysis are those for Vehicle Impact and Lifting Operation. Detailed sub-trees for these events have been developed and are presented at Annex A. Annex B details the judgements leading to the base event frequencies used in the trees at Annex A and, for completeness, the values proposed for Natural Events and Aircraft Crashes. The values derived in the Fault Trees are summed under External Events in Table 1 below together with the Mechanical and Corrosion failures derived from PIPIN.

Table 1 Derived Failure Frequencies (/m/yr)

	External Events	**Mech.**	**Corr.**	**Total**
Rupture	$6.5.10^{-9}$	8.10^{-12}	10^{-11}	$6.5.10^{-9}$
Large	$3.3.10^{-8}$	8.10^{-12}	10^{-11}	$3.3.10^{-8}$
Small	$6.7.10^{-8}$	2.10^{-11}	10^{-11}	$6.7.10^{-8}$
Pin	$7.2.10^{-8}$	9.10^{-8}	10^{-9}	$16.3.10^{-8}$

Table 2 Comparison with Existing MSDU Frequencies for Pipework (/m/y)

	Derived for Above Ground Pipelines	MSDU Pipework (>150 mm)	PIPIN	
			Rural[1]	**Suburban[1]**
Rupture	$6.5.10^{-9}$	$4.10^{-8} – 2.10^{-7}$	$2\ .10^{-8}$	$8\ .10^{-8}$
Large Hole	$3.3.10^{-8}$	$1.10^{-7} – 4.10^{-7}$	$1.6.10^{-9}$	$5.3.10^{-9}$
Small Hole	$6.7.10^{-8}$	$4.10^{-7} – 7.10^{-7}$	$1.2.10^{-8}$	$1.9.10^{-8}$
Pin Hole	$16.3.10^{-8}$	$7.10^{-7} – 1.10^{-6}$	$1.7.10^{-7}$	$2.5.10^{-7}$

Discussion

11. Table 2 allows the derived values for Above Ground Pipelines (AGP), MSDU Pipework and PIPIN (Buried Pipelines) to be compared.

<u>AGP vs Pipework</u>

12. The derived values for Above Ground Pipelines are considerably lower than those currently used by MSDU for pipework. This seems reasonable since the construction standards applied to pipelines may be more rigorous than those for general piping. Also there are other differences between general pipework and above ground pipelines that might be expected to lead to greater reliability and less need for engineering interventions. Above Ground Pipelines are;
- Less complex
- Minimal variability in process fluid and conditions
- Generally more robust
- Less vulnerable to impact damage.

<u>AGP vs PIPIN</u>

13. In making this comparison it should be recognised that the mechanism by which Third Party damage may occur is completely different in the two cases. With buried pipelines, this will generally be by impact from construction equipment whilst with those above ground it will be predominantly from lifting operations and vehicles. Consequently only a general comparison can be made along the lines of, ‘is it more likely that a pipe will be subject to damage by construction equipment when buried underground or by lifting/vehicle operations when above ground?’. The results suggest that damage (but not rupture) to above ground pipework is more likely, which does not seem an unreasonable position. When the individual contributions to the total AGP frequency are reviewed, it is clear that the dominant contributor is that from lifting operations. Such lifting operations are judged to have a much larger effect on the lower damage

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[1] Arithmetic mean of values across the whole NTS

categories compared to rupture. This leads to lower failure frequencies for rupture and higher failure frequencies for holes than is the case for buried pipelines.

Proposal

14. This work has derived failure frequencies for above ground pipelines at AGIs that are different to those currently in use for general pipework and pipelines. Some reasons have been suggested to account for these variations.

