A TOOL TO ESTIMATE THE FAILURE RATES OF CROSS-COUNTRY PIPELINES

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This paper provides a description of the different databases and various influencing factors in the development of a tool to estimate the failure rate of cross-country pipelines. 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.

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 worldwide, 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: a major flash fire following a gas pipeline rupture in Virginia, USA in September 2008. 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).

In order to predict the level of risk to people and the environment, data is required that will predict the likelihood of failures and material release. Such data can be obtained from a number of sources on the internet and elsewhere [e.g. 1, 2, 3].

From these data, and the experience of the authors in analysing such data and discussions with experts over several years, a model has been developed to estimate the annual failure frequency of cross-country pipelines, taking into account a number of parameters, for example:

- wall thickness,
- depth of burial,
- protection mechanisms, such as concrete slabbing,
- corrosion protection,
- intelligent pigging operations,
- location type (urban or rural),
- the natural environment.

This paper provides a description of the different databases used in the development of the model. The databases available cover a number of different materials transported: the CONCAWE database is applicable to crude oil and petroleum products pipelines [1], EGIG data are applicable to natural gas pipelines [2], whilst both liquid and gas pipelines are included in the US DoT database [3].

It should be noted that the numerical data in this document only applies to onshore cross-country pipelines outside the UK, as the performance of UK pipelines is much better on average due, in the main, to being well operated, maintained and regulated right from the onset of the National Transmission System.

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 to 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, although there is a slight increase in the 2001–2006 data from that of 1991–2006, which is most likely due to the inclusion of pipeline from Eastern Europe, particularly as illegal hot-taps are more prevalent in this region.

EGIG has compiled data collected by a group of 15 major gas transmission operators in Western Europe over the period 1970 to 2007 [2]. Failure rates for the whole of this period are provided in Table 1, but again, data taken from more recent years show that the performance of gas pipelines has generally improved.

Figure 1. Gas pipeline incident in Virginia, USA in September 2008

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 about 24%, although the overall failure rate is still below that of EGIG.

The overall failure rate data show a remarkable similarly: certainly those of liquid pipelines from the CONCAWE and DoT databases in the most recent years are relatively close at 2.8 E-4 per km-year compared with 3.4 E-4 per km-year. The overall failure rates from the gas pipeline databases are not as close, but at 1.6 E-4 per km-year compared with 8.9 E-5 per km-year, the differences are by no means extreme. Data from the most recent years is recommended 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 a concrete slabbing at crossings to reduce the likelihood of external interference failures

It should be noted that the data are an average over different countries in Europe and over different states in the USA. As previously discussed, the addition of Eastern European liquid pipelines into the CONCAWE database has resulted in a slight increase in the overall failure rate data, due to the inferior performance of these pipelines.

Table 1. Comparison of various international pipeline failure data

Source	Period	Overall (i.e. unmodified) failure frequency (per km-year)
CONCAWE	1971–2006	3.8 E-4
	1981–2006	3.1 E-4
	1991–2006	2.7 E-4
	2001–2006	2.8 E-4
EGIG	1970–2007	4.5 E-4
	1980–2007	3.4 E-4
	1990–2007	2.3 E-4
	2000–2007	1.6 E-4
US DoT, Liquids	1988–2001	4.9 E-4
	2002–2007	3.4 E-4
US DoT, Natural gas	1988–2001	7.2 E-5
	2002–2007	8.9 E-5

CONCAWE DATA

The CONCAWE data apply to crude oil and petroleum products pipelines. Approximately 35,000 km of pipelines are now covered and the reported spillage incidents are analysed by cause.

Detailed data over the period from 1971 to 2006 have been included, although it is recommended that data from the most recent years (e.g. 2001–2006) are used for statistical analyses due to improved performance. Certainly, data from pre-1981 are not recommended in a frequency analysis, as these data include relatively high failure rates due to corrosion of pipelines operating at raised temperatures. The overall failure rate by year is shown in Figure 2 and the five-year moving average, which shows the downward trend, is shown in Figure 3. Only those incidents that

