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Pipelines for transporting CO_2 in the UK

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Abstract

National Grid is currently pursuing plans to develop a pipeline system in the North Yorkshire and Humber areas of the United Kingdom (UK) to transport dense phase carbon dioxide (CO_2) from a major industrial emitter to a saline aquifer off the Yorkshire coast. The company's longer term aspiration is to develop the first pipeline into a network configuration that links up multiple CO_2 emitters in the Yorkshire and Humberside area. The planned developments are supported by European Union grants which have been used to partly fund the required technical studies.

CO_2 is a hazardous substance which in the unlikely event of an accidental release, could cause harm to people. Compliance with UK safety legislation requires compliance with recognised pipeline codes. Currently, the UK pipeline standard and code for high pressure pipelines do not directly apply to dense phase CO_2, but do allow the use of quantified risk assessmnt (QRA) in cases which are not fully covered by the documents. National Grid has completed the COOLTRANS (**CO2L**iquid pipeline **TRANS**portation) research programme, and the results of this research have been used to develop a comprehensive QRA methodology for dense phase CO_2 pipelines, which has been used in routeing and design studies to ensure that the principles of the UK standards and codes are correctly applied.

This paper describes the routeing and design principles specified in the UK pipeline standard and code of practice, and explains how the COOLTRANS research findings have been used in the development and application of a QRA methodology for CO_2 pipelines, which ensures the principles are applied to these pipelines.

Keywords: CO_2 pipelines; quantified risk assessment QRA; pipeline routeing: pipeline design

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1. Introduction

National Grid is currently pursuing plans to develop a pipeline system in the North Yorkshire and Humber areas of the United Kingdom (UK) to transport dense phase carbon dioxide (CO_2) from a major industrial emitter to a saline aquifer off the Yorkshire coast. The company's longer term aspiration is to develop the first pipeline into a network configuration that links up multiple CO_2 emitters in the Yorkshire and Humberside area. The planned developments are supported by European Union grants which have been used to partly fund the required technical studies.

CO_2 is a hazardous substance which in the event of an accidental release, could cause harm to people. UK safety legislation requires that the risks associated with high pressure pipelines are as low as reasonably practicable (ALARP). Demonstration of this generally requires compliance with recognised pipeline codes, however as current pipeline codes do not directly apply to dense phase CO_2, the ALARP demonstration required by legislation cannot be confirmed through code compliance. However, the UK standard for high pressure natural gas pipelines, and the code of practice for high pressure pipelines transporting other hazardous fluids allow the use of quantified risk assessment (QRA) in cases which are not fully covered by the documents.

In order to resolve the knowledge gaps relating to the safe design and operation of onshore pipelines for transporting high pressure dense phase CO_2 and CO_2 rich mixtures from industrial emitters to storage sites and to demonstrate that the risks are ALARP, National Grid has completed the COOLTRANS (**CO2L**iquid pipeline **TRANS**portation) research programme. The results of this research have been used to develop a comprehensive QRA methodology for dense phase CO_2 pipelines, which has been used in routeing and design studies to ensure that the principles of the UK standards and codes are correctly applied.

This paper describes the principles specified in the UK pipeline standard and code of practice for the safe routeing and design of high pressure hazardous pipelines in the UK, and explains how the findings of the COOLTRANS research have been used in the development and application of a QRA methodology for CO_2 pipelines, which ensures the principles are applied to these pipelines.

2. UK code requirements for routeing and design of hazardous pipelines

UK pipelines are subject to legislative control under the Pipelines Safety Regulations 1996 (PSR 96) [1]. The Regulations cover general duties for the safe management of all pipelines in the UK relating to design, construction, operation, maintenance and decommissioning. In addition, the Regulations specifically define Major Accident Hazard Pipelines (MAHPs), which are pipelines that convey 'dangerous fluids' and for which the consequences of failure would present a major accident resulting in significant danger to people. Additional duties are defined for these pipelines, including notification, preparation of a Major Accident Prevention Document (MAPD), emergency procedures and arrangements, and provision of information to Local Planning Authorities for inclusion in the Emergency Response Plan for the area. CO_2 is not currently classified as a 'dangerous fluid' in the Regulations, but as it is toxic and is an asphyxiant in large concentrations, it is considered cautious to design and operate dense phase CO_2 pipelines as if they are classed as Major Accident Hazard Pipelines (MAHPs). This means that the design requirements which are established and have been proved for natural gas and other hazardous fluids should be applied to CO_2 pipelines.

These design requirements as presented in IGEM/TD/1 [2] and PD 8010-1 [3] are summarised below.

2.1 UK pipeline standards

Pipeline design requirements for high pressure steel transmission pipelines are specified in the standard IGEM/TD/1 [2] for natural gas pipelines, and the approved code of practice PD 8010-1 [3] for all other high pressure pipelines. The UK design requirements are integrity based in that design principles and requirements prescribe design parameters to be applied in order to ensure pipeline integrity and consequently safety. However, where requirements are not definitive or conditions which fall outside the prescribed requirements are being addressed, the use of QRA as a decision tool is allowed. In addition, both IGEM/TD/1 and PD 8010-1 allow the use of individual and societal risk levels calculated using QRA to be used to route pipelines and to carry out site specific risk assessments.

