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Update of pipeline failure rates for land use planning assessments

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EXECUTIVE SUMMARY

The Health and Safety Executive (HSE) use a software package PIPIN for the determination of failure frequencies for pipelines. The PIPeline INtegrity software (PIPIN) was developed on HSE's behalf by WS Atkins Limited. PIPIN calculates failure rates for pipelines, which are then used as inputs to other tools such as MISHAP, HSE's pipeline consequence and risk assessment model, which calculates land use planning zones around such pipelines. PIPIN contains two models for the determination of failure rates: a model based on operational experience data, which is able to estimate failure rates for the four main failure modes (mechanical failures, natural events, corrosion and third party activity); and a predictive model that uses structural reliability techniques to predict the failure frequency due to third party activity only.

Objectives

The operational experience failure rates currently used by PIPIN are, in some cases, over 10 years old. Therefore, HSE commissioned the Risk Assessment Team of the Health and Safety Laboratory (HSL) to undertake a review of the failure rates currently used by PIPIN and, where appropriate, generate new failure rates taking into account more up-to-date fault and failure data.

The objectives were to:

- estimate pipeline failure rates based on available failure data sources;
- recommend failure rates for use in PIPIN; and
- replace the historical data used within PIPIN Version 2.3 with more up-to-date data.

Main Findings

This report details the analysis of pipeline failure data and presents updated failure rates for use within PIPIN for land use planning assessments. The updated failure rates are presented in the main report.

Recommendations

The following recommendations are made:

1. The failure rates presented in this report should be adopted by HSE and replace those currently used by HSE in PIPIN for land use planning assessments of pipelines; and

2. The failure rates should be updated on a regular basis as more failure data is published.

1 INTRODUCTION

The Health and Safety Executive (HSE) use a computer code PIPIN (PIPeline Integrity) [1, 2] for the determination of failure frequencies of major hazard pipelines. PIPIN was developed on HSE's behalf by WS Atkins Limited. PIPIN calculates the failure rates for four categories of failure (pinhole, small hole, large hole and rupture) of pipelines, which are used in other tools, such as MISHAP [3] to calculate the level of risk and therefore land use planning zones around pipelines. PIPIN contains two approaches for the determination of failure rates: an approach based on operational experience data, which generates failure rates for four principle failure modes (mechanical failures, natural events, corrosion and third party activity); and a predictive model that uses structural reliability techniques to predict the failure frequency due to third party activity (TPA) only.

1.1 OBJECTIVES

The operational experience failure rates currently used by PIPIN are, in some cases, over 10 years old. Therefore, HSE commissioned the Risk Assessment Team of the Health and Safety Laboratory (HSL) to undertake a review of the failure rates currently used by PIPIN and, where appropriate, generate new failure rates taking into account more up-to-date fault and failure data.

The objectives were to:

- estimate pipeline failure rates based on available failure data sources;
- recommend failure rates for use in PIPIN; and
- replace the historical data used within PIPIN Version 2.3 with more up-to-date data.

1.2 STRUCTURE OF REPORT

The remainder of the report is structured as follows:

- Section 2 presents background information to the analysis;
- Section 3 includes analysis of CONCAWE (CONservation of Clean Air and Water in Europe) products pipeline failure data;
- Section 4 includes analysis of CONCAWE crude oil pipeline failure data;
- Section 5 includes analysis of UKOPA (United Kingdom Onshore Pipelines Association) pipeline failure data;
- Section 6 presents recommended failure rates for both of the data sources (CONCAWE and UKOPA);
- Section 7 presents and compares the current and recommended failure rates for various substances; and
- Section 8 presents the main findings and recommendations.

2 BACKGROUND

This section provides background to the analysis of the different pipeline failure datasets, generic assumptions and the overall calculation approach adopted.

2.1 CALCULATION OF FAILURE RATES

2.1.1 Calculation approach

Throughout the analysis presented in this report, failure rates have been calculated as the number of failures reported in the historical data divided by the pipeline population; this is shown in Equation 1.

$$\lambda_{(Failure\ type)} = \frac{Number\ of\ events}{Population\ (km\ yr)} \qquad \text{(Equation 1)}$$

The same approach has been used to calculate failure rates for different pipeline diameters, wall thicknesses and failure modes by using the relevant number of events and size of population.

2.1.2 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 comes in how the failure rate should be estimated. Previous calculations of failure rates for pipelines have added one extra event into each failure mode [4], or one extra event across a range of failure modes [5]). 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 [5, 6] 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 get 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 5 failures in total rather than 4) 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 between (i.e. 1/10 each) between pin holes and small holes giving each a failure rate of 0.1/(200*20) = 2.5x10^{-5} per km yr.

2.2 DATA SOURCES

Pipeline failure rates have been calculated using data from the following organisations:

- CONCAWE – CONservation of Clean Air and Water in Europe;
- UKOPA – United Kingdom Onshore Pipelines Association; and
- EGIG – European Gas pipeline Incident Group.

CONCAWE collate details of failure events in crude and white product pipelines, which are published in annual reports. The CONCAWE database has collected data on the safety and environmental performance of oil and oil product pipelines since 1971. Information on annual throughput and traffic, spillage incidents and operational elements are gathered yearly via questionnaires sent out to oil pipeline operation companies. CONCAWE collect data from approximately seventy companies and agencies operating in Europe, transporting crude oil or crude oil products. These operators have over 150 pipeline systems.

The total operating length of pipeline covered by CONCAWE in 2000 was 35,390 km. The most recent report covers 36 years, 1971 to 2006 [7]. The data is presented by year, pipeline type and size, event location, size of spillage, and cause of event. Some events have only partial data available, however.

UKOPA represents the majority of UK onshore pipeline operators. UKOPA collect fault and failure data for the onshore pipelines with similar detail to that of CONCAWE.

UKOPA's raw data has been made available to HSL for this study. This allowed the analysis of the data carried out on behalf of UKOPA [8] to be validated and other conclusions drawn from the data. The UKOPA dataset allows specifically UK failures to be examined without the influence from other European countries.

EGIG is a co-operation between a group of fifteen major gas transmission system operators in Western Europe and is the owner of an extensive gas pipeline incident database.

EGIG collects similar data to CONCAWE, but for natural gas pipelines in Europe. EGIG has a total operating pipeline population of 2.77 million km yr, which is substantially larger than that of CONCAWE at 564,000 km yr. The most recent report from EGIG covers incidents from 1970 to 2007 [9]. EGIG collect data for pipelines only; all fittings are excluded from the dataset. Access to the raw EGIG data is restricted to the members of EGIG, and was not available to HSL for this study. Analysis of EGIG data has therefore not been carried out.

Although the available datasets date back to the 1950s, only the most recent 20 years have been analysed in this study. The failure rates for all pipelines have steadily reduced since 1950, plateauing in recent years. In the early years of the pipeline system there were more failures over a smaller population. The reasons for this may be many, but improved operating procedures and maintenance are commonly quoted as obvious reasons.

For the CONCAWE data, which covers the period 1971 to 2006, a large number of countries and non-commercial pipelines joined the survey in 1988 resulting in a large step increase in the population of pipelines. Therefore, analysis of only the most recent 20 years includes a consistent pipeline population and removes the oldest event data, which may not be as representative of today's practices.

2.3 ASPECTS OF PIPELINES

2.3.1 Commodity type

Major hazard pipelines within Europe are used to transport natural gas, crude oil, oil products and other commodities over long distances. Pipelines may be 'hot', carrying products at elevated temperatures, although these are generally being replaced with cold lines due to the higher corrosive nature of hot petroleum products.

In this report, the pipelines are referred to as 'crude oil', 'clean products' and 'natural gas'. Hot pipelines have been excluded from the analysis, where possible. 'Clean product' lines have not been further distinguished between diesel, gasoline, aviation fuel etc due to insufficient data.

2.3.2 Population

The population data used here is described in kilometre years (km yr), that is the sum of the length of pipeline for each year in service. For example, if a length of pipeline was 1000 km and the analysis was looking at a 5-year period, then the population would be 5000 km yr.

Pipelines consist of many different parts. The pipeline itself can be underground, above ground or crossing natural or artificial barriers. A pipeline can have many fittings, welds and bends, pumping stations and inspection stations. The population used in this report is assumed to be the length of pipeline underground only. The above ground length and that taken by other fittings have been assumed to be small compared to the overall pipeline length. Therefore, the impact of this assumption on the failure rate calculation has been assumed to be negligible.

2.3.3 Pipeline components

The failure rates have been generated using event data from underground pipelines only. Failures of all other pipeline components have been excluded from the analysis.

2.3.4 Failure location

The failure rate of a pipeline may be dependent on its location, for example whether in a rural or suburban area, particularly for the third party activity failure mode. However, although the location of failures may be recorded in the various databases, there is insufficient data that describes how the pipeline population is proportioned between different locations. For this reason, only overall failure rates have been calculated and not failure rates as a function of location.

2.3.5 Pipeline diameter and wall thickness

Pipeline failure rates may be dependent on either the pipeline diameter or wall thickness (or both). This dependency also varies across the different failure modes. To be able to calculate failure rates as a function of pipeline diameter or wall thickness such information must be recorded for each failure in the relevant dataset and the pipeline population must be broken down as a function of pipeline diameter or wall thickness. The availability of such data for each of the data sources is discussed below and summarised in Table 1.

Table 1 Availability of information from different data sources

		CONCAWE	UKOPA	EGIG
Population	Wall thickness	×	✓	✓
	Diameter	✓	✓	✓
Event data	Wall thickness	✓	✓	×
	Diameter	✓	✓	×

CONCAWE present population data as a function of pipeline diameter but not wall thickness. However, both the pipeline diameter and wall thickness of the failed pipeline are recorded in the yearly reports. Failure rates derived from CONCAWE data can therefore only be derived as a function of pipeline diameter, and not as a function of wall thickness.

UKOPA present population data as a function of both wall thickness and pipeline diameter. The failure reports also detail the pipeline diameter and wall thickness. This allows failure rates to be determined as a function of wall thickness or pipeline diameter. Failure rates cannot be generated as a function of both wall thickness and pipeline diameter as population data is not presented for this.

EGIG present the population data for wall thickness and pipeline diameter. However, EGIG do not detail individual failures in their reports [9] and it was not possible to perform any analysis from the information that was available.

Where failure rates were calculated as a function of either pipeline diameter or wall thickness, these were calculated for specific ranges. The actual ranges are not prescribed by PIPIN, and were selected based on the data, particularly by how detailed the population data was recorded.

2.3.6 Hole size

For pipeline risk assessments, HSE require failure rates for four hole sizes: pinhole (<25 mm diameter), small hole (25-<75 mm diameter), large hole (75-110 mm diameter) and rupture (>110 mm diameter). The failure rates derived in this report are calculated for the same four categories of hole size. In order to calculate the failure rates for each hole size, the observed failures in each dataset must be categorised into one of HSE's hole size ranges. The assumptions made for each data source are discussed below.

CONCAWE record the amount of product lost rather than the defect size. Therefore, the amount of product lost has been assumed to be related to the hole size. For consistency, the same approach taken by Atkins in its analysis of CONCAWE data for PIPIN [10] was adopted here. The assumed relationship between product loss and hole size is shown in Table 2, where puncture is assumed to represent a small or large hole. It is assumed that punctures are proportioned between small and large holes in the ratio 2 to 1.

Table 2 Definition of hole sizes [4]

	Amount of material lost as a function of hole size			
Failure mode	***Rupture***	***Puncture***	***Pinhole***	***Specific***
Third Party Activity	> 250 m^3	10 to 250 m^3	< 10 m^3	If Ø <8" then rupture is >45 m^3
Corrosion	> 500 m^3	10 to 500 m^3	< 10 m^3	If Ø <8" then rupture is >100 m^3
Mechanical	> 200 m^3	10 to 200 m^3	< 10 m^3	
Natural	> 200 m^3	10 to 200 m^3	< 10 m^3	If Ø <10" then rupture is >305 m^3

UKOPA record the dimensions of the failures. For each recorded failure an equivalent diameter was calculated (as described in Section 5.2.5) and each failure was categorised against the required four hole size ranges.

2.4 MODES OF FAILURE

Pipelines may fail due to a variety of different reasons. They may fail as a result of the commodity, the pipeline construction, or some external event. The analysis presented in this report has considered four principal failure modes:

- ***Third Party Activity***, including damage from agricultural machinery, damage from heavy plant, damage from drills/boring machines and hot tapping etc;
- ***Mechanical failures***, including mechanical and construction faults;
- ***Corrosion***, including both internal and external corrosion. The data represents pipelines that are both fitted with corrosion protection systems and those that are not; and
- ***Natural***, including land movements due to earthquakes, heavy rains/floods and general subsidence of the surrounding earth.

Each of these failure modes is discussed in the following subsections. For each dataset, the mode of failure is determined by the data owner, e.g. CONCAWE or UKOPA, either at the time of the event or as a result of the subsequent investigation.

2.4.1 Mechanical failures

Mechanical failures are a function of the material and/or construction of the pipeline, and are generally independent of the commodity and locality of the pipeline. They are usually caused by a construction fault, or a fault with the material or design of the pipeline.

2.4.2 Corrosion

Corrosion failures are generally a function of the commodity transported and the wall thickness of the pipeline. The material of the pipeline may also make it more or less susceptible to corrosion. Corrosion may be internal or external. Internal corrosion is caused by the corrosive properties of the commodity being transported. External corrosion is independent of the commodity, and may be a function of the type of soil the pipeline is situated in, the type of coating, the material of construction, the presence of corrosion protection and the age of the pipeline.

2.4.3 Natural

Natural failures are due to external events that occur in the area surrounding a pipeline. They are caused by events such as landslides, earthquakes and lightning strikes. Landslides may be a natural event or they may be caused by human interference. Natural events are likely to be dependent on the location of the pipeline, for example whether in the locality of a fault line.

Other relevant failure modes have been captured under the natural category, for example as a result of operational errors[1].

2.4.4 Third party activity

TPA failures result from damage to pipelines caused by external strikes, which may be accidental, deliberate or incidental. Events of this type may be caused by agricultural or

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[1] *Operational errors are defined by CONCAWE as being caused by human or computer error, and as such are not associated with a defect of the pipeline.*

construction vehicles, terrorism or theft. Terrorist activities from pipelines in the UK and Europe are not common, but there are a number of reported thefts on pipelines. The majority of third party activity events are caused by construction vehicles or equipment (drills etc), or farm machinery striking and damaging the pipeline. The frequency of failure due to TPA events is currently estimated by HSE using a predictive model. This work does not intend to replace or modify the TPA model; however, an analysis of historical TPA events was carried out for completeness.

3 ANALYSIS OF CONCAWE CLEAN PRODUCT DATA

3.1 INTRODUCTION

This section presents the analysis of the CONCAWE clean product pipeline failures and the derivation of the relevant failure rates. CONCAWE record clean product failures separately to pipelines carrying other commodities. Population data is also stated specifically for clean products.

