Assessment of the Applicability of Failure Frequency Models for Dense Phase Carbon Dioxide Pipelines

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Keywords

Failure Frequency; Pipeline; Carbon Dioxide; Third Party External Interference; Dense Phase

The Don Valley Power Project is co-financed by the European Union's European Energy Programme for Recovery
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Abstract

In Carbon Capture, Usage and Storage (CCUS) schemes, Carbon Dioxide (CO_2) is captured from large scale industrial emitters and transported to geological sites for storage. The most efficient method for the transportation of CO_2 is via pipeline in the dense phase. CO_2 is a hazardous substance which, in the unlikely event of an accidental release, could cause people harm. To correspond with United Kingdom (UK) safety legislation, the design and construction of proposed CO_2 pipelines requires compliance with recognised pipeline codes. The UK code PD-8010-1 defines the separation distance between a hazardous pipeline and a nearby population as the minimum distance to occupied buildings using a substance factor. The value of the substance factor should be supported by the results of a Quantitative Risk Assessment (QRA) approach to ensure the safe design, construction and operation of a dense phase CO_2 pipeline.

Failure frequency models are a major part of this QRA approach and the focus of this paper is a review of existing oil and gas pipeline third-party external interference failure frequency models to assess whether they could be applied to dense phase CO_2 pipelines. It was found that the high design pressure requirement for a dense phase CO_2 pipeline typically necessitates the use of high wall thickness linepipe in pipeline construction; and that the

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wall thickness of typical dense phase CO_2 pipelines is beyond the known range of applicability for the pipeline failure equations used within existing failure frequency models. Furthermore, even though third party external interference failure frequency is not sensitive to the product that a pipeline transports, there is however a limitation to the application of existing UK fault databases with to onshore CO_2 pipelines as there are currently no dense phase CO_2 pipelines operating in the UK. Further work needs to be conducted to confirm the most appropriate approach for calculating failure frequency for dense phase CO_2 pipelines, and it is recommended that a new failure frequency model suitable for dense phase CO_2 pipelines is developed that can be readily updated to the latest version of the fault database.

1. Introduction

Carbon Capture, Usage and Storage (CCUS) is recognised by the United Kingdom (UK) Government (Department for Business, Energy & Industrial Strategy, 2017) as one of a suite of solutions required to reduce carbon dioxide (CO_2) emissions into the atmosphere and prevent catastrophic global climate change. In CCUS schemes, CO_2 is captured from large scale industrial emitters and transported, predominantly by pipeline, to geological sites, such as depleted oil or gas fields or saline aquifers, where it is injected into rock formations for storage.

The most efficient method for the transportation of CO_2 is via pipeline in the dense phase, i.e. above the critical pressure but below the critical temperature. This is because, in the dense phase, CO_2 has the density of a liquid but the viscosity and compressibility of a gas (Downie, Race and Seevam, 2007). The presence of impurities in the captured CO_2 will affect the critical temperature and pressure (Wetenhall, Race and Downie, 2014), and pipelines transporting this CO_2 may require operating pressures in excess of 150 barg to ensure single phase flow (Noothout et al, 2014).

The National Grid COOLTRANS (CO2Liquid pipeline TRANSportation) research programme (Cooper and Barnett, 2014a) was carried out to address knowledge gaps in the design, construction and operation of dense phase CO_2 pipelines in the UK. The aim of the programme was to develop a comprehensive Quantitative Risk Assessment (QRA) methodology for dense phase CO_2 pipelines, which could be used in routeing and design studies to ensure that the risk level from the CO_2 pipeline is as low as reasonably practicable in accordance with UK legislation. Calculation of failure frequency is an important part of a pipeline QRA and failure frequencies from all possible failure causes must be determined including corrosion, ground movement, mechanical and third party external interference. As part of the COOLTRANS research programme, a review was conducted to ascertain the technical basis and data on which existing models are used to calculate failure frequency due to third-party external interference and to evaluate the suitability of the models for use as part of a QRA methodology for dense phase CO_2 pipelines. This paper documents part of the review.

2. The Requirement for a Failure Frequency Model for Dense Phase CO_2 Pipelines

Being toxic, CO_2 is a hazardous substance, which in the unlikely event of an accidental release, could cause harm to people. To comply with UK safety legislation, the design and construction of proposed CO_2 pipelines requires compliance with recognised pipeline codes. Given that there are CO_2 pipelines operating in the US (Knoope et al., 2014), it may be desirable to adopt the United States (US) code for use in the UK. In the US, CO_2 pipelines are designed, constructed and operated in accordance with the US Federal Code of Regulations, Title 49, Volume 3, Part 195 - Transportation of Hazardous Liquids by Pipeline and the associate American Society of Mechanical Engineers (ASME) standards B31.4 and B31.8. However, according to the UK Health and Safety Executive (HSE) guidance (HSE, 2008), there are specific issues that prevent the adoption of the US pipeline codes within the UK. Firstly, the US code of regulations applies only to pipelines transporting CO_2 in the supercritical phase and therefore may not be completely relevant to pipelines conveying dense phase CO_2, i.e. a subcooled liquid. Secondly, the standard for gas transportation, ASME B31.8, specifically excludes pipelines carrying CO_2 (in any phase), and whilst the standard for liquid transportation, ASME B31.4, does not exclude pipelines transporting CO_2, it does not include CO_2 on the list of fluids for which the code is intended to apply. It was therefore concluded by the UK HSE guidance (2008) that there may be limited technical benefit in adopting US codes or standards, either in their entirety or in part, for CO_2 pipeline design and construction in the UK.

For the above reasons, it is required that the UK pipeline design code be modified in order to account for the pipelines transporting dense phase CO_2. The UK code PD 8010: Part-1 defines the separation distance between a hazardous pipeline and a nearby population as the minimum distance to occupied buildings (MDOB) using a substance factor which gives cautious estimates of the MDOB according to the hazardous nature of the substance (BSI, 2015). The value of the substance factor should be supported by reference to joint industry or project specific research and guidance on the routeing of pipelines conveying CO_2 (Cooper and Barnett, 2014b). A QRA approach, which involves the numerical estimation of risk from a calculation of the frequencies and consequences of a complete and representative set of credible accident scenarios, is therefore required to ensure the safe design, construction and operation of a dense phase CO_2 pipeline.

The procedure for conducting a risk assessment for pipelines carrying flammable fluids, is well established and embedded in industry guidance and codes of practice. Recommended QRA methodologies based on best practice are published in the supporting Institution of Gas Engineers and Managers (IGEM) standard IGEM/TD/2 (IGEM, 2008) and British Standards

Institution code PD 8010: Part-3 (BSI, 2013). The code PD 8010: Part-3 notes that while the QRA methodology addresses thermal hazards only, its principles can also be applied to toxic hazards.