2.2 Natural gas pipelines

IGEM/TD/1 [2] was originally developed by the UK gas industry to support the development of the National Transmission System (NTS) for natural gas. The principles of the American pipeline code ASME B31.8 [4] were examined for application in the UK. The key principles identified were the requirement to assess the infrastructure within a fixed corridor along the proposed route of a pipeline, classify the area according to the infrastructure, and limit the pipeline operating stress in areas of high levels of infrastructure development. These principles were accepted and modified for application in the higher populated areas in the UK. The modifications involved replacing the fixed corridor width with a multiple of the building proximity distance (BPD), which defines the minimum required separation between the pipeline and existing normally occupied buildings, and limiting the operating stress in highly populated areas to 30% of the pipe material's Specified Minimum Yield Stress (SMYS).

The BPD is derived as the distance to a thermal radiation level of 32 kW/m^2 from a steady state fire, and its definition takes account of the low probability of pipeline failures and the possibility, due to the linear nature of the hazard, of escape or to take cover from the effects of thermal radiation. The BPD is calculated according to the diameter and pressure of the pipeline. In this respect, while the BPD is a hazard distance, how it is used is considered to provide a form of qualitative risk assessment, which recognises that complete protection of people from the consequences of pipeline rupture is not possible. A route corridor either side of the pipeline is defined as 4 x BPD, no occupied buildings are allowed within 1 x BPD, and the number of occupied buildings and people are counted within a corridor of width 8 x BPD centred on the pipeline to obtain the population density.

Where the population in this corridor is less than or equal to 2.5 persons per hectare, the area is classified as rural (R), where the population is greater than 2.5 persons per hectare the area is classed as suburban (S), and where the area includes high population density, multi-storey buildings, dense traffic and numerous underground services, the area is classed as town (T) in which high pressure natural gas pipelines cannot be located.

Pipeline failures occur as leaks or ruptures. The likelihood of leak or rupture is dependent upon the defect size, the design factor, and the pipe diameter and wall thickness. Research into pipeline failure modes has shown that where the design factor is 0.3 or less, the likelihood of rupture is low. The pipeline is therefore designed so that the pipeline design factor is limited to 0.72 in rural areas where the failure mode may be a rupture but the population density is low. The pipeline design factor is limited to 0.3 in suburban areas to ensure that in more densely populated areas, the pipeline failure is likely to occur as a leak. For large diameter pipelines, in which the wall thickness required for 0.3 design factor is equal to or greater than 19.1mm, the design factor may be increased to 0.5. Once the design factor for an 'S' type area is confirmed, the BPD is redefined according to the consequences of a leak whose size is based on wall thickness. The wall thickness limits are related to the likelihood of a through wall puncture, and are defined as follows:

Table 1. Pipeline wall thickness requirements for 'S' type areas

Wall thickness (mm) for pipelines with design factor ≤ 0.3	**Probable leak size**
< 9.5	6"/150mm diameter
≥ 9.5 < 11.9	3"/75mm diameter
≥ 11.9	Negligible

These requirements are supported by the inspection and condition monitoring, surveillance and maintenance requirements in the standard.

2.3 Other fluids

The principles of the pipeline standard IGEM/TD/1 [2] are applied by the UK approved British Standards Institution (BSI) pipeline code PD 8010-1:2004 [3] to all pipelines which transport hazardous fluids. PD 8010-

1:2004 defines Class 1 locations where the population is less than or equal to 2.5 persons per hectare in which the pipeline design factor is limited to 0.72, Class 2 locations where the population is greater than 2.5 persons per hectare and the design factor is limited to 0.3, and Class 3 areas where there is high population density, multi-storey buildings, dense traffic and numerous underground services, in which hazardous pipelines cannot be located. PD 8010-1:2004 defines the separation distance between a hazardous pipeline and population as the minimum distance to occupied buildings (MDOB), the MDOB is equivalent to the BPD for natural gas pipelines, and is calculated using a substance factor, Q, which is defined for fluids categorised as A through to E according to the hazardous nature of the fluid (see summary below). PD 8010-1 also defines the MDOB as the distance to the individual risk level of 1 x 10^{-5} or 10 chances per million (cpm).

2.4 Summary

The pipeline routeing and design requirements defined in IGEM/TD/1 and PD 8010-1 are consistent, and are summarised as follows:

Table 2. UK pipeline standard requirements for routeing

Standard	Separation distance	Corridor width	Population density
IGEM/TD/1	BPD = f(pressure, diameter)	4 x BPD	Determined in a corridor of width 8BPD centred on the pipeline
PD 8010-1	MDOB = Y = $Q\left[\frac{D^2}{32000} + \frac{D}{160} + 11\right]\left[\frac{P}{32} + 1.4\right]$ or distance to 10 cpm risk contour	3 x Y for category C fluids, 4 x Y for category D and E fluids	Determined in a corridor of width 6Y for category C fluids, or 8Y for category D and E fluids centred on the pipeline, or 0.3 cpm contours on either side

Note: Unit of pressure is barg, diameter is in mm.