3.2 ASPECTS OF CLEAN PRODUCT PIPELINES

3.2.1 Commodity type

'Clean Products' are defined as petroleum products that may be transported in a cold pipeline. Hot pipelines are used to transport 'hot' products, carried at elevated temperatures. Hot pipelines are not included in this analysis.

The type of product is not specifically referred to in the CONCAWE database, but may include: aviation fuel, diesel, fuel oil, gas oil, gasoline, kerosene, light fuel oil, light petroleum products, lubricating distillates and naphtha.

3.2.2 Population

The length of pipeline was manually estimated from Figure 1 'CONCAWE pipeline inventory and main service categories' of Reference 7.

The length of pipeline carrying clean products in 2006 was approximately 24,500 km.

The exposure from 1987 to 2006 was estimated from Reference 7 as 421,000 km yr.

3.2.3 Failure location

The location of the failure is recorded by CONCAWE, and is split into above ground or underground pipeline, and different pipeline components. For the purposes of this study, only those events that occurred on underground pipelines were included. Events that occurred on component parts of the pipeline were excluded.

3.2.4 Pipeline diameter and wall thickness

Each failure has detailed information about the pipeline on which the failure occurred, including pipeline diameter, wall thickness and material type. Population data was available from the CONCAWE reports that enabled failure rates to be calculated as a function of pipeline diameter.

CONCAWE do not publish population data as a function of pipeline wall thickness. Therefore, even though the CONCAWE yearly reports include the wall thickness of the pipeline for each of the recorded failures, without population data as a function of wall thickness, the failure rates could not be calculated as a function of wall thickness.

Failure rates were calculated as a function of the diameter of the pipeline. The length by diameter was estimated from Figure 2 'Pipeline diameter distribution and service in 2006' of Reference 7 and is reproduced in Table 4. Additional data was estimated from Figure 1 'Development of pipeline length, diameter and service' of Reference 11, which is presented in Table 3. This data gives more information about the ratio of the pipeline diameters in 1980, 1990 and 2000. As the ratios were similar in 1990 and 2000, and the length of pipeline captured by CONCAWE has not changed significantly since 1988, the distribution in pipeline diameters in 2006 have been assumed to apply for the whole period 1987 to 2006.

Table 3 Ratio of pipeline diameters [11]

Diameter (in)	*1980 (%)*	*1990 (%)*	*2000 (%)*
<8	8.6	10.8	8.8
8 - <12	35.5	49	48.5
12 - <16	26.9	24.5	26.4
≥16	26.9	14.7	15.4

Table 4 Diameter ranges of clean product pipelines in 2006 [7]

Pipeline diameter range (in)	*Percentage of pipeline (%)*	*Exposure (km yr)*
< 8	7.5	31575
8 - <12	52.5	221025
12 - <16	26	109460
16 - <24	11	46310
24 - <30	2	8420
≥ 30	1	4210
(≥16)	(14)	(58940)

Due to the low population of pipelines with a diameter greater than 24", these were grouped together as greater than 16", as shown in the last row of Table 4.

3.2.5 Hole size

CONCAWE record the volume (in m^3) of product spilt as a result of the event rather than the actual hole size. In a previous analysis of CONCAWE data by Atkins [4] the hole sizes were apportioned on the amount of product lost and the failure mechanism; this is shown in Table 2. Although the basis for the relationship was not clearly documented by Atkins, for consistency the same approach has been adopted here.

3.3 FAILURE RATE DETERMINATION

The CONCAWE data used to generate the failure rates was taken from Reference 7, which details the failure events from 1971 to 2006. The raw data used to generate the failure rates is presented in Appendix 1 of this report, which allows the analysis presented in this report to be repeated.

In the 20-year period being considered (1987-2006), a total of 115 failure events were recorded. This gives an overall failure rate of 2.7 x 10^{-4} (115/421,000) per km yr.

In previous studies [10] the ‘hole’ as defined was further divided into a small hole and a large hole by proportioning the overall hole failure rate between the two hole sizes in the ratio 2 to 1 (small to large). The same approach has generally been taken in the analysis presented in this section. In some cases, however, this may not be the most logical approach to take e.g. if all the failures are concentrated at the rupture end of the scale or if there is existing data to indicate what the split between small and large holes should be. In these cases the additional failure may be apportioned differently.

The following sections derive failure rates for the four principal modes of failure, and also as a function of pipeline diameter and hole size. Where no failures were observed a failure rate was estimated using the approach outlined in Section 2.1.2.

3.3.1 Mechanical

In the 20-year period, there were 17 events attributed to mechanical failures. The overall failure rate is therefore 4.0 x 10^{-5} (17/421,000) per km yr.

Table 5 shows the calculation of the failure rate as a result of mechanical failure as a function of pipeline diameter.

Table 5 Mechanical failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	31575	5	1.6 x 10^{-4}
8 - <12	221025	4	1.8 x 10^{-5}
12 - <16	109460	5	4.6 x 10^{-5}
≥16	58940	3	5.1 x 10^{-5}

Table 6 shows the calculation of the failure rate as a result of mechanical failure as a function of hole size. The table also shows application of the 2:1 ratio between small and large holes. In this case the chance of a rupture occurring appears greater than that of a large hole, which may be unrealistic and is as a result of the small data sample.

Table 6 Mechanical failure rate as a function of hole size

Hole size	*Number of events* [2]	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	3	7.1 x 10^{-6}	3	7.1 x 10^{-6}
Large hole	8	1.9 x 10^{-5}	2.67	6.3 x 10^{-6}
Small hole			5.33	1.3 x 10^{-5}
Pinhole	5	1.2 x 10^{-5}	5	1.2 x 10^{-5}

The failure rates derived in Table 7 are a function of both hole size and pipeline diameter. When the second factor is taken into consideration several categories have no recorded events, resulting in a zero failure rate. The variation in failure rate as a function of diameter and hole size is a result of the small data sample.

[2] *One event listed does not include the release size. As such, the event has been excluded from this calculation.*

Table 7 Mechanical failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	1	2.67	1.33	0
8 - <12	2	0.67	0.33	1
12 - <16	1	2	1	0
≥16	1	0	0	2
	Failure rate (per km yr)			
< 8	3.2×10^{-5}	8.5×10^{-5}	4.2×10^{-5}	0
8 - <12	9.0×10^{-6}	3.0×10^{-6}	1.5×10^{-6}	4.5×10^{-6}
12 - <16	9.1×10^{-6}	1.8×10^{-5}	9.1×10^{-6}	0
≥16	1.7×10^{-5}	0	0	3.4×10^{-5}

Adjustment for zero failures is presented in Table 8, which addresses the categories that have not occurred historically. Two different mechanisms to do this have been used based on the data available. For pipeline diameters of < 8 inches and 12 - < 16 inches, the process described in section 2.1.2 has been applied. For pipeline diameters of ≥ 16 inches, as data was available for both pinholes and ruptures (hence ruptures are more likely to occur than either small or large holes), it was felt that a 2:1 split between small and large holes would be inappropriate and so an equal proportion was given to both of these hole sizes.

The results of the zero rate analysis still show no obvious pattern as illustrated in Figure 1.

Table 8 Mechanical failure rate as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	$1 + {}^{1}/_{6}$	$2.67 + {}^{2.67}/_{6}$	$1.33 + {}^{1.33}/_{6}$	${}^{1}/_{6}$
8 - <12	2	${}^{2}/_{3}$	${}^{1}/_{3}$	1
12 - <16	$1 + {}^{1}/_{5}$	$2 + {}^{2}/_{5}$	$1 + {}^{1}/_{5}$	${}^{1}/_{5}$
≥16	$1 + {}^{1}/_{4}$	${}^{1}/_{8}$	${}^{1}/_{8}$	$2 + {}^{2}/_{4}$
	Failure rate (per km yr)			
< 8	3.7×10^{-5}	9.9×10^{-5}	4.9×10^{-5}	5.3×10^{-6}
8 - <12	9.0×10^{-6}	3.0×10^{-6}	1.5×10^{-6}	4.5×10^{-6}
12 - <16	1.1×10^{-5}	2.2×10^{-5}	1.1×10^{-5}	1.8×10^{-6}
≥16	2.1×10^{-5}	2.1×10^{-6}	2.1×10^{-6}	4.2×10^{-5}

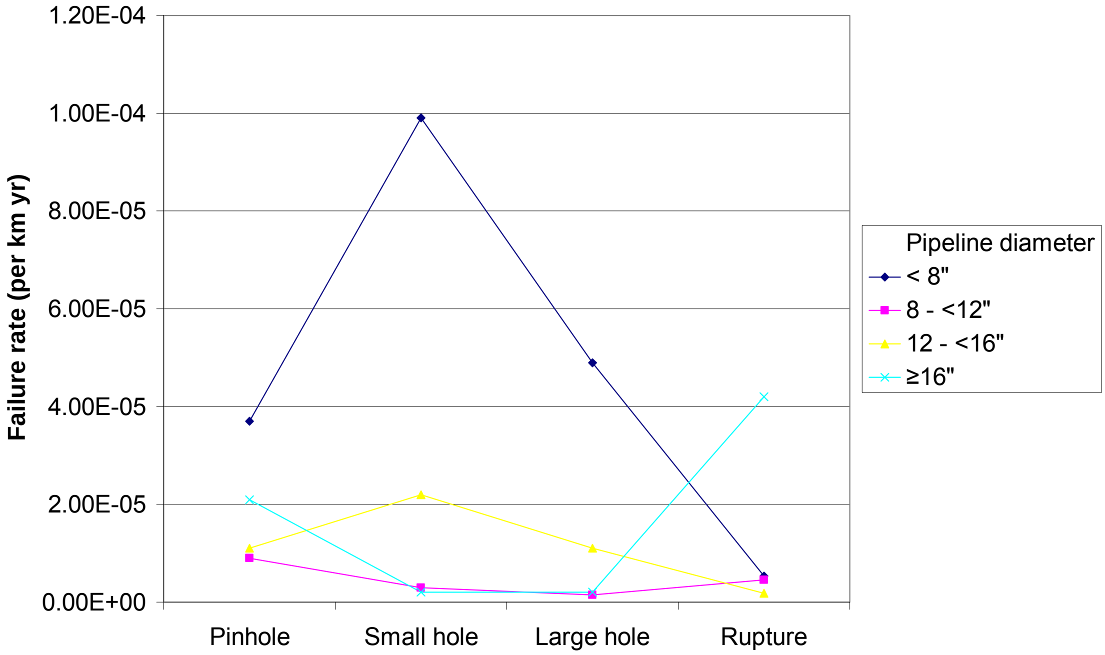

Figure 1 Mechanical failure rate as a function of hole size after adjustment for zero failures

Given the small sample of data and the apparently unintuitive variation in failure rate as a function of hole size and diameter range (shown in Figure 1), it is recommended that the failure rates presented in Table 6 should be applied to all pipeline diameters for use in PIPIN (CONCAWE products dataset).

3.3.2 Corrosion

The overall failure rate for corrosion events was estimated as 4.3 x 10^{-5} (18/421,000) per km yr, with 18 events occurring in a 20-year period. 12 of the events were due to external corrosion, 3 were attributed to internal corrosion and a further 3 due to stress corrosion cracking.

Corrosion failures are assumed to be strongly dependent on wall thickness and only weakly dependent on pipeline diameter. However, as wall thickness population data was not available in the CONCAWE dataset then only variation in failure rate as a function of pipeline diameter could be considered.

Table 9 shows the failure rate for the corrosion failure mode (internal, external and stress corrosion cracking (SCC)) as a function of pipeline diameter. Table 10 shows the calculated failure rate as a function of hole size.

Table 9 Corrosion failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	31575	2	6.3×10^{-5}
8 - <12	221025	8	3.6×10^{-5}
12 - <16	109460	5	4.6×10^{-5}
≥16	58940	3	5.1×10^{-5}

Table 10 Corrosion failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	5	1.2×10^{-5}	5	1.2×10^{-5}
Large hole	12	2.9×10^{-5}	4	9.5×10^{-6}
Small hole			8	1.9×10^{-5}
Pinhole	1	2.4×10^{-6}	1	2.4×10^{-6}

Table 11 shows the calculated failure rate as a function of both pipeline diameter and hole size, with Table 12 presenting the failure rates after adjustment to account for the zero failure rates. For pipeline diameters of less than 8", as the only available data was in the pinhole category, the extra 1/3 of an event was split in the ratio 50:25:25 (based on expert judgement) between small holes, large holes and ruptures.

Table 11 Corrosion failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	2	0	0	0
8 - <12	1	4	2	1
12 - <16	1	2.67	1.33	0
≥16	1	1.33	0.67	0
	Failure rate (per km yr)			
< 8	6.3×10^{-5}	0	0	0
8 - <12	4.5×10^{-6}	1.8×10^{-5}	9.0×10^{-6}	4.5×10^{-6}
12 - <16	9.1×10^{-6}	2.4×10^{-5}	1.2×10^{-5}	0
≥16	1.7×10^{-5}	2.3×10^{-5}	1.1×10^{-5}	0

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Table 12 Corrosion failure rate as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	$2 + {}^{2}/_{3}$	${}^{1}/_{3}$ x ${}^{1}/_{2}$	${}^{1}/_{3}$ x ${}^{1}/_{4}$	${}^{1}/_{3}$ x ${}^{1}/_{4}$
8 - <12	1	4	2	1
12 - <16	$1 + {}^{1}/_{6}$	$2\ {}^{2}/_{3} + {}^{4}/_{9}$	$1\ {}^{1}/_{3} + {}^{2}/_{9}$	${}^{1}/_{6}$
≥16	1 + ¼	$1{}^{1}/_{3} + {}^{2}/_{6}$	${}^{2}/_{3} + {}^{1}/_{6}$	¼
	Failure rate (per km yr)			
< 8	8.4×10^{-5}	5.3×10^{-6}	2.6×10^{-6}	2.6×10^{-5}
8 - <12	4.5×10^{-6}	1.8×10^{-5}	9.0×10^{-6}	4.5×10^{-6}
12 - <16	1.1×10^{-5}	2.8×10^{-5}	1.5×10^{-5}	1.5×10^{-6}
≥16	2.1×10^{-5}	2.8×10^{-5}	1.4×10^{-5}	4.2×10^{-6}