15. It is therefore proposed that the following frequencies are adopted for the assessment of above ground pipelines;

Rupture: $6.5.10^{-9}$ /m/yr
Large Hole: $3.3.10^{-8}$ /m/yr
Small Hole: $6.7.10^{-8}$ /m/yr
Pinhole: $16.3.10^{-8}$ /m/yr

Recommendations

16. The above frequencies should be used for the above ground pipeline when assessing Transco Above Ground Installations and similar sites.
17. Where above ground pipelines at different kinds of sites need to be assessed the Topic Specialist should be consulted for specific advice on failure frequencies.
18. The Topic Specialists should review early assessments of AGIs to see what effect using these data within an agreed assessment policy for AGIs has on the overall assessment outcome.
19. After review, the failure frequencies adopted should be incorporated into PCAG 6K.
20. Any comments from Panel would be welcome.

S C Pointer
CI5B

July 2004

ANNEX A – Fault Trees

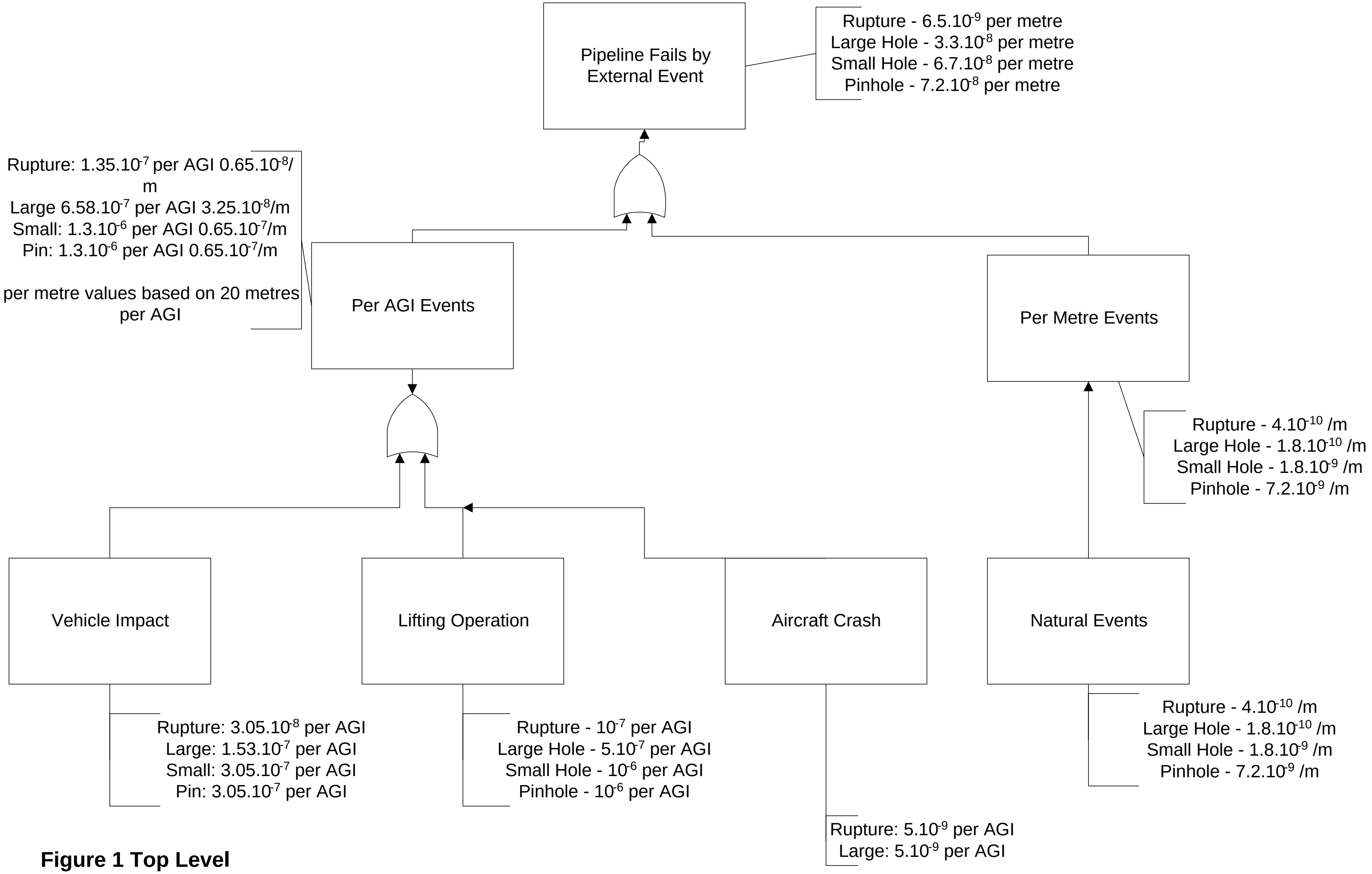


Figure 1 Top Level Fault Tree

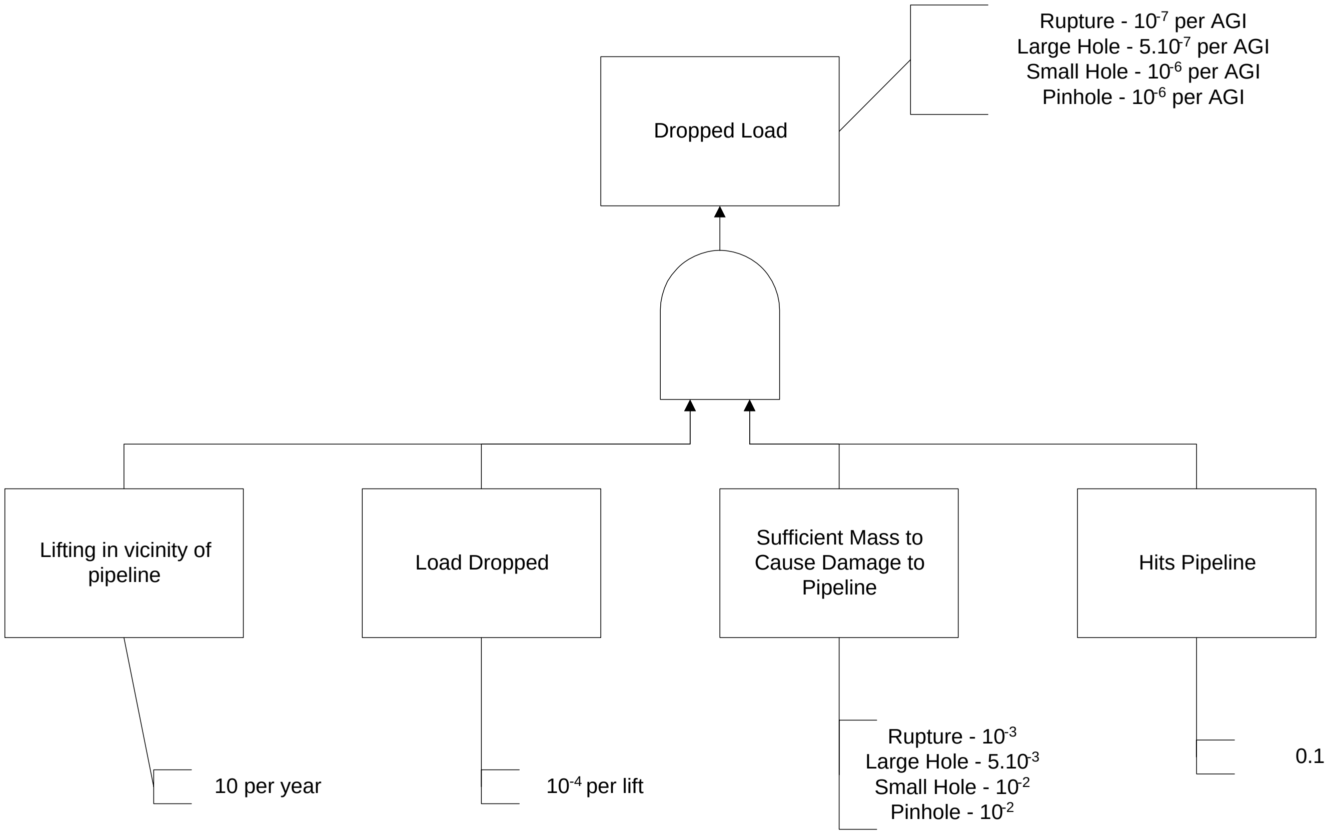


Figure 2. Dropped Load Sub-Tree

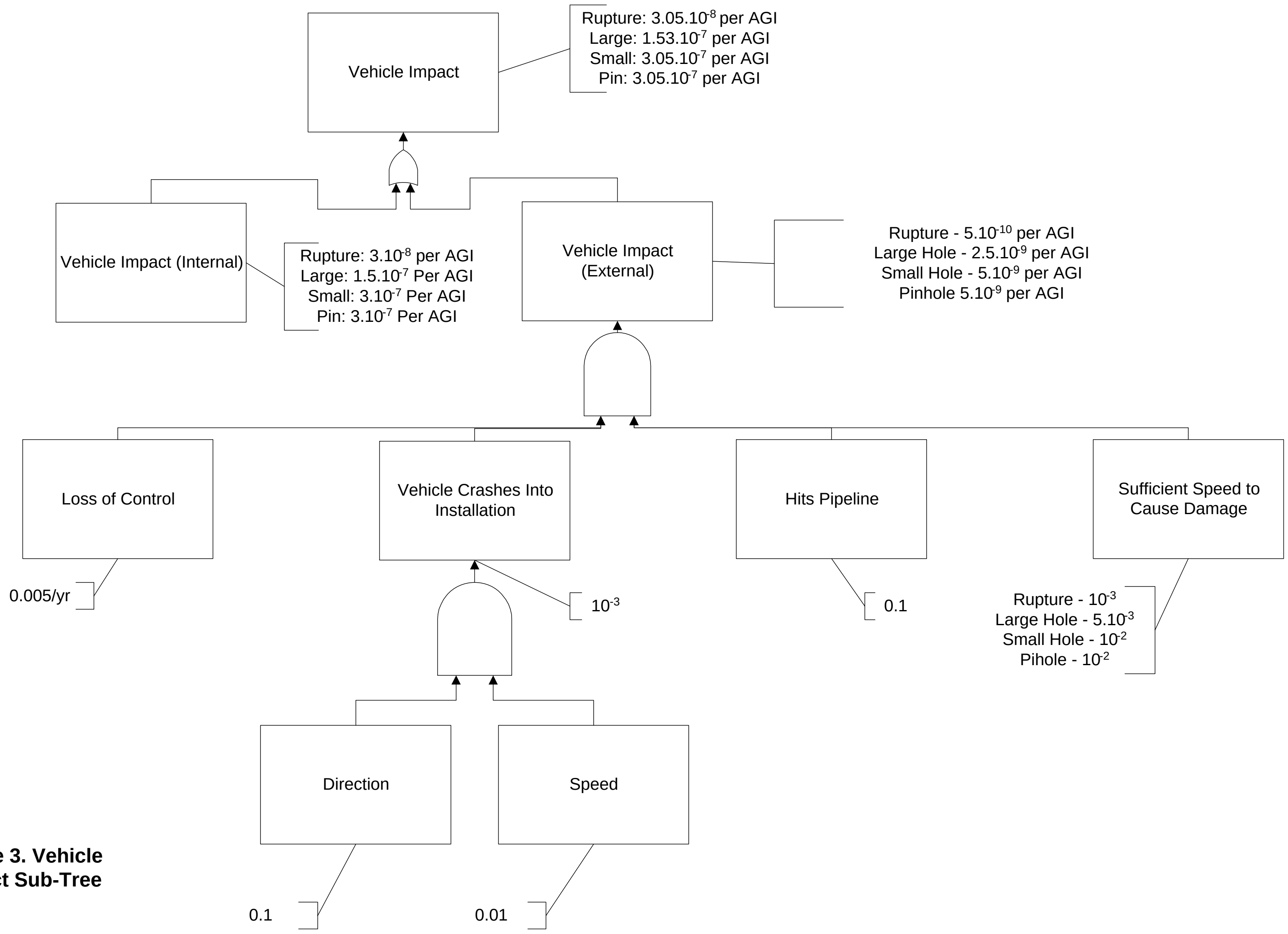
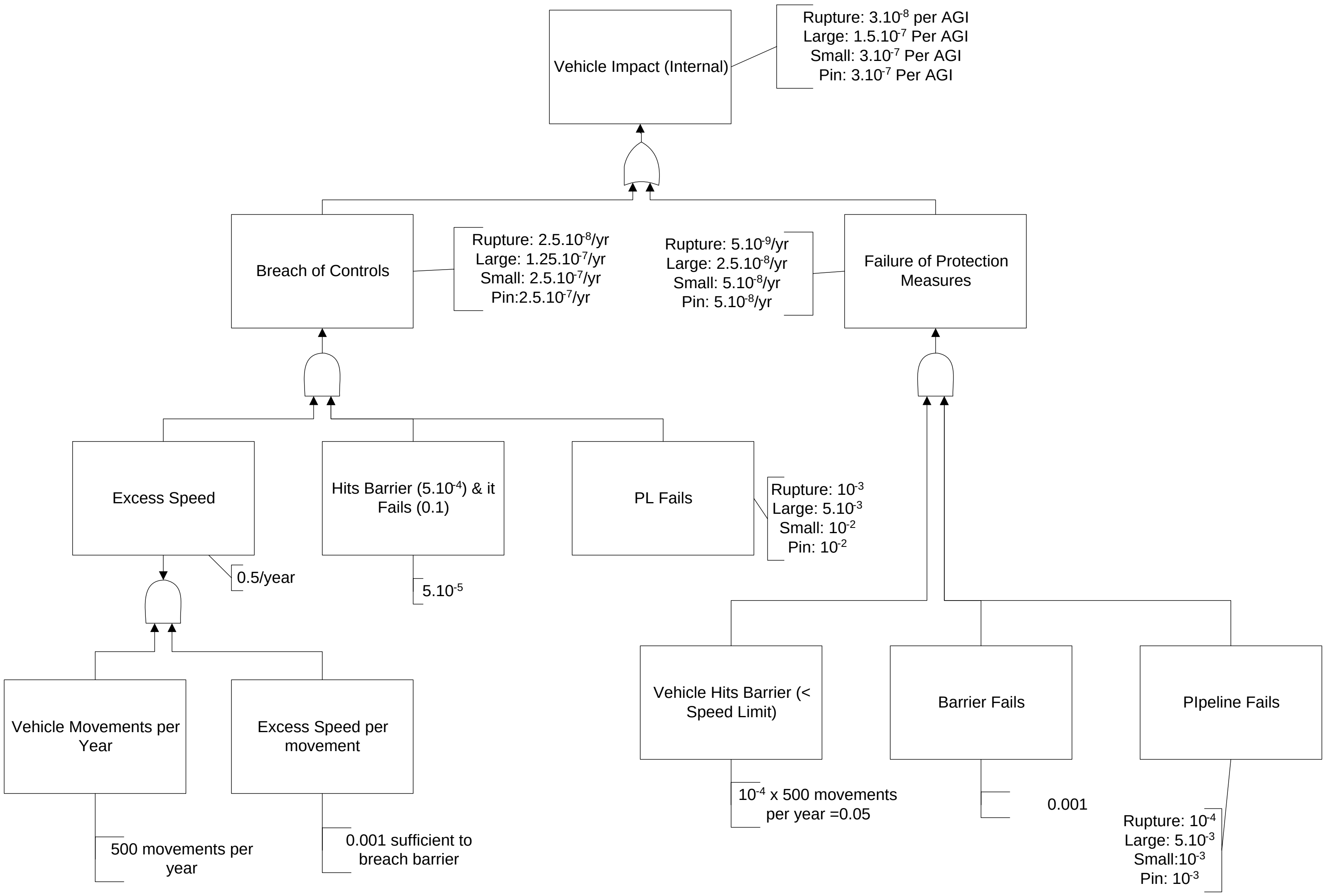