The above equation for MDOB/Y was developed using data supplied to the BSI committee responsible for the development of the pipeline standard BS 8010:Section 2.8:1993, by IGEM (then IGE) in relation to the development of the BPD for natural gas pipelines. The BSI committee included the proximity distances for natural gas as provided by IGE in Figure 2 of BS 8010:1993, and extended these to other fluids using the substance factor Q. The Q factor represents the hazardous potential of the fluid, and values were derived using the results of QRAs for a range of hazardous pipelines, made available at the time by pipeline operators and HSE. Details of the work are not available, but values for the Q factor agreed at the time are given in BS 8010 Table 2, which range from 0.3 for category C fluids to 2.5 for ammonia. The above equation for MDOB/Y and the original Q factor values are included in the current edition of PD 8010-1, which superseded BS 8010:Section 2.8:1993.

A revision of PD-8010-1 is to be published, which has been updated to include CO_2 with a suggested Q factor of 2.0. Work carried out by National Grid using the risk assessment methodology described later in the paper has shown that different values of Q could be inferred for different pipelines. This suggests that the choice of a single Q value is problematic and, given that its use could be widespread, may well have to err overly on the side of caution compared with factors for other fluids. Hence, at this stage, it is considered that it will be necessary to check the application of this factor by using risk assessment as the preferred approach.

Table 3. UK pipeline standard requirements for design

Population density	Area classification	Design factor	Failure mode
≤ 2.5 persons/hectare	Rural/Class 1	0.72	Rupture
> 2.5 persons/hectare	Suburban/Class 2	0.3 0.5 if wall thickness ≥ 19.1mm	Leak

Table 4. UK pipeline standard wall thickness requirements for resistance to puncture (for 'S' type/Class 2 pipelines)

Wall thickness (mm)	Consequences (puncture diameter)
< 9.5	6"/150mm
< 9.5 with protection	3"/75mm
≥ 9.5 < 11.9	3"/75mm
≥ 11.9	No consequence based proximity requirements

2.5 Use of quantified risk assessment (QRA) for pipeline routeing

In the 1990s, the UK Health and Safety Executive (HSE) introduced land use planning (LUP) requirements for hazardous pipelines. A risk based 'Consultation Zone' around the pipelines transporting dangerous fluids is calculated by HSE using the pipeline details notified by the pipeline operator as required by PSR 96 [1]. Any new planning developments within this zone are assessed by Local Planning Authorities in accordance with HSE advice.

The assessment process developed by HSE uses risk-based inner, middle and outer zones and the type of development which is proposed, to assess the acceptability of the development with respect to the pipeline risk, categorising the levels of individual risk, defined as dangerous dose or worse [5] at each zone boundary.

Following the introduction of the risk based LUP requirements for hazardous pipelines, the use of risk assessment for routeing was included in the pipeline codes in order to ensure alignment between the acceptability of the proximity of developments and people to the pipeline in routeing and LUP. The procedure for pipeline routeing defines zone 1, which is taken as equivalent to the BPD or MDOB, as the distance to the 1×10^{-5} cpm risk level, and the width of the route corridor is the distance to the 0.3×10^{-6} cpm risk level. In addition, pipelines pose a societal risk to populations in their vicinity. A societal risk criterion was introduced in Edition 4 of the standard IGEM/TD/1, the requirement for societal risk analysis is included in the revision of the code PD 8010-1, and the methodology for societal risk assessment is covered in the standard IGEM/TD/1 and the code PD 8010-3.

3. QRA of CO_2 pipelines

National Grid is applying PD 8010-1 to the design of the proposed dense phase CO_2 Yorkshire and Humber Carbon Capture and Storage (CCS) pipelines, supplemented where appropriate by the requirements of IGEM/TD/1. In applying PD 8010-1, National Grid has applied the cautious assumption that the highest fluid hazard category (E) applies to dense phase CO_2, and has applied the design requirements accordingly. PD 8010-1 does not specify a Q factor for dense phase CO_2. This means that the existing approach for the calculation of the MDOB cannot be applied, and a QRA approach to pipeline routeing is required. Recommended QRA methodologies based on best practice are published in the supporting standard IGEM/TD/2 [6] and code PD 8010-3 [7]. The code PD 8010-3 notes that while the QRA methodology it covers addresses thermal hazards only, the principles presented can be applied to toxic hazards.

3.1 Requirements for a QRA methodology for CO_2 pipelines

The purpose of a pipeline QRA is to evaluate the risks to people in the vicinity of the pipeline posed by a failure of the pipeline. An overview of the stages of the QRA methodology is given in Figure 1.