The purpose of a CO_2 pipeline QRA is to determine the risks posed by the pipeline to people located nearby. The procedure involves the identification of hazard scenarios and considers both the probability and consequences of failure in order to calculate values for the individual and societal risks. The QRA process is outlined by the flow chart in Figure 1, indicated by the shaded boxes on the left hand side of the chart. This chart has been adapted from Figure 3 of PD 8010: Part-3 (BSI, 2013) by modifying the consequence calculations to make them appropriate for a toxic, rather than flammable fluid. The probability of failure is calculated through determination of the failure frequencies for all credible threats to the pipeline. The consequences of failure are calculated by considering the dose of CO_2 which an individual may be subjected to following a pipeline release. The consequences of failure therefore require prediction of the dispersion behaviour of a cloud of CO_2 following release. The consequence modelling has been extensively researched (Molag and Dam, 2011; Koornneef et al., 2009), however far less work has been published regarding CO_2 pipeline failure frequencies.

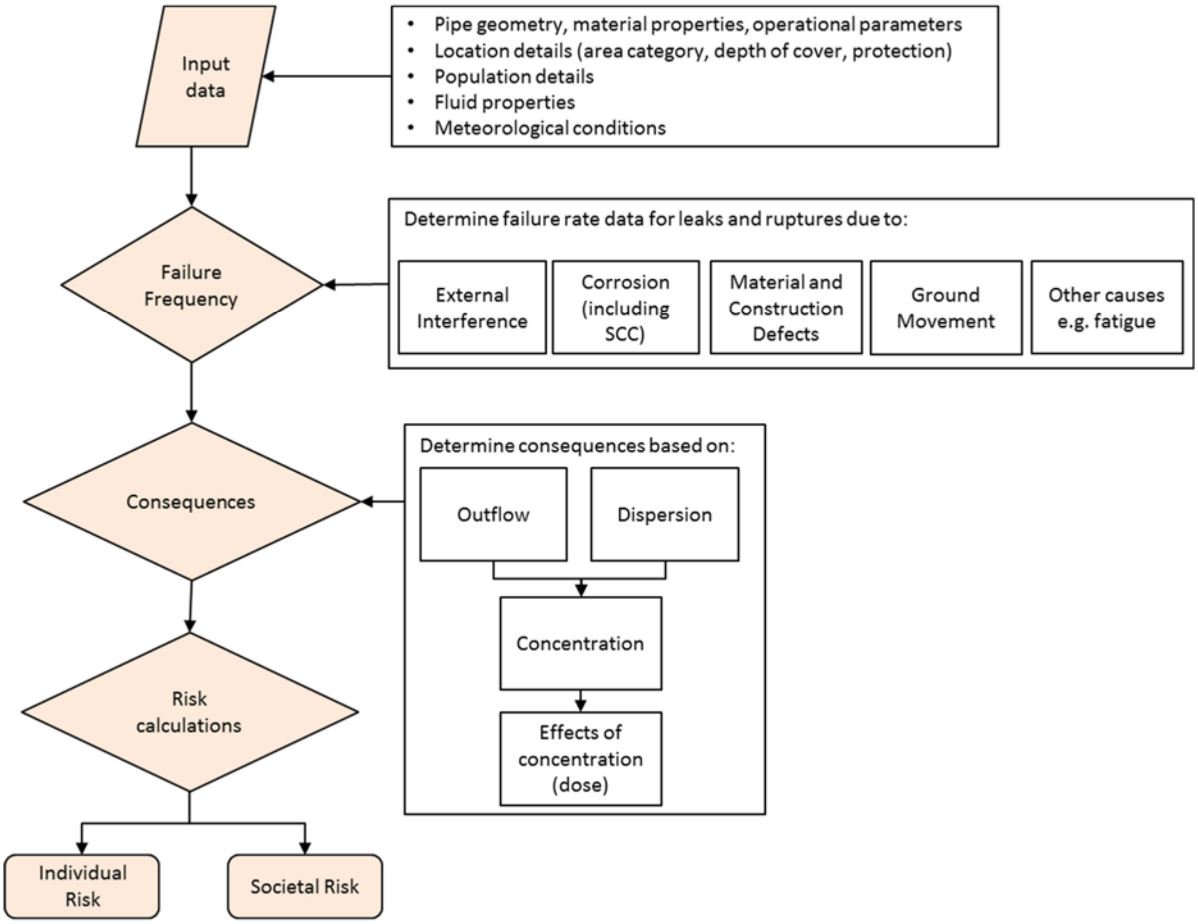

Figure 1: – Risk calculation flow chart for CO_2 pipelines

CO_2 pipeline failure can occur due to numerous different mechanisms including third party external interference, corrosion (internal and external), material and construction defects, natural events such as ground movement and other causes such as fatigue; all of which must be considered as part of the assessment (Goodfellow, 2006). This paper focuses on third party external interference for two reasons; firstly, accidental or intentional human actions are one of the main causes of pipeline failures (Cooper and Barnett, 2014b); and secondly this damage cause may be random and is typically outside of the direct control of the pipeline operator. External interference of a pipeline by a third party can result in mechanical damage to that pipeline, which can occur in the form of dents, gouges, a combination of dents and gouges and punctures. A dent will cause an area of local stress concentration and is a deformation of the wall of the pipeline as shown in Figure 2, where *D* is the pipeline external diameter; *H* is the depth of dent in the pipeline and *t* is the pipeline wall thickness. A gouge is a defect which is defined by a loss of material from the pipe wall and is illustrated in Figure 3, where c is half of the axial defect length; d is defect depth. A gouged dent (see Figure 4) is a combination of both a dent defect and a gouge defect. Third party interference can also result in damage to branches and fittings on a pipeline; failure can occur if these attachments are severely damaged or severed from the pipeline. From a risk assessment point of view, the most important factor in pipeline failure is whether the failure will occur as a leak or as a rupture. A leak is defined as a failure which is stable. A rupture is defined as a failure which is unstable and is significantly worse than a leak in consequence terms.

