National Institute for Public Health
and the Environment
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On-site natural gas piping

Scenarios and failure frequencies

Report 620550004/2011

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Colophon

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This investigation has been performed by order and for the account of Minstry of Infrastructure and the Environment, within the framework of M/620550/10/RI.

Abstract

On-site Natural Gas Piping

RIVM has been commissioned by the Ministry of Infrastructure and the Environment to derive failure frequencies and scenarios for above-ground gas pipelines at natural gas establishments. These are part of the natural gas infrastructure. Flange connections are considered separately. The failure frequencies and scenarios can be used to determine third-party risks, using the risk methodology for natural gas establishments which is currently being developed. This methodology will be part of the Reference Manual Bevi Risk Assessments, which is to be used according to the External Safety (Establishments) Decree. This study was conducted because the current manual does not specifically address these types of establishments.

Two standard scenarios have been examined: leaks and ruptures. The failure frequencies for piping are derived from European data for transmission pipelines. This was decided because there is no useful specific information present for above-ground natural gas pipelines in literature or databases. Moreover, the Dutch gas industry data contain no relevant leaks or ruptures. For flange leaks, the failure frequency is based on statistics for the Dutch gas industry. Flange connections themselves cannot rupture. However, a leak from a flange connection can lead to a rupture of a pipe; it is therefore recommended to take this domino effect into account in risk calculations.

This study also shows that the contribution of external events, such as vehicle impact and lifting operations, should be included in the accident scenarios and failure frequencies. It is recommended to validate current models for these events. Another recommendation is to improve Dutch accident databases to make them suitable for detailed analysis of incidents and to determine failure frequencies.

Key words:
QRA, natural gas, piping, failure frequency

Rapport in het kort

Aardgasleidingen op inrichtingen

Het RIVM heeft in opdracht van het ministerie van Infrastructuur en Milieu ongevalskansen van scenario's bepaald voor bovengrondse aardgasleidingen op aardgasinrichtingen. Dit zijn onderdelen van de aardgasinfrastructuur waarbij apart is gekeken naar 'flensverbindingen', die leidingdelen met elkaar verbinden. De scenario's en ongevalskansen kunnen worden gebruikt om de risico's voor de omgeving in kaart te brengen. Dit gebeurt met de rekenmethodiek voor aardgasinrichtingen die momenteel wordt ontwikkeld. Deze methodiek zal deel uitmaken van de Handleiding risicoberekeningen bij het Besluit externe veiligheid inrichtingen. Het onderzoek is uitgevoerd omdat aardgasinrichtingen onder dit Besluit komen te vallen, maar de bijbehorende Handleiding nog niet specifiek op deze inrichtingen ingaat.

Er zijn twee standaardscenario's onderzocht: lekken en breuken. De ongevalskansen van de leidingen zijn afgeleid uit Europese gegevens van transportleidingen. Hiervoor is gekozen omdat er geen bruikbare specifieke gegevens voor de bovengrondse hogedruk aardgasleidingen in literatuur of databanken aanwezig zijn. Bovendien bevatten de gegevens van de Nederlandse gasindustrie geen relevante lekken of breuken. Voor flenslekkages is de ongevalskans gebaseerd op de statistieken van de Nederlandse gasindustrie. Flensverbindingen zelf kunnen niet breken. Wel kan een lekkage van een flensverbinding tot een breuk van een leiding leiden, waardoor wordt aanbevolen dit domino-effect mee te nemen in een risicoberekening.

Verder blijkt uit dit onderzoek dat de bijdrage van externe gebeurtenissen, zoals aanrijdingen en hijswerkzaamheden, moet worden meegenomen in de ongevalskansen en scenario's. Hier vloeit de aanbeveling uit voort om de huidige modellen voor deze gebeurtenissen te valideren. Een andere aanbeveling is om de Nederlandse ongevalsdatabanken zo te verbeteren dat ze ook geschikt zijn om incidenten gedetailleerder te analyseren, en om ongevalskansen te bepalen.

Trefwoorden:
QRA, aardgas, leidingen, faalfrequentie

Contents

Summary

Onshore natural gas establishments are mentioned in the Dutch External Safety (Establishments) Decree (Bevi). Therefore, a formal methodology needs to be available. This methodology for onshore natural gas establishments is currently under development. The available failure frequencies for leaks and ruptures of on-site pipelines or piping are generically defined and broadly applied and it is investigated whether it is possible to create specific scenarios and failure frequencies for natural gas piping on establishments.

As manager of the risk assessment methodology, RIVM initiated an investigation on the failure data of high-pressure natural gas piping. The results of the investigation should lead to a new section in the risk method for mining establishments and other relevant methods.

In the Netherlands, third-party risk calculations are bound to prescribed calculation methods. Basically, these calculation methods are applicable to all situations that may arise within their scope. For the implementation of structural adjustments, such as a revision of scenarios and failure frequencies, an assessment framework is being used, describing the elements to be discussed. This approach includes guidelines for adjustments in the four key elements of a calculation method: scenarios and modelling; failure frequencies; mitigating measures and event probabilities. To substantiate proposals for updating a calculation method, requirements have to be met concerning transparency, verifiability, robustness and validity of the data available.

To obtain an overview of information already available, a data survey has been carried out. From international literature, failure data on piping and flanges, (potentially) resulting in a Loss of Containment (LoC) are collected. From this survey it is concluded that no database with specific data for the aboveground high-pressure gas piping on establishments is available. However, two analogies emerge as possibly suitable: offshore and transmission pipelines. For offshore the HCRD (HydroCarbon Release Database) is mentioned. For transmission lines, there are several options including the EGIG database.

Initially, for both piping and flange connections, two standard scenarios have been identified: leak and rupture. As pinholes do not contribute to third-party risk, this scenario is not taken into account. The realism of a rupture of a flange connection has been investigated using fracture mechanics. It is concluded that a flange connection can withstand a larger impact and stress than the pipeline it is connected to. Therefore, ruptures of flange connections can be excluded from the risk calculations.

For piping scenarios one issue is the transition from a large leak to a rupture. Due to propagation, a large leak will result in a full bore rupture. Based on the results of the calculations of the Gasunie and in accordance with the Dutch guideline, the maximum leak size proposed is a leak with a diameter of 50 mm. This leads to the following relevant scenarios.

Table 1 Relevant scenarios

	Scenario	Leak size (Diameter)
Flange connection	Leak	10% D (max. 50 mm)
	Rupture	-
Piping	Leak	10% D (max. 50 mm)
	Rupture	100% D

Data is supplied from the Dutch natural gas industry by Gasunie, NAM, TAQA and Vermillion. These data are aggregated to derive a failure frequency for both flange connections and piping. No relevant events for piping are present in the data supplied by the industry. This is the same for the other data sources considered, such as databases from the State Supervision of Mines (a governmental organisation) and NOGEPA (Netherlands Oil and Gas Exploration and Production Association). As no relevant events for piping are present, the analogue systems are considered for deriving failure frequencies.

For the offshore data, the UK Hydrocarbon Releases Database (HCRD) System has been analysed. The HCRD is not selected as the most suitable analogy. Firstly because the HCRD does not contain full bore ruptures but ends with a category of holes with a diameter larger then 100 mm. Further, the experience (number of system years) in the HCRD is smaller than the experience of the Dutch natural gas industry. With regard to the natural gas transmission lines, the conclusion is that these could be used as an analogy for aboveground pipelines within establishments.

With regard to the natural gas transmission lines, the EGIG data from transmission lines in Europe have been selected as the best matching option for piping, after rating several options using four basic criteria (transparency, verifiability, robustness and validity). The table below shows a summary of the results concerning piping based on EGIG data.

Table 2 Failure frequencies for piping based on EGIG data

Event type	Events	Experience [m·years]	Failure frequency [$m^{-1} \cdot year^{-1}$] Average	95[th] percentile
Leak	63	3.15×10^9	2×10^{-8}	2.5×10^{-8}
Rupture	17	3.15×10^9	5.5×10^{-9}	8×10^{-9}

Flange connections will have to be treated separately, as they are generally not used for buried pipelines. It is therefore concluded that for flange leakages the failure frequency for the leak is to be based on the statistics of the Dutch gas industry.

Table 3 Failure frequency for flange connections based on Dutch industry data

Event type	Events	Experience [years]	Failure frequency [$year^{-1}$] Average	95[th] percentile
Leak	1	1,802,355	5.5×10^{-7}	2.6×10^{-6}

Leaks of aboveground pipelines or flange connections are identified as possible initiating events for pipeline ruptures. A conditional probability of about 0.001 pipeline ruptures as a result of a leak has been determined. E.g., for flanges, this results in an additional failure frequency of 5.5×10^{-10} (average) or 2.6×10^{-9} (95th percentile) per year for the piping sections, which could fail as a result of the domino effect.

In addition to these frequencies, the contribution of external events such as vehicle impact and lifting operations should be taken into account for the aboveground pipelines within establishments. As lifting activities and vehicle impact might dominate the failure frequency of aboveground pipelines, it is recommended to do some further work on validating the current impact models.

For the derivation of failure frequencies, the reports of HCRD, EGIG and UKOPA could be used. Dutch generic incident databases (NOGEPA and from the State Supervision of Mines) were not suitable for the derivation of frequencies. It is therefore recommended to improve the Dutch databases in such a way they will also be suitable for more detailed incident analysis and the determination of frequencies for risk assessments.

1 Introduction

Onshore natural gas establishments (including gas treatment, production and injection facilities) will be included in the Dutch External Safety (Establishments) Decree (Bevi) [1] in 2011. Therefore, a formal quantitative risk assessment (QRA) methodology must be available. This methodology for onshore natural gas establishments is currently under development. The available failure frequencies for leaks and ruptures of on-site pipelines or piping are generically defined and broadly applied and it is investigated whether it is possible to identify specific scenarios and failure frequencies for natural gas piping within establishments. From the literature, flanges were identified as a topic of interest as flange ruptures were identified as possible Loss of Containment (LoC) events for aboveground pipelines [2]. The study focuses on aboveground piping.

As manager of the risk assessment methodology, RIVM has initiated an investigation on the failure data of high-pressure natural gas piping. The results of the investigation should lead to a new section in the risk method for mining establishments and other relevant methods (e.g., section 3.8 of the Reference Manual Bevi Risk Assessments, Module C [3]).

The results of the research have been written in this report. Background reports have been written by N.V. Nederlandse Gasunie about flange connections [4], by DNV concerning the Hydrocarbon Release Database (HCRD) [5] and by GL Noble Denton concerning the use of data from (buried) natural gas transmission pipelines [6]. These three documents are annexed to this report.

The research described in this report was conducted in consultation with an international study group with members from industry and government institutions (see Appendix 1).

2 Framework

Within the Dutch quantitative risk assessment method, generic failure frequencies are laid down for the various Loss of Containment events (LoCs) [3] [7]. The current failure frequencies for aboveground pipelines are generically defined and broadly applied and it is suggested to use specific failure frequencies for natural gas piping in establishments.

2.1 Aim

The aim of the project is to derive scenarios and frequencies for the failure of onshore aboveground high-pressure natural gas piping within establishments. The aspects addressed are the scenario descriptions and frequencies with their underlying causes.

2.2 Scope

In short, the project is about 'on-site natural gas piping'. To be more specific, the scope is limited to aboveground, high-pressure natural gas piping (> 16 bar; > 2-inch diameter) on onshore natural gas establishments with dry gas and wet gas with a condensate/gas ratio $\leq 80\ m^3/10^6$ normal m^3.

In this report the term 'piping' is used for the aboveground pipelines within establishments. This term has been chosen to make a difference with 'pipework' (related to (small) process pipelines with a lot of equipment and significant pressure or temperature changes) and 'pipelines' (related to – often buried – transmission pipelines for the transport between establishments).

The presence of flange connections is one of the differences between aboveground and buried pipelines. As mentioned in the introduction, flanges were identified as possible Loss of Containment (LoC) events for piping [2] [8]. Therefore, the project also concerns 'flange connections' as a relevant topic for the failure of aboveground pipelines within establishments. A 'flange connection' or 'flanged joint' consists of two flanges with a gasket in between. The two flanges are held together using a bolted connection.

This project is about piping and flange connections; other equipment such as valves are out of the scope of this study and are not taken into account.

The quantitative risk assessment is based on various LoC events. Initially, for both piping and flange connections, two standard scenarios have been identified: leak and rupture. As pinholes do not contribute to third-party risk, this scenario is not taken into account.

2.3 Approach

Third-party risk calculations are bound to prescribed calculation methods. Basically, these calculation methods are applicable to all situations that may arise within their scope. During the development of the calculation methodologies, choices were made reflecting a balance between uniformity and location-specific modelling. In some situations, the prescribed method may not be adequate. Therefore, a user has the possibility of using specific data on some occasions. Location specific modelling needs to be justified, with the considerations and choices being documented.

There can be various reasons to incorporate new insights into existing calculation methodologies. This may lead to structural adjustments in a calculation methodology. For the implementation of structural adjustments an assessment framework [9] has been defined, which describes the elements that must be discussed. This approach includes guidelines for adjustments in the four key elements of a calculation methodology: release scenarios; failure frequencies; mitigating measures and event probabilities. To substantiate proposals for updating a calculation methodology, requirements have to be met concerning transparency, verifiability, robustness and validity of the data available [10]. The use of the assessment framework ensures a consistent approach for implementing adjustments in the calculation methods.

The derivation of failure frequencies needs to be unambiguous. Specific aspects of failure frequencies are:

- Transparency: is it clear? The selection of incidents and the population used for the derivation is clearly described, understandable and unambiguous. If the derivation is transparent, each expert should come to the same conclusions for the same situation.
- Verifiability: is it traceable? The selection and derivation are well documented and the data are traceable to the original sources, which should be available.
- Robustness: is it solid? The derivation follows a realistically safe (or conservative) approach in case of uncertainty. If there is a large uncertainty, estimates are conservative (e.g., using a 95^{th} percentile). If more information is available, the estimate will be closer to the realistic value.
- Validity: is it true? The outcome should be realistic. Aspects that play a role are completeness and the scientific basis. Applicability (representation) is also important.

In Figure 1 the different steps in the derivation [9] are presented. Step 1 (statistics) and step 2 (analogy) are taken during this project and are discussed in the following sections. Step 3 (expert judgement) has not been used in this project and will thus not be discussed any further.

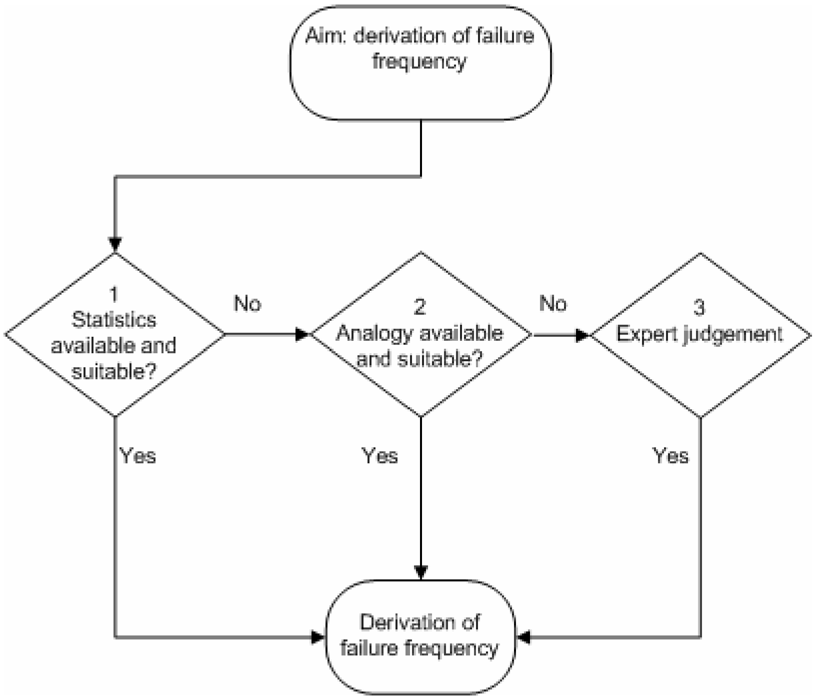

Figure 1 Flowchart for the derivation of failure frequencies

2.3.1 *Statistics*

To derive failure frequencies based on statistics, the data collected should at least include:

- the number of events;
- the number of observations.