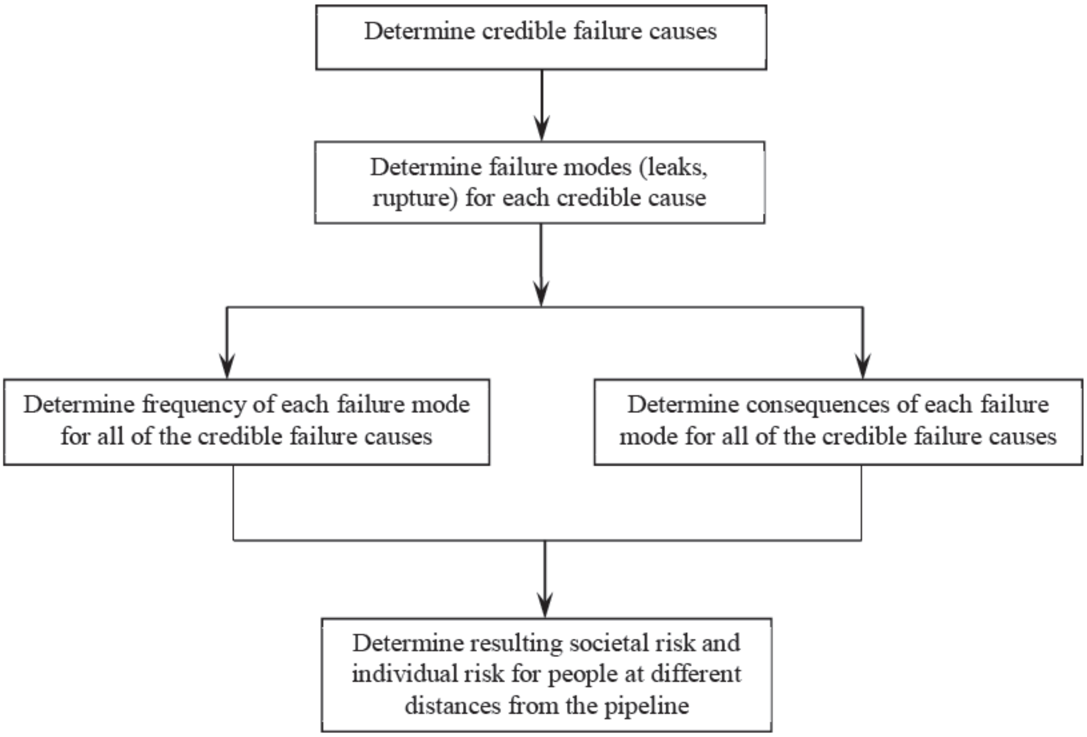


Figure 1. Overview of pipeline QRA

3.2 Prediction of failure frequency of dense phase CO_2 pipelines

Pipeline failures occur as a result of defects in or damage to a pipeline. Primary causes of pipeline defects/damage are:

- External interference/third party damage;
- Corrosion (external and internal);
- Material and construction defects;
- Ground movement or environmental loading;
- Other (e.g. overpressure, operator error, fatigue).

Of the above damage causes, material and construction defects are addressed through material specifications, material pre qualifications, material and construction quality assurance and inspection; ground movement and environmental loading are addressed first through pipeline routeing to avoid problematic locations and second through surveillance and operational response, and ’other‘ damage causes are addressed through design, staff training and the application of rigorous operational procedures. External corrosion is addressed through the application of corrosion protection and the design and installation of cathodic protection, and internal corrosion is addressed by the fluid quality specification. The main causes of damage which must be considered for CO_2 pipelines are external interference and internal corrosion.

3.2.1 Failure frequency due to external interference

Current UK best practice is to apply predictive models which use fracture mechanics failure equations and damage size probability distributions and an event rate obtained from operational data. This data is recorded by UK pipeline operators and is reported by United Kingdom Onshore Pipeline operators Association (UKOPA) [8]. The predictive model used by National Grid for its natural gas pipelines is known as FFREQ.

Existing models, like FFREQ, for the prediction of failure frequency due to the dent and dent-gouge types of damage which is caused by external interference are semi-empirical, and are based on empirical failure data from hydraulic tests, fracture mechanics models and damage probability distributions derived from the statistical analysis of operational damage data. The technical basis and data on which these models are based has been reviewed in the COOLTRANS research programme by Newcastle University. The work has involved confirmation of the validity of the fracture mechanics equations for thick wall pipes containing CO_2, and analysis and interpretation of the damage data. An updated model for application to thick wall pipelines (i.e. pipelines of wall thickness greater than 12.7mm, for which there is limited data) has been developed by Newcastle University. A detailed comparison of predictions obtained by Newcastle University using this model with predictions from the FFREQ model, which has been used in the CO_2 pipeline QRA studies carried out by DNV GL for thicker walled pipelines (i.e. wall thickness ≥ 11.9mm), have confirmed that FFREQ predictions are cautious. The predicted total failure frequency (rupture and puncture) for a 610mm outside diameter pipeline with a design factor of 0.72 reduces significantly as the pipeline wall thickness increases, as shown in Figure 2.