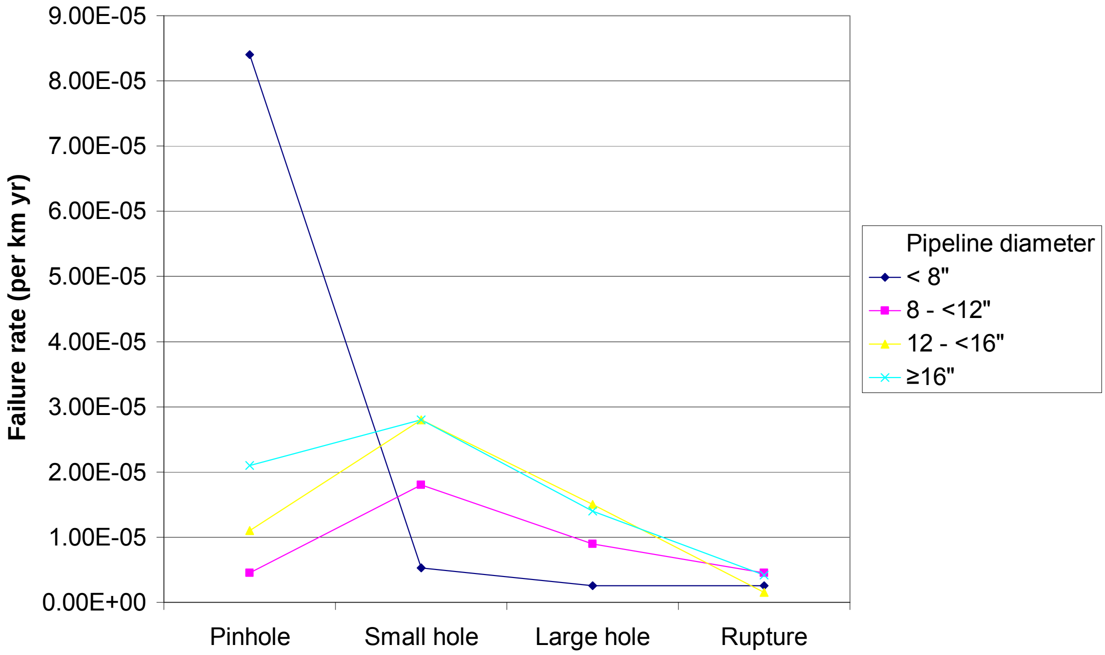

Figure 2 Corrosion failure rate as a function of hole size after adjustment for zero failures

After the failure rates had been adjusted to account for the zero failures, as shown in Table 12, some pattern was observed for pipelines with a diameter greater than 8", as can be seen in Figure 2. For corrosion events it can be assumed that pinholes occur more frequently than larger holes: corrosion is a slow process and any pinholes may be detected before the hole size increases. The pattern shown in Figure 2 indicates that for pipelines with a diameter greater than 8 inches the probability of a small hole is greater than that of a pinhole. This may be an artefact of the way that hole sizes have been deduced from the amount of product lost; a pinhole is assumed where less then 10 m^3 of product is lost. For example, if a pinhole was not discovered for some time, then more than 10 m^3 of product could be lost resulting in the pinhole incorrectly being classified as a hole or rupture. However, given the small dataset a lot of scatter in the failure rates is still observed, with an order of magnitude difference in cases that might be expected to be similar, for example pinholes compared to small holes for pipelines with diameters less than 8".

Notwithstanding the above discussion, it is recommended that the failure rates detailed in Table 12 should be used in PIPIN (CONCAWE products dataset) for the corrosion failure mode.

3.3.3 Natural and other events

The overall failure rate for natural events was estimated as 1.4 x 10^{-5} (6/421,000) per km yr, with 6 events occurring in a 20-year period.

Table 13 details the derivation of the failure rate due to natural events as a function of pipeline diameter and Table 14 details the derivation of the failure rate due to natural events as a function of hole size.

Table 13 Natural failure rate as a function pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	31575	0	0
8 - <12	221025	1	4.5 x 10^{-6}
12 - <16	109460	4	3.7 x 10^{-5}
≥ 16	58940	1	1.7 x 10^{-5}

Table 14 Natural failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	2	4.8 x 10^{-6}	2	4.8 x 10^{-6}
Large hole	3	7.1 x 10^{-6}	1	2.4 x 10^{-6}
Small hole			2	4.8 x 10^{-6}
Pinhole	1	2.4 x 10^{-6}	1	2.4 x 10^{-6}

Table 15 shows the derivation of the natural failure rate as a function of both pipeline diameter and hole size. Given the very small number of observed events, it was not sensible to try and estimate failure rates for the categories with zero events.

Table 15 Natural failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	0	0	0	0
8 - <12	0	$^2/_3$	$^1/_3$	0
12 - <16	0	1 $^1/_3$	$^2/_3$	2
≥16	1	0	0	0
	Failure rate (per km yr)			
< 8	0	0	0	0
8 - <12	0	3.0×10^{-6}	1.5×10^{-6}	0
12 - <16	0	1.2×10^{-5}	6.1×10^{-6}	1.8×10^{-5}
≥16	1.7×10^{-5}	0	0	0

Given the very small number of observed failures as a result of the natural failure mode, it is recommended that the values in Table 14 are used in PIPIN (CONCAWE products dataset) for the natural failure mode.

3.3.4 Third party activity

74 failures due to the TPA failure mode were recorded as occurring over the 20-year period. This gives an overall failure rate of 1.8×10^{-4} (74/421,000) per km yr.

The derivation of the TPA failure rate as a function of pipeline diameter is given in Table 16 and as a function of hole size, in Table 17.

Table 16 TPA failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	31575	15	4.8×10^{-4}
8 - <12	221025	37	1.7×10^{-4}
12 - <16	109460	8	7.3×10^{-5}
≥ 16	4210	14	2.4×10^{-4}

Table 17 TPA failure rate as a function of hole size

Hole size	*Number of events*[3]	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	9	2.1×10^{-5}	9	2.1×10^{-5}
Large hole	43	1.0×10^{-4}	14.33	3.4×10^{-5}
Small hole			28.67	6.8×10^{-5}
Pinhole	21	5.0×10^{-5}	21	5.0×10^{-5}

TPA failure rates as a function of both pipeline diameter and hole size are given in Table 18. Just one entry has no recorded events, a pipeline with a diameter of less than 8" resulting in a rupture. Table 19 shows the calculation of the failure rates to account for the observed zero. Figure 3 shows graphically how the failure rate varies as a function of hole size and pipeline diameter. The failure rate generally decreases as the diameter increases, as expected for TPA failures. The resultant hole size depends on the size of the initial damage and what caused the damage, for example a drill or an excavator.

Table 18 TPA failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	6	6	3	0
8 - <12	7	$17\ ^{2}/_{3}$	$8\ ^{1}/_{3}$	3
12 - <16	3	$2\ ^{2}/_{3}$	$1\ ^{1}/_{3}$	1
≥16	5	$2\ ^{2}/_{3}$	$1\ ^{1}/_{3}$	5
	Failure rate (per km yr)			
< 8	1.9×10^{-4}	1.9×10^{-4}	9.5×10^{-5}	0
8 - <12	3.2×10^{-5}	8.0×10^{-5}	3.8×10^{-5}	1.4×10^{-5}
12 - <16	2.7×10^{-5}	2.4×10^{-5}	1.2×10^{-5}	9.1×10^{-6}
≥16	8.5×10^{-5}	4.5×10^{-5}	2.3×10^{-5}	8.5×10^{-5}

[3] *One event listed does not include the release size. As such, the event has been excluded from this calculation.*

Table 19 TPA failure rate as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 8	6 $^{6}/_{16}$	6 $^{6}/_{16}$	3 $^{3}/_{16}$	$^{1}/_{16}$
8 - <12	7	17 $^{2}/_{3}$	8 $^{1}/_{3}$	3
12 - <16	3	2 $^{2}/_{3}$	1 $^{1}/_{3}$	1
≥16	5	2 $^{2}/_{3}$	1 $^{1}/_{3}$	5
	Failure rate (per km yr)			
< 8	2.0×10^{-4}	2.0×10^{-4}	1.0×10^{-4}	2.0×10^{-6}
8 - <12	3.2×10^{-5}	8.0×10^{-5}	3.8×10^{-5}	1.4×10^{-5}
12 - <16	2.7×10^{-5}	2.4×10^{-5}	1.2×10^{-5}	9.1×10^{-6}
≥16	8.5×10^{-5}	4.5×10^{-5}	2.3×10^{-5}	8.5×10^{-5}

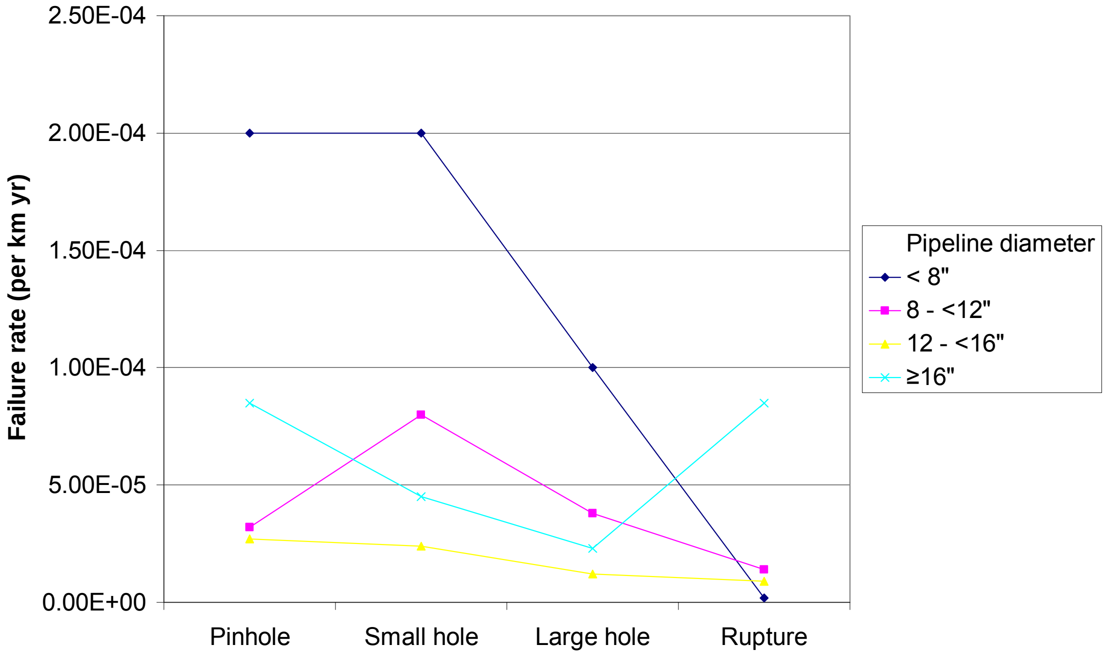

Figure 3 TPA failure rate as a function of hole size after adjustment for zero failures

It is recommended that the failure rates quoted in Table 19 are used by PIPIN for the TPA failure mode (CONCAWE products dataset).

4 ANALYSIS OF CONCAWE CRUDE OIL DATA

4.1 INTRODUCTION

This section presents the analysis of the CONCAWE crude oil pipeline failure data and the derivation of the relevant failure rates. CONCAWE record events that occur on crude oil pipelines and have population data specifically for crude oil pipelines.

4.2 ASPECTS OF CRUDE OIL PIPELINES

4.2.1 Commodity type

Only crude oil is considered here. CONCAWE make no distinction between ‘spiked’ or ‘un-spiked’ oil.

4.2.2 Population

Cumulative crude oil pipeline length has been estimated from Figure 1 ‘CONCAWE pipeline inventory and main service categories’ of Reference 7. The length of crude oil pipelines in service in 2006 was 11,000 km and the estimated exposure for 1987 to 2006 is 178,000 km yr.

4.2.3 Failure location

The location of the failure is recorded by CONCAWE, and is split into above ground or underground pipeline, and different components. For the purposes of this study, only those events that occurred on underground pipeline were included. Events that occurred on component parts of the pipeline were excluded.

4.2.4 Pipeline diameter and wall thickness

Each recorded failure has detailed information about the pipeline on which the failure occurred, including the pipeline diameter, wall thickness and material type. Population data was available from the CONCAWE reports, which enabled the failure rates to be calculated as a function of pipeline diameter. CONCAWE do not publish population data as a function of pipeline wall thickness.

Failure rates were calculated as a function of the diameter of the pipeline. The length by diameter was estimated from Figure 2 ‘Pipeline diameter distribution and service in 2006’ of Reference 7 and is reproduced here in Table 20. Additional data for 1980, 1990 and 2000 was estimated from Figure 1 ‘Development of pipeline length, diameter and service’ of Reference 11.

Table 20 Diameter ranges of crude oil pipelines

Pipeline diameter range (in)	*Percentage of pipeline (%)*			
	1980	***1990***	***2000***	***2006***
< 8	4	4	3	2
8 - <12	5	7	7	4.25
12 - <16	5	4	4	6.25
16 - <24	32	36	35	39.5
24 - <30	23	26	28	30
≥ 30	31	23	23	18

4.2.5 Hole size

As discussed in Section 3.2.5, CONCAWE record the amount of product spilt as a result of the event rather than the actual hole size. Therefore, as with the clean products analysis a relationship between volume spilt and hole size was assumed; this is shown in Table 2.

4.3 FAILURE RATE DETERMINATION

The CONCAWE data used to generate the failure rates was taken from Reference 7, which details the failure events from 1971 to 2006. The raw data used to generate the failure rates is presented in Appendix 1 of this report, which allows the analysis presented in this report to be repeated.

The CONCAWE data covers the period 1971 to 2006. However, in 1988 a number of countries joined the survey resulting in a large step increase in the population of pipelines. The analysis in this report covers specifically the years 1987 to 2006, a 20-year period. This removes the oldest event data (pre 1987), which may not be representative of today's industry practices.

In the 20-year period being considered, a total of 26 events were recorded giving an overall failure rate of 1.5×10^{-4} (26/178,000) per km yr.

The following sections derive failure rates for the four principle modes of failure, and also as a function of pipeline diameter and hole size. Where no failures were observed a non-zero failure rate was estimated using the approach outlined in Section 2.1.2.

In previous studies [4] the 'hole' as defined was further divided into a small hole and a large hole by proportioning the overall hole failure rate between the two hole sizes in the ratio 2 to 1 (small to large). The same approach was generally taken in the analysis presented in this section.

4.3.1 Mechanical

In the 20-year period, there were 8 failures attributed to the mechanical failure mode. The overall failure rate is therefore 4.5×10^{-5} (8/178,000) per km yr.

Table 21 shows the calculation of the failure rate as a result of mechanical failure as a function of pipeline diameter and Table 22 shows the calculation of the failure rate as a function of hole size. Table 22 also shows how the 2:1 split in failure rate between small and large holes was applied.

Table 21 Mechanical failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	3560	0	0
8 - <12	7565	1	1.3×10^{-4}
12 - <16	11125	0	0
16 - <24	70310	4	5.7×10^{-5}
24 - <30	53400	2	3.7×10^{-5}
≥ 30	32040	1	3.1×10^{-5}

Table 22 Mechanical failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	3	1.7×10^{-5}	3	1.7×10^{-5}
Large hole	4	2.2×10^{-5}	$1\ ^1/_3$	7.5×10^{-6}
Small hole			$2\ ^2/_3$	1.5×10^{-5}
Pinhole	1	5.6×10^{-6}	1	5.6×10^{-6}

Table 23 details the derivation of the mechanical failure rate as a function of both pipeline diameter and hole size. Pipeline diameters of less than 16" have been merged to create one entry due to the limited amount of data that were available and the low population of these pipelines. Table 24 shows a similar analysis, but with adjustments carried out to remove the zero failure rates. Figure 4 also shows graphically how the calculated failure rate varies as a function of hole size and pipeline diameter.

