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AN UPDATE TO THE UKOPA PIPELINE DAMAGE DISTRIBUTIONS

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ABSTRACT

The United Kingdom Onshore Pipeline Operators Association (UKOPA) was formed by UK pipeline operators to provide a common forum for representing operators interests in the safe management of pipelines. This includes providing historical failure statistics for use in pipeline quantitative risk assessment and UKOPA maintain a database to record this data.

The UKOPA database holds data on product loss failures of UK major accident hazard pipelines from 1962 onwards and currently has a total length of 22,370 km of pipelines reporting. Overall exposure from 1952 to 2010 is of over 785,000 km years of operating experience with a total of 184 product loss incidents during this period. The low number of failures means that the historical failure rate for pipelines of some specific diameters, wall thicknesses and material grades is zero or statistically insignificant. It is unreasonable to assume that the failure rate for these pipelines is actually zero.

However, unlike the European Gas Incident data Group (EGIG) database, which also includes the UK gas transmission pipeline data, the UKOPA database contains extensive data on measured part wall damage that did not cause product loss. The data on damage to pipelines caused by external interference can be assessed to derive statistical distribution parameters describing the expected gouge length, gouge depth and dent depth resulting from an incident. Overall 3rd party interference incident rates for different class locations can also be determined. These distributions and incident rates can be used in structural reliability based techniques to predict the failure frequency due to 3rd party damage for a given set of pipeline parameters.

The UKOPA recommended methodology for the assessment of pipeline failure frequency due to 3rd party damage is implemented in the FFREQ software. The distributions of 3rd party damage currently used in FFREQ date from the mid-1990s. This paper describes the work involved in updating the analysis of the damage database and presents the updated distribution parameters. A comparison of predictions using the old and new distributions is also presented.

INTRODUCTION

UKOPA

The United Kingdom Onshore Pipeline Operators Association (UKOPA) was founded in 1997 to represent the views and interests of UK pipeline operators responsible for major accident hazard pipelines (MAHPs) regarding safety, legislative compliance and best practice. Its current members include:

- BGE (UK)
- BP
- BPA
- E.On
- Essar Oil (UK)
- ExxonMobil
- GreyStar
- Ineos
- National Grid
- Northern Gas Networks
- OPA
- Sabic
- Scotia Gas Networks
- Shell
- Total
- Wales & West Utilities

UKOPA exists to provide the recognized and authoritative view of UK Pipeline Operators on strategic issues relating to safety management, operations and integrity management of pipelines. It seeks to effectively influence the development and implementation of pipeline related legislation and standards for the mutual benefit of all stakeholders and promote best practice in the pipeline industry.

One of UKOPA's strategic aims is to assist in the risk management of hazardous pipelines by collecting and publishing failure and fault statistics.

Management and Operation of Hazardous Pipelines in the UK

Pipelines in the UK are designed, built, operated and managed in accordance with the goal-setting Pipeline Safety Regulations 1996 (PSR 96)[1] which set out duties to ensure that risk levels from pipelines are "as low as reasonably practicable" (ALARP). The guidance to these regulations[2] states that British Standards provide a sound basis for the design of pipelines and it is generally accepted by the UK safety regulator that a pipeline designed, built and operated to an established UK code, such as PD 8010[3] or IGEM/TD/1[4], is ALARP.

Pipelines are routed on 3rd party land and are therefore susceptible to damage by 3rd parties. Hazardous pipelines are routed to avoid population developments. In the UK the area through which the pipeline is routed is classified according to the population density in a corridor centred on the pipeline. The width of the corridor is defined by the relevant pipeline code according to the hazardous category of the product being transported and vary with pressure and diameter. Where the population density within this corridor is less than or equal to 2.5 persons per hectare, the pipeline is designed to operate at a design factor of 0.72, where the population exceeds 2.5 persons per hectare, the pipeline is designed to operate at a design factor not exceeding 0.3.

Changes in land use adjacent to the pipeline are likely to occur over the design life which can result in increases in population density and buildings constructed in close proximity to the pipeline. This can result in the pipeline becoming non-compliant with the design code.

The UK codes require the pipeline operator to assess infrastructure changes along the route at regular intervals to identify situations where the pipeline no longer complies with the code routing and design requirements, and may pose unacceptable risks to the population. In such cases, the codes allow the use of quantitative risk assessment (QRA) to assess whether the risk levels remain acceptable or if additional risk mitigation measures, such as relaying the pipeline in thicker wall pipe or installing impact protection slabs, are required.

Quantitative Risk Assessment

Risk is generally expressed as a function of the probability and consequences of failure. For pipelines, the failure we are primarily concerned with is of the pipe wall causing a loss of containment and release of pipeline contents.