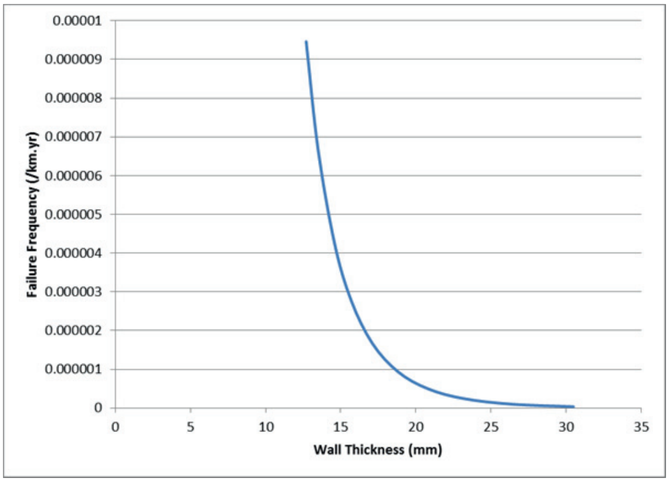


Figure 2. Predicted failure frequency with increasing wall thickness

3.2.2 Failure frequency due to internal corrosion

Anthropogenic CO_2 (CO_2 rich mixtures including impurities) captured from industrial emitters invariably contains water, leading to the potential for water to enter the pipeline. In this event, the water could combine with the CO_2 and possibly with other impurities in the dense phase CO_2 to form carbonic acid and other corrosive solutions which would present an internal corrosion hazard.

The primary control to avoid or limit the impact of internal corrosion will be achieved by ensuring that the CO_2 delivered by the CO_2 emitter is dry, and the presence of free water is avoided. Provided the CO_2 dryness is maintained, free water will not form in the pipeline within the range of operating pressures and temperatures to which the pipeline will be exposed.

The failure rates due to corrosion of CO_2 pipelines for use in a risk assessment have been considered in papers published by Cleaver et al [9] and Cleaver and Hopkins [10], in which it is proposed that although the failure rate is negligible in pipelines with rigorous dehydration control to minimise the water level, historical experience of corrosion in pipelines transporting oil can be used to estimate an upper bound failure rate, as suggested in a paper [11] published by the Health and Safety Laboratories (HSL) and the HSE.

3.3 Prediction of consequences

In the event of a release due to a leak or rupture, the dense phase CO_2 will decompress, expand to atmospheric pressure and then disperse as a heavier than air gas at atmospheric pressure according to the environmental conditions at the location. The decompression and expansion of dense phase CO_2 involves a change of phase from dense phase/liquid to the gaseous phase, possibly involving solid phase formation at intermediate stages. The initial release outflow conditions are momentum driven as a result of the significant pressure reduction. This process involves a decrease in temperature in the fluid, during which particles of solid CO_2 can form. These particles would be carried in a momentum driven jet. As the jet reaches atmospheric pressure, depending on the size of the release, the dispersion is governed by buoyancy and wind turbulence as well as momentum.

Advanced analyses of the CO_2 behaviour at all stages of the release have been modelled in COOLTRANS by academic experts using state of the art computation fluid dynamic (CFD) models. University College London (UCL) have studied the outflow and decompression behaviour of a release of dense phase CO_2. The University of Leeds developed a complex CFD model to analyse the highly transient conditions associated with the fast expansion in the near field, and using the outflow results provided by UCL, analysed the near field dispersion. Kingston University and the University of Warwick have analysed the far field dispersion behaviour of the CO_2 cloud taking account of the conditions at the end of the expansion zone predicted by the University of Leeds. DNV GL have linked and assessed the results of these academic CFD studies and have assessed the experimental data generated under the COOLTRANS research programme at DNV GL Spadeadam. They have used this to develop and validate their simpler pragmatic model used in the QRA studies they have carried out for National Grid. A summary is given below.

3.3.1 Outflow

The outflow and decompression behaviour was investigated by UCL using CFD to consider non-homogeneous behaviour when two-phase flows are produced in the pipeline and to study the impact of valve closure on the flow, for CO_2 and mixtures of CO_2 with impurities. The results produced by UCL were compared with the outflow rate predicted by the simple model SLURP, in the FROST package used by DNV GL to carry out QRA studies carried out for National Grid. The comparison for a simple case involving the rupture at the midpoint of a 96 kilometres long 600mm (24”) nominal diameter pipeline with initial conditions of 150 barg and 30° C, is shown in Figure 3. The pipeline block valves, which are spaced at nominally 16 kilometres spacing, at 8 kilometres either side of the rupture, were closed 900 seconds after the start of the release. This comparison confirms that the simpler model used in the QRA provides an accurate prediction of the outflow for this typical case.