An **event** in this case is an **incident** that falls within the definition of a representative LoC. The **observations** are the number of **experience** years for the component.

When collecting appropriate statistics, the validity of the data of interest is important. A general aim is to pool the data of incidents and observations, to make them as representative and as large as possible. In practice, these two requirements are contradictory. In a representative dataset the number of observations will often be small. As for a dataset with a large number of observations, concessions have to be made regarding the representativeness of the data.

Data can be obtained by industry surveys using literature and incident databases or from guidelines used in other countries. In identifying the incidents it should be evaluated whether these still apply to the Dutch situation. If an event is excluded, this has to be substantiated and reported. It has to be shown that a complete overview is given of the incidents that have occurred. If (known) data do not fully reflect the Dutch situation, an analysis must be made as to whether or not a (new) failure frequency can be derived based on the data.

2.3.2 *Analogy*

With an analogy, the failure frequency is determined using another, comparable, system (source system). An analogy is used when there are little or no statistics available to derive a specific failure frequency or if no incidents have occurred. If one or more relevant incidents have taken place, it should be determined whether an analogy can be applied.

A further analysis may be used to bring the systems in line with each other (e.g., excluding irrelevant failure causes and incidents of systems that do not match the initial system).

The source system should be representative of the initial system. They should at least be comparable. The following points should be taken into account regarding the systems:

1. The function of the systems is similar.
2. The construction of the systems is similar.
3. Maintenance and inspection regimes of the systems are similar.
4. The process and / or storage conditions are similar.
5. The intensity of the use of the systems must be at least comparable to each other.
6. The failure causes of the system are similar.

If more than one analogy is used, condition 1 prevails over condition 2, et cetera.

2.4 Structure of the report

A survey of the relevant literature, databases and international methods is given in Chapter 3. In Chapter 4 the available statistics of the Dutch natural gas industry (step 1 of Figure 1) are presented and analysed. Step 2 is the description of analogies. In this project two different analogies are considered: offshore data and transmission pipelines. This is done in Chapter 5. The derivation of the scenarios and failure causes based on the results of Chapters 3 to 5 are presented in Chapters 6 and 7. The last chapter contains the discussion and conclusions of the project.

3 Survey

Summary and conclusion

To obtain an overview of information already available, a data survey has been carried out. From international literature, failure data on piping and flanges (potentially) resulting in a Loss of Containment (LoC) are collected.

Based on the survey, the conclusion is that no published database can be used directly. There is no publicly available database with specific data for the aboveground high-pressure gas piping within establishments. On the other hand, from the survey two analogies emerge as possibly suitable: (1) offshore pipework and piping and (2) transmission pipelines. For offshore the HCRD (HydroCarbon Release Database) is mentioned. For transmission lines there are several options, including the EGIG database.

An overview is also made on how piping is included in risk assessments in other countries (UK, France and Belgium) and the basis thereof. In the UK, statistical information is being used for the derivation of failure frequencies. Although the background information of the UK method is not completely clear, the method itself (scenarios together with frequencies) matches the Dutch approach. In France, pipeline rupture scenarios are excluded if some conditions are met. Frequencies used in Flanders, Belgium are outdated, as they are based on a 30-year old study from DNV.

It can be concluded that the data used in other countries cannot be adopted directly in the Dutch method. The method in France does not match with the Dutch approach because all failure causes cannot be excluded from the very start. The data of Flanders are outdated. The UK method is worth analysing further if there is no other useful data from industry or analogies.

3.1 Literature

For a selection of the relevant literature, the Scopus database is used [11]. Scopus contains articles and papers from many different sources, such as scientific journals and publications of congresses. Keywords such as risk assessment, failure rate, frequency, natural gas, pipelines, high-pressure and aboveground are selected for the first search. This results in the selection of more than 120 abstracts. A quick scan of the abstracts reduces the number of more or less relevant abstracts to 21. The subjects of these articles can be divided into different categories, such as:

- Risk assessment approaches
- Computer models for risk assessments
- Databases
- Ignition probability
- Failure rates, failure frequency
- Fault tree analysis
- External interference
- Consequence analysis

None of the articles found are specifically related to aboveground high-pressure natural gas piping. Almost all of them concern either data from the offshore industry or assessments of underground transmission pipelines. Highlights of the articles are mentioned in the next sections.

3.1.1 *Offshore data*

Regarding offshore data, two papers of DNV are worth discussing. The papers deal with the question whether offshore data (i.e., HCRD) can be considered valid for the onshore industry and used for an onshore system QRA [2] [12]. Based on the underlying failure causes in HCRD, it is concluded that the relevant failure causes for offshore and onshore systems are similar. These failure causes are:

Design fault:
- Equipment fault
- Corrosion/erosion
- Mechanical defect
- Material defect
- Other

Operational fault:
- Incorrectly fitted
- Improper operation
- Dropped/impact
- Left open/opened
- Other

Procedural fault:
- Non compliance
- Deficient procedure
- Other

The contributions of failure causes specifically relating to the offshore environment (salt water corrosion, sand erosion, dropped objects) are relatively small. This suggests that offshore data can be used for a QRA of an onshore system. However, the HCRD data are not unequivocal, thus different analysts can process the data in different ways. Therefore, DNV developed general leak functions based on the data of the HCRD. However, to use these leak functions choices have to be made and uncertainties arise. One of the assumptions is the extrapolation of leak frequencies into data areas where no or fewer leaks have been reported. DNV mentions that the uncertainty 'tends to be greatest for large hole sizes, for equipment sizes far from the centres of the ranges of validity above and for equipment types where fewer leaks have been recorded' [12].

3.1.2 *Transmission lines*

In [13] a survey of incident databases of natural gas transmission lines is given along with a list of underlying causes and failure frequencies of the transmission lines in the US and Europe. In this publication, the EGIG (European Gas Incident Group) and the DOT (US Department of Transportation, Office of Pipeline Safety) databases are used to make a comparison between the US and the European situation.

The article gives six cause categories based on the databases (the same causes are mentioned in other articles [14] [15]):

1. external interference or third-party activity;
2. corrosion;
3. construction defect and mechanical or material failure;
4. ground movement or natural hazards in general;

5. hot tap by error[1], and
6. other or unknown causes.

For the incidents mentioned in EGIG, external interference is the most important cause and the EGIG data show a decrease of the external interference with increasing diameter. The overall failure frequency derived by EGIG is 5.75×10^{-4} per km·year (1970–1992) or 3.81×10^{-4} per km·year (1988–1992). The same EGIG data are used in other articles [15] [17]. From the US DOT database the overall failure frequency is 7.4×10^{-4} per km·year (1970–1985) or 1.7×10^{-4} per km·year (1984-1992).

3.1.3 *OGP reports*

In March 2010, the International Association of Oil and Gas Producers (OGP) published the Risk Assessment Data Directory (RADD). The corresponding reports contain frequencies for different systems and subsystems of facilities from the oil and gas industry.

Report 434-4 gives release frequencies for risers and pipelines [18]. The failure frequencies for the onshore gas pipelines are based on data from EGIG. The release frequencies of process equipment, such as process pipes and flanges, are included in report 434-1 [19]. These data are based on the HCRD and for the results, DNV's leak function [2] is used. The overall frequencies have been divided into full, limited and zero pressure frequencies. The report mentions that the data are suitable for onshore pipes within process units but not for inter-unit pipes or cross-country pipelines [19]. The data can be used also for onshore facilities handling hydrocarbons. In a footnote of the report the justification for using the offshore data for onshore facilities is given: "The justification for using offshore data for onshore facilities is two-fold. First, no public domain dataset for onshore facilities is available that is comparable to HCRD, considering both the equipment population and completeness of recording releases. Second, although offshore facilities operate in a more challenging (e.g., more corrosive) environment, this is compensated for in the design, inspection and maintenance. Hence, there is no apparent reason why onshore and offshore release frequencies should differ significantly (…)" [19].

Finally, the report gives modification factors to use the frequencies for steel pipes also for inter-unit pipes (factor 0.9) and transfer pipes (factor 0.8). The factors are based on data from confidential DNV reports.

3.2 Data sources

3.2.1 *Survey*

There are several databases and other possible sources of failure frequency information. A review has been carried out of possible sources of historical data relevant to aboveground installations [6]. The review considers fifteen data sources:

- Hydrocarbon Release Database (HCRD) (UK HSE)
- Land Use Planning Guidelines (UK HSE)

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[1] The term 'Hot tap by error' means that a connection has been made by error to a high-pressure gas transmission pipeline, which has been incorrectly identified as another pipeline [16].

- Incident Identification Study (International LNG Importer's Group - GIIGNL)
- New Generic Leak Frequencies for Process Equipment (DNV)
- Gas Pipeline Incident reports (European Gas Incident Group - EGIG)
- Cross-country Oil Pipelines Performance reports (CONCAWE oil pipelines management group)
- Pipeline Performance in Alberta (Alberta Energy and Utilities Board - EUB)
- Analysis of Incidents for Gas Transmission and Gathering System Pipelines – DoT US data (Pipeline Research Council International - PRCI)
- PIPESAFE (predictive structural reliability models)
- Handbook Failure Frequencies 2009 for drawing up a Safety Report (Flemish Government)
- Purple Book (Ministry of Housing, Spatial Planning and the Environment, Netherlands)
- Reference Manual Bevi Risk Assessments (RIVM, Netherlands)
- Lees' Loss Prevention in the Process Industry (textbook)
- IIity Engineering failure rate database (Internet site)
- OREDA 2009 (Offshore Reliability Data 5th Edition)

None of these databases and references specifically applies to onshore high-pressure gas installations or aboveground piping in particular. No relevant publicly available source of historical failure statistics has been found. Therefore, in risk assessments for onshore sites, data derived from offshore operations is often used, involving comparable pipework and associated equipment, for example, the HCRD published by the UK HSE covering offshore installations in the North Sea.

A comprehensive report of the review of data sources for estimating the failure frequencies for aboveground natural gas piping is given in [6].

3.2.2 MHIDAS

MHIDAS (the Major Hazard Incident Data Service) is a database of incidents involving hazardous materials that had an off-site impact or had the potential to have an off-site impact. Such impacts include human casualties or damage to plant, property or the natural environment. MHIDAS has a worldwide coverage but with a focus on incidents occurring in the UK and USA.

In order to investigate possible failure causes for natural gas pipelines within establishments, the MHIDAS database [20] is evaluated. In the MHIDAS database, 16,225 incident entries are included. Two separate selections have been made:

1. Selection of all incidents with natural gas pipelines in establishments.
   The selection resulted in 10 remaining relevant entries. The main failure causes from these entries are:
   - 3 mechanical failure (1 corrosion)
   - 3 human (2 maintenance, 1 general operations)
   - 1 external
   - 3 not given (unknown?)
2. Selection of all incidents where flanges (leaks and ruptures) are involved. This selection is chosen as flanges were identified a specific subject for investigation [8].

Four incidents describe a flange being broken or ruptured. For the ruptures, the following substances were involved: crude oil (1), vinyl chloride (1), sulphuric acid (1) and trichlorosilane (1). From the other 34 incidents with flange leaks it can be concluded that flange leakages not only occur during maintenance, but also during normal operation. However, as no entry is related to a release of natural gas and as a number of incidents occur, for example, during transfer, i.e., loading or unloading operations using rigid pipework (6 entries) or storage (1), it cannot be concluded that this will also be the case for piping or pipelines with natural gas.

Based on these selections and the few remaining entries after selection, it is concluded that no reliable conclusive remarks can be made on the distribution of the relevant failure causes for pipeline leaks and ruptures. Further information on the MHIDAS database selection is given in Appendix 1.

3.3 International approaches

3.3.1 United Kingdom

HSE advises planning authorities on land use planning developments near hazardous installations. This advice is based on the results of a risk assessment in which three different zones are calculated [21].

For risk assessments for land use planning, a HSE report with failure frequencies is available [22]. In this document the failure frequencies of vessels, components (such as valves and flanges), pipework, pipelines, tankers, et cetera, are listed. The failure frequencies for aboveground pipelines are presented in Table 4.

Table 4 Failure frequencies aboveground pipelines

Failure category	Failure frequency (m^{-1} $year^{-1}$)
Rupture (>1/3 diameter)	6.5×10^{-9}
Large Hole (1/3 diameter)	3.3×10^{-8}
Small Hole (5 mm – 25 mm diameter)	6.7×10^{-8}
Pin Hole (≤5 mm diameter)	1.6×10^{-7}

The values of Table 4 are applicable to general natural gas aboveground installations and are subject to the following limitations:

- Pipeline not to be more than 1.5 metres aboveground level.
- Aboveground section of pipeline under assessment to be entirely within a secure compound.
- Sites containing high-speed rotating machines (e.g., compressor stations) should be referred to the Topic Specialist for advice.
- Sites where the presence of the pipeline is ancillary to the main activity (e.g., processing plants) should be referred to the Topic Specialist for advice.
- The Topic Specialist should be informed on each occasion that these failure frequencies are used.

It is mentioned that the origin of the derivation of the failure frequencies is uncertain and no references are mentioned in [22]. However, another document contains the derivation of the failure frequencies based on fault tree assessments [23]. The underlying causes of pipeline failures are mechanical failure, corrosion and external events. The last one is studied by fault trees of four components:

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

The summation of the frequencies of mechanical failures, corrosion and external events leads to the total failure frequencies as shown in Table 4. The background information of the derivation of the underlying frequencies is not described in [23]. The HSL/HSE study group members mentioned that current values are based on either EGIG [16] or UKOPA [24] data.

The failure frequencies of flanges and gaskets are based on the comparison of different sources [22]. The next tables show the failure frequencies of flanges and gaskets and the frequency for the fixed pipe flange.

Table 5 Failure frequencies gaskets

Event	**Failure frequency (per flange connection per year)**	**Notes**
Failure of one segment of a gasket.	5.0×10^{-6}	The hole size is calculated as the distance between two bolts and the gasket thickness.
Failure of Spirally-Wound Gasket	1.0×10^{-7}	Hole size calculated as gasket thickness multiplied by pipe circumference.

Table 6 Spray release frequency fixed pipe flange

Category	**Frequency (per flange per year)**	**Effective length of crack**
Fixed pipe flange	5.0×10^{-6}	Pipe diameter (max. 150mm crack length)

In the report a spray release is defined as a release where the spray from a hole is broken into droplets small enough to not rain out. Spray releases are normally only considered when assessing risks from toxic substances that would otherwise have very small hazard ranges because of their low volatility [22]. So the spray release means a small release from a very narrow breach.

3.3.2 *France*

In the French regulatory framework industrial activities are classified according to their potential risk. This section gives the French approach for defining the relevant scenarios for a risk assessment of natural gas piping in an underground gas storage facility. In particular, the conditions are described which have to be fulfilled in order to exclude the pipe rupture scenario from the quantitative risk analysis. These principles are defined by the French regulatory framework in the "circulaire du 10 Mai 2010" [25].

