

## KEY FACTORS FOR THE ESTIMATION OF CROSS-COUNTRY PIPELINES FAILURE RATES

Glenn Pettitt, Environmental Resources Management, UK

This paper provides a description of the different databases and various influencing factors for the estimation of cross-country pipelines failure rates. The databases available cover a number of different materials transported: crude oil and liquid products, and natural gas. The various databases give excellent base data to estimate the likelihood of failures of cross-country pipelines. However, it is not sufficient to rely on these databases alone in predicting the failure rate. One needs to include the various factors: design, operating, and environmental in the estimation of the failure rate, which may change along the pipeline ROW. This paper also provides a discussion of how risk reduction mechanisms would affect the failure rate of the material failure release mechanism. Materials failure is a key release mechanism in estimating the overall failure rate from a cross-country pipeline, and several factors should be taken into account when conducting a pipeline risk assessment.

**KEYWORDS:** Pipelines, failure rate, external interference, corrosion, natural hazards, material failures

### INTRODUCTION

Underground cross-country pipelines are widely used in the Oil & Gas and Petrochemical Industries to transport raw materials and products, e.g. crude oil, natural gas and gasoline. The loss of mechanical integrity of such pipelines has occurred on numerous occasions world-wide, due to a variety of causes such as corrosion, external impact, defects, operational errors and natural hazards. With materials being transported at very high pressures, pipeline failures may result in major releases of hazardous materials. An example is shown in Figure 1: the destruction of many houses after a major fire following a gas pipeline rupture in San Bruno, California, USA in September 2010. Such failures present a risk to people (in the case of ignition of high pressure gas) and the environment (in the case of oil and other liquid products).

There are a number of recognised failure rate databases for cross-country pipelines, such as CONCAWE (European liquid pipelines) [1], EGIG (European gas pipelines) [2] and the US DoT (both liquids and gas pipelines) [3]. It is remarkable how close the base data from the different systems are, which leads to some confidence that the figures are sufficiently robust to be used in risk analyses.

For each database there is a number of failure modes included, such as corrosion, third party impact, material defects, natural hazards. For some of these failure modes, the databases have shown that there is a correlation between the failure rates and various risk reduction mechanism, such as heavy wall thickness. In particular, a reduction in failure rate can be applied for the corrosion and third party impact failure modes for heavy wall thickness.

However, for other failure modes, in particular material defects, the databases show no correlation between the failure rate and key risk reduction mechanisms such as heavy wall thickness. It would seem logical that the failure rate for material defects should decrease with increasing wall thickness, but for frequency assessments this has often been a constant in past studies, by simple use of statistics from the various databases.

The author has extensive experience of assessing the risks associated with pipeline systems, having been heavily involved in the design and subsequent operation of a number of high-profile pipelines world-wide (from a risk perspective). This experience has been applied to the analysis of the various failure modes in order to determine how various risk reduction techniques can reduce the frequency of failure. This includes the assessment of statistics where there is no immediate correlation from the various databases for specific failure modes.

The paper discusses how such data can be applied where logic would suggest that there should be a reduction in failure rates, although this is not immediately apparent from the various databases.

### HISTORICAL DATABASES

Table 1 provides a summary of historical pipeline failure data from some of the best sources of data for onshore pipeline systems. All these sources provide raw data on failure incidents and pipeline length and an analysis of the failure causes. The most relevant and up to date databases available are those of:

- CONCAWE,
- European Gas Pipeline Incident Data Group (EGIG),
- US Department of Transportation (US DoT).

The CONCAWE database [1] applies to crude oil and petroleum pipelines that are located in Western Europe, although since 2001, pipelines from a number of Eastern European countries have also been included in the database. Data are collected for the pipeline network every year. A number of figures are provided in Table 1 that show that the general trend of pipeline incidents is decreasing.

EGIG has compiled data collected by a group of 15 major gas transmission operators in Western Europe over the period 1970 to 2010 [2]. Failure rates for the whole of this period are provided in Table 1, but again, more recent



**Figure 1.** Gas Pipeline Incident in San Bruno, California, USA in September 2010

data show that the performance of gas pipelines has generally improved.

The US DoT collects annual statistics on pipeline failures from reportable incidents. Results can be obtained from the internet back to 1988 [3]. Data from 2002 onwards are more detailed in terms of the failure mode, hence the split in the periods shown in Table 1. It is interesting to note that whilst the failure rate has again decreased for liquid pipelines in the later period shown in Table 1, the failure rate for natural gas pipeline has bucked the trend and has increased by approximately 50% (probably due to improved reporting in recent years), although the overall failure rate is still below that of EGIG.

The overall failure rate data show a relatively good similarity. Data from the most recent years is recommended

**Table 1.** Comparison of Various International Pipeline Failure Data

Source	Period	Overall (i.e. unmodified) Failure Frequency (per km · year)
CONCAWE	1971–2010	3.5 E-4*
	1981–2010	2.8 E-4*
	1991–2010	2.4 E-4*
	2001–2010	2.2 E-4*
EGIG	1970–2010	3.5 E-4
	1981–2010	2.9 E-4
	1991–2010	2.0 E-4
	2001–2010	1.7 E-4
US DoT, Liquids	1988–2001	4.9 E-4
	2002–2011	4.5 E-4
US DoT, Natural Gas	1988–2001	7.2 E-5
	2002–2011	1.1 E-4

\* These frequencies have been filtered to include those only from the cross-country sections.

for estimating failure rates due to the improving performance. These data take into account improved mechanisms for pipeline integrity, such as superior pipeline coatings and better cathodic protection systems to reduce the likelihood of corrosion failures; improved mill quality control and construction techniques to reduce the likelihood of material fault failures; and enhanced protection methods, such as concrete slabbing at crossings to reduce the likelihood of external interference failures. However, a number of the older pipeline systems still do not have such enhanced protection mechanisms and data that includes earlier years may be more appropriate for these.