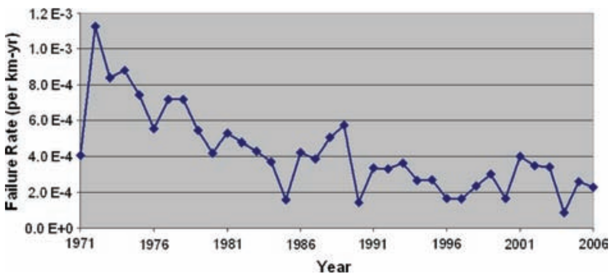

Figure 2. Overall failure rates vs time for CONCAWE data (line pipe only)

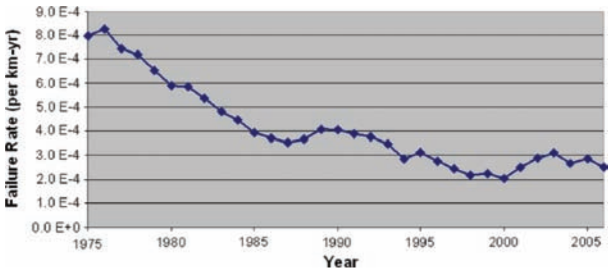

Figure 3. Five-year moving average for CONCAWE data (line pipe only)

Table 2. CONCAWE failure rate data by failure mode

Failure mode (group)	Failure mode	1971–2006	1981–2006	1991–2006	2001–2006
Mechanical failure	Construction fault	2.9 E-5	2.9 E-5	2.3 E-5	3.3 E-5
	Materials fault	3.0 E-5	2.9 E-5	2.7 E-5	3.3 E-5
Operational	System malfunction	0.0 E + 0	0.0 E + 0	0.0 E + 0	0.0 E + 0
	Human error	1.0 E-5	1.2 E-5	1.2 E-5	4.8 E-6
Corrosion	External	1.0 E-4	5.6 E-5	4.1 E-5	3.8 E-5
	Internal	2.1 E-5	2.3 E-5	2.0 E-5	1.4 E-5
	Stress cracking	4.4 E-6	5.5 E-6	5.9 E-6	4.8 E-6
Natural hazard	Ground movement	1.3 E-5	6.9 E-6	3.9 E-6	0.0 E + 0
	Other	1.1 E-6	0.0 E + 0	0.0 E + 0	0.0 E + 0
Third party activity	Accidental	1.2 E-4	9.8 E-5	8.2 E-5	7.6 E-5
	Malicious	1.9 E-5	2.1 E-5	2.9 E-5	5.2 E-5
	Incidental	2.7 E-5	2.5 E-5	2.1 E-5	1.9 E-5
Total		3.8 E-4	3.1 E-4	2.7 E-4	2.8 E-4

occurred along underground line pipe have been included in the analysis, i.e. incidents at pumping stations, sectioning block valves and from overground sections are not included. In a real pipeline risk analysis these need to be added in separately on an individual basis depending on the number and type, etc.

Table 2 shows the failure rates for the line pipe sections only over a number of time periods for the various failure modes. The data for the periods 1971–2006 and 2001–2006 are illustrated in Figure 4, which shows a proportional increase in the number of failures due to third parties.

In addition, accidents statistics have also been analysed for hole size distribution. 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
- 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 3. The 'rupture' hole size is interpreted as any hole size above 150 mm.