Industrialists are free to choose the methodology to be used for the selection of scenarios, the probability assessment and the consequences calculation, but the relevance of the methodology used must be justified in the safety report. Results of the risk assessment are used for licensing, defining the land-use planning around the establishment and defining external emergency plan scenarios. In this framework, the risk generated by high-pressure natural gas piping on-site aboveground must be assessed. Some of the establishments where this piping is used are underground natural gas storages. In the specific case of piping used in these storages, the French Ministry gives guidance for the definition of scenarios to be used in risk assessment.

The scenarios which have to be studied in the safety report for piping are described in Table 7.

Table 7 Scenarios to be used in risk assessment for aboveground pipes in underground gas storage facilities

Loss of containment	Type of release	Dangerous phenomena
25 mm hole	Horizontal	Jet fire; Vapour Cloud Explosion (to be investigated by the industrialist)
50 mm hole (if a distinction in hole sizes is made)	Horizontal	Jet fire; Vapour Cloud Explosion (to be investigated by the industrialist)
Rupture (hole with diameter > 50 mm)	Horizontal	Jet fire; Vapour Cloud Explosion (to be investigated by the industrialist)

When the scenarios in Table 7 are assessed with regard to their probability, kinetic, intensity and severity, some specific causes are excluded from the analysis. These are:
- falling meteorites;
- earthquakes of an intensity superior to the reference intensity in the area;
- flooding of an intensity superior to the reference intensity in the area;
- climatic events of an intensity superior to the reference intensity in the area;
- airplane crashes if there is no airport in a radius of two kilometres;
- large dam ruptures and large dike ruptures;
- events related to malevolence.

The rupture scenario may be excluded from the quantitative analysis for both the probabilistic and consequence assessment, used for licensing and land-use planning, if specific conditions are fulfilled. The rupture scenario is kept for defining external emergency plan scenarios. The conditions to be fulfilled are the following:
1. Mechanical and thermal external interferences (e.g., vehicle collision and domino effects) must be excluded as a possible cause of accidents and this must be justified in the safety report;
2. Pipes must be protected against external impact resulting from human activities. The mechanical impact of a 32-ton shovel is thought to be representative of these external impacts;
3. Pipes are made of a steel grade suitable for the temperature of transported fluids. In some specific cases reheating installations are

present. Here, the mechanical specifications of the pipe should allow for the gas temperature. In this type of case, industrialists have to justify this specifically;
4. The mechanical specifications of the pipe are suitable with regard to the temperature of the gas transported;
5. If a reheating system is used, the design, exploitation, maintenance, et cetera, of this system must guarantee the compatibility between pipe specifications and gas temperature;
6. Industrialists must provide technical documentation on pipe design and prevention measures implemented for preventing metallurgic defaults, corrosion and hammer effects. Industrialist must also demonstrate to the inspectorate that no rupture caused by these causes has occurred in the statistics;
7. Pipes must be inspected in accordance with a GESIP guide, the UFIP-UIC DT 84 document or the professional guide for the implementation of inspection plans from Gaz de France.
8. Pipes must be designed in order to resist to an earthquake of the reference intensity in the area;
9. Pipes must be weighted in order to avoid loss of containment in case of floods of the reference intensity in the area;
10. Industrialists must study in their risk analysis the maintenance and construction works phases.

These conditions have been agreed on by the French ministry and Gaz de France and ended a long discussion between the ministry and this operator. The text formalises something that had been already decided. The argumentation had a high level of detail. Still, as the exclusion of a scenario is quite sensitive, if a specific lay-out is identified, the inspectorate may ask for more details, for example, on the protection against jet fires.

3.3.3 *Belgium – Flanders*

As part of the safety report, Seveso companies in Flanders have to perform a Quantitative risk assessment (QRA). In 2009 a new version of the guideline concerning the scenarios and failure frequencies for the QRA was published [26]. This is based on the research of SGS [27]. The background information of the guideline is written in a separate report [28]. In the chapter of the SGS report describing the peer-review, it is mentioned that the frequencies of pipelines includes flanges and appendages. The scenarios and frequencies for aboveground pipelines in Flanders [26] are shown in Table 8. These scenarios and frequencies apply to all types of industries.

Table 8 Scenarios and frequencies for pipelines

Event	Frequency (per year)	Note
Small leak	2.8×10^{-7} L/D	d_{eq} = 0.1 D
Middle leak	1.2×10^{-7} L/D	d_{eq} = 0.15 D
Large leak	5.0×10^{-8} L/D	d_{eq} = 0.36 D
Rupture	2.2×10^{-8} L/D	

with:
- L = Length of the pipeline (mm) (at least 10 m)
- D = Internal diameter of the pipelines (mm)
- d_{eq} = equivalent hole size (mm)

These failure frequencies have been derived from the 1978 Gulf data. Based on these data, DNV derived an overall leak frequency equation: $F = 4.72 \times 10^{-7}$ L/D per year [28].

3.3.4 Germany

In Germany no QRA approach with default scenarios and failure frequencies is used. However, for this project one research report of the Federal Institute for Materials Research and Testing (BAM) is relevant [29]. In this research the risks of transmission pipelines were analysed, particularly the effects (damage) of pipeline failures. For the investigation of incidents concerning pipelines with natural gas, the EGIG database [16] and the Alberta EUB database [30] are used. BAM concludes that accident frequencies can be determined on the basis of databases (such as, e.g., EGIG) but that in contrast, there is little information on the extent of effects. Based on the analyses of the possible effects it is also concluded that safety distances should be considered in case of land use planning in the vicinity of transmission pipelines.

4 Statistics Natural Gas Industry

Summary and conclusions

From the Dutch natural gas industry, data is supplied by Gasunie, NAM, TAQA and Vermillion. These data are aggregated in order to derive failure frequencies for both flange connections and piping. Table 9 and Table 10 show the number of events and the associated experience. Using this data an average failure frequency and the upper 95% limit of the one-sided confidence interval of the mean frequency (being the 95th percentile). This confidence interval is calculated assuming the number of incidents is Poisson distributed.

Table 9 Failure frequencies for flange connections based on Dutch industry data

Event type	Events	Experience [years]	Failure frequency [year^{-1}] Average	95th percentile
Leak	1	1,802,355	5.5×10^{-7}	2.6×10^{-6}
Rupture	0	1,802,355	0	1.7×10^{-6}

Table 10 Failure frequencies for piping based on Dutch industry data

Event type	Events	Experience [m·years]	Failure frequency [m^{-1}year^{-1}] Average	95th percentile
Leak	0	2,787,310	0	1.1×10^{-6}
Rupture	0	2,787,310	0	1.1×10^{-6}

No relevant events for piping are present in the data supplied by the industry. This is the same for the other data sources considered, such as databases from the State Supervision of Mines (a governmental organisation) and NOGEPA (Netherlands Oil and Gas Exploration and Production Association). As no relevant events for piping are present, analogue systems are considered for deriving failure frequencies (see Chapter 5).

4.1 N.V. Nederlandse Gasunie

N.V. Nederlandse Gasunie (hereafter Gasunie) is a Dutch gas infrastructure company. The network of Gasunie is one of the largest high-pressure gas networks in Europe. In the Netherlands their network consists of about 12,500 kilometres of transmission pipelines, dozens of plants and approximately 1,100 gas receiving stations. In Table 11 an estimate is presented of the number of flanges per Gasunie station type [4].

In the aboveground part of the Gasunie pipeline system on establishments many connections are flanged. Gasunie has incidents of the last 12 years available in a searchable database. Querying this database resulted in 34 reported incidents with flange leakages [4]. All these leakages concerned equivalent hole sizes of less than 10 mm. At Gasunie stations only one larger incident occurred with a flange fifteen years ago. According to Gasunie this was the only major incident with a flange connection during at least the last 20 years [4]. During maintenance, a crack was initiated in a flange on a valve that was still under pressure, resulting in a leakage. In Table 12 an overview of the gas leakages is given.

Table 11 Aboveground piping length and number of flanges on Gasunie establishments

Category	Number of stations	Total number of compressors / pipes	Length piping [m]	Total piping length [m]	Flange connections [per pipe / compressor]	Total number of flange connections
CS	11	86	30	2,580	5	430
MPRS	1,100	3,000	20	60,000	25	75,000
HPRS	85	220	40	8,800	15	3,300
ES	9	60	60	3,600	10	600
BS	10	40	100	4,000	10	400
Total				78,980		79,730

CS: Compressor station; MPRS: Middle-pressure Reducing station; HPRS: High-pressure Reducing Station; ES: Export Station; BS: Blending Station.

Table 12 Gas releases at Gasunie establishments

Leakage type	Number of incidents	Time period	Experience
Flange leak < 10 mm	34	12 years	956,760 years
Flange leak > 25 mm	1	20 years	1,594,600 years
Flange rupture	0	20 years	1,594,600 years
Pipeline leak	0	12 years	947,760 m·years
Pipeline rupture	0	12 years	947,760 m·years

4.2 Nederlandse Aardolie Maatschappij

NAM (Nederlandse Aardolie Maatschappij) is the largest gas producer in the Netherlands. Slightly more than half of this gas comes from the Groningen gas field and the rest from various smaller fields (both on land and in the North Sea). NAM provides about 75 per cent of total gas production in the Netherlands. An overview of pipes and pipe lengths from the NAM assets is given in Table 13. NAM has estimated the number of flange connections as one per ten metres of piping.

Table 13 Process and gas piping lengths for the onshore part of NAM

Asset	Installation types	Number of installations	Piping length [m]	Total piping length [m]
Groningen				
	Cluster	20	6,600	131,200
	UGS	2	10,000	20,000
	Satellite location	2	3,000	6,000
	Transfer	7	300	2,000
Land				
	Satellite location	72	500	36,000
	Treatment location	100	1,000	100,000
	Flare	89	100	8,900
Den Helder	Treatment location	1	10,000	10,000
Total				314,100

NAM has analysed all gas leakages within the past 5.5 years (2005 to mid-2010) using their annual incident reports. A total of 147 gas leakages occurred in this period [31]. These incidents can partially be attributed to equipment and partially to pipes. Another part is attributable to appliances, leaking PSVs (pressure safety valves) (which are actually not relevant LoC events), leaks during commissioning, et cetera. There have been 48 incidents where a leak in piping (or piping component) is found and reported. Components are, e.g., instrumentation connections, flanges and valves. The location of the leak was not always clearly evident from the description in the reports, it can, e.g., relate to leaks in the connection of a vessel or heat exchanger.

None of these incidents have had a direct impact on the environment [32]. The release rates are small. The release duration is estimated and the total amount released can be obtained. The number of releases and their sources are given in Table 14. There has been no incident involving failure of a pipe or a large leak, so the figures in Table 14 are all about small to very small leaks (all <10 mm).

Table 14 Gas releases at NAM (2005 – mid 2010)

Leakage type	Number of incidents
Flange leakage	17
Valve leakage (stem leakage)	12
Other leakages (including pinholes, unknown)	19
Ruptures	0

4.3 TAQA

In the Netherlands, TAQA Energy operates and produces gas, both onshore and offshore. It has a natural gas storage facility in Alkmaar and interests in pipelines and multiple oil and gas producing fields in the Dutch part of the North Sea. TAQA Energy operates the following onshore installations:

- PGI – Peak Gas installation (1996). This is a gas storage and treatment facility adjacent to the well site in Alkmaar. In the winter this plant supplies extra gas to the Dutch gas transport network from the Alkmaar gas field;

- Bergen Concession – Production facilities and Well sites (1972). This concession consists of gas production from five well sites with a central processing and compression plant in Alkmaar.

In Table 15 the number of pipes and flanges from both TAQA assets are shown [33]. These quantities are determined by TAQA based on a known number of pipes (piping list) and an estimated mean length and number of flanges per pipeline and based on a combination of pipe diameters (from 1½" to about 20"). Instrument tubing and smaller flange sizes are not included.

Table 15 List of piping and flanges per TAQA asset

Asset	Number of pipes (gas service)	Number of flanges (gas service)	estimation total piping length [m]
PGI-locations	490	3,000	10,000
Bergen Concession	310	2,000	6,000
Total	800	5,000	16,000

TAQA Energy has data available from 2003 to 2010 in issue and leak reports [34]. In this period there have been eight reported cases of gas leakage:

- Flange: 1
- PSV (Pressure Safety Valve) failure: 3
- Material (Corrosion / Fatigue / Other): 4

In all cases except the PSV gas leakages (which are actually venting to safe location incidents) it concerns very low gas leakage rates (pinhole dimensions) observed during routine inspections. The leakage duration is often undetermined; total volumes, therefore, are difficult to estimate. The above cases with gas leakages are listed in more detail in Table 16.

Table 16 Gas leakages at TAQA (2003 – 2010)

Description	Calculated leakage	Leakage type	Pipe diameter	Release dimensions
Flange gas leakage	< 1 m^3	Gasket leakage due to too little tension on bolts	Unknown	Unidentifiable
Glass of gauge broken	<0.1 m^3	Gauge was blocked in	About 1 inch (connection)	Volume gauge
Thermowell coupling	1 m^3	Leakage along fatigue crack	1.5 inch	Unidentifiable
Welded elbow	Unknown but > 1 m^3	Corrosion	Unknown	Crack dimensions unknown
Condenser bank	Unknown	Unknown	N/A	Unknown

4.4 Vermilion Oil and Gas Netherlands

Vermilion Oil and Gas Netherlands BV is a subsidiary of the Canadian company Vermilion Energy Trust. Vermilion produces oil and gas in Canada, Australia, France and, since May 2004, in the Netherlands.

Vermilion produces gas from one area in the province of Noord-Holland, from two areas in Friesland and from a location in the Dutch Waddenzee.

Incident data from Vermillion is available for the years 2008 and 2009 [35]. In this period there have been 16 gas leaks. From these, the compressor and fuel gas system leakages have been removed because these accidents are outside the scope of the current investigation. In Table 17 the remaining gas leakages are displayed.

Table 17 Gas leakages at Vermilion in 2008 and 2009

Equipment	Leakage quantity	Principal cause	Leakage type
Turbo expander KO drum	23 m^3	External corrosion under isolation	Pin hole leak
Turbo expander seal gas	6 m^3	External corrosion under isolation	Pin hole leak
Flow line	3 m^3	Internal corrosion	Pin hole leak
Level transmitter line	2 m^3	External corrosion under isolation	Pin hole leak
Gas cooler	Nil	No particular reason	Flange leak

As no data on hole sizes, piping / pipeline lengths and number of flanges has been made available, the data from Vermilion cannot be used for the derivation of failure frequencies. The data does give an indication of the failure causes of the incidents.

4.5 Overview of the Dutch natural gas industry data

Table 18 and Table 19 give an overview of the data used for the derivation of the failure frequencies of flange connections and piping (Table 9 and Table 10). For NV Nederlandse Gasunie, data for flange connections are available for a period of 12 years (zero events) and (at least) 20 years (one event). Although the data for the 20-year period are not documented extensively, it was decided to use the data for the derivation of the failure frequencies of flanges. This choice has however no effect on the derived 95th percentile value of the leak scenario. It has also no effect on the conclusions for the rupture scenario.

Table 18 Overview of events and experience for flange connections from the Dutch natural gas industry

	Events		Number of flange	Number of	Experience
	Leaks	Ruptures	connections	years	[years]
Gasunie	1	0	79,730	20	1,594,600
NAM	0	0	31,410	5.5	172,755
TAQA	0	0	5,000	7	35,000
Vermillion	0	0	Unknown	2	0
Total	1	0			1,802,355

Table 19 Overview of events and experience for piping from the Dutch natural gas industry

	Events		Piping length [m]	Number of	Experience
	Leaks	Ruptures		years	[m·years]
Gasunie	0	0	78,980	12	947,760
NAM	0	0	314,100	5.5	1,727,550
TAQA	0	0	16,000	7	112,000
Vermillion	0	0	Unknown	2	0
Total	0	0			2,787,310

4.6 Other data sources

4.6.1 State Supervision of Mines

State Supervision of Mines (SSM) is a governmental organisation and is situated in the Hague. The department falls under the ministerial responsibility of the Minister of Economic Affairs, Agriculture and Innovation. SSM oversees compliance with statutory regulations applicable to mineral exploration, extraction, storage and transport of minerals, focusing on the aspects of health, safety, the environment, effective extraction and soil movements.