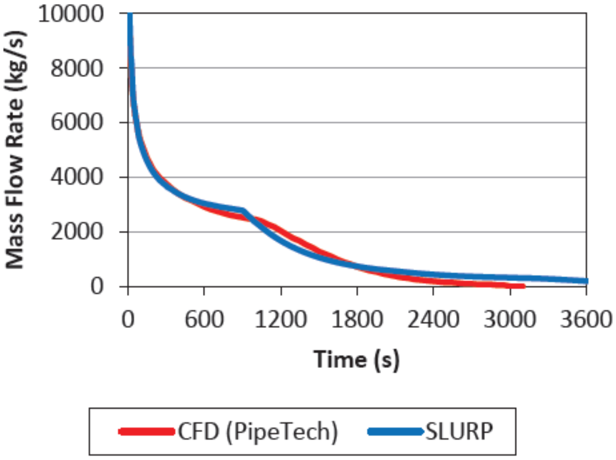


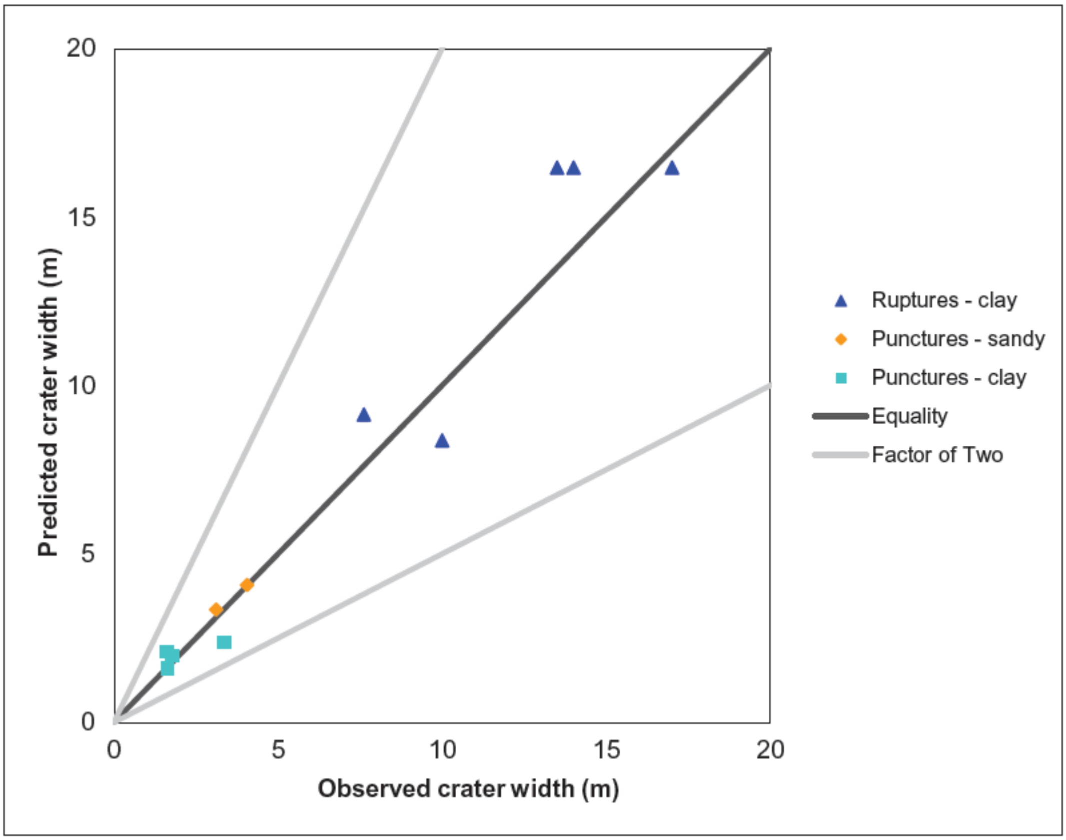
Figure 3: Comparison of predictions of the state of the art UCL CFD model PipeTech with the simple DNV GL model SLURP for a base case 600mm (24”) nominal diameter pipeline

3.3.2 Expansion and dispersion in the near field

The momentum of the larger releases will remove the backfill around the buried pipeline, causing the formation of a crater. The size and shape of the crater influences the expansion and dispersion of the CO_2 in the near field. Near field behaviour is highly non-linear and complex, and the conditions of the fluid when it reaches atmospheric pressure as it emerges from the crater provide the input to, or source conditions for, atmospheric dispersion in the far field.

The CFD model produced by the University of Leeds for the analysis of near field expansion has been extended for use with dense phase CO_2 releases in craters in the COOLTRANS research programme. The model employs a composite equation of state that models the three phases and phase changes of pure CO_2, and includes the effects of the formation of solid particles based on the laboratory scale experimental research carried out by the University of Leeds. The CFD analyses carried out by University of Leeds used input conditions based on the outflow results obtained by UCL. Model predictions compared well with concentrations and temperatures in free CO_2 jets measured experimentally. Three dimensional (3D) predictions provided valuable insight into the behaviour of punctures and ruptures in craters and gave good qualitative agreement with the observed behaviour. They obtained reasonable quantitative agreement with the limited experimental measurements that were taken 1 to 2 metres above the crater in one of the puncture experiments.