Quantitative Risk Assessment (QRA) requires the probability of loss of containment and the subsequent consequences to be calculated and combined to determine individual and societal risk levels. Guidance on pipeline QRA has been published in the UK[5, 6, 7] and many papers on specific aspects of pipeline QRA have been previously published at IPC[8, 9, 10, 11, 12, 13].

External interference, or 3rd party damage, is the primary cause of pipeline failure in Europe and one of the major causes in the USA. Failure due to external interference damage also has a higher probability of rupture than, for example, external corrosion which can be detected prior to loss of containment. The frequency of external interference damage is therefore a key component in any gas pipeline QRA that focuses on safety. Determination of external interference failure frequency in QRAs is typically undertaken either by reference to historic failure statistics or by the use of predictive models based on standard pipeline failure equations and structural reliability analysis[13, 14].

Please note that a QRA should consider all significant failure mechanisms for the pipeline in consideration.

HISTORIC FAILURE STATISTICS

Many organizations around the world collect and publish pipeline failure statistics. In the USA, the Department of Transportation's Pipeline and Hazardous Material Safety Administration (PHMSA) currently publishes data online for the last 20 years[15] but data has been recorded since the early 1970s. The National Energy Board in Canada now publishes an annual comparative analysis of pipeline performance from 2000 onwards[16] and also provides data on pipeline ruptures from 1972 onwards[17].

In Europe, the European Gas Pipeline Incident Data Group (EGIG) have collected data on unintentional releases from gas pipelines since 1982[18], although their database contains failure data from 1970. Failure data on European oil pipelines from 1971 onwards is also collected by CONCAWE[19].

UKOPA also collect and publish failure statistics[20]. The UKOPA database is an extension of the original British Gas database and holds data on product loss incidents on pipelines classed as Major Accident Hazard Pipelines (MAHPs) according to PSR 1996[2] back to 1962. UKOPA provides a report to EGIG on behalf of the UK natural gas pipeline operators.

The frequency of failure from each database, for onshore gas transmission pipelines, is shown in Table 1 below.

At first glance, Table 1 shows that the frequency of North American gas transmission pipeline failures is less than the European experience but that European failure rates are decreasing whilst North American rates are increasing.

However, comparing the data between databases can be difficult for a variety of reasons. Each of the databases records data in a slightly different way with different recording criteria and different leak and rupture definitions. The failures in each database also represent pipelines that operate in very different areas, e.g. a large diameter, thick-walled pipeline that runs through remote mountainous regions, will be subject to different threats and will have a different failure rate to small diameter, thin-walled pipelines located in more built up or developed areas.

Source	Period	Exposure (10^6 kmyr)	No. of Incidents	Frequency (x 10^{-3} kmyr)
PHMSA	1992 - 2010	9.01	1383	0.153
	2006 - 2010	2.39	466	0.195
NEB	2000 - 2009	0.25	29	0.102
	2005 - 2009	0.15	21	0.138
EGIG	1970 - 2010	3.55	1249	0.351
	2006 - 2010	0.65	106	0.162
UKOPA	1962 - 2010	0.78	184	0.234
	2006 - 2010	0.11	10	0.093

Table 1: Onshore Gas Transmission Pipeline Failure Data

Perhaps the most important conclusion to be drawn from Table 1 is that gas transmission pipeline failures from all causes are rare.

Unfortunately, this makes using historic data in a QRA difficult. If you split the data by failure cause there may be no external interference failures with the combination of diameter, and wall thickness that match the pipeline which is being analysed. The exposure of pipelines constructed from modern high grade steels is also limited in comparison to more historic grades.

It is therefore common for risk and reliability practitioners to use predictive models to calculate a failure frequency, especially for external interference damage.

EXTERNAL INTEFERENCE FAILURE FREQUENCY PREDICTION

Pipeline Failure Models

The failure models for pipelines with metal loss[21] or dent-gouge damage[22, 23] were originally developed by Battelle and British Gas's Engineering Research Station. These models are well known and commonly used to calculate the failure pressure of specific defects identified by in-line inspection or measured directly in the ditch. If a pipeline is pressure cycled, external interference damage with a failure pressure less than the operating pressure can also fail at a later date due to fatigue.

The failure models can also be used with structural reliability analysis methods to determine the probability of failure for a pipeline given that external interference damage has occurred by treating the input parameters to the equations as probabilistic variables rather than fixed values.

The pipeline parameters, wall thickness, diameter and yield strength may only have a small degree of variation from nominal values and are often modelled as fixed values. They can be modelled probabilistically if data is available to construct pipeline specific distributions or typical distributions around the nominal or mean value may be used[24]. The key variables that must be modelled probabilistically are the defect parameters: gouge length; gouge depth and dent depth.