All mining industries (including natural gas establishments) are obliged to report accidents and incidents to SSM. A standard reporting form is used. Data from these reports is recorded in a database. Recorded items are: date, company name, installation or location name and an incident description.

The instrumentation involved is not specifically recorded and no data on hole sizes or leakage duration is given. For the reported incidents the data does give an indication of the distribution of failure causes. The release rate and duration are not reported but from sections 4.1 to 4.4 it can be concluded that for these companies no large holes or ruptures are reported in the database. Thus, the distribution of failure causes drawn from the SSM database are valid for small hole sizes (< 10 mm). As the failure cause distribution changes with the hole size [16], no conclusions can be drawn for large holes and ruptures.

4.6.2 NOGEPA

NOGEPA is the Netherlands Oil and Gas Exploration and Production Association. It represents companies that possess permits to drill for and produce oil and gas, both on land and on the Dutch continental shelf. NOGEPA’s 15 members annually produce 75 billion cubic metres of natural gas and 2 million cubic metres of oil from Dutch soil.

NOGEPA keeps a database in which all natural gas accidents and incidents are reported by its members. This database is used for reporting to State Supervision of Mines. For this study, a part of the information from the database is made available. The incident descriptions made available include a short description, equipment type, principle cause, leak quantity and significance.

The available data from the database have a number of limitations that restrict their applicability to this project. One of the major issues is that no information is present about hole sizes. No distinction is also made between onshore and offshore and between above and below ground or water.

All things considered, it can be concluded that the database does not contain the desired data suitable for this study. However the data might give an indication of relevant failure causes for these incidents. As the industry data mentioned in Sections 4.1 to 4.4 is a subset of the NOGEPA dataset, it can be concluded that for these companies no large holes or ruptures are reported in the database. Thus, the distribution of failure causes is only valid for very small hole sizes. As the failure cause distribution changes with the hole size [16], no conclusions can be drawn for large holes and ruptures.

5 Analogies

Summary and conclusion

For this study two possible analogies were identified for further investigation: (1) offshore data and (2) data for transmission pipelines (Chapter 3).

For the offshore data the UK Hydrocarbon Releases Database (HCRD) System has been analysed. The HCRD is not selected as the most suitable analogy. First because the HCRD does not contain full bore ruptures but ends with a category of holes with a diameter larger then 100 mm. Furthermore, the experience (number of system years) in the HCRD is less than the experience of the Dutch natural gas industry.

With regard to the natural gas transmission lines, the conclusion is that these could be used as analogy for aboveground pipelines within establishments.

5.1 Offshore data (HCRD)

The Hydrocarbon Releases Database (HCRD) System contains detailed voluntary information on offshore hydrocarbon release incidents on the UK continental shelf [36]. This information is supplementary to that provided under the 1995 UK RIDDOR legislation [37].

The HCRD was created in response to Recommendation 39 of Lord Cullen's Report into the Piper Alpha disaster. This required that such a database be set up by the regulator (HSE) for and on behalf of the industry and that industry access be given to the data. The data are stored on a web-based system, which became operational in 2003. Prior to that date statistical reports were produced annually by the HSE. Now, standard reports can be generated by duty holders and other authorised users.

The suitability of this analogy has been investigated by DNV [5]. Regarding the points of comparability as mentioned in section 2.3.2, it can be concluded that the <u>function</u> of offshore and onshore systems is quite similar, when only gas data is used from the HCRD.

The <u>construction</u> specifications and codes used in offshore vary for each platform. They vary with the location of the platform, age, maximum pressure, et cetera. In general, it can be concluded that there is a lot more variation in codes than for onshore systems. <u>Maintenance and inspection</u> schemes offshore are generally more detailed than for onshore systems. However, implementation of these schemes might be an issue.

As for <u>process conditions (</u>such as pressure) and <u>the intensity of the use of the system</u>, the offshore system is comparable to the onshore system. On the other hand the ‘external’ conditions of onshore and offshore are different because offshore there is a much harsher environment. However the specific offshore <u>failure causes</u> (salt water corrosion, sand erosion, dropped objects) are relatively minor in the HCRD (see section 3.1.1. and [5]).

The frequencies derived from the database can vary widely because of different interpretations of the data. The data from the database should therefore be interpreted with caution. For the derivation of frequencies, three approaches have been considered [5]. The pros and cons of each of the three methods are given in the following sections.

5.1.1 *HCRD standard reports*

From the HCRD, authorised users can create standard leak frequency reports. Using such a standard report, releases with hole sizes larger than 10 mm are selected for flanges and pipes with a diameter of 3" or more. The data allow no discrimination between leakages and ruptures.

The standard reports contain a number of restrictions which render the results from these reports less useful for this project [5]. The restrictions are:

- the number of leaks does not correspond with data that can be extracted from HCRD;
- there is only one frequency for both small and large leakages and ruptures;
- the experience in the database is fairly limited compared to the Dutch gas industry data.

5.1.2 *DNV method*

As DNV acknowledges that different interpretations of the HCRD data are possible, they have developed a standard interpretation method [12]. The basic principle of the method is the derivation of analytical leak frequency functions. These functions combine both equipment and hole size with a failure frequency.

As the DNV method is an interpretation of the data using analytical functions, there are some considerations regarding the transparency, verifiability, robustness and validity of the method:

- the data selection on which the functions are derived is unknown;
- the parameters of the analytical functions are not publicly available;
- it has not been proven that the functions are valid for the selected flanges and piping;
- interpolation between known incidents might be invalid, considered that discontinuities might occur due to a transition from one design standard to another;
- extrapolation from 100 mm holes to full bore ruptures is questionable because the functions cannot be validated beyond their initial data range.

5.1.3 *Gas data selection*

Specific gas data can be extracted from the HCRD. These data are used to derive specific failure frequencies. From these data, flanges and steel piping can be selected, together with incidents with a hole size of 10 mm or more to match the study boundaries. From the remaining data flares, drains, vents and other offshore specific systems are removed.

The resulting frequencies for flange connections and steel piping are reported in Table 20. In the table, frequencies for flanges are in terms of flange connections per year and for piping are in terms of per metre per year. More detailed information on the causes can be found in [5].

Table 20 Failure frequencies for leakages based on HCRD gas data

Equipment type	Events	Experience	Failure frequency	
			Average	95th percentile
Flange connection >3"	7	646,956 years	1.1×10^{-5}	2.0×10^{-5}
Steel piping >3"	9	1,918,347 m·years	4.7×10^{-6}	8.2×10^{-6}

The gas data selection has a number of restrictions which render the results from these reports less useful for this project. Firstly, there is only one frequency for large leakages and not for ruptures. The experience in the database is also fairly limited compared to the Dutch gas industry data.

5.1.4 *Discussion*

For this project the gas data selection from HCRD fits with the onshore on-site gas pipelines. Nevertheless, the HCRD is not selected as a suitable analogy because ruptures are not reported [5]. It ends with a category of holes with a diameter larger then 100 mm. So using offshore data no rupture frequency can be derived directly. Use of the HCRD for the derivation of ruptures would require a mathematical method (extrapolation) or judgement such as applying the failure frequencies for full holes as derived from HCRD by Spouge [2] for pipeline ruptures.

Furthermore, the number of system years (experience) in the HCRD is less than the number of system years from the statistics for the Dutch gas industry (Section 4). There is also no overlap between confidence intervals of the frequencies using the Dutch gas industry data and HCRD data; the 95th percentile from the Dutch gas industry being 1.1×10^{-6} per metre per year for piping and the 5th percentile using HCRD being 2.4×10^{-6} per year. Underreporting might be an issue, however to get the same frequencies as HCRD, the Dutch gas industry should have underreported 14 to 25 flange releases and 12 to 15 piping events in the last 5 to 12 years.

Therefore, it is concluded that for ruptures failure frequencies should not be derived from the analogy using offshore data.

5.2 Natural gas transmission pipelines

Underground natural gas transmission pipelines might be a useful analogue system for aboveground piping. There are also various methods and databases available with information on the failure of pipelines.

The suitability of this analogy was investigated by GL Noble Denton [6]. Regarding the points of comparability as mentioned in section 2.3.2 between the gas transmission pipelines and on-site (aboveground) natural gas piping it can be concluded that the function of on-site an cross country gas pipelines is similar, that is to transport gas from one installation to another. For on-site piping only the distances are smaller.

Construction and specification for aboveground piping and buried pipelines can be regarded as similar, as for both types of piping similar codes and standards are used for the pipe segments and welds. One difference is that where almost all connections for underground pipelines are welded, for aboveground pipelines mostly flange connections are used in places where equipment such as measuring devices or valves are incorporated in the pipeline system. This makes for easier maintenance or replacement of parts.

Regarding maintenance, for buried pipelines cathodic protection can be regarded as a continuous maintenance system used to mitigate adverse consequences which may arise due to coating defects. For aboveground piping corrosion under isolation programmes should result in the same mitigation with the benefit that for aboveground pipes significant leakages can be noted either visibly or audibly.

As for process conditions (such as pressure) and the intensity of use of the system, the buried transmission pipelines are equal to the on-site piping aboveground. For 'external' conditions there is some difference between aboveground piping and buried pipelines with respect to external interference.

Regarding the failure causes six categories are mentioned [16]):

1. external interference or third-party activity;
2. corrosion;
3. construction defect and mechanical or material failure;
4. ground movement or natural hazards in general;
5. hot tap by error;
6. other or unknown causes.

The main difference concerns the external interference. Where cross-country pipelines cross land over which the operator has limited control (and hence are vulnerable to third-party damage); pipes at an installation are contained within a controlled site, but where they may be exposed to lifting activities and vehicle movements.

For corrosion there are differences in the exposure of buried and aboveground pipelines. This can also be argued for causes such as vibrations and high or low temperatures. It is assumed that these differences are addressed sufficiently in the construction standards used for aboveground pipelines. These differences are recognised but could not be quantified. Further, the causes ground movement and hot tap by error are regarded as not relevant for aboveground piping on-site.

In spite of the differences in the failure causes, it can be concluded that the use of gas transmission pipelines is basically a sound analogy for on-site piping and pipelines. If vehicle impact or lifting activities cannot be excluded, these causes should be addressed separately [6]. Flange connections will have to be treated separately, as they are generally not used for buried pipelines.

Although metering streets are not investigated explicitly, the same approach is used as for piping and pipelines. In [6] it is stated that the analogy by gas transmission pipelines is not intended to be applied to process pipe work, characterised by complex piping and instrumentation arrangements or changes in process fluid composition and temperatures, et cetera. Based on this description metering streets are more defined by piping than by process pipe work and therefore, the same approach as for piping and pipelines is chosen.

6 Derivation of Scenarios

Summary and conclusion

Initially, for both piping and flange connections, two standard scenarios have been identified: leak and rupture. As pinholes do not contribute to third-party risk, this scenario is not taken into account.

The realism of a rupture of a flange connection has been investigated using fracture mechanics. It is concluded that a flange connection can withstand a larger impact and stress than the pipeline it is connected to. Therefore, ruptures of flange connections can be excluded from the risk calculations.

For piping scenarios one issue is the transition from a large leak to a rupture. Due to propagation a large leak will result in a full bore rupture. Based on the results of the calculations of the Gasunie and in accordance with the Dutch guideline, the maximum leak size proposed is a leak with a diameter of 50 mm.

This leads to the following relevant scenarios.

Table 21 Relevant scenarios

	Scenario	Leak size (Diameter)
Flange connection	Leak	10% D (max. 50 mm)
	Rupture	-[1)]
Piping	Leak	10% D (max. 50 mm)
	Rupture	100% D

[1)] Given that flange connections are hydrostatically tested before use.

In the case of a situation in which the failure of one piece of piping or flange clearly leads to the failure of another piece of piping, an internal domino effect needs to be included.

6.1 Flange connections

6.1.1 Leak

A relevant flange leak occurs when a gasket is (partially) blown out from between the two flanges, or when a small crack occurs in the flange itself. As a flange connection is a mechanical connection, small leakages and gas diffusion also may occur but these are considered to be irrelevant for the calculation of third-party risks.

A leak from a flange connection is to be modelled as a leak with an effective diameter of 10% of the nominal diameter, with a maximum of 50 mm [3].

As there is limited statistical information available on the failure causes of relevant flange leakages, there is no differentiation in scenarios between gasket failures or flange body failures.

6.1.2 *Rupture*

A flange rupture is defined as a catastrophic failure of one of the flange bodies, which leads to a full size hole with an effective diameter of 100% of the nominal diameter of the attached pipe.

Within the Dutch gas industry statistics no incidents have been found describing ruptures of flange connections. No conclusive remarks could be made from the MHIDAS database evaluation. Therefore, it has been investigated if an analogy could be applied. However, no fitting analogy could be found for flange ruptures (see also section 5).

As no analogy can be applied, the statistics as given in chapter 3, are to be applied for deriving the rupture frequency. However, as this value is based on zero incidents it has been further investigated whether a flange rupture is truly a realistic scenario [4]. Based on fracture mechanics calculations it is concluded that a flange connection can withstand a larger impact and stress as the pipeline it is connected to. Therefore ruptures of flange connections are to be excluded from the risk calculations. An important requisite for this exclusion is that the flange connection is hydrostatically tested before it is taken into operation. The design and maintenance of the flange connection should also be according to industry standards.

6.2 Piping

6.2.1 *Leak*

A leak from piping is defined as a leak with an effective diameter of 10% of the nominal diameter, with a maximum of 50 mm [3]. The maximum of 50 mm corresponds to the results of Gasunie calculations [4]. For piping it shows that fracture propagation (resulting in a rupture) could take place at larger leaks [4][38]. The leak size of 50 mm is also the transition used in France from leak to rupture (see 3.3.2).

6.2.2 *Rupture*

A rupture of a pipe is defined as a catastrophic failure, which leads to a full size hole with an effective diameter of 100% of the nominal diameter of the piping. This scenario is considered to be representative for all large leaks and full bore ruptures (guillotine). Due to fracture propagation, larger leaks result in full bore ruptures.

6.3 Domino effects

In the case of a situation in which the failure of one installation clearly leads to the failure of another, an internal domino effect needs to be included in a QRA [3]. Leaks from aboveground piping or flange connections are identified as possible initiating events for piping ruptures.

The conditional probability of 0.001 for a piping rupture as a result of a leak has been (conservatively) determined [4]. This additional probability has to be taken into account in the rupture frequency of the receiving piece of piping when domino effects are expected.

7 Derivation of failure frequencies

Summary and conclusion

With regard to the natural gas transmission lines, the conclusion is that these could be used as an analogy for aboveground pipelines within establishments. Here, three options are identified: (1) The HSE method for land use planning, (2) the method for buried transmission lines used in the Netherlands and (3) the EGIG data from transmission lines in Europe. After rating the options using four basic criteria (transparency, verifiability, robustness and validity), the EGIG data has been selected as the best matching option for piping. Table 22 shows a summary of the results concerning piping based on EGIG data.

Table 22 Failure frequencies for piping based on EGIG data

Event type	Events	Experience [m·years]	Failure frequency [$m^{-1} \cdot year^{-1}$] Average	95
Leak	63	3.15×10^9	2×10^{-8}	2.5×10^{-8}
Rupture	17	3.15×10^9	5.5×10^{-9}	8×10^{-9}

In addition to these frequencies, the contribution of external events such as vehicle impact and lifting operations should be taken into account for aboveground pipelines within establishments.