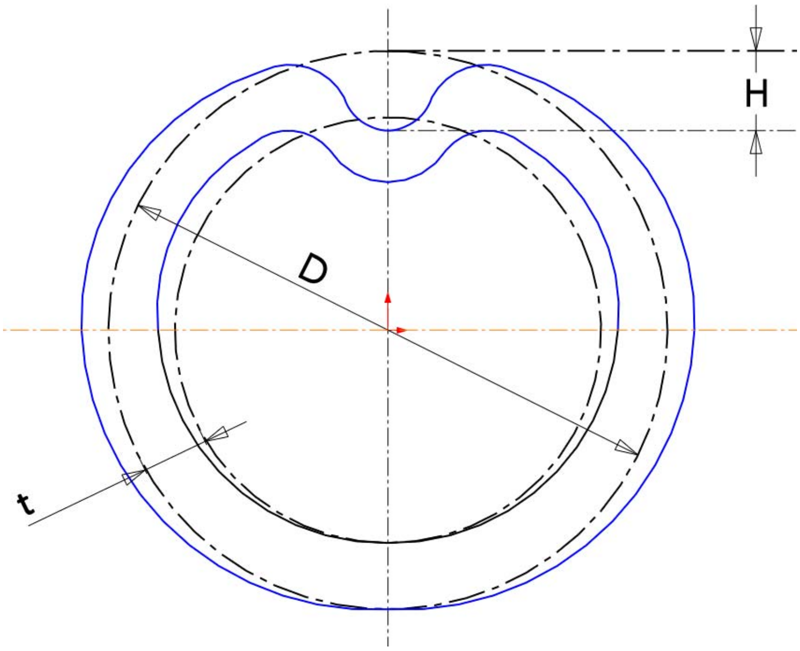

Figure 2: A representation of a pipeline dent

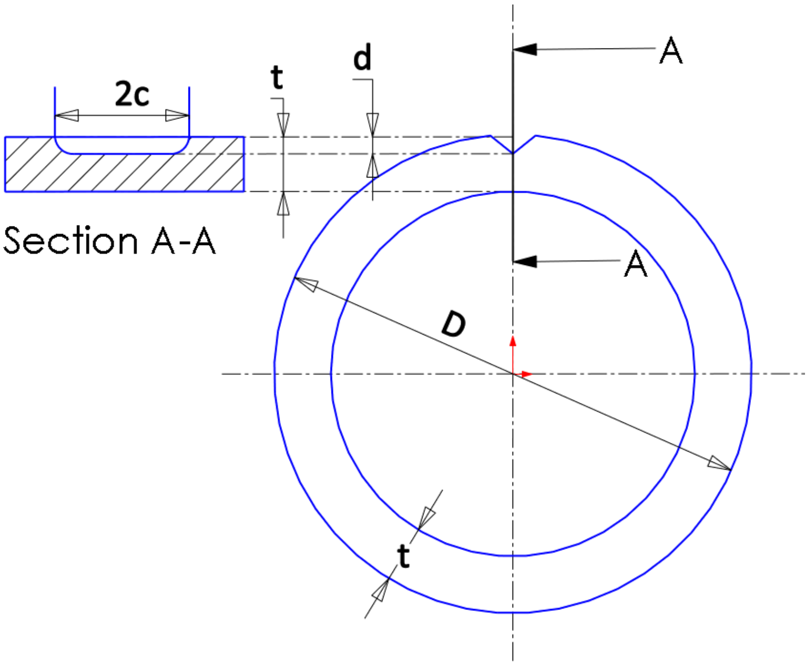

Figure 3: A representation of a pipeline gouge

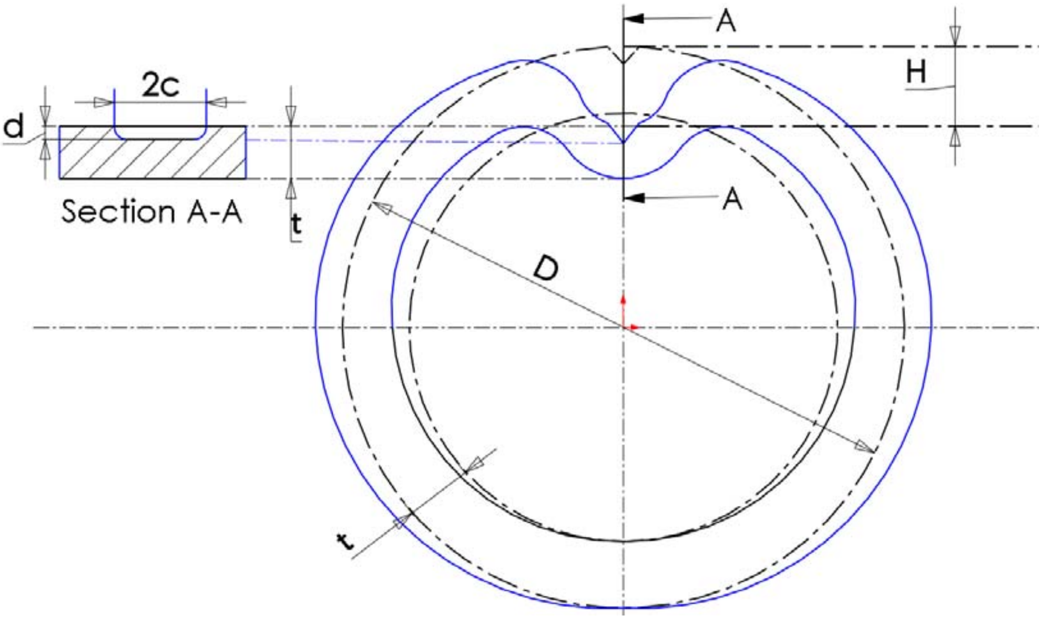

Figure 4: A representation of a gouged dent

Third party external interference failure frequency models have been used in the oil and gas pipeline industry for over 25 years. Given the principles of containment, stress and fracture, and that all high-pressure pipelines are constructed using steel, third party external interference failure frequency, is not sensitive to the product that a pipeline transports. Indeed Parfomak and Fogler (2007) proposed that '*statistically, the number of incidents involving* CO_2 *pipelines should be similar to those for natural gas transmission pipelines*'. Thus, the models used to calculate third party external interference failure frequency for oil and gas pipelines may also be applicable to dense phase CO_2 pipelines. This study is intended to review the current pipeline failure frequency models and assesses whether they may be extended to calculate pipeline failure frequency due to third party external interference for dense phase CO_2 pipelines.

3. Overview of Existing Failure Frequency Models

For oil and gas pipelines, the frequency of pipeline failure due to third party external interference has traditionally been calculated using models based upon probabilistic, structural reliability methods. They are applied by combining the following:

- Limit state functions which are mathematical models which define the conditions for failure (discussed in Section 3.1);
- Probability distributions of selected random variables based on historical data (discussed in Sections 3.2 and 3.3) and
- A mathematical technique to calculate the probability of failure (e.g. Numerical Integration, Monte Carlo, First Order Reliability Methods).

For pipelines, the limit state functions are based on semi-empirical fracture mechanics failure equations; and the probability distributions are based on pipeline damage from historical operational data. Failure probability is converted into failure frequency to take into account the regularity of third party external interference damage.

3.1. Limit State Functions

The limit state functions define the conditions for failure in terms of the size of the defect, the pipeline geometry, and the material properties of the linepipe steel. They are based upon empirical or semi-empirical fracture mechanics failure equations for the failure of defects in linepipe.

For all failure frequency models, separate limit state functions are required to describe the following:

- Leak / rupture
- Gouge failure
- Gouged dent failure

The failure frequency models reviewed in this paper use limit state functions based on the flow stress dependent form of the through-wall NG-18 equation (Kiefner, Maxey, Eiber and Duffy, 1973) to determine whether damage will fail as a leak or rupture, the flow stress dependent form of the part-wall NG-18 equation (Kiefner, Maxey, Eiber and Duffy, 1973) to determine whether a gouge will fail and the British Gas Dent-Gouge Fracture Model (BGDGFM) (Hopkins, 1992) to determine whether a gouged dent will fail.

3.1.1. The NG-18 Equations

The NG-18 equations were developed by the Battelle Memorial Institute in the 1970s (Cosham, 2002) and because of their accuracy and simplicity they have become accepted as the industry standard for defect assessment, have been included as part of defect assessment codes and have been used extensively since their introduction. The equations are semi-empirical and are based upon the Dugdale (1960) strip-yield model and a series of full scale experimental burst tests of vessels with through-wall and part-wall defects (Cosham, 2002).