It should be noted that the data are an average over different countries in Europe and over different states in the US. The addition of Eastern European liquid pipelines into the CONCAWE database resulted in a slight increase in the overall failure rate data when these were first included, due to the inferior performance of these pipelines.

Analysis of the raw data is described in more detail in a previous paper [4], although data from the last few years is not included. This current paper is more concerned with how key factors can be applied for the estimation of cross-country pipelines failure rates.

## FAILURE CAUSES

The historical databases also provide good data on the various failure modes. For all databases the most common failure mode is due to third party interference. Other key failure causes are corrosion, material defects and natural hazards. Certainly with regard to gas transmission pipelines, third party interference is a major cause of full bore ruptures, which is a key focus of this paper. Failure causes are dealt in detail elsewhere and so not discussed in detail in this paper. However, Figures 2 and 3 show the latest data from CONCAWE (cross-country sections only) and Figure 4 shows the latest data from EGIG.

## RELEASE SIZE

A major issue for the potential safety and environmental impact of releases from oil and gas pipelines is the size of the release.

In particular for gas pipelines, serious impact is most likely if there is a full bore rupture; this is generally ‘unzipping of the pipeline’ such that a complete section is lost and gas is released from both ends, initially at a very high release rate. If the failure mode is accompanied by ignition, or if ignition occurs during the early part of a release, then a catastrophic fire may ensue. (If ignition is delayed, there may still be a major fire, although much of the early inventory will be lost as the pipeline rapidly depressurises.) Hence, for high pressure gas pipelines, one is generally concerned with full bore ruptures, with consequences demonstrated as shown in Figure 1. (Leaks may also result in serious fires, but the magnitude of these is relatively small in comparison.)

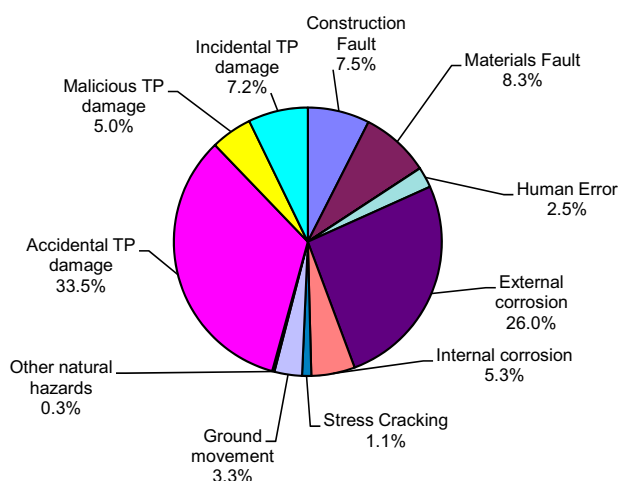


Figure 2. Failure Causes from CONCAWE (1971–2010)

For oil pipelines the size of release is not as significant with regard to environmental impact. A small release has the potential to continue for a large amount of time (possibly many days) if it remains undetected. This may cause significant damage to the local environment. For environmental impact, the amount of oil or petroleum product lost is the key factor rather than the release rate; hence, a small release that continues for many days may be as significant as a large release that is quickly detected and responded to.

#### CONCAWE DATA

Accidents statistics were analysed for hole size distribution [4]. The hole size failure rate by cause is shown in Figure 5. In the CONCAWE data the various hole sizes are described as follows:

- Pinhole: less than 2 mm × 2 mm
- Fissure: 2 to 75 mm long × 10% max wide

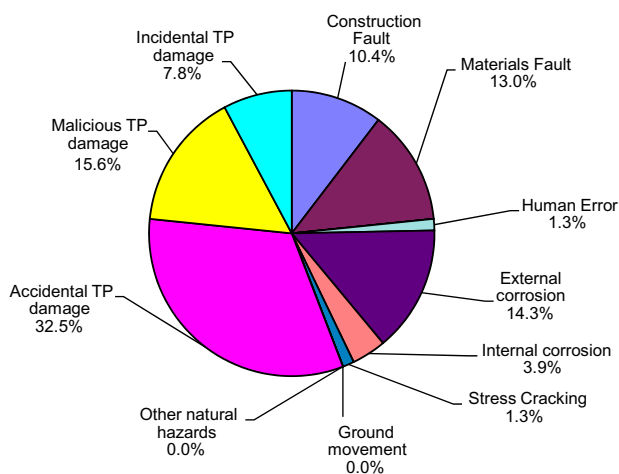


Figure 3. Failure Causes from CONCAWE (2001–2010)