Table 23 Mechanical failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 16	0	$^2/_3$	$^1/_3$	0
16 - <24	0	$1\ ^1/_3$	$^2/_3$	2
24 - <30	1	$^2/_3$	$^1/_3$	0
≥30	0	0	0	1
	Failure rate (per km yr)			
< 16	0	3.0×10^{-5}	1.5×10^{-5}	0
16 - <24	0	1.9×10^{-5}	9.5×10^{-6}	2.8×10^{-5}
24 - <30	1.9×10^{-5}	1.2×10^{-5}	6.2×10^{-6}	0
≥30	0	0	0	3.1×10^{-5}

Table 24 Mechanical failure rate as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 16	$^1/_4$	$^2/_3 + ^1/_3$	$^1/_3 + ^1/_6$	$^1/_4$
16 - <24	$^1/_5$	$1\ ^1/_3 + ^4/_{15}$	$^2/_3 + ^2/_{15}$	$2\ ^2/_5$
24 - <30	$1\ ^1/_3$	$^2/_3 + ^2/_9$	$^1/_3 + ^1/_9$	$^1/_3$
≥30	$^1/_4$	$^1/_4$	$^1/_4$	$1\ ^1/_4$
	Failure rate (per km yr)			
< 16	1.1×10^{-5}	4.5×10^{-5}	2.2×10^{-5}	1.1×10^{-5}
16 - <24	2.8×10^{-6}	2.3×10^{-5}	1.1×10^{-5}	3.4×10^{-5}
24 - <30	2.5×10^{-5}	1.7×10^{-5}	8.3×10^{-6}	6.2×10^{-6}
≥30	7.8×10^{-6}	7.8×10^{-6}	7.8×10^{-6}	3.9×10^{-5}

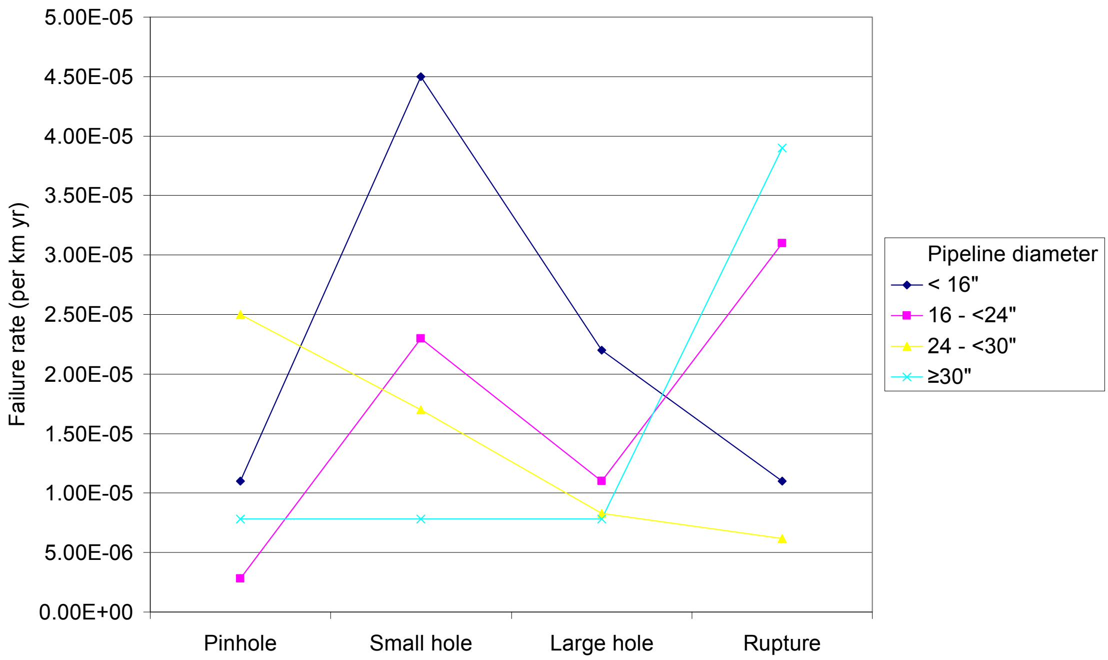

Figure 4 Mechanical failure rate as a function of hole size after adjustment for zero failures

From Figure 4, Table 23 and Table 24 it is clearly seen that because of the paucity of data, presenting the failure rate as a function of both hole size and diameter introduces too great a level of uncertainty. Therefore, it is recommended that the failure rates quoted in Table 22 (as a function of only hole size) are used by PIPIN for the mechanical failure mode (CONCAWE crude dataset) and applied to all diameters.

4.3.2 Corrosion

In the 20-year period, there were 8 failures attributed to the corrosion failure mode. The overall failure rate is therefore 4.5 x 10^{-5} (8/178,000) per km yr. Three of these events were due to external corrosion, with the remaining 5 due to internal corrosion. No failures as a result of stress corrosion cracking were seen.

Table 25 derives the corrosion failure rate as a function of pipeline diameter and Table 26 derives the failure rate as a function of hole size. Table 27 derives the failure rate as a function of hole size after adjustment for the zero events.

Table 25 Corrosion failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	3560	0	0
8 - <12	7565	3	4.0 x 10^{-4}
12 - <16	11125	2	1.8 x 10^{-4}
16 - <24	70310	1	1.4 x 10^{-5}
24 - <30	53400	1	1.9 x 10^{-5}
≥ 30	32040	1	3.1 x 10^{-5}

Table 26 Corrosion failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	0	0	0	0
Large hole	4	2.2 x 10^{-5}	$1\,^1/_3$	7.5 x 10^{-6}
Small hole			$2\,^2/_3$	1.5 x 10^{-5}
Pinhole	4	2.2 x 10^{-5}	4	2.2 x 10^{-5}

Table 27 Corrosion failure rate as a function of hole size with adjustment for zero failures

Hole size	*Events*	*Failure rate (per km yr)*	*Events with large/small applied*	*Failure rate (per km yr)*
Rupture	$^1/_9$	6.2 x 10^{-7}	$^1/_9$	6.2 x 10^{-7}
Large hole	$4\,^4/_9$	2.5 x 10^{-5}	$^{40}/_{27}$	8.3 x 10^{-6}
Small hole			$^{80}/_{27}$	1.7 x 10^{-5}
Pinhole	$4\,^4/_9$	2.5 x 10^{-5}	$4\,^4/_9$	2.5 x 10^{-5}

Tables 28 and 29 derive the corrosion failure rate as a function of hole size and pipeline diameter, with adjustment for zero failures being carried out in Table 29.

Table 28 Corrosion failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
<12	2	$^2/_3$	$^1/_3$	0
12 - <16	1	$^2/_3$	$^1/_3$	0
16 - <24	0	$^2/_3$	$^1/_3$	0
24 - <30	0	$^2/_3$	$^1/_3$	0
≥30	1	0	0	0
	Failure rate (per km yr)			
<12	1.8×10^{-4}	6.0×10^{-5}	3.0×10^{-5}	0
12 - <16	9.0×10^{-5}	6.0×10^{-5}	3.0×10^{-5}	0
16 - <24	0	9.5×10^{-6}	4.7×10^{-6}	0
24 - <30	0	1.2×10^{-5}	6.2×10^{-6}	0
≥30	3.1×10^{-5}	0	0	0

Table 29 Corrosion failure rate as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
<12	$2\ ^1/_2$	$^2/_3 + ^1/_6$	$^1/_3 + ^1/_{12}$	¼
12 - <16	$1\ ^1/_3$	$^2/_3 + ^2/_9$	$^1/_3 + ^1/_9$	$^1/_3$
16 - <24	$^1/_4$	$^2/_3 + ^1/_3$	$^1/_3 + ^1/_6$	$^1/_4$
24 - <30	$^1/_4$	$^2/_3 + ^1/_3$	$^1/_3 + ^1/_6$	$^1/_4$
≥30	$1\ ^1/_2$	$^1/_4$	$^1/_8$	$^1/_8$
	Failure rate (per km yr)			
<12	2.2×10^{-4}	7.5×10^{-5}	3.7×10^{-5}	2.2×10^{-5}
12 - <16	1.2×10^{-4}	8.0×10^{-5}	4.0×10^{-5}	3.0×10^{-5}
16 - <24	3.6×10^{-6}	1.4×10^{-5}	7.1×10^{-6}	3.6×10^{-6}
24 - <30	4.7×10^{-6}	1.9×10^{-5}	9.4×10^{-6}	4.7×10^{-6}
≥30	4.7×10^{-5}	7.8×10^{-6}	3.9×10^{-6}	3.9×10^{-6}

As for the mechanical failure mode (CONCAWE crude) there were very few recorded events, which made analysis by hole size and pipeline diameter difficult. It is therefore recommended that the failure rates quoted in Table 27 (function of hole size only) are used by PIPIN, for the corrosion failure mode, across all pipeline diameters (CONCAWE crude dataset).

4.3.3 Natural and other events

One event caused by a natural failure was recorded in the period 1987 to 2006. The overall failure rate caused by natural events is therefore 5.6×10^{-6} (1/178,000) per km yr. Table 30 shows the derivation of the failure rate as a function of pipeline diameter and Table 31, as a function of hole size.

Table 30 Natural failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	3560	0	0
8 - <12	7565	0	0
12 - <16	11125	0	0
16 - <24	70310	1	1.4×10^{-5}
24 - <30	53400	0	0
≥ 30	32040	0	0

Table 31 Natural failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*
Rupture	0	0
Large hole } Small hole	1	5.6×10^{-6}
Pinhole	0	0

Adjustment for the zero events was not carried out as this would involve too high a level of uncertainty due to only one event being classified as a natural failure.

Given the single event it is recommended that the failure rate 5.6×10^{-6} per km yr is applied to all hole sizes and diameters for this mode of failure (CONCAWE crude dataset).

4.3.4 Third party activity

Nine failures due to the TPA failure mode were recorded as occurring over the 20-year period. This gives an overall failure rate of 5.1×10^{-5} (9/178,000) per km yr.

The derivation of the failure rate as a function of pipeline diameter is given in Table 32 and as a function of hole size, in Table 33.

Table 32 TPA failure rate as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 8	3560	1	2.8×10^{-4}
8 - <12	7565	1	1.3×10^{-4}
12 - <16	11125	3	2.7×10^{-4}
16 - <24	70310	3	4.3×10^{-5}
24 - <30	53400	0	0
≥ 30	32040	1	3.1×10^{-5}

Table 33 TPA failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*	*Number of events with large/small split applied*	*Failure rate (per km yr)*
Rupture	2	1.2 x 10^{-5}	2	1.2 x 10^{-5}
Large hole	4	2.2 x 10^{-5}	1 $^{1}/_{3}$	7.5 x 10^{-6}
Small hole			2 $^{2}/_{3}$	1.5 x 10^{-5}
Pinhole	3	1.7 x 10^{-5}	3	1.7 x 10^{-5}

The TPA failure rate as a function of both hole size and pipeline diameter is shown in Table 34. Table 35 shows the calculation of the failure rates to account for the observed zeros.

Table 34 TPA failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
<12	1	$^{2}/_{3}$	$^{1}/_{3}$	0
12 - <16	1	1 $^{1}/_{3}$	$^{2}/_{3}$	0
16 - <24	1	0	0	2
24 - <30	0	0	0	0
≥30	0	$^{2}/_{3}$	$^{1}/_{3}$	0
	Failure Rate (per km yr)			
<12	9.0 x 10^{-5}	6.0 x 10^{-5}	3.0 x 10^{-5}	0
12 - <16	9.0 x 10^{-5}	1.2 x 10^{-4}	6.0 x 10^{-5}	0
16 - <24	1.4 x 10^{-5}	0	0	2.8 x 10^{-5}
24 - <30	0	0	0	0
≥30	0	2.1 x 10^{-5}	1.0 x 10^{-5}	0

Table 35 TPA failure rate as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
Event data				
<12	$1\,{}^{1}/_{3}$	${}^{2}/_{3} + {}^{2}/_{9}$	${}^{1}/_{3} + {}^{1}/_{9}$	${}^{1}/_{3}$
12 - <16	$1\,{}^{1}/_{4}$	$1\,{}^{1}/_{3} + {}^{1}/_{3}$	${}^{2}/_{3} + {}^{1}/_{6}$	${}^{1}/_{4}$
16 - <24	$1\,{}^{1}/_{4}$	${}^{1}/_{8}$	${}^{1}/_{8}$	$2\,{}^{1}/_{2}$
24 - <30	${}^{1}/_{4}$	${}^{1}/_{4}$	${}^{1}/_{4}$	${}^{1}/_{4}$
≥30	${}^{1}/_{4}$	${}^{2}/_{3} + {}^{1}/_{3}$	${}^{1}/_{3} + {}^{1}/_{6}$	${}^{1}/_{4}$
Failure Rate (per km yr)				
<12	1.2×10^{-4}	8.0×10^{-5}	4.0×10^{-5}	3.0×10^{-5}
12 - <16	1.1×10^{-4}	1.5×10^{-4}	7.5×10^{-5}	2.2×10^{-5}
16 - <24	1.8×10^{-5}	1.8×10^{-6}	1.8×10^{-6}	3.6×10^{-5}
24 - <30	4.7×10^{-6}	4.7×10^{-6}	4.7×10^{-6}	4.7×10^{-6}
≥30	7.8×10^{-6}	3.1×10^{-5}	1.6×10^{-5}	7.8×10^{-6}

As with the other modes of failure for crude oil pipelines, there was little data available from historic events resulting in failure rates that vary significantly as a function of hole size and pipeline diameter. It is therefore recommended that the failure rates in Table 33 are used by PIPIN for the TPA failure mode (CONCAWE crude dataset).

5 ANALYSIS OF UKOPA DATA

5.1 INTRODUCTION

This section presents the analysis of UKOPA failure data. Failure data from onshore pipelines in the UK is collected by UKOPA, specifically by the Fault Database Management Group (FDMG). A report summarising the failure data, the most recent of which is Reference 12, is published bi-annually by Advantica in conjunction with UKOPA.

UKOPA supplied HSL with additional raw data, to that contained in the public reports, in order that HSL could carry out its own analysis. The data provided was made anonymous, with commercially sensitive data removed (such as operator, pipeline location etc). The anonymised raw data is reproduced in Appendix 2.

5.2 ASPECTS OF UK PIPELINES, INCLUDED IN THE UKOPA DATABASE

5.2.1 Commodity type

UK onshore pipelines carry a variety of commodities, including: butane; condensate; crude oil; ethylene; gasoline; hydrogen; LPG; natural gas (dry); propane; propylene; and others. The majority, over 90% by length, is natural gas [12].