Based upon the operating conditions of a pipeline, the through-wall NG-18 equation is used to determine whether an axially oriented through-wall defect will lead to a full-bore rupture or remain as a leak while the part-wall NG-18 equation is used to determine whether an axially oriented part-wall defect (i.e. a gouge) will progress into a through-wall defect.

Both the through-wall and the part-wall NG-18 equations exist in two forms: toughness dependent and flow stress dependent. Flow stress is a measure of the stress at which unconstrained plastic flow occurs. In the failure frequency models, the flow stress dependent form of the through-wall and part-wall NG-18 equations is used over the toughness dependent form due to the high toughness of modern steels used for linepipe. The flow stress was empirically determined from a series of full scale burst tests of vessels.

3.1.2. The British Gas Dent Gouge Fracture Model (BGDGFM)

The BGDGFM is used to determine, based upon the current operating conditions of the pipeline, whether a part-wall gouged dent defect will progress into a through-wall defect. Assuming that part-wall gouged dent failure occurs due to a combination of brittle fracture and plastic collapse, the BGDGFM was developed by British Gas in the early 1980s (Cosham, 2001). It is semi-empirical and is based upon a modified version of the Dugdale strip-yield model and series of experimental ring and vessel tests with artificial gouged dent defects created at zero pressure.

The BGDGFM was calibrated using experimental tests for which the gouged dent damage was created and measured in an unpressurised pipeline.It is noted that the BGDGFM assumes the gouge is of infinite length and gouge length is not explicably included.

3.2 Incident Rates

The frequency with which a pipeline is subject to a gouge or gouged dent is known as an incident rate and is based upon historical data. In the UK, this historical database is the United Kingdom Onshore Pipeline Operators’ Association (UKOPA) Fault Database (Cosham, 2007) which is subject to an annual update to include new data. The UKOPA database includes data from the Engineering Research Station (ERS) Fault Database, a database encompassing all of the transmission pipelines in the onshore gas transmission system in the UK. The database records details of all known pipeline faults and failures, which were subject to an excavation and on-site assessment, from 2016 dating back to 1962.

An Incident-Rate value is derived from the number of third party external interference mechanical damage incidents and a value for operational exposure. This is then used, alongside the probability of failure, to calculate the total failure frequency rate.

3.3 Probability Distributions and Calculating the Probability of Failure

The failure frequency models described in this paper use random variables in the calculation of the probability of failure. These variables appear in the limit state functions as, for example, gouge length, gouge depth or gouge dent depth. The majority of the failure frequency models reviewed here use fitted Weibull cumulative probability distributions to describe the random variables. The Weibull distributions were fitted based on pipeline damage data and were chosen due to their versatility in allowing a wide variety of physical quantities to be accurately represented.

In a failure frequency model the cumulative distribution functions for each random damage variable then allow the probability of a gouge or gouged dent damage of a certain size or greater to be calculated using numerical integration or by statistical methods. The total failure frequency can then be calculated by combining the probability of failure with the incident rate.

4. Review of Existing Failure Frequency Models

The various models currently in use within the oil and natural gas pipeline industry differ in their subtleties; however all are based upon a methodology originally developed by British Gas. They are briefly described in the following sub-sections starting with the British Gas Engineering Research Station (ERS) Hazard Analysis Model.

4.1. The British Gas ERS Hazard Analysis Model

A model to calculate pipeline failure frequency due to third party external interference was developed at the British Gas ERS in the 1980s. The model uses a combination of structural reliability methods and trends derived from historical operational data to calculate a value for failure frequency. Failure frequency is calculated for a user defined pipeline based upon its diameter, wall thickness, operating pressure, steel grade, fracture toughness and area type (Matthews, 1984; Corder, 1985a; Corder, 1985b; Corder, 1986).

4.1.1. Hazard Analysis Model Structural Reliability Component and Limit States

The structural reliability based component of the Hazard Analysis model considers the failure of part-wall damage and through-wall punctures. In this part of the model, pipeline failure is considered to occur via one of three damage failure mechanisms:

- Failure of a gouge.
- Failure of a gouged dent.
- Direct breach of a pipe wall.

In the model, pipeline failure frequency is therefore dependent on:

- The frequency with which a pipeline is subjected to a gouge;
- The frequency with which a pipeline is subjected to a gouged dent;
- The probability of failure of a gouge; and
- The probability of failure of a gouged dent.

Additionally, the model considers that pipeline failure will result in either a leak or a rupture.

The limit state functions used in the Hazard Analysis model define the conditions for failure in terms of the size of the defect, the pipeline geometry and the material properties of the linepipe steel. In order to determine whether damage will fail as a leak or rupture, a critical defect length is defined using the flow stress dependent form of the through-wall NG-18 equation. In order to determine whether a gouge will fail, a critical gouge depth is defined using the flow stress dependent form of the part-wall NG-18 equation (Kiefner, Maxey, Eiber and Duffy, 1973). In order to determine whether a gouged dent will fail, a critical dent depth is defined using the BGDGFM (Hopkins, 1992).

4.1.1.1. Hazard Analysis Model Incident Rates

In the Hazard Analysis model four different incident rates are used. In addition to the different values required for gouges and gouged dents, the incident rates are also split depending on whether the land through which a pipeline is routed is rural (R-type) or suburban (S-type) as different machinery operating in different areas produced different damage profiles. The incident rates are based upon an analysis of the ERS Fault Database.

4.1.1.2. Hazard Analysis Model Probability Distributions

The Hazard Analysis model uses six random variables to describe the size of the gouge or dent defect within the limit state functions: Gouge Length, Gouged Dent Gouge Length, Gouge Depth in Rural Type Areas, Gouge Depth in Suburban Type Areas, Gouged Dent Gouge Depth and Gouged Dent Depth. Six separate Weibull probability distributions were derived to describe the six random variables using defect size data from the ERS Fault Database. All of the other variables, describing pipeline geometry and material properties, in the limit state functions were assumed to be deterministic quantities.

4.1.1.3. Hazard Analysis Model Probability of Failure of a Gouge and a Gouged Dent

The probability and frequency of failure for gouge and gouged dent damage in the Hazard Analysis model are calculated using numerical integration with the trapezium rule (Matthews, 1984; Corder, 1985a). However, it is noted that the gouge length Weibull distribution was truncated at 1,397 mm. The leak, rupture and total failure frequency are then calculated by combining the incident rate with the probability of failure.

4.1.2. Hazard Analysis Model Historical Data Component

The historical data component of the Hazard Analysis model considers through-wall damage only. In this part of the model, a value for failure frequency is determined for failures resulting from damage to branches and fittings on the pipeline. The failure frequency is determined directly from historical operational data for failures of this type contained in the ERS Fault Database. The overall leak, rupture and total failure frequency are calculated by combining the results from the structural reliability component and the historical data component.