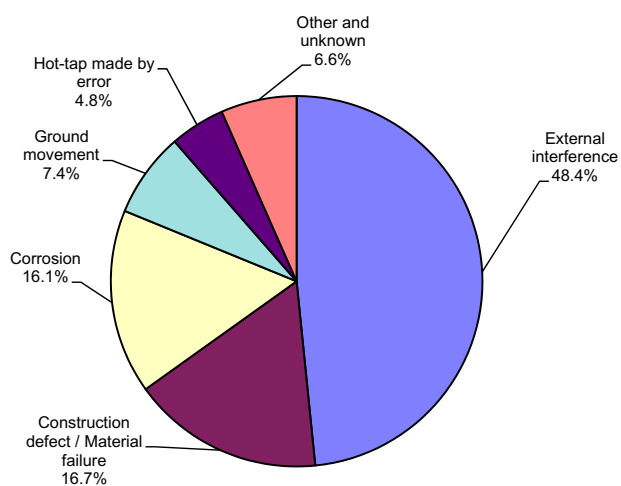


Figure 4. Failure Causes from EGIG (1970–2010)

- Hole: 2 to 75 mm long × 10% min wide
- Split: 75 to 1000 mm long × 10% max wide
- Rupture: > 75 mm long × 10% min wide

In terms of terms of their equivalent diameter, (required for consequence modelling in a risk analysis) these have been interpreted as shown in Table 2. The 'rupture' hole size is interpreted as any hole size above 150 mm.

#### EGIG DATA

Accidents statistics have also been analysed for hole size distribution. The hole size distribution by cause is shown illustrated in Figure 6, which shows the overall failure rates. A 'pinhole/crack' is interpreted as a 5 mm equivalent hole and a 'hole' is interpreted as a 50 mm hole.

#### RISK REDUCTION MECHANISMS

There are a number of risk reduction mechanisms that will have an influence on the overall failure rate of the pipeline. These can be listed under the various failure modes.

In this section all potential risk reduction mechanisms are discussed. For 'external interference/third party activity' and 'corrosion', the risk reduction mechanisms have been discussed in a previous paper presented at Hazards XXI in November 2009, and there has been little change in the analysis. However, for 'material failures' further research has been carried out on the potential risk reduction mechanisms and this is described in more detail in this paper.

#### EXTERNAL INTERFERENCE/THIRD PARTY ACTIVITY

Probably the most significant effort in risk reduction is made to reduce the chance of pipeline failures due to third party activities, whether these are accidental, intentional or incidental. (Incidental failures are which there is an external impact, which does not cause a failure at that time, but

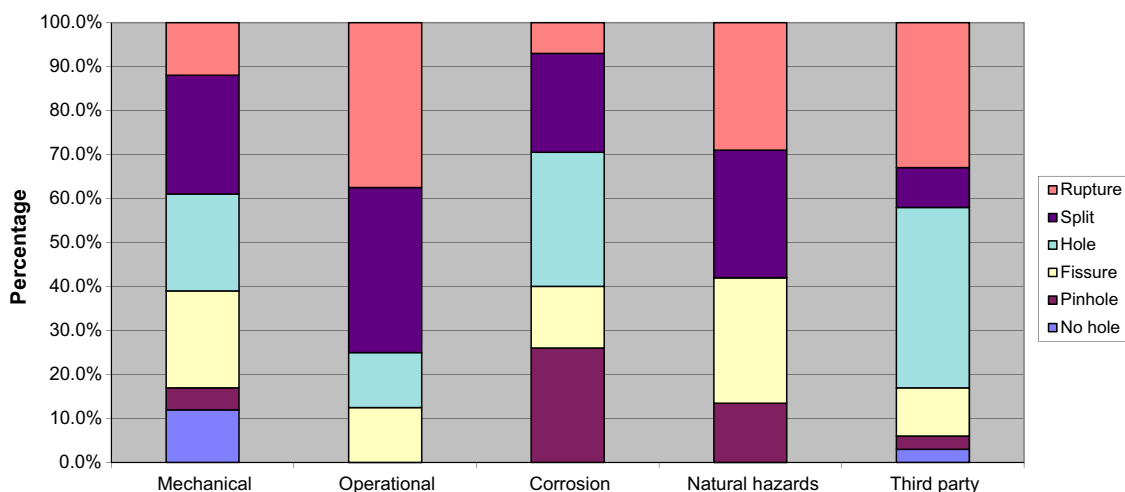


Figure 5. Hole Size Failure Distribution by Cause (CONCAWE)

where a loss of containment eventually occurs, as the integrity of the pipeline reduces at that point.)

Some of the more common risk reduction mechanisms are as follows:

- Pipeline safety zones,
- Increased wall thickness,
- Increased depth of cover,
- Warning marker posts,
- Plastic marker tape,
- Concrete slabbing,
- Physical barrier within pipeline trench,
- Vibration detection,
- Regular inspections of pipelines ROW,
- Intelligent pigging.

Pipeline safety zones may be established during the pipeline construction. The intention is to avoid construction activity along or near the right-of-way (ROW). Regular inspections of a pipeline ROW would help to decrease the failure rate due to third party activity, certainly accidental and intentional, and an appropriate reduction factor may be applied depending on the inspection interval.