Monte-Carlo simulation, numerical integration or FORM/SORM techniques can be used to calculate the probability that a given pipeline will fail following an external interference incident.

The probability that a given pipeline will fail following an external interference incident is then multiplied by the incident frequency (or 'hit rate') to obtain the predicted pipeline failure frequency.

Factors which modify the frequency of external interference incidents occurring[5, 6], such as location class, depth of cover, surveillance interval and physical protection measures – like concrete slabbing – can be applied to give a location specific failure frequency.

The current UKOPA recommended methodology for the prediction of failure frequency is implemented in the FFREQ software. The UKOPA version of FFREQ includes the probabilistic defect parameters, expressed as Weibull parameters, as well as the hit rate and modification factors appropriate to pipeline operations in the UK.

The Weibull function describes a versatile distribution that can take on the features of several other types of distribution, depending on the characteristic parameters and is therefore widely used in reliability engineering.

UKOPA DATABASE

The UKOPA database holds pipeline product loss incident data from onshore UK MAHPs operated by National Grid, Scotia Gas Networks, Northern Gas Networks, Wales & West Utilities, Shell UK Ltd. (now Essar Oil (UK) Ltd.), Shell EPE, BP, Ineos, SABIC and E-On UK.

The total length of the participating companies MAHPs is 22,370 km and the total exposure from 1952 to the end of 2010 is 785,385 km years. There are 184 recorded product loss incidents in the database between 1962 and 2010, where a product loss incident is defined as:

- An unintentional loss of product from the pipeline within the public domain outside the fenceline of installations and excluding associated equipment.

The overall average product loss incident frequency is therefore 0.234 x 10^{-3} per km year. Figure 1 shows how the overall average product loss incident frequency since 1962 has declined as the effects of improved steel making, quality control and inspection have removed pipe and weld defects as significant causes of product loss incidents.

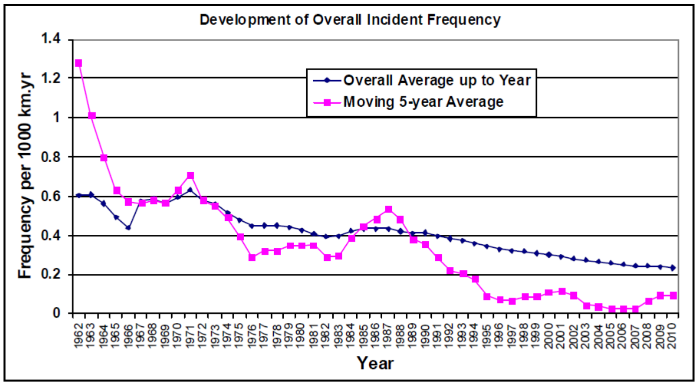

Figure 1: UKOPA Product Loss Incident Frequency

Fault Data

The UKOPA database is unique in that it also holds records of faults, that did not result in pipeline failure and loss of containment.

A fault is defined as any feature that has been confirmed by field investigation, excavation and measurement. Features that are identified by intelligent pig or Close Interval Potential Surveys (CIPS) but have not been verified in the field are not included. There may be several individual defects, e.g. dents or gouges, associated with each fault.

For each fault there are 40 database fields covering the pipeline details at the fault location, details of how the fault was discovered and the dates of previous aerial, CIPS and in-line inspections. For each defect, there are 5 additional fields on defect type, dimensions and orientation.

Up to the end of 2009, the database holds records of 3091 faults and 5122 associated individual defects. Of these, 1293 were caused by external interference.

At the time of writing, no external interference defects had been reported in 2010 but not all member companies have completed their data submission.

CALCULATION OF UPDATED WEIBULL PARAMETERS

Distributions can be generated for the defect data recorded in the UKOPA database. If it is assumed that the defect dimensions are independent of the pipeline that they occurred on, then the distributions will represent the probability of a defect of a certain size resulting given an external incident has occurred.

The independence of the defect dimension from the pipeline is easier to accept for gouge depth and length where the size of damage is more dependent on the power of the excavating machinery causing the damage than the thickness of the wall or diameter of the pipeline.

When denting is considered, the pipeline diameter, wall thickness, internal pressure and the stiffness of the backfill are all likely to influence the dent depth. The denting force of the excavating machine is independent of the pipeline but is more difficult to ascertain than the measured depth.

The distributions included in FFREQ are the gouge length, gouge depth and dent depth.