4.1.3. Summary of Hazard Analysis Model

The Hazard Analysis model uses the combination of a structural reliability component (including the NG-18 Equations and BGDGFM) and an historical data component. Developed in the 1980s, it uses the old ERS Fault Database and has been replaced by other models described in the following sections.

4.2. FFREQ

FFREQ is the current UK pipeline industry standard model for calculating pipeline failure frequency due to third party external interference. The model was developed by British Gas as an update to the Hazard Analysis model described in Section 4.1 (Corder, 1993; Corder, 1995) and exists in the form of a software package. As with Hazard Analysis, FFREQ uses the combination of a structural reliability component and an historical data component in order to calculate a value for failure frequency. Certain modifications and augmentations were made to the failure frequency calculation methodology used in Hazard Analysis in order to produce FFREQ, but these were poorly documented.

This model offers comprehensive features and includes additional functionality to take into account the resistance of pipes to denting, the pipeline depth cover (pipelines that are buried deeply are less prone to damage) and the option to include a sleeve (an additional layer of protection) analysis. However, users do not have access to the FFREQ source code and can only enter input data and receive an output. This was compounded by the lack of definitive documentation as to the exact content of the model. It is therefore not possible to determine the exact changes made between Hazard Analysis and FFREQ. However, the limit state functions used are identical to those used in the Hazard Analysis model (Corder, 1993; Corder, 1995) meaning that the structural analysis in FFREQ is based on the NG-18 Equations and the BGDGFM.

4.3. PIPIN

PIPeline INtegrity model (PIPIN) is the model used by the HSE to determine failure frequencies for the four largest causes of failure (construction defects, natural events, corrosion and third party external interference), for a user defined pipeline. The model was developed for the HSE by W.S. Atkins in the late 1990s (HSE, 2003). Certain elements of the PIPIN model are based upon the pipeline failure frequency methodology developed by British Gas and used in the Hazard Analysis model. However, due to differences in application; changes to the methodology; and updated statistics, the PIPIN and Hazard Analysis models appear notably different to each other. In PIPIN, the structural reliability component and the historical data component are completely distinct and produce failure frequency values relating to different causes. Failure frequencies for construction defects, natural events and corrosion are determined using the historical data component. The structural reliability component of PIPIN is directly analogous to the structural reliability component of the Hazard Analysis model and is used to calculate the failure frequencies for third party external interference. Failure stress is determined by the NG-18 Equation. For the gouged dent limit state function, PIPIN uses a limit state function based on the Dugdale strip-yield model (as in the BGDGFM model). Like FFREQ, the PIPIN model includes the effect of depth of cover.

When compared with other models, there are many unique features to the PIPIN model. Firstly, the limit state function for leak/rupture is defined using the British Energy R6 rev. 3 assessment procedure (Milne, Ainsworth, Dowling and Stewart, 1988) and this introduces a brittle fracture component to the failure; secondly, additional distributions are used to describe uncertainty in parameters such as the pipeline diameter, wall thickness and the limit state functions themselves in an attempt to produce a more realistic representation of failure frequency; and finally, the probability and frequency of failure for gouges and gouged dents in PIPIN are calculated using the Monte Carlo method. Like FFREQ, PIPIN also includes additional functionality to take into account the resistance of pipes to denting.

However, there is some uncertainty regarding the use of operational data within the PIPIN model. For example it is not clear, whether data from both S-type and R-type areas in the UKOPA Fault Database were included in the derivation of the PIPIN gouge depth distribution; the source of the random variable distributions for the limit state functions; and how data regarding punctures and failure from damage to branches and fittings were treated in the derivation of the damage dimension distributions.

4.4. PIE

In the 20 year period since the development of the Hazard Analysis model, FFREQ had been widely adopted within the pipeline industry to calculate third party external interference failure frequencies for QRA. The reliance on FFREQ however raised concern, given the somewhat opaque nature of the model. It was also felt that since FFREQ was developed in 1993, there existed many years of additional operational data, which could be used to provide updated and more accurate probability distributions and incident rates. To address this, the PIE model was developed by Pipeline Integrity Engineers (PIE) in 2006 (Lyons, 2006; Haswell, 2008; Lyons, 2008) as a reproduction of the failure frequency methodology from the Hazard Analysis model. The model was developed for UKOPA in order to address the above issues, and to investigate and understand the impact of pipeline parameters on failure frequency due to external interference, and the significance of the damage data recorded in the UKOPA Pipeline Fault Database.

The PIE model was developed using the original documentation relating to the development of the Hazard Analysis model, in addition to the 2005 UKOPA Fault Database. Although the model was an attempt to directly reproduce the Hazard Analysis model with updated operational data, it is somewhat simplified in comparison. In particular, the model does not include an historical data component. The six random variables from the Hazard Analysis model were consolidated in the PIE model with data from both gouges and gouged dents being used together to derive single distributions for gouge depth and gouge length distributions and no distinctions are made between data from S-type and R-type areas. Additionally, the incident rate also makes no distinction between gouges and gouged dents.

4.5. Cosham Model

In 2007, UKOPA commissioned a study to investigate "*risk reduction factors*", which were included in the pipeline integrity management code supplement PD 8010: Part-3 (BSI, 2013). As part of this study a probabilistic model was developed, hereafter referred to as the "Cosham model", which could be used to calculate the probability of failure of a pipeline due to mechanical damage. This model was used to determine probabilistic risk reduction factor values which could then be compared with the deterministic values included in the code (Cosham, 2007).

The Cosham model is based upon the Hazard Analysis Model and its limit state functions are almost identical to those used in the Hazard Analysis Model (it uses different coefficient values). However, it does not calculate the pipeline failure frequency as with the other models reviewed; instead it is concerned only with the probability of failure and it uses direct integration rather than numerical integration to produce its output. Additionally, the model does not include an historical data component, basing its output entirely on structural reliability methods. Like FFREQ, the Cosham model considers the resistance of pipes to denting, and also includes a relationship to account for the "re-rounding" effect of internal pressure. Similar to the PIE model, the Cosham model uses consolidated damage variables which make no distinction between gouge and gouged dent damage in terms of the gouge length and gouge depth, or between S and R area types.

4.6. Penspen Damage Distributions Update

The development and publication of the PIE model instigated a discussion within UKOPA regarding future recommendations on models to calculate pipeline failure frequency due to third party external interference. UKOPA ultimately decided that FFREQ would remain the recommended model for use in the industry. It was acknowledged however, that updates of the incident rates and probability distributions used in FFREQ were required to take account of more recent operational data; and that these updates should be continuous and take place on a regular basis. In 2010 UKOPA commissioned Penspen to update the probability distributions and incident rates for FFREQ (Goodfellow, 2012) using the most up to date data (as of 2009).

Despite the fact that the motivation for the study was to provide an update to FFREQ, the probability distributions and incident rate derived by Penspen are actually more suited to the simplified nature of the PIE model. The variables make no distinction between gouge and gouged dent damage in terms of the gouge length and gouge depth, or between S and R area types. Additionally, the incident rate makes no distinction between gouges and gouged dents.