Probably the risk reduction mechanism with the largest influence is the wall thickness (WT). This shown by the EGIG data (Figure 7), where there is a large drop in

failure rate for pipelines with a WT above 10 mm and no failures for a WT above 15 mm. Unsurprisingly, the failure rate is much higher for pipelines with a WT of less than 5 mm. In deriving failure rates for a specific pipeline, the WT should be taken into consideration, but the maximum allowable operating pressure (MAOP) should also be considered, particularly with regard to liquid pipelines, as this would be taken into account in the pipeline design, e.g. a liquid pipeline that traverses a mountainous route may have a thicker wall at the bottom of a slope than at the top, due to the change in pressure head. (For gas pipelines, essentially the MAOP will not vary with change in elevation.)

The depth of cover may also influence the failure rate, again as shown by Figure 8 for EGIG data. Certainly, where the depth of cover is less than 0.8 m, the failure rate due to third party interferences increases significantly. One would expect that the failure rate decreases significantly as the depth of cover increases to, say, 2 m, but there is not the data to support this, probably as the nominal depth for most pipelines is in the order of 0.9 to 1.0 m.

The other risk reduction mechanisms listed above would also have an influence on the failure rate due to third party activity. Mechanisms such as warning posts, concrete slabbing and plastic marker tape are often used at road crossings, for example, although the crossing itself may warrant

Table 2. Estimated Hole Size by Failure Mode (CONCAWE)

Failure Mode	Hole Size (%)			
	5 mm	50 mm	100 mm	Rupture
Mechanical failure	50.0	38.0	8.0	4.0
Operational	18.8	43.8	25.0	12.5
Corrosion	55.3	37.8	4.7	2.3
Natural hazard	42.0	29.0	19.3	9.7
Third party activity	37.5	29.5	22.0	11.0

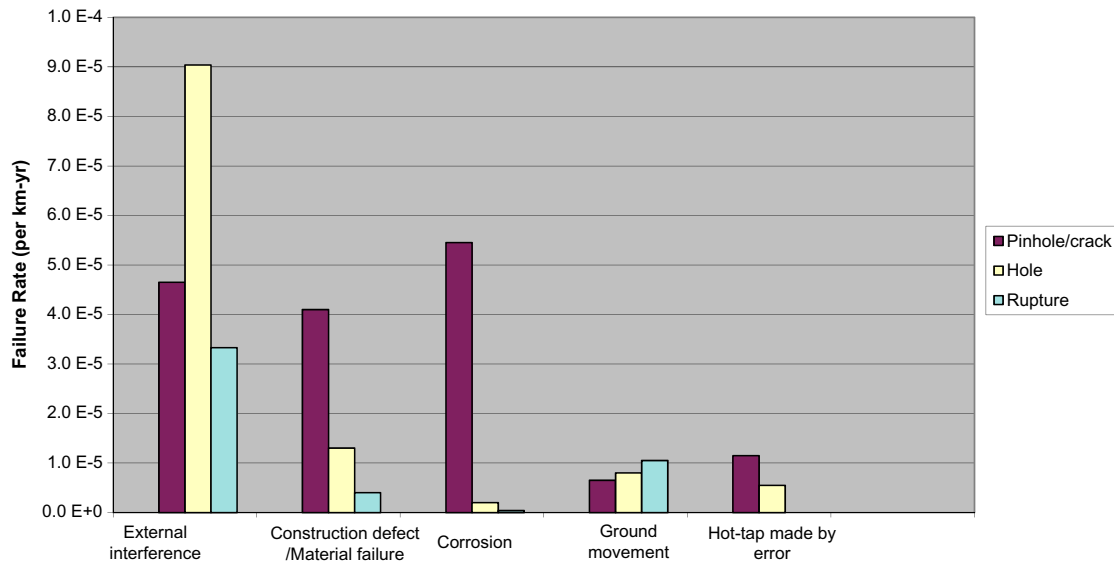


Figure 6. Hole Size Failure Distribution by Cause (EGIG)

an increase in the failure rate at that point, and so the risk reduction mechanisms may serve to keep the failure rate the same, i.e. the failure rate at a crossing would be increased from that on the rest of the pipeline if there were no mechanisms such as concrete slabbing. Work by British Gas, summarised by Morgan 1996 [5], found that a combination of slabbing with a visual warning such as plastic marker tape was particularly effective in preventing accidental damage. These techniques may therefore be usefully deployed in other sensitive areas to reduce the likelihood of damage by machinery.

Some pipelines may include mechanisms to guard against illegal hot-taps (intentional third party failures),

such as a physical barrier in the trench and vibration detection. Also, there may be increased patrols by military personnel. In such cases, the failure rate due to illegal hot-taps would become very small, although the failure rate due to intentional activity would change depending on the country or area that the pipeline runs through, as illegal hot-taps are a significant problem in some locations.