5.2.2 Population

Pipelines have been in operation in the UK since at least 1950. The total pipeline length, for all products, captured within the UKOPA failure database in 2006 was 21881.85 km and the cumulative length for 1952 to 2006 is 700463.16 km yr [12].

To be consistent with the analysis of CONCAWE data, only the last 20 years of data has been analysed. The cumulative length for the period 1988 to 2007 is 414733 km yr (see Appendix 2).

5.2.3 Failure location

The failure data requested from UKOPA gave no indication as to whether the pipeline was above or below ground. For the purposes of this report, the entire pipeline population was assumed to be underground.

5.2.4 Pipeline diameter and wall thickness

Each failure had detailed information recorded about the pipeline on which the failure occurred, including pipeline diameter, wall thickness, and material type. Population data was also supplied which enabled failure rates to be calculated as a function of either pipeline diameter, Table 36, or wall thickness, Table 37.

Table 36 Population of UK pipelines as a factor of wall thickness

Wall thickness (mm)	*Exposure (km yr)*
< 5	23846.44
5 - <10	202697.6
≥10	188190

Table 37 Population of UK pipelines as a function of pipeline diameter

Pipeline diameter (in)	*Exposure (km yr)*
< 8	43575.63
8 - <12	59145.94
12 - <16	53638.92
16 - <24	74609.36
24 - <30	62857.04
≥ 30	120907.1

5.2.5 Hole size

The failure reports in the UKOPA database included the length, width and depth of the failures. Some events also had the failure area recorded. For the purpose of this report, the equivalent hole diameter was calculated using an idealised failure shape of a circle. This allowed the area of the failure to be transformed into a circle and the diameter calculated using Equation 2.

$$Equivalent\ diameter(mm) = \sqrt{\frac{4A(mm^2)}{\pi}} \qquad \text{(Equation 2)}$$

5.3 FAILURE RATE DETERMINATION

UKOPA provided information about the failures that occurred between 1988 and 2007, along with a variety of population figures. A summary of the information provided is presented in Appendix 2. A summary of the analysis carried out is presented in Table 38. Where appropriate, comparisons to previous analyses by UKOPA [12] and HSE [5] have been made.

Table 38 Summary of overall failure rates

	This work	*UKOPA*	*Comments*
Population (km)	22310 in 2007	21882 in 2006	
Exposure (km yr)	414733.95 (1988 to 2007)	684426 (1967 to 2006)	
Failure events	71	167	70% of the incidents recorded occurred pre 1986
Overall failure rate (per 1000 km yr)	1.7×10^{-4}	2.4×10^{-4}	
Reference	Appendix 2	Reference 12	

The following sections derive the failure rates for the four principal modes of failure, and also as a function of either wall thickness or pipeline diameter and the hole size.

5.3.1 Mechanical

Over the 20-year period, 36 events were recorded which were attributed to mechanical failure. This gives a failure rate of 8.7 x 10^{-5} (36/414734) per km yr. This figure is consistent with the previous analyses by HSE [5] (9 x 10^{-5} per km yr) and UKOPA [12] (8.2 x 10^{-5} per km yr).

All hole sizes were less than 10 mm equivalent diameter, except one, which was greater than 110 mm. The holes less than 10 mm were classified as pinholes and the single hole at 160 mm as a rupture. No small or large holes 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 39, and the pipeline diameter, shown in Table 40, to determine if any relationship existed between the failure rate and either of these two variables.

Table 39 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 x 10^{-3}
5 – 10	202697.6	11	5.4 x 10^{-5}
10 +	188190	1	5.3 x 10^{-6}

Table 40 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 x 10^{-4}
8 - <12	59145.94	4	6.8 x 10^{-5}
12 - <16	53638.92	2	3.7 x 10^{-5}
16 - <24	74609.36	2	2.7 x 10^{-5}
24 - <30	62857.04	1	1.6 x 10^{-5}
≥ 30	120907.1	1	8.3 x 10^{-6}

The failure rates shown in Tables 39 and 40 indicate a greater chance of a failure occurring on smaller diameter or thinner walled pipelines.

Tables 41 and 42 show the failure rate as a function of hole size, where Table 42 shows adjustments for the zero failure events. There is data for both pinholes and ruptures which suggests that ruptures are more likely than either small or large holes which in turn suggests that the assumption that small holes are more likely than large holes is not valid. The large number of pinholes, however, implies the opposite. Given the uncertainty in this case, it was decided to apply a ratio of 1:1 between small and large holes rather than the 2:1 ratio that has been applied elsewhere.

Table 41 Mechanical failure rate as a function of hole size

Hole size	*Number of events*	*Failure rate (per km yr)*
Rupture	1	2.4×10^{-6}
Large hole	0	0
Small hole	0	0
Pinhole	35	8.4×10^{-5}

Table 42 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	1	$= 1 + (^{1}/_{37})$ = 1.0270	2.5×10^{-6}
Large hole	0	$= 0 + (^{1}/_{37})/2$ = 0.0135	3.3×10^{-8}
Small hole	0	$= 0 + (^{1}/_{37})/2$ = 0.0135	3.3×10^{-8}
Pinhole	35	$= 35 + (^{35}/_{37})$ = 35.946	8.7×10^{-5}

Table 43 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 43 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	1
	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	3.9×10^{-6}

Table 44 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 44 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	$3 + {}^{3}/_{5}$	${}^{1}/_{5} \times {}^{1}/_{2}$	${}^{1}/_{5} \times {}^{1}/_{2}$	$1 + {}^{1}/_{5}$
	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	1.4×10^{-5}	3.9×10^{-7}	3.9×10^{-7}	4.6×10^{-6}

Given the number of zero events in Table 43 it is judged that the best representative failure rates are given, with the exception of pinholes, by the failure rates presented in Table 42. For pinholes, it is recommended that the failure rates given in Table 43 are used by PIPIN (mechanical failure mode, UKOPA dataset). The recommended failure rates are shown in Table 45.

Table 45 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}	3.3×10^{-8}	2.5×10^{-6}
8 - <12	6.8×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
12 - <16	3.7×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
≥ 16	1.2×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}

5.3.2 Corrosion

Sixteen failures due to corrosion were recorded as occurring over the 20-year period of interest. Of these, 10 events were caused by external corrosion, 1 by internal corrosion, and the remaining 5 were attributed to stress corrosion cracking. This gives an overall failure rate of 3.9×10^{-5} (16/414734) per km yr.

The failure rate due to corrosion is dependent on the pipeline wall thickness, the material of construction and the external environment (soil type, temperature, humidity etc). As wall thickness is a dominant factor, failure rates were derived only as a function of the wall thickness; table 46 shows the derivation of these failure rates.

Table 46 Corrosion failure rate as a function of wall thickness

Wall thickness (mm)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
< 5	23846.44	7	2.9×10^{-4}
5 - <10	202697.6	9	4.4×10^{-5}
≥10	188190	0	0

Table 46 indicates that a pipeline with a wall thickness in the range 5-10mm is approximately 6 times less likely to fail than a pipeline with a wall thickness than 5 mm. The reported wall thickness of the failures were in the range 4.4 to 6.6 mm.

Table 47 shows the derivation of the corrosion failure rate as a function of hole size and Table 48, as a function of hole size and pipeline wall thickness. These show that the corrosion failure rates are greatest for the smaller hole sizes, as such leaks would normally be expected to be detected before a large hole or rupture could develop.

Table 47 Corrosion 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	16	3.9×10^{-5}

Table 48 Corrosion failure rate as a function of wall thickness and hole size

Wall thickness (mm)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 5	7	0	0	0
5 - <10	9	0	0	0
≥10	0	0	0	0
	Failure rate (per km yr)			
< 5	2.9×10^{-4}	0	0	0
5 - <10	4.4×10^{-5}	0	0	0
≥10	0	0	0	0

Table 49 shows the derivation of the corrosion failure rate after making adjustments to account for the zero failures. The values for pipelines with a wall thickness greater than 10 mm were estimated based on expert judgement given that there were no observed events. For the wall thickness ranges < 5 mm and 5 - <10 mm, it was assumed that a small hole was twice as likely as either a large hole or rupture.

Table 49 Corrosion failure rate as a function of wall thickness and hole size after adjustment for zero failures

Wall thickness (mm)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
	Event data			
< 5	7 7/8	1/16	1/32	1/32
5 - <10	9 9/10	1/20	1/40	1/40
≥10	0	0	0	0
	Failure rate (per km yr)			
< 5	3.3×10^{-4}	2.6×10^{-6}	1.3×10^{-6}	1.3×10^{-6}
5 - <10	4.9×10^{-5}	2.5×10^{-7}	1.2×10^{-7}	1.2×10^{-7}
≥10	10^{-7}	10^{-8}	10^{-8}	10^{-8}

It is recommended that the failure rates quoted in Table 49 are used by PIPIN for the corrosion failure mode (UKOPA dataset).

5.3.3 Natural and other events

This category covers landslides, lightning strikes, flooding and other naturally occurring events. For the purpose of this determination, it also covers manmade landslides. Five failures due to the natural failure mode were recorded as natural failures over the 20-year period. This gives an overall failure rate of 1.2×10^{-5} (5/414734) per km yr.

One event was excluded as this was caused by an electrical cable arc strike. In a previous study [5] events caused by this mechanism were excluded from the analysis because they were deemed to be incapable of occurring on underground pipelines; this was considered to remain a valid assumption.

The chance of a natural event occurring are strongly dependent on the location of the pipeline. As pipelines in susceptible areas are more likely to have recognised the hazard and have additional measures installed, it is assumed that the average failure rate is representative of all situations (both in and outside susceptible areas). This assumption is consistent with Reference 5.

Tables 50, 51 and 52 summarise the derivation of the failure rate as a function of wall thickness, pipeline diameter and hole size respectively.

Table 50 Natural 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	0	0
5 – 10	202697.6	5	2.5×10^{-5}
10 +	188190	0	0

Table 51 Natural 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	0	0
8 - <12	59145.94	0	0
12 - <16	53638.92	3	5.6×10^{-5}
16 - <24	74609.36	2	2.7×10^{-5}
24 - <30	62857.04	0	0
≥ 30	120907.1	0	0

Table 52 Natural 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	1	2.4×10^{-6}
Pinhole	4	9.6×10^{-6}

Table 53 shows the derivation of the failure rate as a function of hole size after making adjustments to account for the zero failures.

Table 53 Natural failure rate as a function of hole size after adjustment for the zero failures

Hole size	*Number of events*	*With zero incorporated*	*Failure rate (per km yr)*
Rupture	0	$= ({}^{1}/_{6})/_{2}$ = 0.08	2.0×10^{-7}
Large hole	0	$= ({}^{1}/_{6})/_{2}$ = 0.08	2.0×10^{-7}
Small hole	1	$= 1 + ({}^{1}/_{6})$ = 1.17	2.8×10^{-6}
Pinhole	4	$= 4 + ({}^{4}/_{6})$ = 4.67	1.1×10^{-5}

The failure rates that are recommended for use in PIPIN (UKOPA dataset) for the natural failure mode are those in Table 53.

5.3.4 Third party activity

Over the 20-year period, 12 events were attributed to third party activity, with an overall failure rate of 2.9×10^{-5} (12/414734) per km yr.

The failure rate was derived as a function of wall thickness (Table 54) and pipeline diameter (Table 55). The failure rate as a function of hole size is given in Table 56.

Table 54 TPA failure rate as a function of wall thickness

Wall thickness (mm)	*Exposure (km yr)*	*Number of events*	*Failure rate (per km yr)*
<5	23846.44	5	2.1×10^{-4}
5 - <10	202697.6	6	3.0×10^{-5}
≥10	188190	1	5.3×10^{-6}

Table 55 TPA 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	3	6.9×10^{-5}
8 - <12	59145.94	5	8.5×10^{-5}
12 - <16	53638.92	4	7.5×10^{-5}
16 - <24	74609.36	0	0
24 - <30	62857.04	0	0
≥ 30	120907.1	0	0

Table 56 TPA 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	3	7.2×10^{-6}
Pinhole	9	2.2×10^{-5}

The derivation of the TPA failure rate as a function of hole size and pipeline diameter is given in Table 57, with adjustment for zero failures in Table 58. Although there were a limited number of events, adjustment for zero failures was still carried out. Due to the large number of zeros, many of the derived failure rates will be the same for the different hole sizes across a diameter range.

Table 57 TPA failure rate as a function of pipeline diameter and hole size

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
Event data				
< 8	3	0	0	0
8 - <12	4	1	0	0
12 - <16	2	2	0	0
≥16	0	0	0	0
Failure Rate (per km yr)				
< 8	6.9×10^{-5}	0	0	0
8 - <12	6.8×10^{-5}	1.7×10^{-5}	0	0
12 - <16	3.7×10^{-5}	3.7×10^{-5}	0	0
≥16	0	0	0	0

PIPIN's third party activity predictive model was used to ascertain what relationship there is between the failure rates for each of the hole sizes for the various pipeline diameters. This indicated that rupture and pinholes have very similar failure frequencies and that these are higher than for small holes which, in turn, are higher than the frequencies for large holes. The operational data, however, implied that nearly all failures occurred at the pinhole level. In the zero rate analysis, giving the opposing evidence, it was therefore decided to give equal weight to the events added across all holes sizes (where zero events) for each specific pipeline diameter range.

Table 58 TPA failures as a function of pipeline diameter and hole size with adjustment for zero failures

Pipeline diameter (in)	*Pinhole*	*Small hole*	*Large hole*	*Rupture*
Event data				
< 8	$3\ ^{3}/_{4}$	$^{1}/_{12}$	$^{1}/_{12}$	$^{1}/_{12}$
8 - <12	$4\ ^{4}/_{6}$	$1^{1}/_{6}$	$^{1}/_{12}$	$^{1}/_{12}$
12 - <16	$2\ ^{2}/_{5}$	$2\ ^{2}/_{5}$	$^{1}/_{10}$	$^{1}/_{10}$
≥16	$^{1}/_{4}$	$^{1}/_{4}$	$^{1}/_{4}$	$^{1}/_{4}$
Failure Rate (per km yr)				
< 8	8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
8 - <12	7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
12 - <16	4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥16	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

Although limited data was available, a general pattern in the estimated failure rates was observed, with a decrease in the failure rate as the pipeline diameter increased; see Figure 5.