Flange connections will have to be treated separately as they are generally not used for buried pipelines. Therefore, it is concluded that for flange leakages the failure frequency for the leak is to be based on the statistics of the Dutch gas industry.

Table 23 Failure frequency for flange connections based on Dutch industry data

Event type	Events	Experience [years]	Failure frequency [$year^{-1}$] Average	95^{th} percentile
Leak	1	1,802,355	5.5×10^{-7}	2.6×10^{-6}

7.1 Flange connections

Within the Dutch gas industry statistics, only one incident has been found describing a flange leak. As only one incident was found, an analogy has been investigated. Two analogies have been examined: offshore data and gas transmission pipelines.

For the offshore data [5] the number of observations is less than the number of observations from the Dutch gas industry statistics (Section 4). The number of incidents is also significantly larger than the Dutch statistics. Thus for flange connections leaks the offshore data is not a suitable analogy. Gas transmission pipelines are also not suitable as an analogy, as flange connections are rare in the Dutch underground transmission pipeline systems.

Therefore, it is concluded that for flange leakages the failure frequency should be based on the statistics of the Dutch gas industry (see

Table 9). As mentioned before, ruptures of flange connections are excluded (section 6.1.2).

7.2 Piping

The failure frequencies for piping are derived using an analogy.
Two options have been investigated and the analogy with transmission pipelines has been selected as the best analogy to be used.

Three options are identified for deriving base failure frequencies for on-site piping from the data for transmission pipelines: (1) HSE LUP method, (2) the Dutch buried gas transmission lines method and (3) the EGIG data.

The first one is the method for aboveground pipelines used in the United Kingdom, as described in section 3.3.1. The second option is the Dutch risk methodology for cross-country buried gas transmission pipelines, which has become statutory as of January 2011. The third option is the use of the EGIG data. EGIG is the European Gas pipeline Incident data Group and the EGIG database contains pipeline incident data of fifteen major gas transmission operators in Europe. The N.V. Nederlandse Gasunie is one of the participants in EGIG.

As a counterpart of the EGIG data there is a database of pipeline product loss incidents in the United Kingdom from UKOPA [24]. The UKOPA database contains incidents concerning pipelines with different products (oil and gas), but more than 90% of the pipeline lengths concern natural gas. For this research it is worth considering the UKOPA data besides the EGIG data. Because (i) the EGIG data also contains Dutch data from the Gasunie, (ii) the EGIG data is just about natural gas incidents and (iii) the total exposure of the EGIG data is larger than the UKOPA data (3.15×10^9 metre years versus 7.41×10^8 metre years), the EGIG data are chosen as an option above the UKOPA data. The UKOPA data will be used to compare and verify the EGIG data.

The options are given in sections 7.2.1 to 7.2.3; in the last section the comparison of EGIG with the UKOPA data is also made. In section 7.2.4 lifting activities and vehicle impact are discussed separately. This section ends with a discussion and conclusion.

7.2.1 HSE LUP frequencies

GL Noble Denton modified the HSE LUP frequencies for the on-site piping and pipelines [6] [23]. The HSE LUP Methodology (see section 3.3.1) considers the failure causes external events, mechanical failures and corrosion, whereby external events are sub-divided into:

- vehicle impact;
- lifting operations;
- natural events;
- aircraft crashes.

The last one (aircraft crashes) is only relevant for sites in the vicinity of an airport. This is also the approach in the Netherlands [3]. This leads to the figures listed in Table 24.

Table 24 Generic failure frequencies for aboveground pipelines derived from HSE LUP Methodology[6]

Description	Lifting Impact [per lifting per year]	Vehicle Impact [per on-site movement per year]	Mechanical [$m^{-1}year^{-1}$]	Corrosion [$m^{-1}year^{-1}$]	Natural and Other [$m^{-1}year^{-1}$]
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}	1.6×10^{-9}	9×10^{-8}	1×10^{-9}	9.6×10^{-9}

For vehicle impacts and lifting operations the HSE LUP Methodology provides default frequencies based on fault tree analysis. GL Noble Denton proposes a simple model to take site specific and pipeline specific factors into account for the calculation of the impact frequency (see section 7.2.4).

In [6], the failure cause 'natural events' is discussed. If this only contains 'ground movement' then this cause should be excluded because the contribution of ground movement for aboveground piping on-site is irrelevant. However, HSE indicates that 'natural events' concern also underlying causes such as lightning and operator errors.

Another issue is the background of the failure frequencies for mechanical failure and corrosion. The derivation of the data is not completely clear and it is suggested to update them [6]. HSL notes that current values are based on either EGIG or UKOPA data and they are currently updating the frequencies. One of the issues for the update is the derivation of frequency in case of zero failures. A summary of the method used has been provided by HSL. One (conservative) approach is to add an event and calculate the frequency based on that extra (and only) event. In the HSE method an extra event is shared across the different categories (pin hole, small leak, large leak, rupture). Hereby an assumption is made of the likelihood of small holes in comparison to large holes or ruptures. This method for dealing with zero failures is shown in Appendix 2. Using this method it is possible to derive a failure frequency of a rupture based, e.g., only on pinhole events.

7.2.2 *Dutch method for cross-country buried gas transmission pipelines*

For cross-country buried gas transmission pipelines a standard risk methodology is available in the Netherlands [38] [40] [41]. It can be considered to be consistent to use the same approach for both cross-country and on-site piping and pipelines.

In the Dutch standard risk methodology for transmission pipelines, external interference due to digging activities and corrosion are taken into account. External interference is by far the most important cause. For the buried and aboveground on-site pipelines the failure cause 'external interference' can be excluded, as no third parties are present without notification and working instructions. This is in line with [6] and [23]. As a result, using this methodology only corrosion will remain as a failure cause for on-site pipelines.

Using the corrosion model from the standard methodology, failure frequencies can be derived as a function of diameter, wall thickness and pressure. Results for some of the combinations are given in Table 25 and Table 26 [38] [42] [43]. The values in the tables are frequencies expected for a pipeline after 50 years of service without any measures being taken. This basic principle gives conservative results for pipeline ruptures but underestimates the leak frequencies, as leaks will eventually propagate into a rupture if not detected and no measures are taken. Thus, the corrosion model is only conservative when looking at ruptures. In the risk methodology for the natural gas transmission pipelines, the leak frequencies are not used because leaks do not significantly contribute to the risk [38].

Table 25 Base corrosion leak frequencies for transmission pipelines

Diameter [inch]		**Steel Grade**	**Wall thickness [mm] and pressure**			**Leak frequency [m^{-1}year^{-1}]**		
			40 bar	**66.2 bar**	**80 bar**	**40 bar**	**66.2 bar**	**80 bar**
2	DN50	Grade B	5.5	5.5	5.5	7.7×10^{-9}	7.6×10^{-9}	7.6×10^{-9}
6	DN150	Grade B	6.3	6.3	6.3	1.2×10^{-8}	1.1×10^{-8}	8.8×10^{-9}
8	DN200	Grade B	6.3	7.9	7.9	1.2×10^{-8}	1.2×10^{-8}	1.0×10^{-8}
12	DN300	Grade B	7.1	11.0	11.0	2.6×10^{-10}	5.7×10^{-11}	1×10^{-12}
16	DN400	Grade B	8.7	14.2	14.2	4.1×10^{-10}	2.2×10^{-10}	1×10^{-12}
24	DN600	X60		9.3	11.1		1×10^{-12}	1×10^{-12}
36	DN900	X60		13.9	16.4		2.8×10^{-10}	1.8×10^{-10}

Table 26 Base corrosion rupture frequencies for transmission pipelines

Diameter [inch]		**Steel Grade**	**Wall thickness [mm] and pressure**			**Rupture frequency [m^{-1}year^{-1}]**		
			40 bar	**66.2 bar**	**80 bar**	**40 bar**	**66.2 bar**	**80 bar**
2	DN50	Grade B	5.5	5.5	5.5	1.5×10^{-10}	1.5×10^{-10}	2.5×10^{-10}
6	DN150	Grade B	6.3	6.3	6.3	2.7×10^{-10}	1.8×10^{-9}	2.6×10^{-9}
8	DN200	Grade B	6.3	7.9	7.9	7.2×10^{-10}	1.5×10^{-9}	2.2×10^{-9}
12	DN300	Grade B	7.1	11.0	11.0	1.1×10^{-9}	8.8×10^{-10}	1.5×10^{-9}
16	DN400	Grade B	8.7	14.2	14.2	8.0×10^{-10}	3.8×10^{-10}	7.5×10^{-10}
24	DN600	X60		9.3	11.1		1.2×10^{-9}	1.0×10^{-9}
36	DN900	X60		13.9	16.4		4.3×10^{-10}	3.1×10^{-10}

The overall rupture failure frequency for transmission pipelines has been fitted using statistics. This has been done using N.V. Nederlandse Gasunie rupture data [40]. All ruptures have external interference due to digging activities as the underlying failure cause [38]. Even though external interference has been identified as the only cause from statistics, corrosion has been added as a failure cause [40]. Other failure causes such as material defects and construction failures and ground movement and others have not been observed in the Netherlands and thus can be omitted, since they can be neglected relative to external interference.

7.2.3 Data from EGIG

In Table 27, failure frequencies based on EGIG [16] (1970-2007) are presented. Failure data for external interference due to digging activities, ground movement and hot tapping by error are excluded as a failure causes for on-site aboveground piping and pipelines. Both external interference and hot tapping by error are caused by third-party activities, which are not present within establishments. Ground movements such as landslides are natural events which, like flooding, are not considered. This means that the causes 'construction defect/mechanical failure', 'corrosion' and 'other/unknown' remain.

Table 27 Failure frequencies for piping based on EGIG data

Event type	Events	Experience [m·years]	Failure frequency [m^{-1}·$year^{-1}$] Average	95th percentile
Leak	63	3.15×10^{9}	2×10^{-8}	2.5×10^{-8}
Rupture	17	3.15×10^{9}	5.5×10^{-9}	8×10^{-9}

It should be noted that the derivation of the relative contribution of holes and ruptures from EGIG is an estimate because these are only given in a figure (exact numbers are confidential). The contribution from the Dutch industry through N.V. Nederlandse Gasunie is one leak with an experience of 2.47×10^{8} m·years [42] [44]. To improve the quality of this analogy, RIVM has requested the EGIG-group secretary to deliver some background information [45]. However, the delivery of more information has been vetoed by members of EGIG [46]. Thus no additional information could be given by the EGIG secretary. As the holders of the data refused to provide details on failure causes, any derived failure frequencies from this dataset will be conservative and ways to reduces risks cannot be given.

It is investigated whether the EGIG data are representative for the Dutch situation using a Poisson regression model. The conclusion is that the leak data from Gasunie and EGIG for transmission pipelines (without external interference) differ significantly ($p = 0.03$), with EGIG giving larger frequencies. The rupture data however do not differ significantly ($p = 0.1$).

In Table 28 the relative contributions of the underlying failure causes are shown. Construction defect/mechanical failure is the main cause. Corrosion leads only to leak scenarios.

Table 28 Relative contribution of underlying failure causes from EGIG

Failure cause	Leak	Rupture
Construction defect or material failure	0.72	0.89
Corrosion (external)	0.22	0
Other or unknown	0.06	0.11

Another approach is to use the 5-year moving average that is presented by EGIG. GL Noble Denton proposed to use this approach as it would give a better representation of current practise. This would result in an average rupture frequency of 1.5×10^{-9} per metre per year [6]. As the protocol [9] sets as a minimum period to be included a period of 10 years and also the derived frequencies are in the same magnitude of order as the frequencies derived from the total period (1977–2008), it was decided not to follow this approach.

<u>Comparison of EGIG with UKOPA data</u>
As noted previously, the UKOPA data are used to compare the results from the EGIG data. The failure frequencies based on UKOPA [24]

(from the period 1962–2008) are given in Table 29. The failure causes external interference and ground movement are excluded as failure causes for on-site pipelines. The remaining causes in the database are ‘construction defect/mechanical failure’ (including girth weld defects, seam weld defects and piping defects), ‘corrosion’ (internal and external) and ‘other/unknown’.

Table 29 Failure frequencies for piping based on UKOPA data

Event type	Events	Experience [m·years]	Failure frequency [$m^{-1}\cdot year^{-1}$] Average	95th percentile
Leak	28	7.4×10^{8}	3.8×10^{-8}	5.1×10^{-8}
Rupture	2	7.4×10^{8}	2.2×10^{-9}	7.5×10^{-9}

The derivation of the relative contribution of holes and ruptures from UKOPA is an estimate because these are based on a graph. The categories of holes of 6–20 mm, 20–40 mm and 40–110 mm are put together as ‘leaks’ and the categories of holes of 110 mm – full bore rupture and full bore rupture and larger are combined to ‘rupture’.

The derived failure frequencies from UKOPA are of the same order of magnitude as the failure frequencies based on EGIG data. However, two remarks are made:

- The two ‘rupture incidents’ are from the category of holes of 110 mm – full bore. Aligned with UKOPA, it can also be decided to mark them as leaks instead of ruptures. This will lead to a rupture failure frequency of 4×10^{-9} $m^{-1}\cdot year^{-1}$ (95th percentile).
- The relative contribution of the underlying causes of UKOPA differs from EGIG. Based on EGIG data ‘Construction defect or material failure’ is the most important cause. From UKOPA the cause ‘Other/unknown’ is the most important, followed by ‘External corrosion’.

7.2.4 *Lifting activities and vehicle impact*

For lifting and vehicle impact, a model already exists (Spider), developed by Advantica [47]. With this model the probability of pipeline failure can be calculated. Considered failure modes are denting and bending due to vehicle impact or lifting activities, using energy equations and hit probability assumptions. The size of the failure (pinhole, small leak or rupture) cannot be determined.

For the determination of the leak size, it was therefore proposed [6] to use the same ratios as by HSE-LUP [23]. This would result in conditional probability of about 0.25 on a pipeline rupture (= rupture and large hole) and 0.75 for a leak (= small hole and pinhole).

7.2.5 *Discussion and conclusions*

For the use of transmission lines as an analogy for aboveground pipelines within establishments, three options have been described:

- A. the HSE LUP method (section 7.2.1),
- B. the Dutch method for transmission pipelines (section 7.2.2) and
- C. the EGIG data (section 7.2.3).

For the evaluation of these options the four criteria as mentioned in section 2.3 are used: transparency, verifiability, robustness and validity. All three methods are compared using these criteria.

Transparency

- Method A shows the failure causes (lifting, vehicle impact, mechanical, corrosion and natural/others) with their frequencies (divided for rupture, large hole, small hole and pinhole) in a clear way.
- Method B uses a structural reliability model. The background information is only available within the model, making it somewhat less transparent.
- Data from method C are published in a public report [6]. This report gives current information with an insight into trends, number of incidents, failure causes (external interference, construction / material failure, corrosion, ground movement, hot-tap, other/unknown) and frequencies, et cetera.

Verifiability

- The source of the data from method A and the way derivations have been done is not laid down in a publicly available document, making verification difficult (this is one of the reasons the method is currently being revised by HSL).
- For method B, background information is available within the model, being the original data source.
- Data from method C are available from the public report, also giving information on contributing companies. However, the background information from the individual incidents is not available.

Robustness

- Method A results in failure frequencies being smaller than can be justified using a statistical approach.
- In method B average numbers are used based on statistics.
- In the failure frequencies from method C, the uncertainties are also quantified.