Intelligent pigging may reduce the risk of latent incidental third party failures, by detecting a potential failure before this becomes critical after the initial damage has occurred. CONCAWE reports [1] that over the past 40 years, 51 spills have been caused by mechanical damage

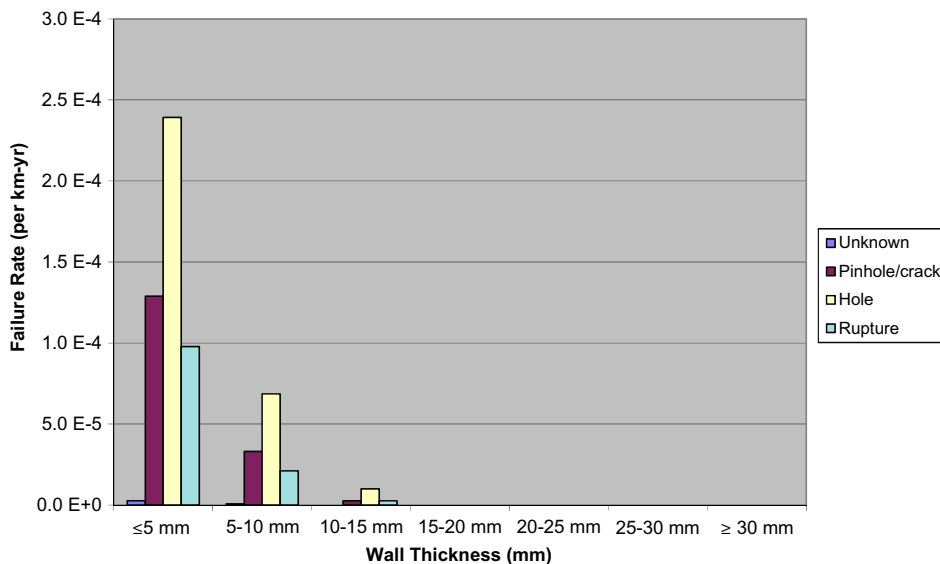


Figure 7. Failure Rate vs Wall Thickness for Third Party Activity (EGIG)

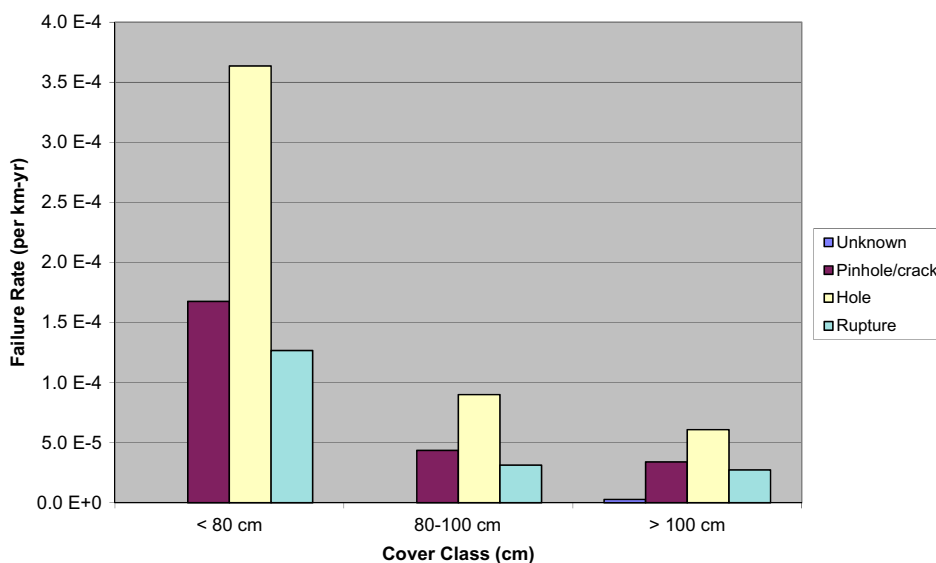


Figure 8. Failure Rate vs Depth of Cover for Third Party Activity (EGIG)

(including incidental damage by third parties) or faulty welds that could, in principle, have been detected by intelligent pigs.

Risk reduction factors for external interference are also discussed in detail in PD 8010-3 [6], which applies to steel pipelines on land, and IGEM/TD/2 [7], which applied to natural gas pipelines only.

#### CORROSION

A significant effort is also made to reduce the risk of pipeline failure due to corrosion (internal and external). Risk reduction mechanisms include:

- Increased wall thickness,
- Pipeline coating,
- Cathodic protection (CP) system,
- Internal lining,
- Intelligent pigging.

Similarly to external interference, the WT plays a major role in determining the failure rate due to corrosion. Again, this is shown by the EGIG data (Figure 9), where there is a large drop in failure rate for pipelines with a WT above 10 mm and no failures for a WT above 15 mm.

The relationship between pipeline coating, CP and failure rate due to corrosion has been analysed by de la Mare et al. [8] in a study on US gas transmission pipelines. The study showed that during the years 1970–1973, on average, the corrosion failure rate was reduced by a factor of about five for pipelines that had either a coating or CP. Most pipelines now have an external coating, CP, or both and this is reflected in the base data. Review of the CONCAWE data shows that where there was a failure due to external corrosion, this is generally due to a failure of

the external coating or of the CP system. Hence, it would be appropriate to increase the failure rate due to corrosion if a pipeline was not protected, rather than reduce the failure rate if it was protected, particularly if there was an aggressive soil type or in areas where the soil was wet, i.e. where there may be more of a potential for external corrosion.

An internal lining may reduce the potential for internal corrosion, although such linings are often used if the internal fluid is corrosive, e.g. sour gas.

Certainly, if the pipeline fluid is transported at elevated temperatures due to a high viscosity at ambient temperatures, then it may be appropriate to increase the failure rate data due to corrosion, as this failure mechanism is enhanced at elevated temperatures, shown by CONCAWE data.

One would not expect high corrosion rates for newly laid pipelines, but this would change with time, so a reduction factor would not be expected, as one should be studying the pipeline over its life-cycle. It may be appropriate to increase the failure rate for older pipelines, e.g. pre-1960, but there are little data to substantiate such an increase in the case of CONCAWE.