Figure 3. Vehicle Impact Sub-Tree


Vehicle Impact (Internal)
Rupture: 3.10^{-8} per AGI
Large: $1.5.10^{-7}$ Per AGI
Small: 3.10^{-7} Per AGI
Pin: 3.10^{-7} Per AGI
Breach of Controls
Rupture: $2.5.10^{-8}$/yr
Large: $1.25.10^{-7}$/yr
Small: $2.5.10^{-7}$/yr
Pin:$2.5.10^{-7}$/yr
Rupture: 5.10^{-9}/yr
Large: $2.5.10^{-8}$/yr
Small: 5.10^{-8}/yr
Pin: 5.10^{-8}/yr
Failure of Protection Measures
Excess Speed
0.5/year
Hits Barrier (5.10^{-4}) & it Fails (0.1)
5.10^{-5}
PL Fails
Rupture: 10^{-3}
Large: 5.10^{-3}
Small: 10^{-2}
Pin: 10^{-2}
Vehicle Movements per Year
500 movements per year
Excess Speed per movement
0.001 sufficient to breach barrier
Vehicle Hits Barrier (< Speed Limit)
10^{-4} x 500 movements per year =0.05
Barrier Fails
0.001
PIpeline Fails
Rupture: 10^{-4}
Large: 5.10^{-3}
Small:10^{-3}
Pin: 10^{-3}

ANNEX B – BASE EVENT FREQUENCY JUDGEMENTS

Dropped Load

Lifting in the Vicinity of Pipeline – assumed at 10 lifts per year.

Load Dropped – 10^{-4} per lift, based on data from ‘Survey of Crane Operating Experience at US Nuclear Plant 1968 to 2002’. A rate of 0.02 per reactor year for all lifts is quoted in the report. It has been assumed that the number of lifts at a reactor will be between 100 and 1000 per year and a rate at the top end of the resulting range of frequency per lift was chosen.

Sufficient Mass to Cause Damage to Pipeline – Judgemental, 1 in 1000 lifts assumed have the potential to cause rupture, 1 in 500 Large Hole and 1 in 100 for Small Hole and Pin Hole.

Hits Pipeline – Assumed that 1 in 10 lifts are directly over the pipeline when the failure occurs.

Values have been determined per site and then an assumption of 20 metres of pipeline made to produce a failure frequency per metre.

Vehicle Impact

In developing this fault tree consideration was given to the potential for vehicles within the installation and those external to it to cause damage to the pipeline. Depending on the type and location of the installation it is likely that one or the other will predominate. This assessment includes both in the value obtained for vehicle impact.

External

Loss of Control – Obtained from Highways Agency Data, Report of Highway Agency Working Group to Review the Standards for the Provision of Nearside Safety Barriers on Major Roads – Annex 4 Road Accident Data. Published 2002. This leads to a rate of 0.005 per installation per year for vehicles leaving the road. The figure is based on the rate of vehicles leaving the road for non-trunk roads and assuming a 'length at risk' of 0.25 km for each installation.

Vehicle Enters Installation – Whether or not a vehicle actually enters the installation will depend upon direction (assumed at 1 in 10 loss of control incidents) and speed (sufficient speed to breach boundary fence assumed in 1 in 100 incidents)
Hits Pipeline – It is assumed that 1 in 10 vehicles entering the installation will hit the pipeline
Sufficient Speed to Cause Damage – The speed and mass of the vehicle, angle of impact and location of impact with pipeline will vary. Probabilities for various outcomes are judged to be; Rupture 0.001, Large Hole 0.005, Small Hole 0.01, Pinhole 0.01.

Values have been determined per site and then an assumption of 20 metres of pipeline made to produce a failure frequency per metre.

Internal

Vehicle Movement – An average of approximately 500 movements per year has been assumed.

Excess Speed – It is assumed that for 1 in 1000 movements the speed will be sufficient to cause failure of the normal protective barriers around the pipeline or its supports.

Hits Barrier – It is assumed that a vehicle travelling at normal speeds hits a barrier once in every 10000 movements, and more frequently if speeding.