The CFD model developed by the University of Leeds has been used to provide results for a range of sensitivity cases, including misalignment of pipe ends in the crater, extended fracture lengths and deposition of solid CO_2 in the crater. DNV GL have used these CFD predictions together with experimental data generated in the COOLTRANS research programme to derive a series of correlations for the crater dimensions. The experimental work used to develop the correlations involved three instrumented burst tests, eight puncture release tests, two full scale fracture propagation tests and three scaled rupture tests. An example of the performance of the use of the correlations to predict the crater width and length are shown in Figure 4.



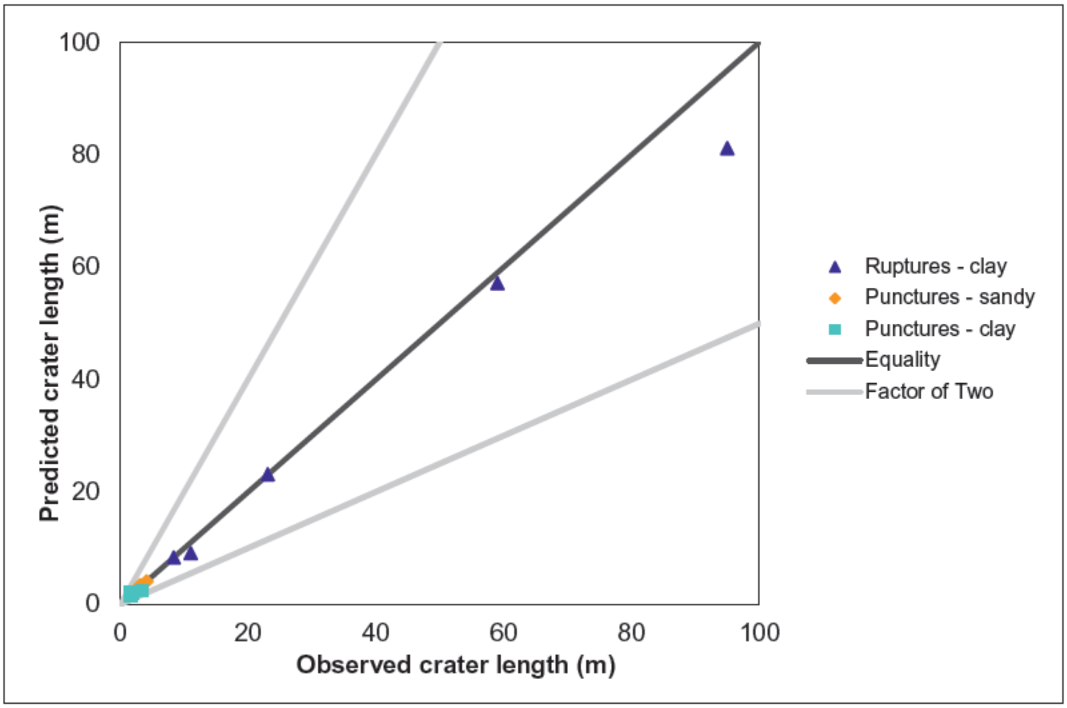


Figure 4. Comparisons of observed and predicted crater width and length for punctures and ruptures

Similarly, correlations were produced to describe the mass concentration and speed of the flow emerging from the crater. The plot of the University of Leeds' values for the mass concentration against non-dimensional path length is compared with the simpler correlation model developed by DNV GL in Figure 5.

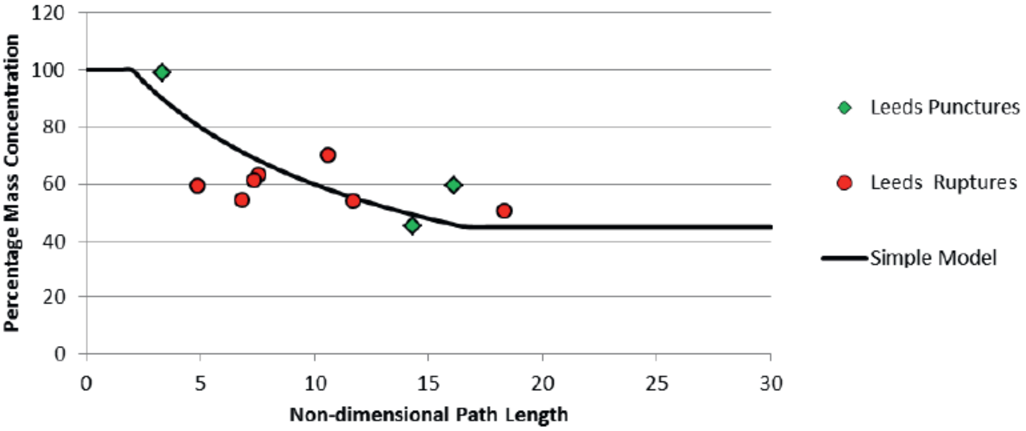


Figure 5. Comparison of percentage mass concentration against non-dimensional path length from University of Leeds data with DNV GL simple correlation model

Values inferred from limited experimental observations of the height of the plume rise above the release location were used to confirm the accuracy of this aspect of the modelling.