5. Comparison of Existing Failure Frequency Models

All of the existing failure frequency models are rooted in probabilistic, structural reliability methods. The models use similar or identical semi-empirical fracture mechanics failure equations to define limit state functions and probability distributions based on historical operational pipeline damage data. Some have augmented their structural reliability procedure with an additional historical data component.

The majority of the models use the same failure equations for the limit state functions, namely the NG-18 equations for leak/rupture and gouge failure, and the BGDGFM for gouged dent failure. The one exception to this is the PIPIN model, which uses the British Energy R6 rev. 3 assessment procedure. It can be shown however, that the methods used in this procedure are very similar to those of the BGDGFM.

In terms of operational data, each model has used the most up to date version of the UKOPA/ERS Fault database available at the time of the model's construction. Models produced later therefore include all of the operational data from the earlier models supplemented by data from the additional years of pipeline operation.

Despite the similarities between the models noted above, each model is constructed in its own individual way with different choices having been made regarding failure modelling and data manipulation. Based on the relative merits of these choices, each model can be considered to have its own advantages.

It is important to note that the structural reliability methods used in the failure frequency models are not dependent upon pipeline wall thickness or any other quantity related to the transportation of dense phase CO_2 by pipelines. The methods themselves are non-specific and are used for a wide variety of applications throughout engineering. The applicability of a structural reliability method to any given situation depends entirely upon the applicability of the models and data contained within them.

6. Applicability of Existing Failure Frequency Models to Dense Phase CO_2 Pipelines

In order to ascertain the applicability of existing failure frequency models to dense phase CO_2 pipelines, firstly, the minimum required wall thicknesses for different dense phase CO_2 pipeline designs was estimated. Then the applicability of existing failure frequency models is discussed in terms of whether their structural reliability methods and historical data meet the design requirements of typical dense phase CO_2 pipelines.

6.1. Minimum Required Wall Thickness Estimations for Dense Phase CO_2 Pipelines

It is important to estimate the minimum required wall thicknesses for different dense phase CO_2 pipeline designs scenarios in order to understand whether they could potentially be outside the range of applicability of current failure frequency models. The minimum required wall thicknesses can be calculated using the following thin wall formula for allowable hoop stress in PD 8010: Part-1 (BSI, 2015):

$$\sigma_H = \frac{PD}{20t} \leq e\ a\sigma_{SMYS} \qquad (1)$$

where P is internal pressure, $D$is outside diameter, t is wall thickness, e is the weld factor (assumed to be 1), a is the design factor and σ_{SMYS} is the Specified Minimum Yield Stress (SMYS).

CO_2 pipeline data (Noothout et al, 2014) from existing projects indicates that the minimum operational pressure may exceed 150 barg. Assuming typical CO_2 pipelines with diameters of 610mm (24'') and 914mm (36''), and a maximum operational pressure of 150 barg, the minimum required wall thicknesses are calculated using formula (10) for different materials (API 5L X52, X65 and X80) with different design factors (0.3, 0.5 and 0.72) and are listed in Table 2. The range is in line with data from existing UK projects such as the White Rose project which proposed an onshore pipeline with 610 mm (24") outside diameter, carbon steel grade L450/(X65) and 19.1 mm minimum wall thickness (White Rose, 2016).

P	**D**	**API 5L Material**	**SMYS**	**Design factor 'a'**	**Weld factor 'e'**	**Maximum Hoop Stress $e.a.\sigma_{SMYS}$**	**Minimum Wall Thickness 't'**
(bar)	(mm)		(N/mm^2)			(N/mm^2)	(mm)
150	610	X52	360	0.3	1	108	42
150	610	X52	360	0.5	1	180	25
150	610	X52	360	0.72	1	259.2	20
150	610	X65	450	0.3	1	135	36
150	610	X65	450	0.5	1	225	22.2
150	610	X65	450	0.72	1	324	14.2
150	610	X80	555	0.3	1	166.5	27
150	610	X80	555	0.5	1	277.5	17.5
150	610	X80	555	0.72	1	399.6	12.5
150	914	X52	360	0.3	1	108	63
150	914	X52	360	0.5	1	180	40
150	914	X52	360	0.72	1	259.2	28.0
150	914	X65	450	0.3	1	135	51
150	914	X65	450	0.5	1	225	32
150	914	X65	450	0.72	1	324	22.2
150	914	X80	555	0.3	1	166.5	41
150	914	X80	555	0.5	1	277.5	25
150	914	X80	555	0.72	1	399.6	17.5

Table 2: Estimation of the minimum required CO$_2$ pipeline wall thicknesses

In the following sections these wall thicknesses will be used to illustrate the applicability of the components making up current failure frequency (and hence the models themselves) to dense phase typical CO$_2$ pipelines.

6.2. The Range of Applicability of the NG-18 Equations

Being semi-empirical, the NG-18 equations were calibrated using experimental tests of vessels with through-wall and part-wall defects. The range of applicability of each equation with regards to wall thickness can be inferred from the range of vessel wall thicknesses used in the corresponding set of burst tests used to derive it.

The through-wall NG-18 equations were calibrated using the results of 92 burst tests on vessels with axially orientated, artificially machined, through-wall defects while the part-wall NG-18 equations were calibrated using the results of 48 burst tests on vessels with axially orientated, artificially machined, part-wall defects (v-shaped notches). The tests were carried out by Battelle between 1965 and 1974. The range of experimental parameters for the through-wall and the part-wall tests is shown in Tables 3 and 4 respectively (Cosham, 2002).

Parameter	Minimum Value	Maximum Value
Pipe Diameter (mm)	167.6	1219.2
Wall Thickness (mm)	4.9	21.9
Grade (API 5L)	A	X100
Yield Strength (Nmm^{-2})	220.6	735.0
Tensile Strength (Nmm^{-2})	337.9	908.1
2/3 Charpy V-Notch Impact Energy (J)	13.6	90.9
Defect Length (*2c*) (mm)	25.4	508.0
Burst Pressure (Nmm^{-2})	2.21	18.69
Burst Stress (Nmm^{-2})	97.9	486.8
Burst Stress (% Yield)	22.6	135.8

Table 3: Battelle through-wall defect burst test parameter ranges

Parameter	Minimum Value	Maximum Value
Pipe Diameter (mm)	406.4	1066.8
Wall Thickness (mm)	6.4	15.6
Grade (API 5L)	X52	X65
Yield Strength (Nmm^{-2})	379.2	509.5
Tensile Strength (Nmm^{-2})	483.3	633.7
2/3 Charpy V-Notch Impact Energy (J)	13.6	46.1
Defect Length (*2c*) (mm)	63.5	609.6
Defect Depth (*d*) (mm)	3.1	11.2
Burst Pressure (Nmm^{-2})	1.84	12.4
Burst Stress (Nmm^{-2})	61.4	506.1
Burst Stress (% Yield)	13.7	132.5

Table 4: Battelle part-wall defect burst test parameter ranges

The parameter ranges in Table 3 and Table 4 suggest that the through-wall NG-18 equations are applicable to pipelines with a wall thickness between 4.9 mm and 21.9 mm and the part-wall NG-18 equations are applicable to pipelines with a wall thickness between 6.4 mm and 15.6 mm.