Again, intelligent pigging may reduce the risk of corrosion failures, by detecting a potential failure before this becomes critical. One would need to take into consideration how often intelligent pigging is conducted. CONCAWE reports [1] that over the past 40 years, there have been 102 spillages related to external corrosion and 25 to internal corrosion, at least some of which could have been detected. (Nearly two thirds of the 102 spillages related to external corrosion occurred in 'hot' pipelines, most of which have now been retired.)

Risk reduction factors for corrosion are also discussed in detail in PD 8010-3 [6], which applies to steel pipelines on land, and IGEM/TD/2 [7], which applied to natural gas pipelines only.

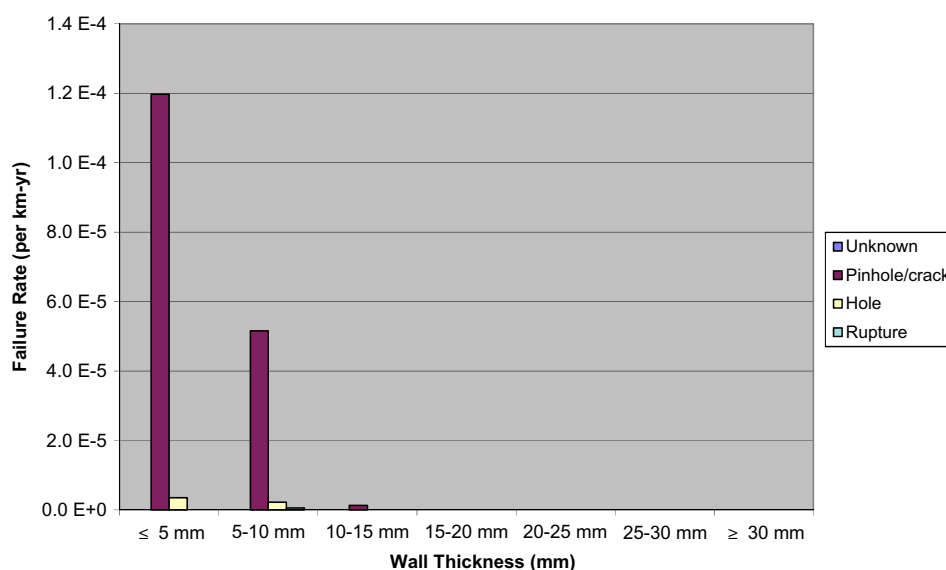


Figure 9. Failure Rate vs Wall Thickness for Corrosion (EGIG)

#### NATURAL HAZARDS

The base failure data contain a background rate for natural hazards, although in reality, this is due to the environment where some pipelines in the database pass through. Where a pipeline crosses, for example, rivers, seismic fault lines and areas susceptible to landslides, the failure rate should be increased at that point, unless there are substantial measures taken in the pipeline design to mitigate against such hazards. Natural hazards are particularly relevant where a pipeline passes through mountainous regions, where all three examples of potential failure mentioned above may exist.

Such mitigation measures may include micro-tunnels for river crossings, in particular where there may be a severe washout hazard during a spring melt of snow, seismic fault design, and ensuring that a pipeline is laid in the direction of a potential landslide area rather than across it. Soil erosion control and geohazard monitoring may also be factors in reducing the potential stress on a pipeline and hence the likelihood of failure.

There is insufficient historical data to establish a relationship between ground movement failure data and individual pipeline parameters [7]. For example, the pipeline wall thickness is not taken into consideration. The failure frequency for natural hazards along the pipeline ROW should be assessed on the particular natural hazards encountered at specific locations and the particular mitigation mechanisms should be taken into consideration. For example guidance on the pipeline rupture rate is given in IGEM/TD/2 for different slopes where a landslide may be present, as shown in Table 3 [7].

With regard to landslides, there are a number of experts who can provide judgements as to the likely occurrence of a landslide and whether these may cause a rupture of the pipeline. Such experts have worked with the author to provide value judgements at potential landslide areas.

Measures can be taken for modern pipeline systems (and current systems) to mitigate the effects, certainly by designing the pipeline route such that landslide areas are avoided, or where this may not be possible, such that the pipeline runs in the direction of the potential landslide and not across it.

#### MATERIAL FAILURES

There are no significant mechanisms to reduce the risk of material failures or construction faults once a pipeline is laid, other than intelligent pigging, which may detect potential weak points before these become critical. As noted above, CONCAWE reports [1] that over the past 40 years, 51 spills have been caused by mechanical damage (including incidental damage by third parties) or faulty welds that could, in principle, have been detected by intelligent pigs. However, it should be noted that faulty welds

Table 3. Failure Rate due to Landslide from Different Slope Types

Description	Pipeline Rupture Rate (per km · year)
Slope instability is negligible or unlikely to occur, but may be affected by slope movement on adjacent areas	0–9 E-5
Slope instability may have occurred in the past or may occur in future – is present and may occur in the future	1 E-4–2.14 E-4
Slope instability is likely and site specific assessment is required	>3 E-4

come under the category of ‘construction faults’; the spill sizes from these tend to be much smaller than ‘material faults’ (by a factor of about 40 on average), as shown by Figure 10. Hence, if only faulty welds may be discovered by intelligent pigging, this may not reduce the risk of a much larger failure due to a fault in the material.