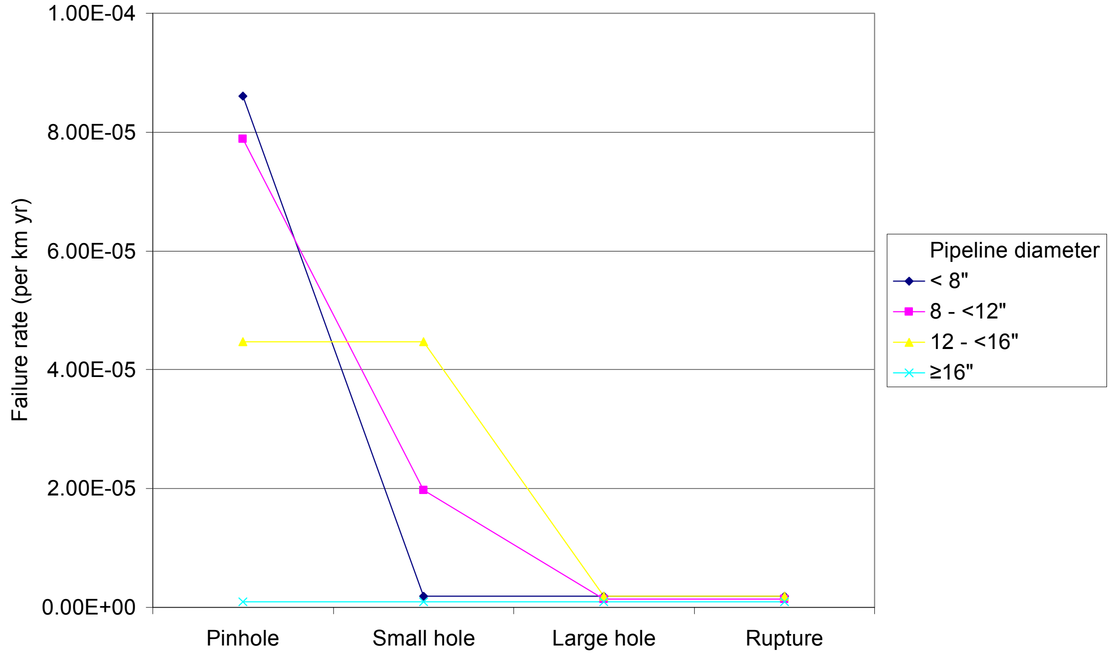

Figure 5 TPA failure rate as a function of hole size after adjustment for zero failures

Notwithstanding the limited data, given the trend observed in the failure rate as a function of pipeline diameter, it is therefore recommended that the failure rates in Table 58 are used for the TPA failure mode (UKOPA dataset).

6 SUMMARY OF DATA SOURCE FAILURE RATES

This section summarises the recommended failure rates based on CONCAWE, UKOPA and EGIG (not updated) data. Failure rates are presented for the four principle failure modes for each of the data sources.

Table 59 CONCAWE product failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
All	1.2×10^{-5}	1.3×10^{-5}	6.3×10^{-6}	7.1×10^{-6}
	Corrosion			
< 200	8.4×10^{-5}	5.3×10^{-6}	2.6×10^{-6}	2.6×10^{-6}
200 - < 300	4.5×10^{-6}	1.8×10^{-5}	9.0×10^{-6}	4.5×10^{-6}
300 - < 400	1.1×10^{-5}	2.8×10^{-5}	1.5×10^{-5}	1.5×10^{-6}
≥ 400	2.1×10^{-5}	2.8×10^{-5}	1.4×10^{-5}	4.2×10^{-6}
	Natural			
All	2.4×10^{-6}	4.8×10^{-6}	2.4×10^{-6}	4.8×10^{-6}
	TPA			
< 200	2.0×10^{-4}	2.0×10^{-4}	1.0×10^{-4}	2.0×10^{-6}
200 - < 300	3.2×10^{-5}	8.0×10^{-5}	3.8×10^{-5}	1.4×10^{-5}
300 - < 400	2.7×10^{-5}	2.4×10^{-5}	1.2×10^{-5}	9.1×10^{-6}
≥ 400	8.5×10^{-5}	4.5×10^{-5}	2.3×10^{-5}	8.5×10^{-5}

Table 60 CONCAWE crude oil failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
All	5.6×10^{-6}	1.5×10^{-5}	7.5×10^{-6}	1.7×10^{-5}
	Corrosion			
All	2.5×10^{-5}	1.7×10^{-5}	8.3×10^{-6}	6.2×10^{-7}
	Natural			
All	5.6×10^{-6}	5.6×10^{-6}	5.6×10^{-6}	5.6×10^{-6}
	TPA			
All	1.7×10^{-5}	1.5×10^{-5}	7.5×10^{-6}	1.1×10^{-5}

Table 61 UKOPA failure rates

		Failure rates (per km yr)			
Pipeline diameter (mm)		***Pinhole***	***Small hole***	***Large hole***	***Rupture***
		Mechanical failure			
< 200		6.0×10^{-4}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
200 - < 300		6.8×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
300 - < 400		3.7×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
≥ 400		1.2×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
	Thickness (mm)	***Corrosion***			
	< 5	3.3×10^{-4}	2.6×10^{-6}	1.3×10^{-6}	1.3×10^{-6}
All	5 - <10	4.9×10^{-5}	2.5×10^{-7}	1.2×10^{-7}	1.2×10^{-7}
	≥10	10^{-7}	10^{-8}	10^{-8}	10^{-8}
		Natural			
All		1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
		TPA			
< 200		8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300		7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400		4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400		9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

Table 62 EGIG failure rates

Pipeline diameter (mm)		*Failure rates (per km yr)* *Pinhole*	*Small hole*	*Large hole*	*Rupture*
		Mechanical failure			
All		5.67×10^{-5}	1.33×10^{-5}	6.67×10^{-6}	8.30×10^{-6}
	Wall thickness (mm)	***Corrosion***			
All	0 - < 5	1.55×10^{-4}	8.93×10^{-7}	4.47×10^{-7}	1.34×10^{-6}
	5 - < 10	8.42×10^{-5}	2.42×10^{-7}	4.83×10^{-7}	7.25×10^{-7}
	10 - < 15	4.49×10^{-6}	1.29×10^{-8}	2.57×10^{-8}	3.86×10^{-8}
	≥ 15	4.34×10^{-7}	1.24×10^{-9}	2.49×10^{-9}	3.73×10^{-9}
		Natural			
All		3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
		TPA			
0 - < 112		2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275		1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425		4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575		1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725		7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875		3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875		1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

NB These figures are based on an analysis of EGIG data from 1970-1997 as more recent information has not been made available.

7 SUBSTANCE DATASETS

This section recommends pipeline failure rates for specific substances. The following substances are considered:

- natural gas (Section 7.1);
- ethylene (Section 7.2);
- spiked crude (Section 7.3);
- vinyl chloride (Section 7.4);
- gasoline (Section 7.5); and
- liquefied petroleum gas (LPG) (Section 7.6).

The failure rates presented in this section are based on the recommended data source failure rates presented in Section 6. It is important to note that the failure rates quoted may not all come from the same dataset, e.g. for a specific substance the corrosion figures may come from the CONCAWE products dataset whilst the mechanical failure rates may come from the UKOPA dataset.

The recommended failure rates are also compared with those currently used by HSE.

7.1 NATURAL GAS

For natural gas, the failure rates currently used in PIPIN are shown in Table 63. These data were based on an analysis of UKOPA data for the natural and mechanical failure modes [5]; and a previous analysis of EGIG data based on data from 1970-1997 for the corrosion and third party activity failure modes [10].

Table 63 Current natural gas failure rates

Pipeline diameter (mm)		*Failure rates (per km yr)* *Pinhole*	*Small hole*	*Large hole*	*Rupture*
		Mechanical failure			
All		9.0×10^{-5}	2.0×10^{-8}	8.0×10^{-9}	8.0×10^{-9}
	Thickness (mm)	***Corrosion***			
All	< 5	1.55×10^{-4}	8.93×10^{-7}	4.47×10^{-7}	1.34×10^{-6}
	5 - < 10	8.42×10^{-5}	2.42×10^{-7}	4.83×10^{-7}	7.25×10^{-7}
	10 - < 15	4.49×10^{-6}	1.29×10^{-8}	2.57×10^{-8}	3.86×10^{-8}
	≥ 15	4.34×10^{-7}	1.24×10^{-7}	2.49×10^{-9}	3.73×10^{-9}
		Natural			
All		3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
		TPA			
0 - < 112		2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275		1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425		4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575		1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725		7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875		3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875		1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

It is proposed that the updated analysis of the UKOPA data presented in this report is now used for all failure modes for natural gas pipelines. The recommended failure rates are listed in Table 64. For the mechanical and natural failure modes this is consistent with the failure rates currently used by PIPIN. However, for the corrosion and TPA failure modes this represents a change to current practice. In terms of the corrosion failure mode, EGIG data was previously used because of limited UKOPA data; UKOPA data is likely to be most representative of UK natural gas pipelines as they represent the vast majority of the population in this data. However, as there is now more UKOPA corrosion data, failure rates based on this data have been used. In terms of the TPA failure mode failure rates based on UK data (i.e. UKOPA data) are likely to be the most representative, irrespective of the pipeline commodity. For TPA, use of UKOPA data has been recommended for all substances considered. It is noted however, that the operational TPA failure rates are unlikely to be used as the PIPIN TPA predictive model is recommended in this case.

Table 64 Proposed natural gas failure rates

		Failure rates (per km yr)			
Pipeline diameter (mm)		***Pinhole***	***Small hole***	***Large hole***	***Rupture***
		Mechanical failure			
< 200		6.0×10^{-4}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
200 - < 300		6.8×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
300 - < 400		3.7×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
≥ 400		1.2×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
	Thickness (mm)	***Corrosion***			
	< 5	3.3×10^{-4}	2.6×10^{-6}	1.3×10^{-6}	1.3×10^{-6}
All	5 - <10	4.9×10^{-5}	2.5×10^{-7}	1.2×10^{-7}	1.2×10^{-7}
	≥10	10^{-7}	10^{-8}	10^{-8}	10^{-8}
		Natural			
All		1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
		TPA			
< 200		8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300		7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400		4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400		9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

As can be seen from Tables 63 and 64, the key differences in the recommended failure rates for natural gas are:

- Mechanical failure rates are now more refined as they are given as a function of pipeline diameter for the pinhole;
- With the exception of diameters < 200 mm, the recommended mechanical failure rates for pinholes are reduced
- Mechanical failure rates for small holes, large holes and ruptures have increased, with the rupture failure rate increasing significantly (based on a single event);
- The mechanical rupture failure rate now appears to dominate the overall rupture failure rate; and
- The natural failure rates have all reduced, by up to an order of magnitude.

7.2 ETHYLENE

For ethylene, the failure rates currently used in PIPIN are shown in Table 65. These data were based on an analysis of UKOPA data for the natural failure mode [5], CONCAWE products data for the mechanical and corrosion failure modes [10] and EGIG data for the third party activity failure mode [10].

Table 65 Current ethylene failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
0 - < 200	7.71×10^{-5}	4.90×10^{-5}	2.45×10^{-5}	2.94×10^{-5}
200 - < 300	7.54×10^{-5}	4.79×10^{-5}	2.40×10^{-5}	2.88×10^{-5}
300 - < 400	7.42×10^{-5}	4.72×10^{-5}	2.36×10^{-5}	2.83×10^{-5}
400 - < 600	7.26×10^{-5}	4.61×10^{-5}	2.31×10^{-5}	2.77×10^{-5}
600 - < 760	7.06×10^{-5}	4.49×10^{-5}	2.25×10^{-5}	2.70×10^{-5}
≥ 760	6.98×10^{-5}	4.44×10^{-5}	2.22×10^{-5}	2.66×10^{-5}
	Corrosion			
0 - < 200	1.67×10^{-4}	1.00×10^{-4}	5.00×10^{-5}	9.84×10^{-6}
200 - < 300	1.41×10^{-4}	8.40×10^{-5}	4.20×10^{-5}	8.28×10^{-6}
300 - < 400	1.26×10^{-4}	7.47×10^{-5}	3.73×10^{-5}	7.38×10^{-6}
400 - < 600	1.06×10^{-4}	6.29×10^{-5}	3.15×10^{-5}	6.21×10^{-6}
600 - < 760	8.58×10^{-5}	5.11×10^{-5}	2.56×10^{-5}	5.05×10^{-6}
≥ 760	7.83×10^{-5}	4.67×10^{-5}	2.33×10^{-5}	4.60×10^{-6}
	Natural			
All	3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
	TPA			
0 - < 112	2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275	1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425	4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575	1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725	7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875	3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875	1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

As a result of a recent review [13] it is proposed that ethylene be treated in line with natural gas and hence that the updated analysis of the UKOPA data presented in this report is now used for all failure modes. The recommended failure rates are listed in Table 66. This represents a change to current practice for all failure modes other than natural and is as a result of reviewing ethylene fault and failure data, which indicated that there was no statistically significant difference between ethylene and natural gas pipeline data. The comments on the UKOPA data in Section 8.1 also apply in this instance.

Table 66 Proposed ethylene failure rates

Pipeline diameter (mm)		Pinhole	Small hole	Large hole	Rupture
		Failure rates (per km yr)			
		Mechanical failure			
< 200		6.0×10^{-4}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
200 - < 300		6.8×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
300 - < 400		3.7×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
≥ 400		1.2×10^{-5}	3.3×10^{-8}	3.3×10^{-8}	2.5×10^{-6}
	Thickness (mm)	***Corrosion***			
	< 5	3.3×10^{-4}	2.6×10^{-6}	1.3×10^{-6}	1.3×10^{-6}
All	5 - <10	4.9×10^{-5}	2.5×10^{-7}	1.2×10^{-7}	1.2×10^{-7}
	≥10	10^{-7}	10^{-8}	10^{-8}	10^{-8}
		Natural			
All		1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
		TPA			
< 200		8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300		7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400		4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400		9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

As can be seen from Tables 65 and 66, the key differences in the recommended failure rates for ethylene are:

- The data for mechanical failure rates are coarser for larger diameter pipelines as there is now only one category for pipelines ≥ 400 mm;
- The mechanical failure rates for small and large holes, and ruptures are significantly lower;
- The mechanical failure rates for pinholes are larger for diameters < 300 mm and lower for pipelines with diameter ≥ 300 mm;
- Corrosion failure rates are now based on wall thickness rather than pipeline diameter;
- Corrosion failure rates are lower in all cases other than for pinholes at wall thicknesses of < 5mm; and
- The natural failure rates have reduced for all hole sizes, by up to an order of magnitude.

7.3 SPIKED CRUDE

The failure rates currently used in PIPIN for spiked crude are shown in Table 67. These data were based on an analysis of CONCAWE crude data for mechanical and corrosion failure modes [10], UKOPA data for natural failure modes [5] and EGIG data for the third party activity failure mode [10].