6.3. The Range of Applicability of the British Gas Dent-Gouge Fracture Model

The BGDGFM is also semi-empirical and it was calibrated using the experimental results of 111 ring and 21 vessel tests with artificial gouged dent defects created at zero pressure. The tests were carried out by British Gas in 1982. The range of applicability of the BGDGFM with regards to wall thickness can be inferred from the range of wall thicknesses used in the experimental tests to derive it. The range of experimental parameters for the tests is shown in Table 5 (Cosham, 2001):

Parameter	**Minimum Value**	**Maximum Value**
Pipe Diameter (mm)	323.9	1066.8
Wall Thickness (mm)	6.6	16.4
Grade (API 5L)	X42	X65
Yield Strength (Nmm^{-2})	348.2	522.6
Tensile Strength (Nmm^{-2})	494.0	577.8
2/3 Charpy V-Notch Impact Energy (J)	15.0	70.5
Dent Depth (H) (mm)	1.9	77.7
Gouge Depth (d) (mm)	0.2	7.9
Burst Stress (% Yield)	7.1	144.9

Table 5: British Gas gouged dent ring and burst test parameter ranges

The parameter ranges in Table 5 suggest that the BGDGFM is applicable to pipelines with a wall thickness between 6.6 mm and 16.4 mm.

6.4. Summary of the Range of Applicability of the Failure Models

On the basis of the experimental test data used in their derivation, the upper limit for validity of the NG-18 equations is 21.9 mm for through-wall defects and 15.6 mm for part-wall defects. Similarly, the upper limit for validity of the BGDGFM is 16.4 mm.

6.5. The Applicability of the Failure Models to Typical Dense Phase CO_2 Pipelines

The minimum required wall thicknesses determined in Section 6.1 are now compared with the upper limits of applicability of the NG-18 Equations and BGDGFM. Figures 5 and 6 show the minimum required wall thickness for three grades of pipe across a range of design factors for pipelines with diameters of 610 mm (24 ʺ) and 914 mm (36 ʺ) respectively.

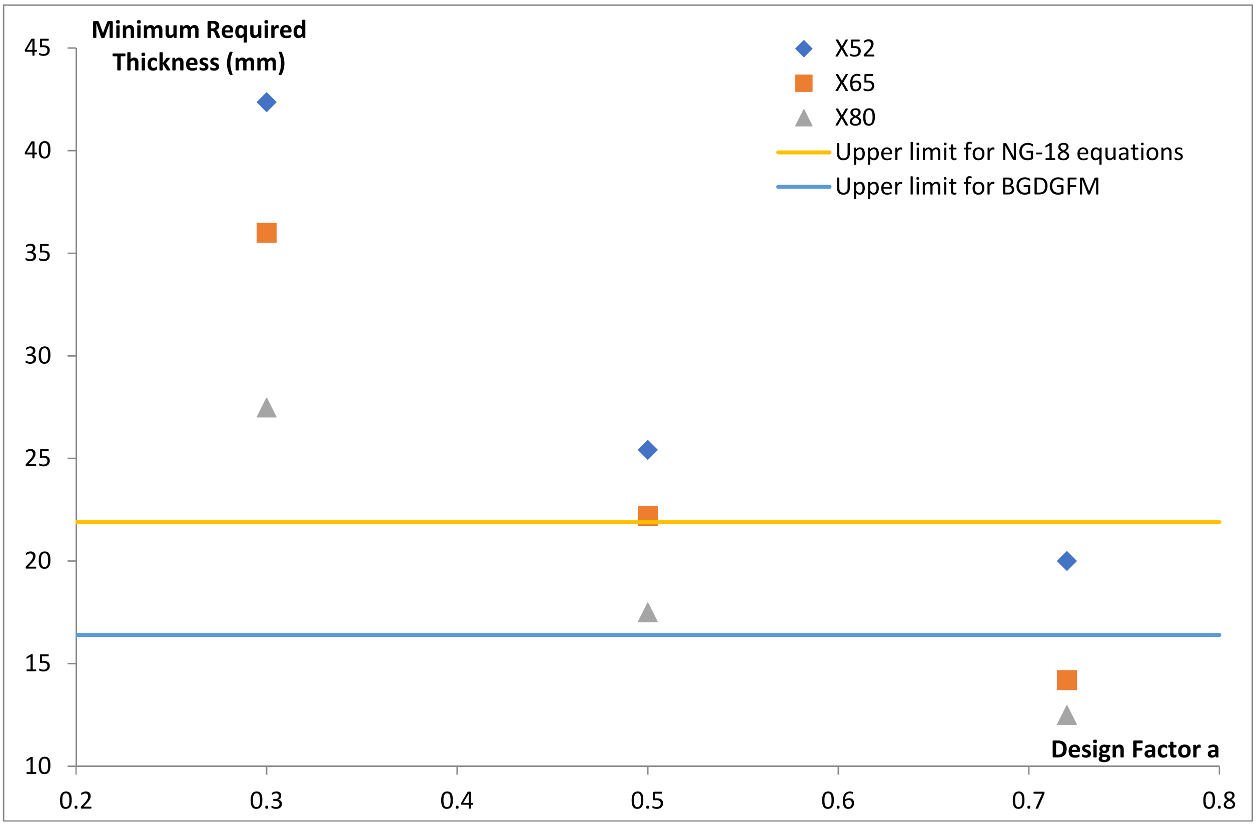

Figure 5: Minimum required wall thicknesses for CO_2 pipeline with diameter of 610 mm (24 ʺ)