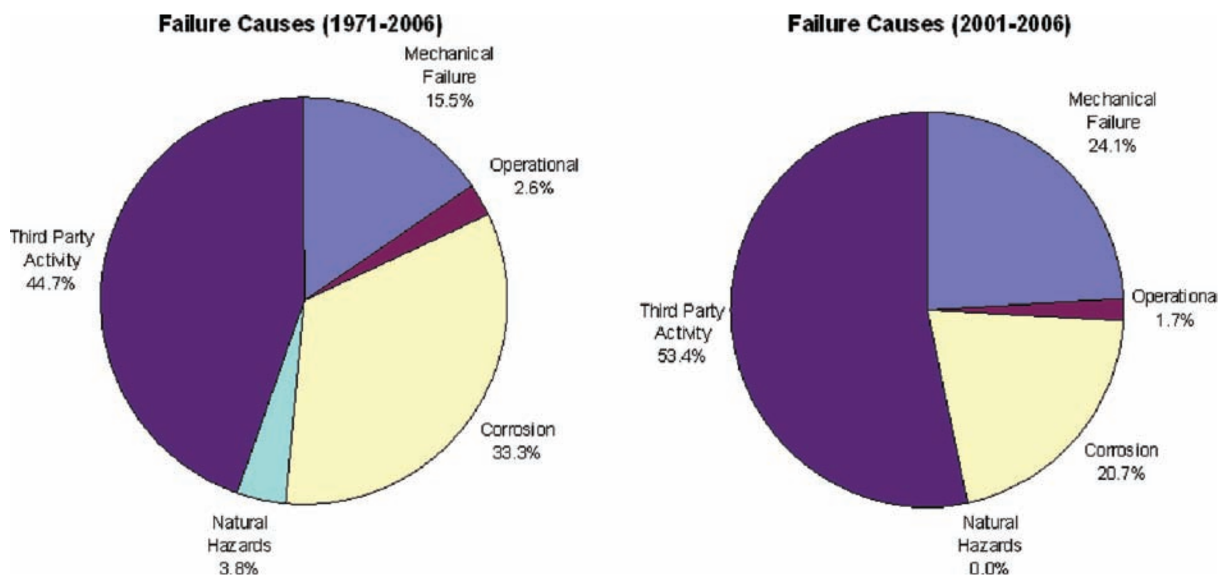

Figure 4. Proportion of failures due to various causes (CONCAWE)

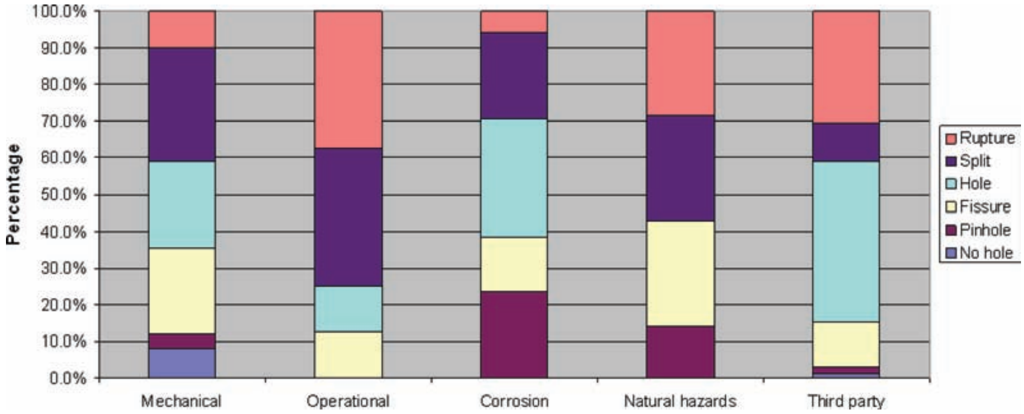

Figure 5. Hole size failure distribution by cause (CONCAWE)

Table 3. CONCAWE failure rate data by failure mode

	Hole size			
Failure mode	5 mm	50 mm	100 mm	Rupture
Mechanical failure	47.3%	42.8%	6.7%	3.3%
Operational	18.8%	43.8%	25.0%	12.5%
Corrosion	54.5%	39.5%	4.0%	2.0%
Natural hazard	43.0%	28.5%	19.0%	9.5%
Third party activity	37.0%	32.5%	20.3%	10.2%

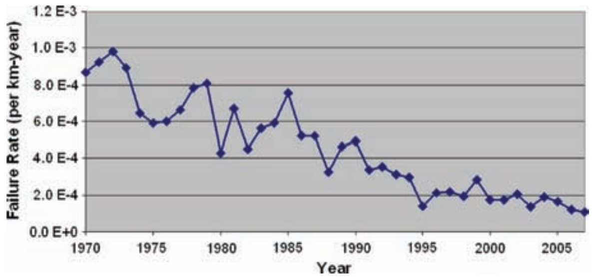

Figure 6. Overall failure rates vs time for EGIG data

EGIG DATA

The European Gas Pipeline Incident Data Group (EGIG) [2] provides failure data collected by a group of 15 major gas transmission system operators in Western Europe for onshore natural gas pipelines with a design pressure of greater than 15 barg. The total pipeline length covered by the study is about 3.15 million km for the period 1970–2007. Pipelines operated by natural gas transmission companies in Denmark, Spain, Belgium, Finland, The Netherlands, France, Germany, Italy, Switzerland, UK, Czech Republic, Portugal, Sweden, Ireland and Austria are included. It should be noted that these data as are not applicable to gas pipelines operating at low pressure.