Validity

- Method A uses a best estimate method for dealing with the derivation of frequencies in case of zero failures. One of the issues with this method is the assumption of the likelihood of small holes in comparison to large holes or ruptures. For example, if there are a lot of pinhole incidents, the derived frequency of a rupture will be smaller than if only a few pinholes have occurred.
- In method B only the failure causes external interference and corrosion are considered, where external interference is the most important cause. Other causes such as, e.g., construction failures are not considered. For aboveground pipelines external interference (due to excavating, drilling or piling) is not important and can be de-selected. As the method is completely based on external interference, its validity is limited when the main cause is removed.
- Regarding method C, figures from the report had to be interpreted before the information could be used because the numbers on which the figures are based are not given in the report. Further refinement of the analysis (e.g., to focus on leaks and ruptures relevant for the Dutch situation) is not possible. As the holders of the data refused to provide details, any derived failure frequencies from this dataset will be conservative and ways to reduce risks cannot be given.

The remarks as given above have resulted in Table 30, where all three methods are mentioned using the four criteria.

Table 30 Comparison of the three methods

Criterion	A	B	C
Transparency	●●●●●	●●●●	●●●●●
Verifiability	●●	●●●●	●●●
Robustness	●●	●●●	●●●●
Validity	●●	●●	●●●

Based on this comparison, the EGIG data has been selected as the best matching analogy. A request for background information by RIVM to improve the quality and validity of the analogy has been vetoed by members of EGIG. [46]. As the holders of the data have refused to provide details on failure causes, any derived failure frequencies from this dataset will be conservative and ways to reduce risks cannot be given.

The selection of the EGIG data as an analogy has several consequences. The use of EGIG data leads to frequencies **with no diversification** due to pipeline parameters such as diameter, material, wall thickness and pressure. The frequencies can only be divided into the contributions of the underlying failure causes 'construction', 'corrosion' and 'other causes' (see Table 28). For external impact it was decided to take the lifting and vehicle impact into account. This can be seen as an additional failure cause next to the failure causes mentioned in EGIG. An option is to adopt the Spider model [6] for this failure cause.

Another issue is the failure frequencies might be considered to be **conservative** in comparison with the other two options (HSE LUP method and the Dutch method for buried transmission lines). At RIVM's request, GL Noble Denton used the EGIG data for the update of the HSE LUP frequencies [6]. The failure frequencies for 'mechanical/construction failure', 'corrosion' and 'other' were updated using the EGIG data and the lifting and vehicle impacts were replaced by the Spider model. The results of two cases show that the contribution from impact is negligible compared to the other causes. With the HSE LUP method this would not be the case.

Thus, the frequencies derived from the EGIG data will be higher than the frequencies from the HSE LUP method and also higher than the frequencies predicted by structural analysis techniques (such as Pipesafe). On the other hand, the comparison with UKOPA data shows that the results based on EGIG are of the same magnitude as the frequencies based on UKOPA data. Further, the choices made in the methodology for deriving frequencies, such as applying a confidence interval, also contribute to the robustness of the EGIG data.

Because the Dutch method for transmission lines is based on structural analysis techniques, the choice of the EGIG data will keep the **difference** between buried transmission lines outside and aboveground pipelines within establishments. To avoid this inconsistency, GL Noble Denton recommends the development of structural analysis models for aboveground pipelines within establishments [6]. Such a model is available for corrosion but not for mechanical/construction failures and other causes, while the failure cause 'Construction defect or material failure' is dominant (see Table 28). At the moment, it is not possible to select a structural analysis model which incorporates all the relevant failure causes mentioned by EGIG.

8 Discussion and conclusions

8.1 Scenarios and failure frequencies

This report concerns the derivation of the scenarios and failure frequencies of aboveground high-pressure pipelines and flange connections within establishments. Using the protocol for the adjustment of quantitative risk assessment calculation methodologies [9], first the statistics for pipelines and flange connections of the Dutch gas industry have been investigated (Chapter 4). The failure frequencies derived from this analysis are given in Table 9 and Table 10. For both piping and flange connections no ruptures occurred and therefore an analogy could be investigated. This is also true for the pipeline leaks.

Two analogies have been identified: offshore data and gas transmission pipelines (see Chapter 5). The gas transmission pipelines have been selected as a best analogy for aboveground high-pressure pipelines. In Chapter 6 the relevant and representative scenarios for the aboveground high-pressure piping and the flange connections have been described. The derivation of the failure frequencies for these scenarios is based on EGIG data for the piping scenarios. For flange connections the data from the Dutch gas industry have been used (Chapter 7).

The combination of scenarios and derived failure frequencies are shown in the next two tables.

Table 31 Scenarios for flange connections

Scenario	Leak size (Diameter)	Frequency [$year^{-1}$] Average	Frequency [$year^{-1}$] 95th percentile
Leak	10% D with max. 50 mm	5.5×10^{-7}	2.6×10^{-6}
Rupture	Not included		

Table 32 Scenarios for piping

Scenario	Leak size (Diameter)	Frequency [$m^{-1} \cdot year^{-1}$] Average	Frequency [$m^{-1} \cdot year^{-1}$] 95th percentile
Leak	10% D with max. 50 mm	2×10^{-8}	2.5×10^{-8}
Rupture	100% D	5.5×10^{-9}	8×10^{-9}

An important requisite for the exclusion of ruptures of flange connections is that the flange connection is hydrostatically tested before it is taken into operation. The design and maintenance of the flange connection should also be according to industry standards.

The contribution of external events, such as vehicle impact and lifting operations, should be taken into account for aboveground piping within establishments. To do this, some further work must be done.

8.2 Domino effects

Only in the case of a situation in which the failure of one installation clearly leads to the failure of another installation does an internal domino-effect need to be included in a QRA [3]. Leaks of aboveground piping or flange connections are identified as possible initiating events for piping ruptures. A conditional probability of about 0.001 piping ruptures as a result of a leak has been (conservatively) determined [4]. E.g., for flanges, this results in an additional failure frequency of 5.5×10^{-10} (average) or 2.6×10^{-9} (95^{th} percentile) per year for the piping sections which could fail as a result of a domino effect.

8.3 Further work

8.3.1 Vehicle impact and lifting activities

If vehicle impact or lifting activities cannot be excluded during normal operation of the plant, it is proposed to evaluate the proposed model [6] [47]. As lifting activities and vehicle impact can dominate the failure frequency of aboveground pipelines it is recommended:

- to check the by GL Noble Denton proposed model using Finite Element (FE) modelling and to derive well-founded conditional probabilities on pipeline leaks and ruptures
- to investigate the kind of detail to be taken into account in the calculation of the failure frequency. For vehicle impact, besides pipeline parameters such as wall thickness and yield strength, the weight and maximum speed are of importance. For the impact of lifting activities the maximum load and maximum load height are of importance. It should therefore be investigated whether it is workable solution to incorporate these parameters.

8.3.2 Incident reporting

For the derivation of failure frequencies the reports of HCRD [5], EGIG [6] and UKOPA [24] could be used. Dutch generic incident databases (NOGEPA or from the State Supervision of Mines) were not suitable for the derivation of frequencies. Therefore, the recommendation is to improve the Dutch databases in such a way that they will also be suitable for more detailed incident analysis and the determination of frequencies for risk assessments. To do this at least the following information has to be taken into account:

- the amount of material being released
- hole size dimensions
- the duration of the release
- underlying causes of an incident
- the consequences of an incident

If this information is available it is possible to refine the frequencies based on the contribution of the underlying causes and specific measures.

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Appendix 1 Study group members and memo

The research described in this report was conducted in consultation with an international study group with members from industry and government institutions. The members were (in alphabetical order):

Aart, Marc van der	NL	personally, from DORA (consultation group on risk analysis)
Acton, Mike	UK	GL Noble Denton
Chaplin, Zoe	UK	Health and Safety Laboratory
Crossthwaite, Phil	UK	DNV
Dröge, Marc	NL	NV Nederlandse Gasunie
Frijns, Peter	NL	Ministry of Infrastructure and the Environment
Harper, Peter	UK	Health and Safety Executive
Keesom, Wil	NL	NV Nederlandse Gasunie
Lenoble, Clément	F	INERIS
Pinxteren, Marco van	NL	State Supervision of Mines, Ministry of Economic Affairs, Agriculture and Innovation
Rozendal, Schelte	NL	Nederlandse Aardolie Maatschappij BV

The study group does not unanimously endorse all the results and conclusions of this research. Phil Crossthwaite (DNV) wrote his reservations down in a memo. See the next page.

Memo - Phil Crossthwaite (DNV)

RIVM Report 620550004/2011.
On site Natural Gas Piping. Scenarios and Failure Frequencies.

RIVM assembled a study group to assist in developing a method for derivation of failure frequencies and scenarios for above ground pipelines at natural gas establishments. DNV was part of that group and supports the approach taken. DNV has, however, reservations on the conclusions of the work; these reservations are described below.

The RIVM proposals for piping failure frequencies (Table 2 in the RIVM report) are derived from EGIG data and using the average values are:

- Leak (hole size 50mm diameter) - 2E-08 per m per year
- Rupture (hole size equal to the pipe diameter, D) - 5.5 E-09 per m per year.

In general DNV agrees that:

- The use of failure data for underground high pressure gas pipelines is the best way to derive frequencies for high pressure gas pipelines at above ground installations given the absence of relevant and/or extensive data for above-ground piping.
- The most appropriate data set to use as a basis for frequency derivation is EGIG, provided the findings are consistent with the alternative data set designated suitable for comparison purposes by RIVM (from UKOPA).
- Contributions from failure modes not included in EGIG or UKOPA for underground pipelines (e.g. impact from vehicles etc) should be determined and added to the derived frequencies.

There is, unfortunately, a lack of detail available on the pipeline failures in the EGIG reports (and critically the request for further information on these failures was refused by EGIG) so the use of these data becomes more limited and questionable. Further there is a total lack of consistency between the failure sizes and the failure modes derived from EGIG and those derived from UKOPA, so the use of EGIG as the basis for the failure frequencies is considered unsound.

However, if it is decided that the frequencies derived from EGIG should be used, despite the weaknesses indicated by this and possibly other notes from study members, then the hole sizes for release calculations (the scenarios used in a subsequent risk analysis) should be consistent with the EGIG definitions associated with the frequencies, as these are inextricably linked. There is insufficient information in the EGIG data to change the hole sizes associated with the failure frequencies from those in EGIG to those proposed for use by RIVM.

Given below are the reasons why DNV concludes that the proposed frequencies and scenarios based on the whole EGIG data set are unsound and suggests that the lack of detail in EGIG means that more consideration should be given to a derivation from UKOPA. However, if more details than are given in the public reports cannot be obtained on the UKOPA data, such a derivation may also be unsound and it may be necessary to consider other data sets to derive the required frequencies.

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EGIG Data

The EGIG data are separated into the following initial causes:

- External interference
- Corrosion
- Construction defect/material failure
- Hot tap made by error
- Ground movement
- Other and unknown.

Three of these causes would not be contributors to failures of above ground piping in secure installations in the Netherlands, so the three initial causes of relevance for above ground piping are therefore:

- Corrosion
- Construction defect/material failure
- Other and unknown.

The EGIG data indicate that of these the dominant cause is construction defect/material failure, corrosion is not important for ruptures and 'other' is relatively unimportant (see Table 1, and as given in Table 28 of RIVM report).

Table 1 Relative Contribution - Failure causes from EGIG

Cause	Relative Contribution to Leak	Relative Contribution to Rupture	Leak Failure frequency Per m per y	Rupture Failure frequency Per m per y
Construction defect/material failure	0.72	0.89	1.44E-08	4.90E-09
Corrosion	0.22	0	4.40E-09	0.00E+00
Other and unknown	0.06	0.11	1.20E-09	6.05E-10
Total			2E-08	5.4E-09

AllGasData/RIVM

Detailed information on the underlying contributions to the above is not given in the public reports but is necessary in order to develop robust failure frequencies. A request made by RIVM for more information was refused by the EGIG committee. This response is extremely disappointing (and difficult to comprehend). As a consequence failures that are not relevant to above ground natural gas piping could not be excluded, (in the same way that the failure groups for external interference, hot tap and ground movement were excluded) nor could anything be concluded on the circumstances of the failures and therefore measures that could be taken to reduce the frequencies. As a result, use of these limited EGIG data would only be appropriate if the data used for comparative purposes (UKOPA) was consistent; an examination of the UKOPA data is therefore necessary once the EGIG data have been considered further.

The main information in EGIG 7 regarding construction defect/material failure is in S 3.3.3.3 (see below as Figure 1).

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Figure 1 Information about Construction Defects/Material Failure.

3.3.3.3 Relationship between construction defect/material failure, size of leak and year of construction class

Figure 24 shows that the older pipelines have higher failure frequencies (due to construction defect/material failures). Technological improvements are thought to have resulted in reduced construction defect/material failures.

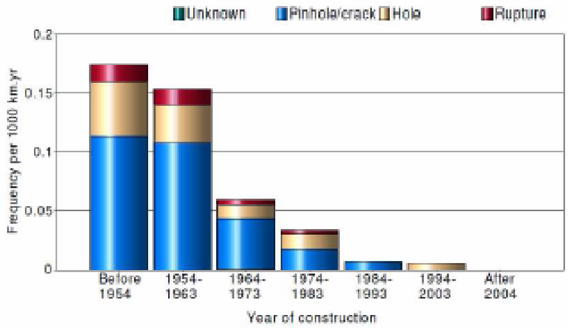

Figure 24: Relationship between construction defect/material failure, size of leak and year of construction class

This indicates that the total failure frequency due to this initial cause is heavily dependent on the year that the pipeline was constructed, and for pipelines constructed after 1983 in addition to the overall failure frequency being less than 20% of the average derived from all the data (0.06 on Figure 1), the recorded failures are either holes or pinholes; there have been no ruptures. These data may, of course, be highly dependent on pipeline diameter and/or thickness, but without the further information the significance of pipeline properties could not be determined.

There is even less useful information in EGIG 7 on 'other and unknown'. What is given is in the GL report (S 3.3.2.4).

A conclusion that could be drawn is that use of the 1970-2007 EGIG data does not give a representative frequency for pipeline rupture caused by construction defect/material failure for pipelines constructed after 1983. Further, as almost 90% of the proposed total rupture frequency is supposed to be due to construction defect/material failure this frequency for pipeline rupture is unsound for pipelines constructed after 1983. Also the EGIG data do not give any indication as to whether the other and unknown failures are or are not relevant for above ground pipelines so the relevance or accuracy of the frequency assigned from other/unknown is also unsound. In the absence of further information from EGIG it is, unfortunately, necessary to conclude that all failures might be relevant and none could be excluded. Critically, the format and detail of the data do not give any indication as to why the failures occurred, whether the failures in the database are

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relevant to the current consideration and what measures are important in order to reduce the frequency of failure.

Rolling Average
One way of incorporating the effects that old pipelines have on the failure frequency is to use recent data rather than all the data. RIVM consider this to be an acceptable approach providing the time period is a minimum of 10 years and the derived frequencies are in the same order as those derived from all the data. The 5 year rolling average is given in EGIG. This data set is often used in risk assessments and was proposed by GL, but rejected by RIVM because of the 5 year period. Previous editions of EGIG indicate that over the periods covered by the reports, the overall frequencies have reduced, see Table 2. Unfortunately the breakdown into failure causes or sizes is not easily extractable from the EGIG reports to develop the recent data in the same way as the full dataset, but the reduction in frequency for the rolling averages again indicates that more information is necessary before the whole dada set can be used with confidence.