Barrier Fails – This is failure of the barrier when struck by a vehicle at or below the site speed limit. It is assumed that the barrier will be designed to withstand such loads and that failure will occur 1 in 1000 times, or 1 in 10 times for a speeding vehicle.

Pipeline Fails – Failures of the pipeline are allocated on the basis of judgement and it is assumed that for each failure category failure is an order of magnitude more likely if the incident is caused by a vehicle exceeding the site speed limit.

Natural Events

The values use for buried pipelines have been reduced by a half an order of magnitude to take account of a perceived lower likelihood of damage due to events such as landslip.

Aircraft Crash

Using the AEAT report on aircraft crash risk an assuming an average site dimension of 50m x 50m, with the background crash rate gives a probability per site of 10^{-8} per year. The total frequency has been split equally between Rupture and Large Holes.

Appendix C Case Studies

C.1 Case 1 Compressor Station

C.1.1 Site Data

The following input details are for an actual compressor site as supplied by Gasunie.

Site Area: 119000m^2

Above-ground Pipeline:

- Diameter: 914mm
- Wall thickness: 13.9mm
- Yield Strength: 415 N/mm^2
- Length: 648m
- Distance between Supports: 6m
- Fixing method: Sliding

Vehicles:

- Maximum Mass: 40 tonnes
- Maximum speed: 15 km/hour
- Frequency: 3 vehicle movements per year

Lifting: No lifting near pipelines

C.1.2 Results from Modified HSE LUP Methodology

Multiplying the frequencies from Table 4 for internal vehicle movements by 3 and with no lifting near the pipeline taking place, the following results are obtained for a 648m pipeline:

Table 7: Failure Frequencies (per year) for Case 1 derived from Modified HSE LUP Methodology

	Lifting Impacts	Vehicle Impacts	Mechanical	Corrosion	Natural and Other	Total
Rupture	0	1.8×10^{-10}	5.2×10^{-9}	6.5×10^{-9}	2.6×10^{-7}	2.7×10^{-7}
Large Hole	0	9×10^{-10}	5.2×10^{-9}	6.5×10^{-9}	1.2×10^{-7}	1.3×10^{-7}
Small Hole	0	1.8×10^{-9}	1.3×10^{-8}	6.5×10^{-9}	1.2×10^{-6}	1.2×10^{-6}
Pin Hole	0	1.8×10^{-9}	5.8×10^{-5}	6.5×10^{-7}	4.7×10^{-6}	6.3×10^{-5}
Total	0	4.7×10^{-9}	5.8×10^{-5}	6.5×10^{-7}	6.2×10^{-6}	6.5×10^{-5}

Note that no contribution from aircraft crash, external vehicle impacts or escalation events have been included and these should be considered and added if appropriate. The calculation relates only to the specified pipeline and would need to be repeated for other above-ground pipelines present on the same site.

C.1.3 Results from Application of EGIG Data with SPIDER Model

Applying the specified inputs to the SPIDER model results in a predicted total failure frequency due to vehicle impacts of 2.86 x 10^{-9} per year for the above-ground pipeline.

Apportioning this frequency across the failure modes in the ratios from Table 5 (i.e. Rupture 4%, Large Hole 58% and Pin Hole 38%) and multiplying the historical EGIG values from the same table by the specified length of pipeline, the following results are obtained:

Table 8: Failure Frequencies (per year) for Case 1 derived from Application of EGIG Data with SPIDER Model

	Lifting Impacts	Vehicle Impacts	Mechanical	Corrosion	Other	Total
Rupture	0	1.1 x 10^{-10}	8.4 x 10^{-7}	0	1.7 x 10^{-7}	1.0 x 10^{-6}
Large Hole (>2cm diameter)	0	1.7 x 10^{-9}	2.5 x 10^{-6}	5.7 x 10^{-7}	4.2 x 10^{-7}	3.5 x 10^{-6}
Pin Hole	0	1.1 x 10^{-9}	7.1 x 10^{-6}	1.4 x 10^{-5}	7.8 x 10^{-6}	2.9 x 10^{-5}
Total	0	2.9 x 10^{-9}	1.0 x 10^{-5}	1.5 x 10^{-5}	8.4 x 10^{-6}	3.3 x 10^{-5}

C.2 Case 2 Export Station

C.2.1 Site Data

The following details are for an actual pipeline at an export station as supplied by Gasunie. However, the number, height and load associated with lifting operations and the frequency of large vehicle movements are fictional in order to demonstrate the application of the method.