Data Review

The Weibull defect distributions embedded in FFREQ were last updated in the mid-1990s. Since then the number of companies contributing to the fault database has increased so there is a significant amount of additional data to take into account and in 2010 the UKOPA Risk Assessment Working Group (RAWG) undertook a programme of work to update the Weibull parameters for gouge depth and length and dent depth.

The UKOPA database contains 1293 external interference defect records ranging from superficial damage to the coating only to severe damage including product loss. Like many databases dating back more than 40 years, the records are of varying quality and detail so it is necessary to review and evaluate the data before filtering it into appropriate groups for analysis.

The data for each external interference defect was reviewed and was filtered to produce a working data-set to fit statistical parameters to.

Data was filtered out for the following reasons:

- Incorrectly categorized – text identifies the damage as caused during construction or at the mill not dent-gouge damage during operation; and,
- Coating damage only – where there was no dent or gouge in the pipeline steel.

Following the filtering exercise, the total number of actual external interference defects recorded is 1033. In some cases, the defect depths have not been recorded in the database although other details give confidence that an external interference incident has taken place. Removing these entries gives a total of 689 external interference defects with non-zero depths. Of these, 66 are dents and 623 gouges with 113 of the gouges associated with dents. Table 2 summarizes the filtering process.

Description	Number of Records
Total Unfiltered	1293
Total Filtered (incorrect categories and coating damage removed)	1033
Total with non-zero depth	689
Total non-zero depth Gouges	623
Total non-zero depth Dents	66

Table 2: Number of Eternal Interference Records

Statistical Fit

The defect variables are represented in FFREQ by Weibull parameters. The Weibull distribution can be represented by the following equations for the probability density function f(x) and the cumulative density function F(x), where:

$$f(x) = \frac{\alpha x^{\alpha-1}}{\beta^{\alpha}} e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$$

and

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$$

Where α is known as the shape parameter and β as the scale parameter. The Weibull distribution is commonly used in risk and reliability engineering as it can be used to model a variety of distribution shapes relatively simply.

The defect data has been fitted to weibull shape and scale parameters using two separate methods:

1. Maximum Likelihood Estimator (MLE), implemented using the commercial software @Risk[25]; and,
2. Least Squares Method.

The MLE method implemented in @Risk finds the distribution which gives the statistically best fit. The MLEs for a distribution function are the parameters of that function (in this case the Weibull shape and scale parameters α and β) that maximize the probability that the given data set would have been selected from a population defined by those parameters.

The Least Squares Method minimizes the root mean square error between a straight line fit of a function of the Weibull parameters and the data. This function is found by taking logarithms of the Weibull cumulative probability function such that a straight line form is given where:

$$\ln\left(\ln\frac{1}{1-F(x)}\right) = \alpha \ln x - \alpha \ln \beta$$

F(x) and x are derived from the data. The Weibull scale and shape parameters are then found from the gradient and intercept of the straight line fit to the function derived using the Least Squares Method. The damage data was divided into bins of constant interval size to derive the population cumulative data for the analysis.

The selection of the appropriate distribution was made taking into account a range of goodness of fit tests[26, 27] (Chi-squared, Kolmogorov-Smirnov and Anderson-Darling) using @Risk.

Sensitivity Study

As the raw data contains a reasonable amount of scatter, consideration was also given to which of the derived fits had the best fit in the key mid-range where real defects likely to cause pipe failure are expected to occur. Small defects are extremely unlikely to cause failure. Large defects possible in the tails of the derived distributions are extremely unlikely to occur, and the failure equations are not sensitive to extreme gouge lengths or depths, once a limiting value has been reached.

The effect of the derived parameters on predicted leak and rupture frequency was also investigated by performing a series of failure frequency calculations using the existing and derived Weibull parameters. The calculations were completed for a range of typical UK pipelines with diameters ranging from 168 mm to 914.4 mm, design factors from 0.2 to 0.72 and grades from X42 to X65, this covers the majority of the pipelines included in the UKOPA database.

The failure frequencies calculated using the distribution parameters derived using the least squares method were more conservative than those based on parameters derived using the MLE method.

The calculations also showed a general trend for a small decrease in predicted failure frequency for smaller diameter, thinner walled pipelines and a small increase in predicted failure frequency for larger diameter, thicker walled pipelines. This may be due to the additional data added to the database since the FFREQ parameters were last derived, and changes in pipeline legislation and safety management.

Weibull Parameters

Following the sensitivity study and a review of the results of the new and old predicted frequencies, the updated Weibull parameters in Table 3 were agreed for publication by UKOPA.