Table 2 5 Year Rolling Averages

Date	Primary Failure Frequency Per m per year	% Due to Construction/ mechanical defect	% Due to corrosion	% Due to other
1997-2001	2.1E-07			
1970-2001	4.4E-07	17	15	6
2000-2004	1.7E-07			
1970-2004	4.1E-07	17	15	7
2003-2007	1.4E-07			
1970-2007	3.7E-07	17	15	7

Other Data - Netherlands
The Netherlands data are considered to be more relevant than EGIG but the set is very small. For the three relevant causes, the failures comprise one leak but no ruptures (para 7.2.3 of RIVM report). Using experience of 2.47E08 m years, a frequency for leaks is derived as 4.1E-09 per m per year, and, if the same ratio of leaks to ruptures as the whole EGIG dataset is used the rupture frequency would be 1E-09 per m per year (considerably lower than a calculated statistical value - 1.2E-08 per m per year).

Other Data - UKOPA
UK data are held by UKOPA. RIVM considered these data suitable for comparison purposes. The UKOPA data (6th Report) are shown in terms of hole sizes in Figure 6 in that report, and these values have been used to give the values in Table 3.

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Table 3 Number of Incidents - UKOPA Data

Cause	No Events	Hole Size 0-6mm	Hole Size 6-20mm	Hole Size 20-40mm	Hole Size 40-110mm	Hole Size 110-FB	Hole Size FB and above
Construction defect/material failure	49	41	7	1	0	0	0
Corrosion	36	29	6	0	0	1	0
Other and unknown	49	35	9	3	1	1	0
Total	134	105	22	4	1	2	0
%		78	16	3	1	1	0

Pipefreq\UKOPA Data

These data are better than EGIG from the standpoint of hole size distribution and details of causes. Although the data set is smaller (134 incidents compared with 344 incidents) the higher quality of the information could offset this, and indeed the UK experience may be closer to the situation in the Netherlands than the wider European experience. Using the above incident numbers and the overall frequencies from Figure 6 in UKOPA 6th report, the frequencies in Table 4 can be derived.

Table 4 Release Frequencies from UKOPA Data

Cause	Total Frequency Per m per y	Hole Size 0-6mm	Hole Size 6-20mm	Hole Size 20-40mm	Hole Size 40-110mm	Hole Size 110-FB	Hole Size FB and above
Construction defect/material failure	6.60E-08	5.47E-08	1.02E-08	1.07E-09			
Corrosion	4.80E-08	3.86E-08	8.33E-09			1.11E-09	
Other and unknown	6.60E-08	4.84E-08	1.16E-08	3.85E-09	8.25E-10	1.38E-09	
Total	1.8E-07	1.42E-07	3.01E-08	4.92E-09	8.25E-10	2.49E-09	0.00E+00

Pipefreq\UKOPA Data

These data then need to be combined for comparative purposes with EGIG (see Table 5) or with the RIVM hole size combinations (see Table 6)

Table 5 Release frequencies for Holes and Ruptures (comparison with EGIG)

Cause	Number of Leaks	Number of Ruptures	% Leak	% Rupture	Leak Frequency	Rupture Frequency
Construction defect/material failure	1	0	14	0	1.07E-09	0
Corrosion	1	0	14	0	1.11E-09	0
Other and unknown	5	0	71	0	6.05E-09	0
Total	7	0			8.23E-09	0

Pipefreq\UKOPA Data

'Leaks' are hole sizes 20-40mm, 40-110mm, and 110mm-full bore, and 'ruptures' are full bore and above.

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Table 6 Release frequencies for Holes and Ruptures (comparison with RIVM)

Cause	Number of Leaks	Number of Ruptures	% Leak	% Rupture	Leak Frequency	Rupture Frequency
Construction defect/material failure	8	0	30	0	1.13E-08	0.00E+00
Corrosion	6	1	22	50	8.33E-09	1.11E-09
Other and unknown	13	1	48	50	1.62E-08	1.38E-09
Total	27	2			3.59E-08	2.49E-09

Pipefreq\UKOPA Data

'Leaks' are hole sizes 6-20mm, 20-40mm and 40-110mm, and 'ruptures' are 110mm-full bore and full bore and above.

Note the following:

- The values derived by DNV are slightly different from those derived by RIVM, probably because the information is presented in graphical format rather than numerical format (there was a similar, but worse, problem with the EGIG data which was resolved by RIVM advising DNV of the data that they had used). The values are sufficiently close for the current purposes however.
- If the precise definition of hole and rupture as used by EGIG is used (for a rupture in EGIG the diameter of the hole is larger than the pipeline diameter), some failures would be excluded and all the remaining failures would be in the hole category; there would be none in the rupture category (see Table 6).
- If the leak range was 20-110mm (rather than 6-110mm) the leak frequency would be reduced from 3.59E-08 per m per year to 5.75E-09 per m per year (although it is likely that these would be changed if more information on the circumstances of the failures was available).
- The relative contribution from the three initial causes with the EGIG combination is significantly different from the three initial causes using (all data) irrespective of the way in which the UKOPA data are combined.
- Similar data are presented in IGEM/TD/2 based on the 5th UKOPA report (rather than the 6th report used for the above). A comparison of the two data sets gives rise to questions (there is a rupture in the 'other/unknown' category in IGEM/TD/2, but there is no rupture in the 5th report or in the 6th report, and the percentages in IGEM/TD/2 do not seem to align with some of the incident numbers in the 5th report).

The UKOPA report also gives a partial breakdown of the number of incidents in the various groups of causes (but not unfortunately linked to leak size) for the material, corrosion and other categories (see Table 7). This breakdown would allow those failure modes which are not relevant for the situation at the above ground installations to be removed, (e.g. many in the 'other' category), with consequent adjustment of the frequencies and also give a better indication as to what type of risk reduction measures might be appropriate to reduce frequencies for the relevant failure modes further.

MANAGING RISK DNV

Table 7 UKOPA Product Loss Causes

Cause Category	Product Loss Cause	No of Incidents
Construction /material	Pipe defect	13
	Seam weld defect	3
	Girth weld defect (1)	33
Corrosion	Internal corrosion	2
	External corrosion	34
Other	Internal cracking due to wet town gas	30
	Pipe fitting welds	4
	Leaking clamps	2
	Lightning	1
	Soil stress	1
	Threaded joint	1
	Electric cable arc strike	1
Unknown		9

(1) The category 'girth weld defect' with 33 incidents is not included in the UKOPA construction/material category, but has been included in the values above (which is consistent with the RIVM analysis).

Rather than making the situation clearer, these data (which are used for analyses in the UK because they are relevant and of good quality) give a significantly different picture for the derivation of both frequencies and causes than that from the EGIG data. This again casts doubt on the robustness of the approach using the whole EGIG dataset.

Wall Thickness

Piping with thick wall is shown in both EGIG and UKOPA to have a significant influence on failures due to external interference and corrosion; pipelines with a wall thickness less than 5mm thick have a failure frequency more than one order of magnitude higher than pipelines with a wall thickness in the range 10-15mm (see EGIG figures 20 and 23, reproduced as Figure 2 and Figure 3). Pipelines with a thicker wall have no failure history. At least in this respect the two datasets give the same picture which indicates that this property is key to the failure frequency and it would be preferable if this property could be taken into account when deriving frequencies for above ground piping.

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Figure 2 Figure 20 from EGIG 7

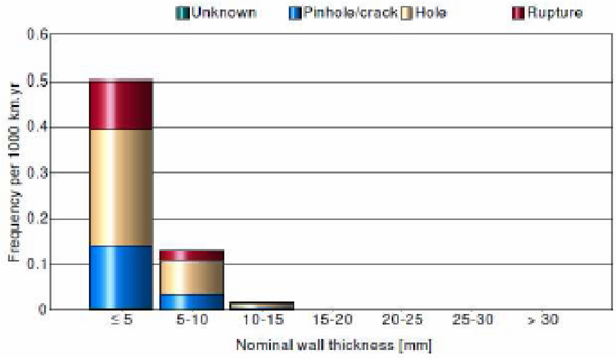

Figure 20: Relationship between external interference, size of leak and wall thickness class

Figure 3 Figure 23 from EGIG 7

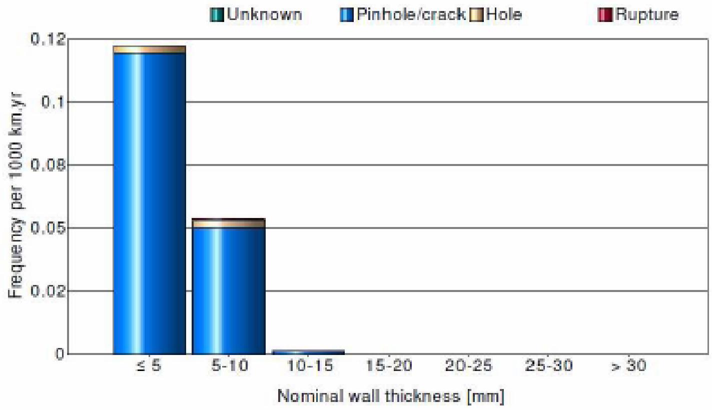

Figure 23: Relationship between corrosion, size of leak and wall thickness class

Impact

As indicated above, the wall thickness is a critical factor in most if not all piping failures, particularly in impact failures as shown by Figure 2, and so would be important in the determination of additional failures due to vehicle impacts or dropped objects. Failures due to these causes are not included in data from underground pipelines and, as is the case when failure data are transferred from one situation to another (i.e. underground to above ground), such failures need to be included. This endorses the view that any model

MANAGING RISK DNV

for failure frequency of above ground piping should take account of both impact and the wall thickness. DNV agrees with the proposals that a model like that developed by GL should be used.

Scenarios

The two hole sizes proposed by RIVM to represent the spectrum of potential hole sizes is 10%D with a maximum of 50mm for a 'leak' and 100%D for the 'rupture' category. The EGIG data are based on a hole size in the range 20mm to full bore for the 'hole' ('leak') category and a hole size more than D for the 'rupture' category. In the selection of an appropriate size for the 'leak' category for a QRA a consideration of the critical crack size should be made (IGEM/TD/2 A4.2.5) as this is important in the selection of a representative diameter for the 'leak' category. RIVM have selected 50mm as the maximum hole size for the 'leak' category based on Gasunie calculations which show that fracture propagation could occur for larger leaks (RIVM para 6.2.1). If the EGIG data are to be used to derive the frequencies of leak and rupture, and a hole size of 50mm is to be used for the leak scenario, then this scenario is representative of holes in the range 20mm to D, and the rupture frequency is associated with a hole size represented by a greater area (e.g. two open ends which typically follow fracture propagation). The use of the UKOPA data would allow a more appropriate split into the selected RIVM hole sizes of 50mm and D because of the better split of the UKOPA data in terms of hole sizes.

Conclusions

1. Although it would have been preferable to use European (EGIG) data to derive a frequency for use with above ground piping, the published data do not give sufficient information for them to be used with confidence. As the holders of the data have refused further information that might have made it possible, by an understanding of the failure causes relevant for above ground piping, to derive sound frequencies, this cannot be done.
2. Consideration of the slightly smaller UKOPA data set gives a different picture of significant failures for the failure causes of importance, but could possibly, with more information regarding the size and time distribution, provide a reasonably sound basis for the derivation of both frequencies and failure causes. The contributions of the failure causes to the overall failure frequency are as important as the frequency itself. If additional data can be obtained from UKOPA it would be worthwhile investigating further to see whether a coherent picture of the relevant failure causes can be derived.
3. Frequencies for holes (50mm) and ruptures (D) derived from UKOPA would be 5.8E-09 and 2.5E-09 per m per year (compared with the RIVM frequencies of 2E-08 and 5.5 E-09 per m per year) and frequencies of 4.1E-09 per m per year, and 1E-09 per m per year from Netherlands data (although RIVM would not use the latter but would base the value on a 95% confidence, 1.2E-08 per m per year). However, the frequencies derived from UKOPA could be reduced further if non relevant failures were excluded.
4. All potentially important causes not included in the underground data (i.e. impact from dropped objects and vehicle impacts) must be included in the frequency estimate for above ground piping as should important risk reduction features of the system (pipe wall thickness and possibly year of construction) by adding failures due to these modes to the failures derived from underground experience.

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5. The scenarios used for the analysis of consequences must align with the hole sizes which are used by the data set used to derive the frequencies. If EGIG data are used, the format of the data do not allow hole sizes other than 50mm (as recommended from fracture mechanics by Gasunie) and a hole size in the range D-2D. However, the greater detail in the UKOPA data would allow frequencies to be grouped into the hole size ranges proposed by RIVM.

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Appendix 2 MHIDAS

Incidents involving natural gas pipelines on establishments
In the MHIDAS database 10 database entries (from the original 16,225 entries) can be assigned to incidents at establishments with natural gas pipelines (possibly aboveground). For this, the following selections were made in the database:
1. Selection on the substance involved (natural gas (incl. natural gas condensate (1 entry) and natural gas liquid(s) (12 entries)). This resulted in 563 remaining entries;
2. Selection on the origin/location of the incident. Entries with origin "unknown" (6), "domestic/ commercial" (24), "transport" (431) and "warehouse" (1) were removed. This resulted in 101 remaining entries;
3. Selection on the equipment involved (pipework, pipeline and unknown). This resulted in 59 remaining entries. In MHIDAS, pipework is defined as 'all process piping within the plant boundary, and associated valves and joints';
4. In the last selection, entries were manually removed based on incident descriptions.

The selections resulted in 10 remaining relevant entries. The main failure causes from these entries are:
- 3 mechanical failure (1 corrosion)
- 3 human (2 maintenance, 1 general operations)
- 1 external
- 3 not given (unknown?)

Based on these 10 entries it can be concluded that no reliable conclusive remarks on the distribution of the relevant failure causes for pipeline leaks and ruptures can be made.

Description of incidents with natural gas pipelines

1. Allied Chemical Corp compressor pump station. Three compressor units, building and pipeline heavily damaged. One of the compressor discharge lines ruptured + the release was ignited. Plant (1 mile) west of station extracts natural gas from casing head gas.
2. Seven workers burned at Phillips petroleum plant when caught between two fires in ruptured pressurised pipelines during routine maintenance. Fire led to three explosions. Fire extinguished five hours after first explosion.
3. A 34.5 bar pipe at a gas oil separation plant developed a leak which grew in size but eventually broke, releasing a large gas cloud. Ignition source 450 m away. Seven-metre section of pipe struck a spheroid 120 m away causing a second cloud ignited by first.
4. Six workers were injured during maintenance work on flare line.
5. Residents were evacuated for about three hours after a volatile gas cloud formed over a natural gas facility. The source of the leak was tracked down to a section of pipe, which was repaired.
6. Explosion and fire occurred when workers carrying out maintenance on a high-pressure flare line. Men admitted to hospital and

two later died. Fire extinguished in 30 minutes, no major damage to plant.
7. Gas pipeline exploded at a gas works facility. A section of nearby interstate was closed as the fire service fought the fire. Some residents voluntarily left their homes although they were not under threat. Some effect on gas pressure supplied to customers.
8. Natural gas pipeline leak at power plant of recycled newsprint mill resulted in massive explosion. Slowly leaking gas was probably ignited by a spark a from passing car.
9. The metering unit of the natural gas distribution station was rocked by an explosion. A fire also occurred.
10. Valves on some pipelines leading to LNG storage tank where men were working were left open. When pipes were tested, gas seeped into tank. Men never noticed unodourised gas + may have lit a cigarette causing the explosion.

Incidents involving flanges

In the MHIDAS database, there are 38 database entries concern flanges on pipework at establishments. The following selections were made in the database:
1. Selection on flanges. This resulted in 79 entries.
2. Selection on the origin/location of the incident and the equipment involved (pipework, pipeline and unknown) was made. This is done similarly to the selections for the 'natural gas' incidents and resulted in 38 remaining incidents. None are however related to a release of natural gas.