The main characteristics of the EGIG database are listed below:

- The data are for pipelines over 15 bar (US gas transmission data are for pipelines over 7 bar);
- The data cover natural gas pipelines only;
- A significant number of km-years is included in the database;
- The causes of pipeline failures are well documented and these can be analysed separately;
- Data are separated for different pipeline diameters (and the causes are analysed separately); and
- Data are supplied on the size of failures.

The overall failure rate by year is shown in Figure 6 and the five-year moving average, which shows the downward trend, is shown in Figure 7. Table 4 shows the failure rates for the line pipe sections only over a number of time periods for the various failure modes. It should be noted that the failure cause proportions are constant over this period as interpreted from the data, and illustrated in Figure 8.

In addition, accidents statistics have also been analysed for hole size distribution. The hole size distribution by cause is shown in Table 5 and illustrated in Figure 9, 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.

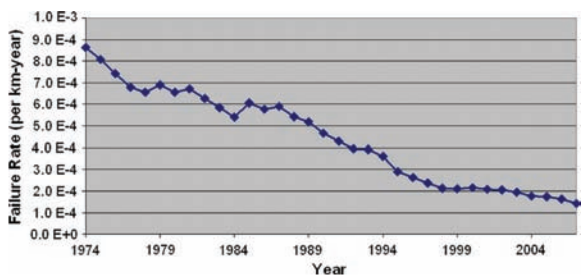

Figure 7. Five-year moving average for EGIG data

Table 4. EGIG failure rate data by failure mode

Failure mode	1970–2007	1980–2007	1990–2007	2000–2007
External interference	2.2 E-4	1.7 E-4	1.1 E-4	7.9 E-5
Construction defect/ Material failure	7.5 E-5	5.5 E-5	3.8 E-5	2.6 E-5
Corrosion	7.0 E-5	5.2 E-5	3.5 E-5	2.4 E-5
Ground movement	3.3 E-5	2.5 E-5	1.7 E-5	1.2 E-5
Hot-tap made by error	2.1 E-5	1.5 E-5	1.1 E-5	7.3 E-6
Other and unknown	3.0 E-5	2.3 E-5	1.5 E-5	1.1 E-5
Total	4.5 E-4	3.4 E-4	2.3 E-4	1.6 E-4

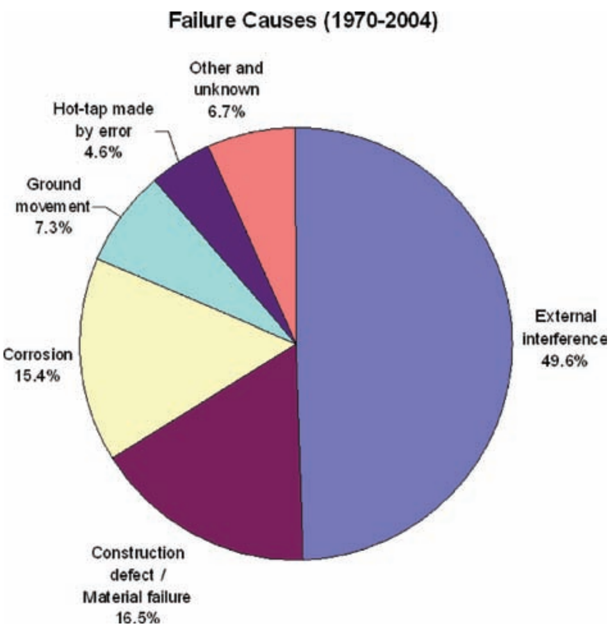

Figure 8. Proportion of failures due to various causes (EGIG)

US DOT DATA

The US Department of Transport (DoT) has a very large database for both hazardous liquids and natural gas pipelines that is available on the internet [3]. The overall numbers show similar failure rate to those of the European pipelines, which reinforces the underlying numbers. Only the failure rate by mode of failure are given here, shown in Table 6 and Table 7 for liquid pipelines and gas transmission pipelines, respectively; further details can be obtained from the internet. The five-year moving averages are shown in Figure 10 and Figure 11 for liquid and gas pipelines, respectively. Interestingly, whilst Figure 10 shows a downward trend in the failure rate for liquid pipelines, similar to CONCAWE, Figure 11 shows that for US gas transmission pipelines, there is actually a slightly increasing failure rate, contrary to EGIG data. This could be due to a change in the data gathering system, where further details are collected; however, the reason for this is not definitive and it needs to be investigated further.