Distribution Parameters	Gouge Length	Gouge Depth	Dent Depth
Shape (α)	0.573	0.674	1.018
Scale (β) mm	125.4	0.916	9.382

Table 3: UKOPA External Interference Weibull Parameters

The Weibull cumulative probability distributions are plotted in the figures below.

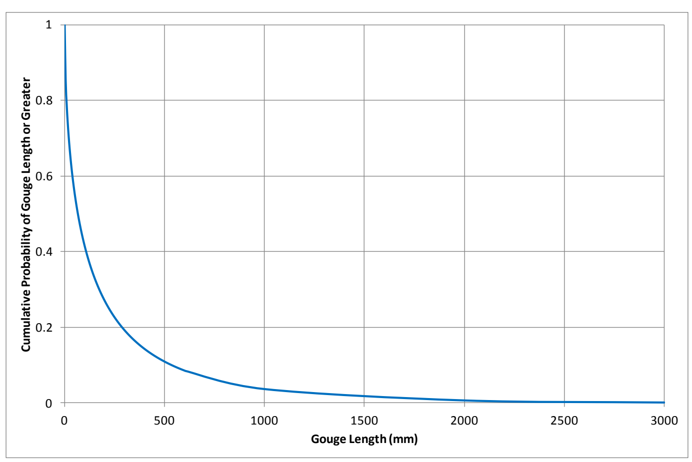

Figure 2: Gouge Length

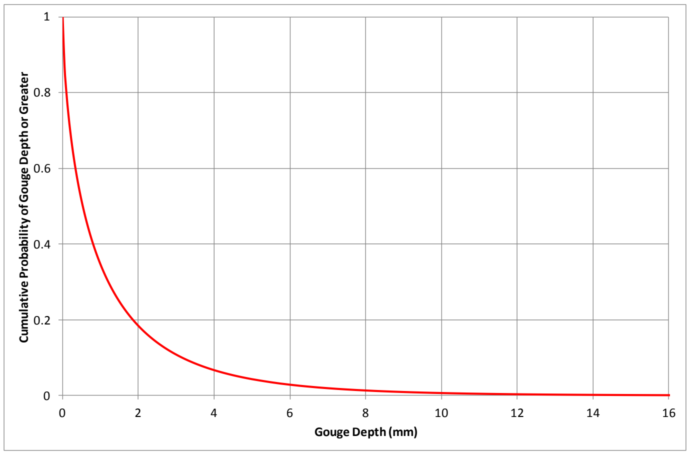

Figure 3: Gouge Depth

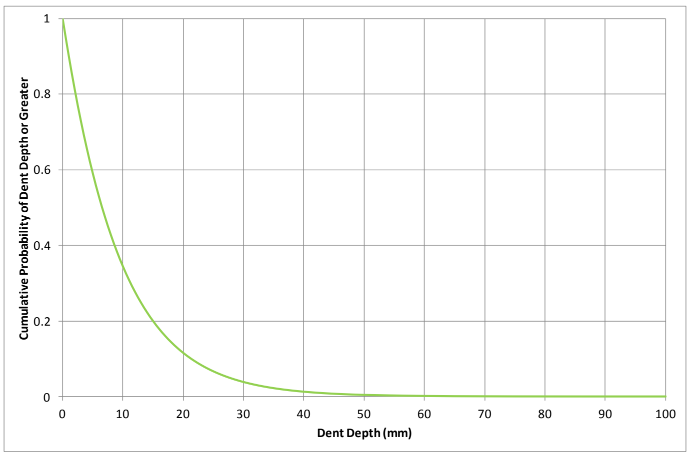

Figure 4: Dent Depth

FREQUENCY OF EXTERNAL INTERFERENCE

The number of individual external interference incidents in the UKOPA database up to the end of 2009, with non-zero depth, is 689 and the corresponding exposure is 763,289 km years.

Therefore the frequency of external interference is 0.903 per thousand km years. This frequency is for UK Rural area types (class location) and is for the average depth of all incidents in the database.

CONCLUSIONS

UKOPA external interference defect data from 1962 to 2009 has been reviewed and filtered and Weibull parameters fitted to the filtered data.

UKOPA recommend the use of these parameters and associated external damage 'hit-rate' for the prediction of pipeline failure frequencies due to external interference in the UK.

These damage distributions are likely to be acceptable for use in other countries where the population of pipelines and excavating equipment is broadly similar but care must be taken with the incident rate, which may vary according to local legislative controls and pipeline management practices. UKOPA recommend that other industry bodies around the world consider collecting defect and exposure data in order to improve predictions of external interference failure frequency.

Consideration should also be given to the use of a denting force distribution rather than dent depth and UKOPA plan to review the data to determine if such a change can be made and the likely effect on predicted failure rates.

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