Four incidents describe a flange being broke or ruptured. For the ruptures, the following substances were involved: crude oil (1), vinyl chloride (1), sulphuric acid (1) and trichlorosilane (1). From the other 34 incidents with flange leaks it can be concluded that flange leakages not only occur during maintenance, but also during normal operation. However, as no entry is related to a release of natural gas and as a number of incidents occur, for example, during transfer, i.e., loading or unloading operations using rigid pipework (6 entries) or storage (1), it can not be concluded that this will also be the case for piping or pipelines with natural gas.

Based on these entries it is concluded that no reliable conclusive remarks on the distribution of the relevant failure causes for pipeline leaks and ruptures can be made.

Description of incidents where a flange broke or ruptured

1. Vinyl chloride escaped from an unbolted flanged connection at a pressure of 5 bar during start-up of polymerisation plant. Gas ignited and exploded destroying unit
2. Six splashed by acid when 500 gallons of sulphuric acid spilled when a flange broke on a pipe leading from a railroad tank car to a building. Three released from hospital and three reported in a stable condition
3. Flange broke and spilled trichlorosilane, which converted to silicone dioxide and hydrochloric acid when it came into contact with moisture in the air. Small fire was put out with dry chemical fire extinguisher. Fire fighters knocked down vapour cloud

4. Rupture of a flange on pipeline 8 km from pump station caused 400 te of crude to leak before line was shutdown. Main pipeline was shutdown and 2 auxiliary lines were brought into operation 5 hours later

Description of other incidents with flanges

1. Serious fire damaged 10 per cent of ICI no1 aromatics plant following leak from flange. Ten fire engines took much of the day to control the fire. No injuries or effects on river traffic
2. Ethylene plant shut down as a result of leak of nitrogen from tank due to valve failure. Entire plant being checked. 400,000 tpy unit was shut down during tests as a result of a flange fire.
3. Defect in new pipeline spilled 1/2 million gallons of aviation fuel. Flange on valve caused leak. Pollution caused 25,000 gallons recovered by booms. Pipeline carries kerosene from storage tanks to fuelling points at airport.
4. Explosion in benzene unit of petrochemical / styrene plant. Crew starting up system increased pressure in hydrogen system. Hydrogen released from a manhead flange and ignited. Benzene released from pipe flange burned for 8 hours. Buildings severely damaged.
5. Chlorination plant shut down because of leaking flange in acid waste line. Acid pool prevented access to switch box. After emptying line benzene/chlorobenzene vapours escaped from flange and ignited by static or acid damage to electrical installation.
6. Butane leak from a flange caught fire killed the operator who was shutting down the plant. Company and state fire fighters took three hours to put out the blaze.
7. Release of chlorine after workman separated flange with liquid still inside. Response seemed to be well organised with gas protection equipment available. High wind 16–18 metres/sec and heavy rain at the time carried gas to buildings in vicinity.
8. Undisclosed amount of chlorine released to the atmosphere by the DOW chemical company of Canada. The injured workers were at a site 0.4–0.8km away. Release due to maintenance worker removing valve bonnet flanges on liquid chlorine line. Between 83–94 injuries.
9. Singapore petroleum company Leak from three-inch water injection flange of desalter in crude distillation unit. After ignition, the fire fed from ruptured overhead receiver and lines.
10. Crude oil leaked from check valve on oil desulphurisation plant pipework and caught fire. The plant was shut down immediately and the fire was extinguished within two hrs. Check valve/pipework flange gasket was loose. Company=general petroleum refinery.
11. A flange fire occurred during start-up after maintenance at an oil refinery. There was minimal damage but one person was injured.
12. Following two shutdowns due to industrial action, a loose flange allowed crude oil to spill out and catch fire. Nearby electrical substation under threat and flights from Sydney airport halted. More than 75 fire fighters responded.
13. Fitter at Monsanto broke pipe flange on vessel and overcome. Claimed he was not told to wear protective clothing. Maintenance staff out in support of demand for better first-aid facilities.

14. Leak from flanged joint or broken thermowell on high-pressure piping caused a spill lasting about 30 min before ignition. Windows broken in 180 m radius. Roofs and ceilings in 4 buildings damaged. Blast had TNT equivalence of >7 kg.
15. Low quality exit flange/sealing on polyethylene reactor responsible for gas leak which ignited sending flames 30 ft high. Line isolated and fire out after 8 min.
16. Leaking flange connection in ethylene oxide plant gave gas cloud which subsequently detonated. Explosion caused overheating of drainage column, which burst and was completely destroyed.
17. Leaking flange in oil refinery distillate hydrotreater released gas-oil/hydrogen vapour, which ignited at nearby furnace. Overhead product pipes fractured, fuelling the blaze. Process lines/vessels were severely damaged. 2000 gallons of distillate destroyed.
18. Leak detected at valve on naphtha distillation line. Line purged with nitrogen but not isolated. Valve removed and flange ground. Grinder sparks ignited hydrocarbon in line.
19. Subcontractor erroneously loosened flange bolts on separating vessel valve during preparation for kerosene/gas oil unit inspection. 30% hydrogen sulphide blew off from condensate separator, causing death/injuries.
20. Explosion in refinery injured 20–21 persons, six seriously. Investigations point to a flange leak on an elevated LPG feed line to the alkylation unit apparently leaking. Fire brought under control within two hours by refinery fire brigade.
21. Chlorination plant shut down because of leaking flange in acid waste line. Acid pool prevented access to switch box. After emptying line, benzene/chlorobenzene vapours escaped from flange and ignited by static or acid damage to electrical installation.
22. Up to 20 gal of oleum leaked from unmatched flanges at Rhone Poulenc at 7.45pm, causing a sulphuric acid cloud. Local roads blocked for 1 hr, residents warned to stay indoors. Company prosecuted under health and safety at work act.
23. Return line from storage to road tanker for reject phthalic anhydride blocked when heating turned off. Maintenance operator died from 55% burns after being sprayed with phthalic anhydride at 150 degrees Celsius when flange ruptured.
24. Power failure caused rupture of expansion joint in refrigeration compressor pipeline. Resulting gas cloud was ignited by furnace 100 m away. Subsequent fire caused additional leaks at flanges. Shock wave estimated at equivalent of 8.8 te TNT.
25. Pipe connecting polymerisation reactor and separating tank in polypropylene unit blocked. Gas leaking through flange ignited due to polypropylene particles becoming charged with static.
26. A leak of 100 gallons of titanium tetrachloride occurred Apparently from a flange on the pipework. A gas cloud was formed which moved towards nearby villages. Residents were warned to keep windows and doors shut. Fire crews swilled residue away.
27. Flange bolts not tightened on pump installed on line to propane and butane receivers. On starting, the pump propane escaped and was ignited by a nearby welding torch. Gas supply shut-off and fire allowed to burn out.
28. Precautionary evacuations after leak of ammonia at phosphoric acid plant. Liquid cargo being prepared for transfer from rail tanker to

storage tanks. Concern that warning siren not sounded. Flange leak sealed. At least nine hospitalised, seven for observation.

29. 1000 l diesel spilled due to flange failure on pipe along sea wall in vicinity of jetty. some spilled to shoreline but most went down drain system. Spill occurred at low tide, assisting company in clean-up.
30. Workmen acted quickly when dimethyl amine gas leaked from the flange of a pipe connected to a road tanker at a chemical products production area.
31. No casualties were reported following an explosion at a refinery. Explosion was thought to have occurred after hydrogen leaked from a flange during unit pressurisation. The explosion and subsequent fire led to the refinery being temporarily closed.
32. Faulty flange released 100,000 litres of petrol forming a lake in the middle of the refinery. Spill blanketed with foam until petrol could be transferred to tankers.
33. A 10-inch valve was prevented from closing by powder build-up. When workmen depressurised the pipe and the flange was opened, powder blew out and liquid butane was released. Ignition took place 100 ft away, flashback occurred. Other process vessels involved in fire.
34. Removal of wrong blind flange led to spill of unknown quantity. Ignited by heater 18 m from spill point.

Appendix 3 HSE/HSL's Method for dealing with zero failures

Zero failure rates can be generated when using historical data to calculate failure rates. The zero implies that no failures occurred for a specific type of event in a given time period; however, it does not indicate that an event will never occur in such circumstances.

In categories where zero failures occur, assumptions have to be made in order to reflect the chance of a failure, even if not seen historically (over the observation period). In these circumstances, the difficultly is in how the failure rate should be estimated. Previous calculations of failure rates for pipelines have added one extra event into each failure mode, or one extra event across a range of failure modes. Both methods have drawbacks, either over- or underestimating the failure rate for the different groups or proportioning the failure rate unevenly or unrealistically between failure modes. However, the former approach appears overly conservative. Therefore, an approach similar to that agreed and previously used by HSE has been adopted. Where deviations to this approach have been made, for example, making use of expert judgement to share events across all categories, this has been discussed in the appropriate place in this report.

If we take, as an example, a case of a 200 km pipeline that has seen 3 ruptures and 1 large hole over a time period of 20 years, then it is possible to calculate an overall failure rate of (3+1)/(200*20) = 0.001 per km yr. It is also possible to calculate failure rates for ruptures (3/(200*20) = 7.5×10^{-4} per km yr) and large holes (1/(200*20) = 2.5×10^{-4}). There is no obvious way, however, to obtain a failure rate for either pin holes or small holes so, in this case, one extra failure will be added to the total (i.e., there are now five failures in total rather than four) and that extra failure will be apportioned to each of the hole sizes as follows:

- 3/5 will be added to ruptures, giving a total number of failures of 3.6 and a failure rate of 3.6/(200*20) = 9×10^{-4} per km yr;
- 1/5 will be added to large holes, giving a total number of failures of 1.2 and a failure rate of 1.2/(200*20) = 3×10^{-4} per km yr;
- 1/5 will be split equally (i.e., 1/10 each) between pin holes and small holes, giving each a failure rate of 0.1/(200*20) = 2.5×10^{-5} per km yr.

Example using mechanical data

NB This is an example only and is not intended to be used in earnest.

Over the 20-year period, 35 events were recorded which were attributed to mechanical failure. This gives a failure rate of 8.4×10^{-5} (35/414734) per km yr.

All hole sizes were less than 10 mm equivalent diameter and were classified as pinholes. No small holes, large holes or ruptures were observed in the data due to this failure mode in the last 20 years.

The failures were further subdivided according to the wall thickness, shown in Table 33, and the pipeline diameter, shown in Table 34, to determine if any relationship existed between the failure rate and either of these two variables.

Table 33 Mechanical failure rate as a function of wall thickness

Wall thickness (mm)	Exposure (km yr)	Number of events	Failure rate (per km yr)
0 – 5	23846.44	24	1.0×10^{-3}
5 – 10	202697.6	11	5.4×10^{-5}
10 +	188190	0	0

Table 34 Mechanical failure rate as a function of pipeline diameter

Pipeline diameter (in)	Exposure (km yr)	Number of events	Failure rate (per km yr)
< 8	43575.63	26	6.0×10^{-4}
8 - <12	59145.94	4	6.8×10^{-5}
12 - <16	53638.92	2	3.7×10^{-5}
16 - <24	74609.36	2	2.7×10^{-5}
24 - <30	62857.04	1	1.6×10^{-5}
≥ 30	120907.1	0	0

The failure rates shown in Tables 33 and 34 indicate a greater chance of a failure occurring on smaller diameter or thinner-walled pipelines.

Tables 35 and 36 show the failure rate as a function of hole size, where Table 36 shows adjustments for the zero failure events. Given that only pinholes have been observed in the last 20 years, it is assumed that small holes are twice as likely as large holes or ruptures.

Table 35 Mechanical failure rate as a function of hole size

Hole size	Number of events	Failure rate (per km yr)
Rupture	0	0
Large hole	0	0
Small hole	0	0
Pinhole	35	8.4×10^{-5}

Table 36 Mechanical failure rate as a function of hole size after adjustment for zero failures

Hole size	Number of events	Modified number of events	Failure rate (per km yr)
Rupture	0	$=0 + (^{1}/_{36})/4 = 0.00694$	1.7×10^{-8}
Large hole	0	$= 0 + (^{1}/_{36})/4 = 0.00694$	1.7×10^{-8}
Small hole	0	$= 0 + (^{1}/_{36})/2 = 0.0139$	3.3×10^{-8}
Pinhole	35	$= 35 + (^{35}/_{36}) = 35.972$	8.7×10^{-5}

Table 37 shows the derivation of the mechanical failure rate as a function of hole size and pipeline diameter. In this case, there were many categories with zero events.

Table 37 Mechanical failure rate as a function of hole size and pipeline diameter

Pipeline diameter (in)	Pinhole	Small hole	Large hole	Rupture
	Event data			
< 8	26	0	0	0
8 - <12	4	0	0	0
12 - <16	2	0	0	0
≥ 16	3	0	0	0
	Failure rate (per km yr)			
< 8	6.0×10^{-4}	0	0	0
8 - <12	6.8×10^{-5}	0	0	0
12 - <16	3.7×10^{-5}	0	0	0
≥ 16	1.2×10^{-5}	0	0	0

Table 38 illustrates the derivation of the mechanical failure rate as a function of hole size and pipeline diameter after a zero rate analysis had been performed.

Table 38 Mechanical failure rate as a function of hole size and pipeline diameter, with zero rate analysis

Pipeline diameter (in)	Pinhole	Small hole	Large hole	Rupture
	Event data			
< 8	$26 + {}^{26}/_{27}$	${}^{1}/_{27} \times {}^{1}/_{2}$	${}^{1}/_{27} \times {}^{1}/_{4}$	${}^{1}/_{27} \times {}^{1}/_{4}$
8 - <12	$4 + {}^{4}/_{5}$	${}^{1}/_{5} \times {}^{1}/_{2}$	${}^{1}/_{5} \times {}^{1}/_{4}$	${}^{1}/_{5} \times {}^{1}/_{4}$
12 - <16	$2 + {}^{2}/_{3}$	${}^{1}/_{3} \times {}^{1}/_{2}$	${}^{1}/_{3} \times {}^{1}/_{4}$	${}^{1}/_{3} \times {}^{1}/_{4}$
≥ 16	$3 + {}^{3}/_{4}$	${}^{1}/_{4} \times {}^{1}/_{2}$	${}^{1}/_{4} \times {}^{1}/_{4}$	${}^{1}/_{4} \times {}^{1}/_{4}$
	Failure rate (per km yr)			
< 8	6.2×10^{-4}	4.2×10^{-7}	2.1×10^{-7}	2.1×10^{-7}
8 - <12	8.1×10^{-5}	1.7×10^{-6}	8.5×10^{-7}	8.5×10^{-7}
12 - <16	5.0×10^{-5}	3.1×10^{-6}	1.6×10^{-6}	1.6×10^{-6}
≥ 16	1.5×10^{-5}	4.8×10^{-7}	2.4×10^{-7}	2.4×10^{-7}

Given the number of zero events in Table 37, it is judged that the best representative failure rates are given, with the exception of pinholes, by the failure rates presented in Table 36. For pinholes, it is recommended that the failure rates given in Table 37 are used. The recommended failure rates are shown in Table 39.

Table 39 Mechanical failure rate as a function of hole size and pipeline diameter

Pipeline diameter (in)	Pinhole	Small hole	Large hole	Rupture
	Failure rate (per km yr)			
< 8	6.0×10^{-4}	3.3×10^{-8}	1.7×10^{-8}	1.7×10^{-8}
8 - <12	6.8×10^{-5}	3.3×10^{-8}	1.7×10^{-8}	1.7×10^{-8}
12 - <16	3.7×10^{-5}	3.3×10^{-8}	1.7×10^{-8}	1.7×10^{-8}
≥ 16	1.2×10^{-5}	3.3×10^{-8}	1.7×10^{-8}	1.7×10^{-8}

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