One major issue is that the manufacture of pipework in terms of the milling process has improved with time, such that modern pipework systems are less likely to develop failures. This can be shown by Figure 11 where the failure rate versus year of construction is considerably reduced (EGIG data). Of course, one key factor is that there are far more km-years for older pipelines in the data set and one would expect a reduction in the number of failures in later years for this reason alone.

Data shown in PD 8010-3 [6] for the failure frequency due to material and construction defects is given in Table 4, which shows that the failure rate decreases as the wall thickness increases. UKOPA data have indicated that the material failures manifest as gas leaks, and that there have been no full bore ruptures within the UK to date. This is contrary to the EGIG data shown in Figure 11, which indicates that there have been a number of full bore ruptures within the rest of Europe.

The failure rate due to material failures in the UK is dependent upon the year of construction and hence the age, design and construction standards, in particular the material selection controls and welding inspection standards applied which have improved significantly since the early 1970s [7]. For pipelines commissioned after 1980, UKOPA states that the material failures failure rate can be assumed to be reduced by a factor of 5, as shown by IGEM/TD/2 [7].

A key point is that there have been no full bore ruptures in pipelines constructed from 1984 onwards in Europe as a whole, not just in the UK. This does not mean

that such an occurrence will not happen; however, there have been over 25 years in this data set from EGIG and it is an encouraging factor that there have been no full bore ruptures due to material failures in pipelines constructed from 1984 onwards. Hence, there is justification for reducing the full bore rupture failure rate significantly for gas transmission pipelines constructed after 1984. This has a major implication on European gas pipeline risk assessments (and possibly beyond), i.e. rather than using a figure of about 4 E-6 per km-year for full bore ruptures, which can be taken from Figure 6, a much reduced level could be applied. If a reduction by a factor of 5 is assumed for pipelines commissioned after 1980, this reduces to 8 E-7 per km-year. However, a further factor can be applied to take into account that there have been no full bore rupture events for pipelines constructed in Europe from 1984 onwards.

If the wall thickness is taken into account as shown in Table 4, then this reduction becomes even greater for heavy wall pipelines. For example, the data in EGIG show that the failure rate for material failures is about 5.8 E-5 per year. This ties in well with the data shown in Table 4. Hence, for a heavy wall pipeline of wall thickness greater than 15 mm and constructed from 1984 onwards, a significant reduction in the failure rate could be justified.

This was demonstrated in a recent quantitative risk assessment conducted by the author for a modern gas pipeline system with heavy wall thickness. A significant reduction in the external interference and corrosion failure rates was applied in an area where there were no significant natural hazards and where a hot tap in error would be extremely remote. In this case, by applying the generic EGIG data, the full bore rupture failure rate due to material failures was calculated to be about 98% of the overall full bore rupture frequency. Certainly this was not logical given the modern pipeline system and the very heavy wall thickness.

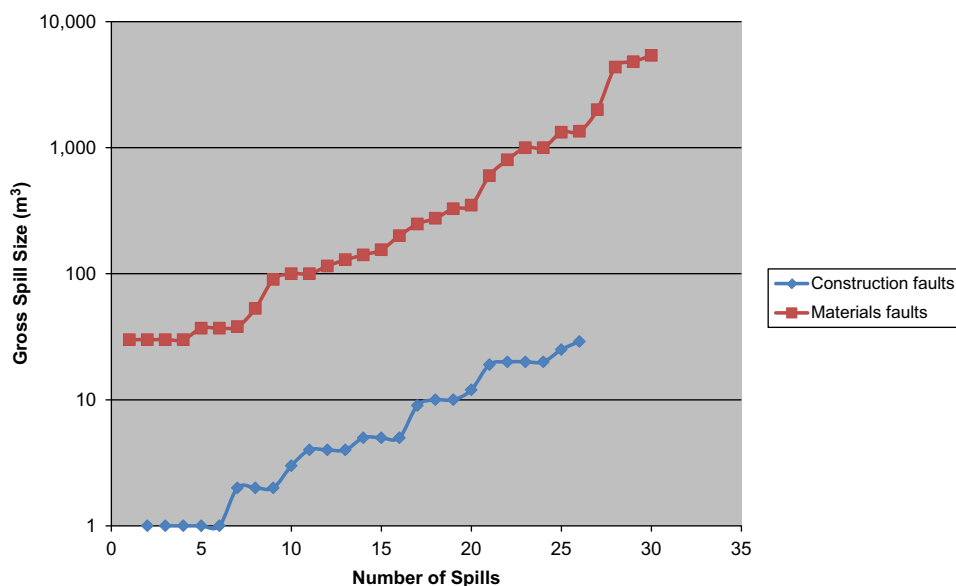


Figure 10. Gross Spill Size vs Number of Spills for Material Failures (CONCAWE)