Table 67 Current spiked crude oil failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
0 - < 200	7.71×10^{-5}	4.90×10^{-5}	2.45×10^{-5}	2.94×10^{-5}
200 - < 300	7.54×10^{-5}	4.79×10^{-5}	2.40×10^{-5}	2.88×10^{-5}
300 - < 400	7.42×10^{-5}	4.72×10^{-5}	2.36×10^{-5}	2.83×10^{-5}
400 - < 600	7.26×10^{-5}	4.61×10^{-5}	2.31×10^{-5}	2.77×10^{-5}
600 - < 760	7.06×10^{-5}	4.49×10^{-5}	2.25×10^{-5}	2.70×10^{-5}
≥ 760	6.98×10^{-5}	4.44×10^{-5}	2.22×10^{-5}	2.66×10^{-5}
	Corrosion			
0 - < 200	2.79×10^{-4}	7.00×10^{-5}	3.50×10^{-5}	5.14×10^{-5}
200 - < 300	1.35×10^{-4}	3.39×10^{-5}	1.69×10^{-5}	2.49×10^{-5}
300 - < 400	8.33×10^{-5}	2.09×10^{-5}	1.04×10^{-5}	1.54×10^{-5}
400 - < 600	4.03×10^{-5}	1.01×10^{-5}	5.07×10^{-6}	7.43×10^{-6}
600 - < 760	1.69×10^{-5}	4.23×10^{-6}	2.12×10^{-6}	3.11×10^{-6}
≥ 760	1.15×10^{-5}	2.87×10^{-6}	1.44×10^{-6}	2.11×10^{-6}
	Natural			
All	3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
	TPA			
0 - < 112	2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275	1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425	4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575	1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725	7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875	3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875	1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

It is proposed that the updated analysis of the CONCAWE crude oil data presented in this report is used for the mechanical and corrosion failure modes, whilst that of the UKOPA dataset is used for natural and third party activity failure modes. The recommended failure rates are listed in Table 68. This is generally consistent with the failure rates currently used by PIPIN, and is based on the assumption that the pipeline commodity is an important factor in the corrosion and mechanical failure rates. The only exception is in the case of the third party activity failure mode where it is considered that failure rates based on UK data (UKOPA) will be more representative for UK pipelines. The TPA failure rates are unlikely to be used, however, as the PIPIN TPA predictive model is recommended in this case.

Table 68 Proposed spike crude oil failure rates

Pipeline diameter (mm)	Pinhole	Small hole	Large hole	Rupture
	Failure rates (per km yr)			
	Mechanical failure			
All	5.6×10^{-6}	1.5×10^{-5}	7.5×10^{-6}	1.7×10^{-5}
	Corrosion			
All	2.5×10^{-5}	1.7×10^{-5}	8.3×10^{-6}	6.2×10^{-7}
	Natural			
All	1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
	TPA			
< 200	8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300	7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400	4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

As can be seen from Tables 67 and 68, the key differences in the recommended failure rates for spiked crude oil are:

- Mechanical failure rates are now coarser as they are not a function of pipeline diameter;
- For all hole sizes, the mechanical failure rate has reduced;
- The mechanical rupture failure rate now dominates the overall rupture failure rate;
- Corrosion failure rates are now coarser as they are no longer a function of pipeline diameter;
- The corrosion rupture failure rate has reduced whilst those for pin, small and large holes all lie within the current range of values; and
- The natural failure rates are lower for all hole sizes by up to an order of magnitude.

7.4 VINYL CHLORIDE

The failure rates for vinyl chloride that are currently used in PIPIN are shown in Table 69. These data were based on an analysis of the CONCAWE products dataset for the corrosion and mechanical failure modes [10], on UKOPA data for the natural failure mode [5] and EGIG data for the third party activity failure mode [10].

Table 69 Current vinyl chloride failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
0 - < 200	7.71×10^{-5}	4.90×10^{-5}	2.45×10^{-5}	2.94×10^{-5}
200 - < 300	7.54×10^{-5}	4.79×10^{-5}	2.40×10^{-5}	2.88×10^{-5}
300 - < 400	7.42×10^{-5}	4.72×10^{-5}	2.36×10^{-5}	2.83×10^{-5}
400 - < 600	7.26×10^{-5}	4.61×10^{-5}	2.31×10^{-5}	2.77×10^{-5}
600 - < 760	7.06×10^{-5}	4.49×10^{-5}	2.25×10^{-5}	2.70×10^{-5}
≥ 760	6.98×10^{-5}	4.44×10^{-5}	2.22×10^{-5}	2.66×10^{-5}
	Corrosion			
0 - < 200	1.67×10^{-4}	1.00×10^{-4}	5.00×10^{-5}	9.84×10^{-6}
200 - < 300	1.41×10^{-4}	8.40×10^{-5}	4.20×10^{-5}	8.28×10^{-6}
300 - < 400	1.26×10^{-4}	7.47×10^{-5}	3.73×10^{-5}	7.38×10^{-6}
400 - < 600	1.06×10^{-4}	6.29×10^{-5}	3.15×10^{-5}	6.21×10^{-6}
600 - < 760	8.58×10^{-5}	5.11×10^{-5}	2.56×10^{-5}	5.05×10^{-6}
≥ 760	7.83×10^{-5}	4.67×10^{-5}	2.33×10^{-5}	4.60×10^{-6}
	Natural			
All	3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
	TPA			
0 - < 112	2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275	1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425	4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575	1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725	7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875	3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875	1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

It is proposed that the updated analysis of the CONCAWE products data presented in this report is used for the mechanical and corrosion failure modes, whilst that of the UKOPA dataset is used for natural and third party activity failure modes. The recommended failure rates are listed in Table 70. This is generally consistent with the failure rates currently used by PIPIN and is based on the assumption that the pipeline commodity is an important factor in the corrosion and mechanical failure rates. The only exception is for the third party activity failure rates where it is considered that failure rates based on UK data (UKOPA) will be more representative for UK pipelines. These TPA failure rates are unlikely to be used, however, as the PIPIN TPA predictive model is recommended in this case.

Table 70 Proposed vinyl chloride failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
All	1.2×10^{-5}	1.3×10^{-5}	6.3×10^{-6}	7.1×10^{-6}
	Corrosion			
< 200	8.4×10^{-5}	5.3×10^{-6}	2.6×10^{-6}	2.6×10^{-6}
200 - < 300	4.5×10^{-6}	1.8×10^{-5}	9.0×10^{-6}	4.5×10^{-6}
300 - < 400	1.1×10^{-5}	2.8×10^{-5}	1.5×10^{-5}	1.5×10^{-6}
≥ 400	2.1×10^{-5}	2.8×10^{-5}	1.4×10^{-5}	4.2×10^{-6}
	Natural			
All	1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
	TPA			
< 200	8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300	7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400	4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

From Tables 69 and 70, it can be seen that the key differences in the recommended failure rates for vinyl chloride are:

- The mechanical failure rates are coarser as they are now no longer a function of the pipeline diameter;
- For all hole sizes, the recommended mechanical failure rates are lower;
- There is now only one set of corrosion failure rates for pipelines ≥ 400 mm in diameter compared to the 3 sets that there were before;
- The recommended corrosion failure rates are lower for all hole sizes; and
- The natural failure rates are up to one order of magnitude lower for all hole sizes.

7.5 GASOLINE

For gasoline, the failure rates currently used in PIPIN are shown in Table 71. These data were based on an analysis of the CONCAWE products dataset for the corrosion and mechanical failure modes [10], on UKOPA data for the natural failure mode [5] and EGIG data for the third party activity failure mode [10].

Table 71 Current gasoline failure rates

	Failure rates (per km yr)			
Pipeline diameter (mm)	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
	Mechanical failure			
0 - < 200	7.71×10^{-5}	4.90×10^{-5}	2.45×10^{-5}	2.94×10^{-5}
200 - < 300	7.54×10^{-5}	4.79×10^{-5}	2.40×10^{-5}	2.88×10^{-5}
300 - < 400	7.42×10^{-5}	4.72×10^{-5}	2.36×10^{-5}	2.83×10^{-5}
400 - < 600	7.26×10^{-5}	4.61×10^{-5}	2.31×10^{-5}	2.77×10^{-5}
600 - < 760	7.06×10^{-5}	4.49×10^{-5}	2.25×10^{-5}	2.70×10^{-5}
≥ 760	6.98×10^{-5}	4.44×10^{-5}	2.22×10^{-5}	2.66×10^{-5}
	Corrosion			
0 - < 200	1.67×10^{-4}	1.00×10^{-4}	5.00×10^{-5}	9.84×10^{-6}
200 - < 300	1.41×10^{-4}	8.40×10^{-5}	4.20×10^{-5}	8.28×10^{-6}
300 - < 400	1.26×10^{-4}	7.47×10^{-5}	3.73×10^{-5}	7.38×10^{-6}
400 - < 600	1.06×10^{-4}	6.29×10^{-5}	3.15×10^{-5}	6.21×10^{-6}
600 - < 760	8.58×10^{-5}	5.11×10^{-5}	2.56×10^{-5}	5.05×10^{-6}
≥ 760	7.83×10^{-5}	4.67×10^{-5}	2.33×10^{-5}	4.60×10^{-6}
	Natural			
All	3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
	TPA			
0 - < 112	2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275	1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425	4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575	1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725	7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875	3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875	1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

It is proposed that the updated analysis of the CONCAWE products data presented in this report is used for the mechanical and corrosion failure modes, whilst that of the UKOPA dataset is used for natural and third party activity failure modes. The recommended failure rates are listed in Table 72. This is consistent with the failure rates currently used by PIPIN except in the case of third party activity where it is considered that failure rates based on UK data will be more representative for UK pipelines. These TPA failure rates are unlikely to be used, however, as the PIPIN TPA predictive model is recommended in this case. Overall failure rates for gasoline have also recently been produced by Nash [14], based solely on CONCAWE products data. It should be noted however that these were not derived for land use planning assessment purposes, but were derived solely to support a Regulatory Impact Assessment. Also, failure rates were not presented for each of the four principal failure modes which means that a comparison of the failure rates calculated by Nash and those presented in Table 72 cannot be performed.

An earlier analysis of CONCAWE data was performed in 1998 [16] with a view to considering land use planning zones around gasoline pipes. This presented failure rates by pipeline diameter but did not apportion them by failure mechanism. It is therefore not possible to do a comparison with these rates and those presented in Table 72.

Table 72 Proposed gasoline failure rates

Pipeline diameter (mm)	*Failure rates (per km yr)* Pinhole	*Small hole*	*Large hole*	*Rupture*
	Mechanical failure			
All	1.2×10^{-5}	1.3×10^{-5}	6.3×10^{-6}	7.1×10^{-6}
	Corrosion			
< 200	8.4×10^{-5}	5.3×10^{-6}	2.6×10^{-6}	2.6×10^{-6}
200 - < 300	4.5×10^{-6}	1.8×10^{-5}	9.0×10^{-6}	4.5×10^{-6}
300 - < 400	1.1×10^{-5}	2.8×10^{-5}	1.5×10^{-5}	1.5×10^{-6}
≥ 400	2.1×10^{-5}	2.8×10^{-5}	1.4×10^{-5}	4.2×10^{-6}
	Natural			
All	1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
	TPA			
< 200	8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300	7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400	4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

The key differences between the current and proposed failure rates for gasoline are:

- The recommended mechanical failure rates are coarser as they are no longer a function of pipeline diameter;
- For all hole sizes, the recommended mechanical failure rates are lower than those currently used;
- Due to limited data, the corrosion failure rates are no longer subdivided by pipeline diameter for diameters greater than 400 mm;
- All of the proposed corrosion failure rates are lower than the figures currently being used; and
- The proposed natural failure rates are lower for all hole sizes than those currently used within PIPIN.

7.6 LIQUEFIED PETROLEUM GAS (LPG)

The failure rates for LPG that are currently used within PIPIN are shown in Table 73. These data are based on an analysis of EGIG data for mechanical, corrosion and third party activity failure rates [10] and on UKOPA data for natural failure rates [5].

Table 73 Current LPG failure rates

		Failure rates (per km yr)			
Pipeline diameter (mm)		***Pinhole***	***Small hole***	***Large hole***	***Rupture***
		Mechanical failure			
All		5.67×10^{-5}	1.33×10^{-5}	6.67×10^{-6}	8.30×10^{-6}
	Wall thickness (mm)	***Corrosion***			
All	0 - < 5	1.55×10^{-4}	8.93×10^{-7}	4.47×10^{-7}	1.34×10^{-6}
	5 - < 10	8.42×10^{-5}	2.42×10^{-7}	4.83×10^{-7}	7.25×10^{-7}
	10 - < 15	4.49×10^{-6}	1.29×10^{-8}	2.57×10^{-8}	3.86×10^{-8}
	≥ 15	4.34×10^{-7}	1.24×10^{-9}	2.49×10^{-9}	3.73×10^{-9}
		Natural			
All		3.6×10^{-5}	9.0×10^{-6}	9.0×10^{-7}	2.0×10^{-6}
		TPA			
0 - < 112		2.02×10^{-4}	2.29×10^{-4}	1.14×10^{-4}	1.74×10^{-4}
112 - < 275		1.20×10^{-4}	1.37×10^{-4}	6.83×10^{-4}	1.04×10^{-4}
275 - < 425		4.57×10^{-5}	5.18×10^{-5}	2.59×10^{-5}	3.94×10^{-5}
425 - < 575		1.88×10^{-5}	2.13×10^{-5}	1.06×10^{-5}	1.62×10^{-5}
575 - < 725		7.70×10^{-6}	8.73×10^{-6}	4.37×10^{-6}	6.60×10^{-6}
725 - < 875		3.10×10^{-6}	3.53×10^{-6}	1.77×10^{-6}	2.70×10^{-6}
≥ 875		1.30×10^{-6}	7.33×10^{-7}	3.67×10^{-7}	6.00×10^{-7}

According to Failure Rate Advice Note 112 [15], and allowing for updates to the UKOPA and CONCAWE datasets, the continued use of EGIG data is recommended. Given that this data has not been updated then the failure rates for corrosion and mechanical failures will be unchanged. For natural and third party activity failure rates, it is proposed that the updated analysis of the UKOPA dataset presented in this report is used. The recommended failure rates are listed in Table 74.

Table 74 Proposed LPG failure rates

		Failure rates (per km yr)			
Pipeline diameter (mm)		***Pinhole***	***Small hole***	***Large hole***	***Rupture***
		Mechanical failure			
All		5.67×10^{-5}	1.33×10^{-5}	6.67×10^{-6}	8.30×10^{-6}
	Wall thickness (mm)	***Corrosion***			
All	0 - < 5	1.55×10^{-4}	8.93×10^{-7}	4.47×10^{-7}	1.34×10^{-6}
	5 - < 10	8.42×10^{-5}	2.42×10^{-7}	4.83×10^{-7}	7.25×10^{-7}
	10 - < 15	4.49×10^{-6}	1.29×10^{-8}	2.57×10^{-8}	3.86×10^{-8}
	≥ 15	4.34×10^{-7}	1.24×10^{-9}	2.49×10^{-9}	3.73×10^{-9}
		Natural			
All		1.1×10^{-5}	2.8×10^{-6}	2.0×10^{-7}	2.0×10^{-7}
		TPA			
< 200		8.6×10^{-5}	1.9×10^{-6}	1.9×10^{-6}	1.9×10^{-6}
200 - < 300		7.9×10^{-5}	2.0×10^{-5}	1.4×10^{-6}	1.4×10^{-6}
300 - < 400		4.5×10^{-5}	4.5×10^{-5}	1.9×10^{-6}	1.9×10^{-6}
≥ 400		9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}	9.7×10^{-7}

As the mechanical and corrosion failure rates are unchanged, the only key difference is in the values for the proposed natural failures rates, which are lower across all hole sizes.