RISK REDUCTION MECHANISMS

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

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 be accidental, intentional or incidental. (Incidental failures are which there is an external impact, which does not cause a failure at that time, but

Table 5. EGIG failure rate data by failure mode

	Hole size			
Failure mode	Unknown	Pinhole/crack	Hole	Rupture
External interference	0.2%	13.2%	26.5%	9.6%
Construction defect/ Material failure	0.1%	11.2%	3.8%	1.4%
Corrosion	0.0%	14.8%	0.5%	0.1%
Ground movement	0.3%	1.8%	2.0%	3.1%
Hot-tap made by error	0.0%	3.0%	1.6%	0.0%
Other and unknown	0.1%	6.2%	0.5%	0.0%

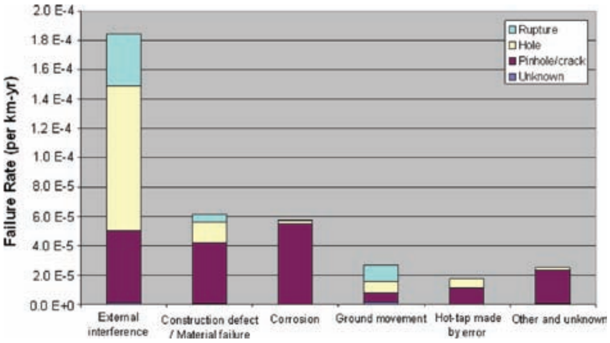

Figure 9. Hole size failure rate by cause (EGIG)

Table 6. US DoT liquid pipelines failure rate data by failure mode

Failure mode	1988–2001	2002–2007
Corrosion	1.1 E-4	
External corrosion		7.0 E-5
Internal corrosion		4.4 E-5
Third party failure – accidental	1.2 E-4	6.7 E-5
Third party failure – intentional		3.8 E-6
Third party failure – incidental		5.1 E-6
Human error	3.7 E-5	2.5 E-5
Material failure	7.7 E-5	4.7 E-5
Natural force damage	1.3 E-5	2.9 E-5
All other causes	1.3 E-4	4.9 E-5
Total	4.9 E-4	3.4 E-4

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,

Table 7. US DoT gas transmission pipelines failure rate data by failure mode

Failure mode	1988–2001	2002–2007
Corrosion	1.3 E-5	
External corrosion		1.7 E-5
Internal corrosion		6.5 E-6
Third party failure – accidental	2.1 E-5	2.0 E-5
Third party failure – intentional		3.3 E-7
Third party failure – incidental		1.0 E-6
Human error		5.1 E-6
Material failure	9.7 E-6	1.6 E-5
Natural force damage	6.0 E-6	6.9 E-6
All other causes	2.3 E-5	1.6 E-5
Total	7.2 E-5	8.9 E-5

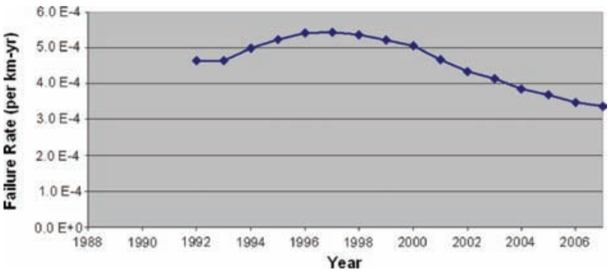

Figure 10. Five-year moving average for US DoT liquid pipelines data

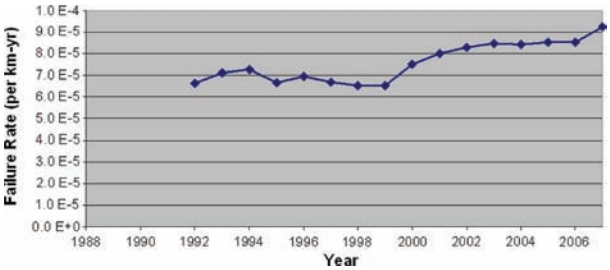

Figure 11. Five-year moving average for US DoT gas transmission pipelines data

- 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 12), 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