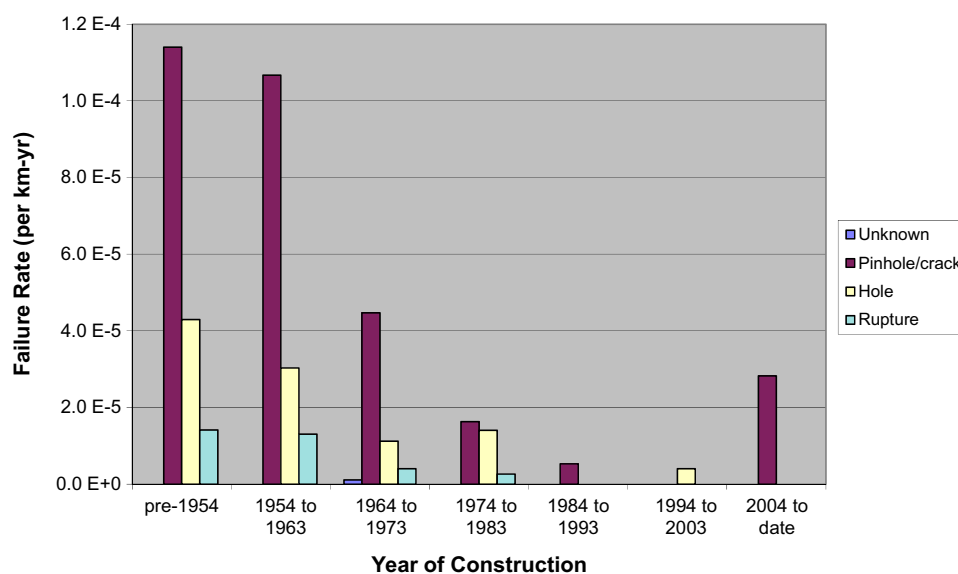


Figure 11. Failure Rate vs Year for Material Failures (EGIG)

By using the reduction mechanisms noted above, the failure rate for material failures became more reasonable, i.e. more in line with the other failure mechanisms where one would expect heavy wall thickness to be an all-round risk reduction factor.

With regard to oil pipelines, those constructed from 1984 onwards would also be expected to have a drop in the failure rate of large failures, as the pipeline construction method (at the mill and at the construction site) do not differ for gas pipelines or oil pipelines. For material defects, the CONCAWE data show only one failure for pipelines constructed from 1984 onwards. (There have also been construction defects for such pipelines, but these failures tend to be small as shown in Figure 10.) For significant releases of oil or petroleum product (although as noted above this may not be for a large leak) there have been a number of failures in recent years, most notably a release of 5,401 m<sup>3</sup> in 2009. However, all significant failures have been in pipelines constructed prior to 1984 (where the pipeline age was noted), which ties in with the data for gas pipelines. Hence, it would also be appropriate to apply

similar reduction factors for oil pipelines based on age and wall thickness.

#### OVERPRESSURE PROTECTION

Liquid pipelines in mountainous area may require overpressure protection. The MAOP and the minimum wall thickness requirements are taken into consideration in the pipeline design. Some pipelines require surge relief (tanks at pump stations or pressure reduction stations), and again, these are considered in the pipeline design due to the potential for a surge, so a reduction in the base failure rate would not be appropriate.

#### DESIGN FACTOR

The pipeline design factor (the ratio of hoop stress to material yield stress) should be taken into consideration when assessing potential hole sizes for gas pipelines. The design factor is a function of the type of steel, pipeline diameter, wall thickness and the MAOP. In particular the WT would have already been taken into account in determining the overall failure rate, but it should be noted that at design factors of 0.3 and WT of >11.91 mm, propagation to rupture is extremely remote [9], i.e. to get a benefit from both effects, it requires a DF achieved through a WT >11.91mm, and not merely from getting a low DF from higher grade steel. (The 0.3 DF relates to leak before break behaviour from crack growth mechanisms. The 11.91 mm relates only to ruptures due to impact from e.g. digger teeth and other external impact implements common in agriculture and construction in the UK during the 1970s.)

However this 0.3 figure for design factor may be considered somewhat conservative, particularly for large diameter, heavy wall pipelines, and therefore the factor is

Table 4. Failure Rate due to Material Failures vs Wall Thickness

Wall Thickness Range (mm)	Failure Rate (per km-year)
WT < 5	5.05 E-4
5 < WT ≤ 8	6.4 E-5
8 < WT ≤ 10	4.6 E-5
10 < WT ≤ 12	3.1 E-5
12 < WT ≤ 15	7 E-6
WT > 15	4 E-6

sometimes increased (i.e. less onerous), e.g. in the UK Institution of Gas Engineers code IGEM/TD/1 [10], to 0.5 for pipelines with a wall thickness over 19.1 mm.

Risk reduction factors for design factor are discussed in detail in IGEM/TD/2 [7], where failure rate predictions for external interference rupture and leak frequencies vs design factor are given for specific diameter and wall thickness pipelines.

### CONCLUSION

The various databases give excellent base data to estimate the likelihood of failures of cross-country pipelines. However, it is not sufficient to rely on these databases alone in predicting the failure rate. One needs to include the various factors: design, operating, and environmental in the estimation of the failure rate, which may change along the pipeline ROW.

A previous paper presented at Hazards XXI [4] discussed how the various risk reduction mechanisms could be applied for the key pipeline failure modes of external interference and corrosion. However, at that time there was no discussion of how risk reduction mechanisms would affect the failure rate of the material failure release mechanism. This paper has provided such a discussion, as materials failure is a key release mechanism in estimating the overall failure rate from a cross-country pipeline, and several factors should be taken into account when conducting a pipeline risk assessment.

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