8 MAIN FINDINGS AND RECOMMENDATIONS

8.1 MAIN FINDINGS

This report has described the analysis of pipeline failure data from the following data sources:

- CONCAWE products pipeline failure data;
- CONCAWE crude oil pipeline failure data; and
- UKOPA pipeline failure data.

Recommended failure rates are given for the four principal failure modes (mechanical failures, natural events, corrosion and third party activity). These are given as a function of hole size (pinhole, small hole, large hole and rupture), and in some cases pipeline diameter or wall thickness.

Section 7 presented recommended failure rates for each of the data sources and Section 8 presented pipeline substance specific recommended failure rates.

8.2 RECOMMENDATIONS

The following recommendations are made:

1. The failure rates presented in Section 8 of this report should be adopted by HSE and replace those currently used by HSE in PIPIN for land use planning assessments of pipelines; and
2. The failure rates should be updated on a regular basis as more failure data is published.

9 APPENDICES

9.1 APPENDIX 1 – CONCAWE DATA

This appendix summarises the CONCAWE failure data, which has been used to derive failure rates in the main report. Clean product pipeline failure events are listed in Section 3 and crude oil pipeline failure events, in Section 4. This data was taken from Reference 7.

9.1.1 Clean product pipeline failures

Spillage ID	*Year*	*Pipeline diameter (in)*	*System part*	*Spillage volume (m^3)*	*Hole size*	*Mode of failure*	*Wall thickness (mm)*
227	1987	20	1	1000	R	A	10
232	1987	12	1	12	H	D	6.35
233	1987	22	1	3	P	E	9.5
234	1987	16	1	300	R	E	8.74
236	1988	12	1	90	H	A	NR
239	1988	11	1	80	H	CA	6.5
242	1988	20	1	40	H	E	6.35
246	1988	16	1	3	P	E	6.35
248	1988	4	1	2	P	E	NR
249	1988	6	1	63	H	E	NR
250	1988	6	1	18	H	E	NR
255	1989	10	1	66	H	B	NR
258	1989	10	1	400	H	CB	5.56
259	1989	16	1	253	R	E	7.14
260	1989	16	1	660	R	E	8.74
262	1989	12	1	298	R	E	6.35
263	1989	6	1	52	H	E	NR
264	1989	8	1	3	P	E	NR
265	1989	8	1	186	H	E	NR
272	1990	11	1	225	H	E	6.35
273	1990	6	1	3	P	E	NR
274	1990	10	1	189	H	E	NR
275	1991	20	1	275	R	A	7.1/14.2
280	1991	12	1	29	H	A	7.14
284	1991	10	1	80	H	CA	5.56
287	1991	8	1	15	H	CB	5
288	1991	8	1	4	P	E	NR
289	1991	6	1	21	H	E	NR
290	1991	6	1	1	P	E	NR
293	1991	8	1	10	P	E	4.78
294	1992	8	1	1000	R	A	NR

Spillage ID	*Year*	*Pipeline diameter (in)*	*System part*	*Spillage volume (m^3)*	*Hole size*	*Mode of failure*	*Wall thickness (mm)*
298	1992	8	1	55	H	A	NR
303	1992	24	1	13	H	CA	NR
304	1992	6	1	3	P	CA	NR
305	1992	12	1	75	H	D	NR
306	1992	8	1	50	H	E	6.35
307	1992	8	1	25	H	E	6.35
314	1993	26	1	10	P	D	7.14
315	1993	9	1	8	P	E	4.78
316	1993	24	1	49	H	E	7.92
317	1993	8	1	3	P	E	NR
319	1993	20	1	3050	R	E	8.74
320	1993	7	1	3	P	E	5.16
324	1994	6	1	1	P	A	7.1
330	1994	9	1	195	H	E	6.35
331	1994	8	1	46	H	E	7.03
335	1995	6	1	115	H	A	5.56
337	1995	10	1	1000	R	CA	7
338	1995	9	1	48	H	E	4.7
339	1995	9	1	20	H	E	6.35
340	1995	13	1	139	H	E	8.38
341	1995	6	1	12	H	E	8
343	1996	14	1	292	R	B	6.35
345	1996	9	1	437	R	E	6.35
346	1996	7	1	19	H	E	5.56
347	1996	10	1	500	R	E	9
348	1997	12	1	19	H	CA	6.35
350	1997	12	1	422	H	CC	6.35
351	1997	12	1	435	H	CC	7.14
353	1997	12	1	40	H	E	7.9
356	1998	13	1	486	R	B	7.92
357	1998	16	1	250	H	CA	6.35
358	1998	10	1	340	R	E	6.7
359	1998	10	1	15	H	E	6.7
360	1998	9	1	176	H	E	6.35
362	1998	8	1	0	P	E	NR
365	1999	11	1	167	H	CA	7.09
366	1999	6	1	1	P	CA	5.6
368	1999	8	1	80	H	E	8.18
369	1999	13	1	84	H	E	8.4
370	1999	6	1	29	H	E	5.6

Spillage ID	*Year*	*Pipeline diameter (in)*	*System part*	*Spillage volume (m^3)*	*Hole size*	*Mode of failure*	*Wall thickness (mm)*
371	1999	8	1	80	H	E	8.18
372	1999	11	1	36	H	E	6.7
373	1999	12	1	1	P	E	7.35
376	2000	12	1	8	P	E	5.6
377	2000	11	1	159	H	E	NR
379	2000	24	1	1	P	E	7.1
382	2001	10	1	5	P	A	7
383	2001	6	1	37	H	A	NR
384	2001	12	1	10	P	A	7.5
386	2001	12	1	4	P	CA	9.52
388	2001	11	1	55	H	E	6.6
389	2001	10	1	10	P	E	7.8
390	2001	6	1	5	P	E	6
393	2001	16	1	2	P	E	17.09
394	2001	8	1	85	H	E	9
395	2002	8	1	10	P	A	9
397	2002	10	1	80	H	CA	6.35
401	2002	13	1	225	H	CC	6.35
404	2002	8	1	170	H	E	7.36
408	2002	8	1	190	H	E	7.36
409	2003	14	1	30	H	A	NR
411	2003	12	1	2	P	E	
412	2003	11	1	83	H	E	6.35
413	2003	11	1	45	H	E	6.35
414	2003	6	1	2	P	E	NR
415	2003	11	1	74	H	E	6.35
417	2003	16	1	28	H	E	7.09
418	2003	16	1	52	H	E	7.09
419	2003	12	1	11	H	E	8
420	2003	20	1	2500	R	E	6.35
421	2004	16	1	2	P	A	6.3
424	2004	8	1	90	H	E	6.35
425	2004	10	1			E	7.6
427	2005	12	1			A	NR
429	2005	6	1	20	H	A	NR
430	2005	6	1	38	H	A	NR
433	2005	10	1	3	P	CA	NR
435	2005	8	1	15	H	E	NR
436	2005	24	1	0	P	E	NR
441	2006	11	1	245	H	E	NR

Spillage ID	***Year***	***Pipeline diameter (in)***	***System part***	***Spillage volume (m^3)***	***Hole size***	***Mode of failure***	***Wall thickness (mm)***
443	2006	11	1	223	H	E	NR
445	2006	20	1	2	P	CB	NR
447	2006	6	1	23	H	E	NR
448	2006	6	1	16	H	E	NR

Notes:

- System part: 1 – underground pipeline
- Hole size: P – pinhole, H – hole, R – rupture
- Mode of failure: A – mechanical, B – operational, C – corrosion, D – natural, E – TPA
- Wall thickness: NR – not recorded

9.1.2 Crude oil

Spillage ID	*Year*	*Pipeline diameter (in)*	*System part*	*Spillage volume (m^3)*	*Hole size*	*Mode of failure*	*Wall thickness (mm)*
229	1987	9	1	25	H	AB	8
231	1987	9	1	8	P	CB	8
243	1988	3	1	2	P	EA	3.25
244	1988	10	1	14	H	EA	6.3
251	1989	26	1	3	P	AA	9.52
254	1989	26	1	155	H	AB	9.52
256	1989	9	1	25	H	CA	8
266	1989	40	1	40	H	EC	8.74
277	1991	20	1	20	H	AA	10
308	1993	34	1	248	R	AA	7.92
321	1994	16	1	200	H	AB	6.35
322	1994	16	1	1350	R	AB	6.35
336	1995	16	1	132	H	BB	5.56
349	1997	10	1	2	P	CB	7.8
374	2000	12	1	10	P	CB	10
385	2001	34	1	6	P	CA	12.7
391	2001	12	1	10	P	EB	NR
392	2001	12	1	17	H	EB	NR
396	2002	20	1	100	H	CA	7.11
405	2002	16	1	750	R	EA	5
406	2002	20	1	280	R	EA	8
407	2002	12	1	40	H	EB	5
416	2003	16	1	5	P	EB	5.5
428	2005	20	1	350	R	AA	NR
434	2005	24	1	64	H	CB	NR
446	2006	12	1	10	H	CB	NR

Notes:

- System part: 1 – underground pipeline
- Hole size: P – pinhole, H – hole, R – rupture
- Mode of failure: – AA/AB – mechanical, BB- operational, CA/CB – corrosion, D – natural, EA/EB – TPA
- Wall thickness: NR – not recorded

9.2 APPENDIX 2 – UKOPA DATA

This appendix summarises the UKOPA failure data, which has been used to derive failure rates in the main report.

Fault ID	*Discovery date*	*Transported product*	*Wall thickness (mm)*	*Diameter (in)*	*Diameter (mm)*	*Hole size - equivalent diameter (mm)*	*Fault cause*
363	1997	Natural gas (NG)	0	5.9	150	1.1	Mechanical
366	1991	NG	4.8	8.6	218	24.0	TPA
400	1998	NG	0	4.0	102	2.8	Corrosion
401	1998	NG	0	4.0	102	2.8	Corrosion
402	1999	NG	5.2	8.6	218	3.6	Corrosion
417	1998	NG	5.2	8.6	218	3.2	Corrosion
422	1999	NG	6.6	8.6	218	3.6	Corrosion
425	2000	NG	6.6	8.6	218	1.1	Corrosion
719	1988	NG	7.1	8.6	218	6.2	TPA
728	1990	NG	6	6.6	168	1.1	Corrosion
730	1994	NG	6.4	18.0	457	1.1	Corrosion
1117	1993	NG	12.7	36.0	914	160.1	Mechanical
1185	1998	NG	10.4	15.7	400	20.0	TPA
1193	1990	NG	9.5	16.0	406	25.0	TPA
1361	1994	NG	9.5	24.0	610	1.1	Mechanical
1388	1998	NG	8	18.0	457	2.3	Natural
1424	1990	NG	4.5	4.5	114	3.6	SCC
1460	2001	NG	6.35	12.7	323	3.6	Natural
1489	1989	NG	6.4	12.8	325	3.6	Natural
1490	1989	NG	6.4	12.8	325	1.1	Natural
1503	1989	NG	5.2	8.6	218	7.0	SCC
1560	1989	NG	6.4	12.8	325	56.2	TPA
1645	1992	NG	7.1	8.6	218	5.5	TPA
1710	1989	NG	7.9	14.0	356	3.6	Mechanical
1740	1988	NG	9.5	20.0	508	3.6	Mechanical
1842	1992	NG	9.5	17.7	450	1.1	Mechanical
1875	1989	NG	5.2	6.6	168	11.3	Mechanical
1876	1989	NG	6.4	8.6	218	11.3	Mechanical
1886	1990	NG	4.4	6.6	168	11.3	Mechanical
1887	1990	NG	4.4	6.6	168	11.3	Mechanical
1900	1989	NG	5.2	12.8	325	11.3	Mechanical
1901	1990	NG	6.4	11.8	300	3.6	Mechanical
1909	1989	NG	4.4	4.0	102	11.3	Mechanical
1910	1989	NG	4.4	4.0	102	11.3	Mechanical

Fault ID	***Discovery date***	***Transported product***	***Wall thickness (mm)***	***Diameter (in)***	***Diameter (mm)***	***Hole size - equivalent diameter (mm)***	***Fault cause***
1911	1990	NG	4.4	4.0	102	11.3	Mechanical
1912	1990	NG	4.4	4.0	102	11.3	Mechanical
1913	1990	NG	4.4	4.0	102	11.3	Mechanical
1914	1990	NG	4.4	4.0	102	11.3	Mechanical
1915	1990	NG	4.4	4.0	102	11.3	Mechanical
1916	1990	NG	4.4	4.0	102	11.3	Mechanical
1917	1990	NG	4.4	4.0	102	11.3	Mechanical
1918	1990	NG	4.4	4.0	102	22.6	TPA
1919	1990	NG	4.4	4.0	102	11.3	Mechanical
1925	1989	NG	4.4	6.6	168	11.3	Mechanical
1926	1989	NG	4.4	6.6	168	11.3	Mechanical
1927	1989	NG	4.4	6.6	168	11.3	Mechanical
1928	1990	NG	4.5	5.9	150	11.3	Mechanical
1932	1988	NG	6.4	12.8	325	1.6	TPA
1934	1993	NG	6.4	14.0	356	1.1	SCC
1940	1990	NG	4.4	6.6	168	11.3	Mechanical
1947	1990	NG	4.4	4.0	102	3.6	Mechanical
1948	1997	NG	4.4	3.9	100	11.3	Corrosion
1949	1997	NG	4.4	3.9	100	3.6	Mechanical
1950	1998	NG	4.4	3.9	100	1.1	Corrosion
1972	1990	NG	4.5	3.5	89	3.6	Mechanical
1973	1990	NG	4.5	5.9	150	11.3	Mechanical
1985	1988	NG	4	3.0	76	11.3	TPA
1987	1990	NG	4.8	6.6	168	23.9	TPA
1996	1993	NG	4.8	6.6	168	1.1	Mechanical
1998	2001	NG	4.8	5.9	150	24.5	SCC
2028	1990	NG	4.8	5.9	150	11.3	Mechanical
2054	1988	NG	6.4	8.6	218	1.1	SCC
2055	1989	NG	6.4	8.6	218	11.3	Mechanical
2069	1990	NG	6.4	8.6	218	3.6	Mechanical
2078	1989	NG	5.6	5.9	150	11.3	Mechanical
2152	1991	NG	7.9	18.0	457	74.8	Natural
2527	2004	NG	6	8.6	219	6.0	TPA
2529	2004	NG	0	36.0	914	0.0	Other
2569	2005	NG	4.7	6.4	163	1.1	Corrosion
2783	2006	NG	4.5	8.6	219	25.0	TPA
2872	2000	NG	9.52	18.0	457	27.8	Natural

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