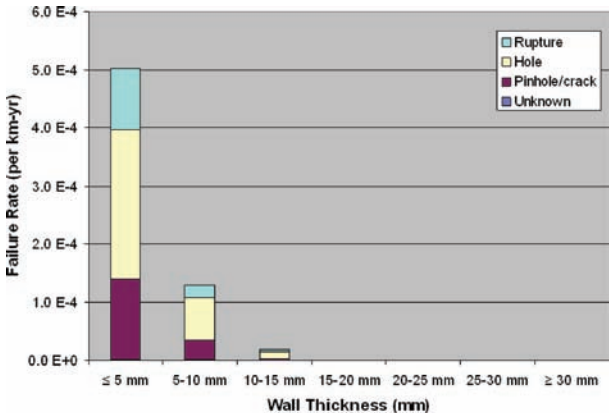

Figure 12. Failure rate vs wall thickness for third party activity (EGIG)

change in elevation.) Certainly, where the WT does not change over a mountainous route, an external impact of a similar magnitude is more likely to cause a failure in a valley rather than at a peak as the pipeline wall will under greater stress in the valley.

The depth of cover may also influence the failure rate, again as shown by Figure 13 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 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 [4], 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.

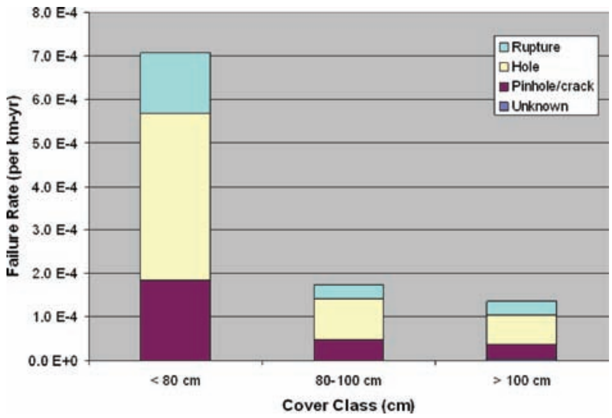

Figure 13. Failure rate vs depth of cover for third party activity (EGIG)

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 shown by the EGIG data (Figure 14), 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.

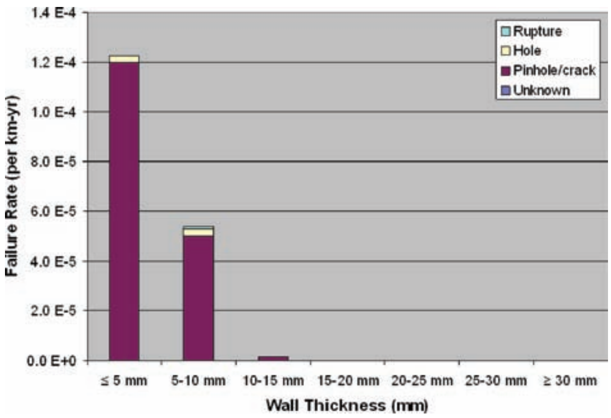

Figure 14. Failure rate vs wall thickness for corrosion (EGIG)

The relationship between pipeline coating, CP and failure rate due to corrosion has been analysed by de la Mare et al. [5] 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 lining are often used if the internal fluid is corrosive in natural, 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 folder 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.

NATURAL HAZARDS

The base failure data contains 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 example 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 deign 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.

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.

OVERPRESSURE PROTECTION

Liquid pipeline 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 are 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 wall thickness 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, propagation to rupture is virtually impossible, as shown by a study conducted by Townsend et al. [6].

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 sometimes increased (i.e. less onerous), e.g. in the UK Institution of Gas Engineers code IGE TD/1, to 0.5 for pipelines with a wall thickness over 19.1 mm. This issue is discussed in further detail in Morgan 1996 [4].

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 spreadsheet tool has been developed by the authors to derive these frequencies from the base data with the appropriate input to modify the based data for the pipeline-specific factors highlighted above.

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