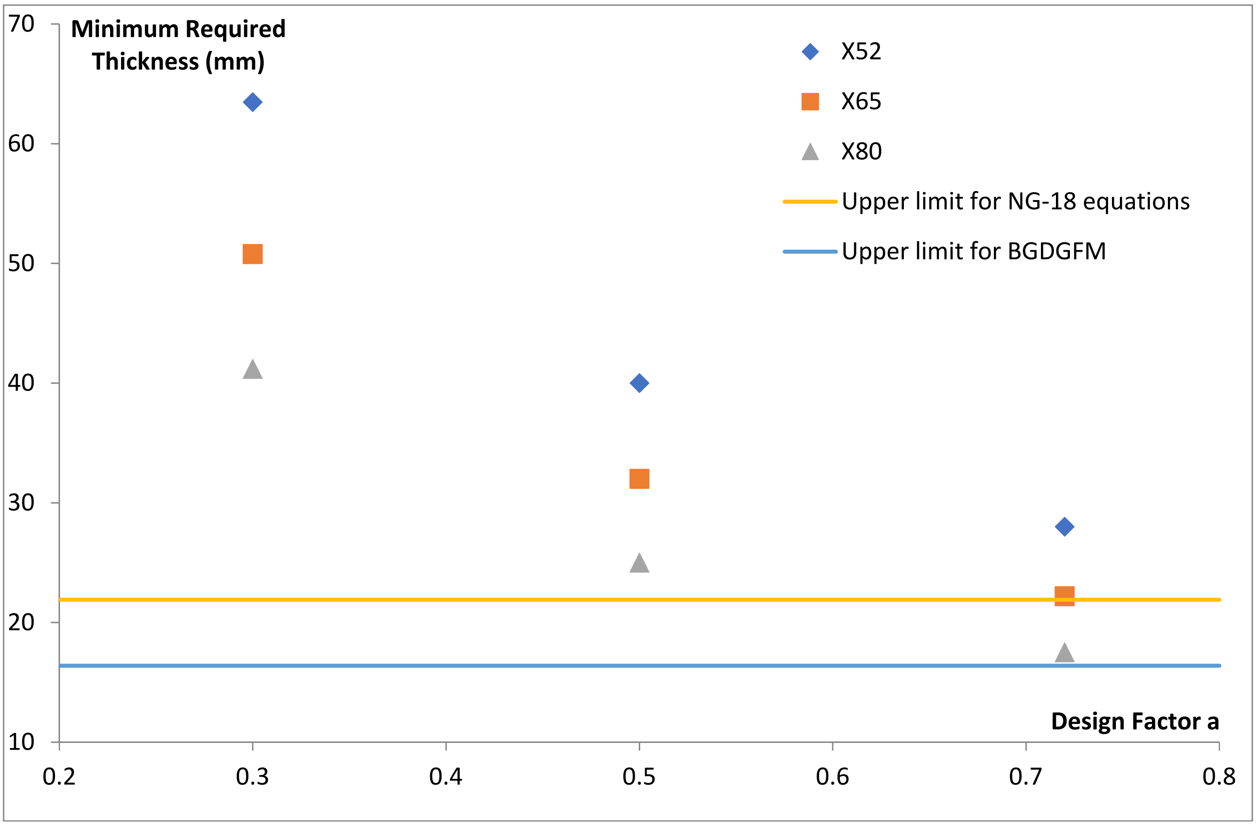

Figure 6: Minimum required wall thicknesses for CO_2 pipeline with diameter of 914 mm (36′′)

On the basis of this analysis, the minimum required CO_2 pipeline wall thickness, under 150 barg operational pressure, may be between 12.5 mm and 63 mm depending on pipe diameter, material and design factor used. It is noted that in 13 of the 18 cases considered, the minimum required wall thickness for CO_2 pipelines exceeds 21.9 mm. For the 610 mm (24′′) diameter pipelines, there are about half cases (5 out of the 9 cases) with the minimum required wall thickness greater than 21.9 mm while for 914 mm (36′′) diameter pipelines there is only one case out of the 9 cases with the minimum required wall thickness less than 21.9 mm. This means that in the majority of cases, the required minimum CO_2 pipeline wall thickness is outside of the known ranges of applicability of the NG-18 equations and the BGDGFM. In other words, in the majority of cases, current failure frequency models cannot be used to reliably estimate the failure frequency of dense phase CO_2 pipelines.

7. The Applicability of Historical Operational Data to Dense Phase CO_2 Pipelines

The historical operational data used in the existing failure frequency models originates from either the UKOPA Fault Database or its predecessor the ERS Fault Database. Currently this is the only pipeline fault database which provides sufficient information from which cumulative probability distributions and incident rates suitable for a failure frequency model based on structural reliability methods can be derived.

In order to apply the existing failure frequency models to dense phase CO_2 pipelines, the most appropriate historical operational data to use would ideally originate only from operational dense phase CO_2 pipelines in the UK. More specifically, the data would concern dense phase CO_2 pipelines with wall thicknesses covering the full range over which the model could potentially be applied. However, since there are currently no dense phase CO_2 pipelines operating in the UK and therefore no historical operational data regarding them, a compromise must be made. Given the principles of containment, stress and fracture, and that all high-pressure pipelines are constructed using steel linepipe, third party external interference failure frequency is not sensitive to the product that a pipeline transports. The most recent UKOPA Fault Database may therefore be the most appropriate source of historical operational data to use in order to calculate the failure frequency for dense phase CO_2 pipelines.

It is noted that the wall thicknesses contained in the UKOPA Fault Database are limited by operational pipelines. Since there are no onshore dense phase CO_2 pipelines currently in operation, it is not yet known whether the database contains data covering the required wall thickness range. At present there is no solution to this problem, however the future construction and operation of dense phase CO_2 pipelines will ensure the data source becomes more relevant with time.

8. Discussion of the Applicability of Existing Failure Frequency Models to CO_2 Pipelines

The review of the failure equations used in existing failure frequency models showed that they are all based on both the NG-18 equations for the failure of gouges and leak/rupture behaviour and the BGDGFM for the failure of a gouged dent. It was concluded that the largest wall thickness in the experimental tests used to derive the NG-18 equations was 21.9 mm for the through-wall equations and 15.6 mm for the part-wall equations. Similarly, 16.4 mm is the maximum wall thickness used to derive the BGDGFM. In terms of the UKOPA database, which contains details of faults and failures which have previously affected operating onshore pipelines in the UK, the largest wall thickness is 19.1 mm. In the majority of the design studies illustrated in this paper, the minimum wall thickness for dense phase CO_2 pipelines must be greater than 21.9 mm. Therefore, based on the results of this paper, it is concluded that current failure frequency models for third party external interference may not be suitable for dense phase CO_2 pipelines due to their typical design requirements. Further work needs to be conducted to confirm the most appropriate approach for calculating failure frequency for dense phase CO_2 pipelines.

9. Conclusions

For oil and natural gas pipelines, the frequency of pipeline failure due to third party external interference is calculated using models based upon structural reliability methods. These models combine semi-empirical pipeline failure equations with probability distributions derived from historical operational damage data. A review of the available failure frequency models was performed in order to assess their applicability to dense phase CO_2 pipelines.

It was shown that the high design pressure requirement for a dense phase CO_2 pipeline typically necessitates the use of high wall thickness linepipe in pipeline construction.

It is concluded that the applicability of the existing failure frequency models to typical dense phase CO_2 pipelines may be beyond the known range of applicability for the pipeline failure equations used within existing failure frequency models due to the high wall thickness linepipe requirements of typical CO_2 pipelines.

Furthermore, even though third party external interference failure frequency is not sensitive to the product that a pipeline transports, there is however a limitation to the UKOPA Fault Database with regards to its application to CO_2 pipelines because there are currently no dense phase CO_2 pipelines operating in the UK.

Further work needs to be conducted to confirm the most appropriate approach for calculating failure frequency for dense phase CO_2 pipelines. It is recommended that a new failure frequency model suitable for dense phase CO_2 pipelines is developed that is applicable to thick wall linepipe and can be readily updated to the latest version of the UKOPA Fault database. As part of this, a definitive assessment as to the applicability of the NG-18 equations and BGDGFM to thick wall dense phase CO_2 pipelines is needed. Examples of demonstrating applicability include conducting a detailed numerical analysis including finite element analysis or an experimental test programme.

10. Acknowledgements

This work has been conducted under the auspices of the National Grid COOLTRANS research programme and the authors gratefully acknowledge the financial support of National Grid for this research.

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