Site Area: 41000m^2

Above-ground Pipeline:

Diameter: 324mm

Wall thickness: 11mm

Yield strength: 140 N/mm^2

Length: 115m

Distance between supports: 6m

Fixing method: Sliding

Vehicles:

Maximum mass: 40 tonnes

Maximum speed: 15 km/hour

Frequency: 52 vehicle movements per year

Lifting:

Maximum mass: 1 tonne

Maximum height: 2m

Frequency: 10 lifting operations in vicinity of pipeline per year

C.2.2 Results from Modified HSE LUP Methodology

Multiplying the frequencies from Table 4 for internal vehicle movements by 52 and with 10 lifting operations near the pipeline taking place per year, the following results are obtained for a 115m long pipeline:

Table 9: Failure Frequencies (per year) for Case 2 derived from Modified HSE LUP Methodology

	Lifting Impacts	Vehicle Impacts	Mechanical	Corrosion	Natural and Other	Total
Rupture	1×10^{-7}	3.1×10^{-9}	9.2×10^{-10}	1.2×10^{-9}	4.6×10^{-8}	1.5×10^{-7}
Large Hole	5×10^{-7}	1.6×10^{-8}	9.2×10^{-10}	1.2×10^{-9}	2.1×10^{-8}	5.4×10^{-7}
Small Hole	1×10^{-6}	3.1×10^{-8}	2.3×10^{-9}	1.2×10^{-9}	2.1×10^{-8}	1.1×10^{-6}
Pin Hole	1×10^{-6}	3.1×10^{-8}	1.0×10^{-5}	1.2×10^{-7}	8.3×10^{-7}	1.2×10^{-5}
Total	2.6×10^{-6}	8.1×10^{-8}	1.0×10^{-5}	1.2×10^{-7}	1.1×10^{-6}	1.4×10^{-5}

Note that no contribution from aircraft crash, external vehicle impacts or escalation events have been included and these should be considered and added if appropriate. The calculation relates only to the specified pipeline and would need to be repeated for other above-ground pipelines present on the same site.

C.2.3 Results from Application of EGIG Data with SPIDER Model

Applying the above artificial inputs to the SPIDER model results in a predicted total failure frequency for the pipeline due to vehicle impacts of 3.1×10^{-7} per year and a total failure frequency of 6.0×10^{-8} per year for lifting operations.

Apportioning this frequency across the failure modes in the ratios from Table 5 (i.e. Rupture 4%, Large Hole 58% and Pin Hole 38%) and multiplying the historical EGIG values from the same table by the specified length of pipeline, the following results are obtained:

Table 10: Failure Frequencies (per year) for Case 1 derived from Application of EGIG Data with SPIDER Model

	Lifting Impacts	Vehicle Impacts	Mechanical	Corrosion	Other	Total
Rupture	2.4×10^{-9}	1.2×10^{-8}	1.5×10^{-7}	0	3.0×10^{-8}	1.9×10^{-7}
Large Hole (>2cm diameter)	3.5×10^{-8}	1.8×10^{-7}	4.4×10^{-7}	1.0×10^{-7}	7.5×10^{-8}	8.3×10^{-7}
Pin Hole	2.3×10^{-8}	1.2×10^{-7}	1.3×10^{-6}	2.4×10^{-6}	1.4×10^{-6}	5.2×10^{-6}
Total	6.0×10^{-8}	3.1×10^{-7}	1.9×10^{-6}	2.5×10^{-6}	1.5×10^{-6}	6.3×10^{-6}