For lighter than air gas releases, the behaviour of the flow emerging from the crater can be predicted using a simple, integral model in which the dilution of a ‘slice’ of the flow is predicted as the slice moves forwards through the plume. However, as noted in [12], the CO_2 puncture experiments have shown that under certain conditions, the release will stall above the crater and fall back on itself to form a ‘blanket’ around the source. This situation is more complex, and it was necessary to define a set of criteria for when blankets would be produced and to define the size and location of an equivalent, ground level source in order to predict the subsequent dispersion behaviour. These two cases are shown in Figure 6.

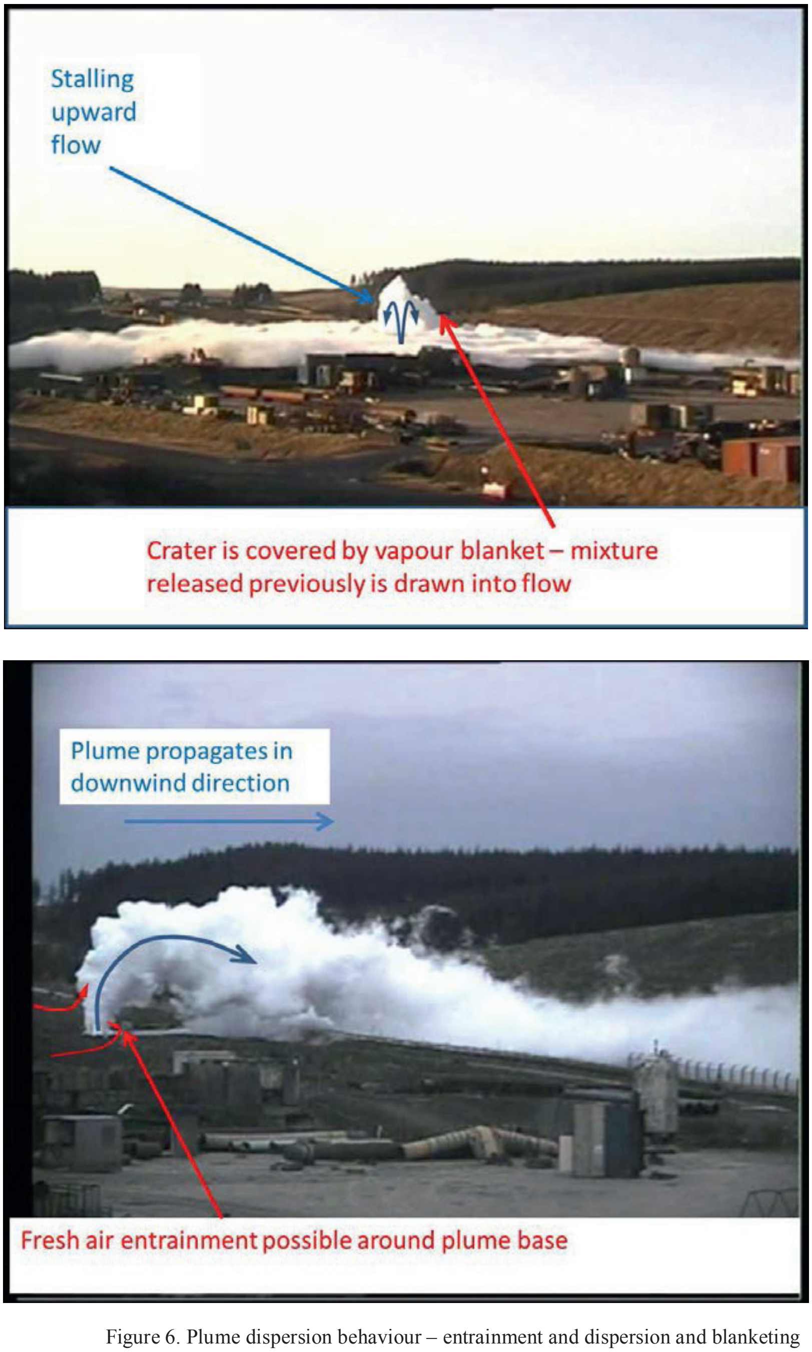


Figure 6. Plume dispersion behaviour – entrainment and dispersion and blanketing

3.3.3 Dispersion to atmosphere

Once the release leaves the crater and any source blanket that might be formed, it can disperse freely in the atmosphere. Work was carried out by Kingston University and the University of Warwick using a range of CFD models to study the dispersion once the flow is away from the immediate neighbourhood of the crater.

Any dispersion model that is used must take account of:

- The presence of solids and changes of phase during dispersion,
- The interaction of cold CO_2 with moist air,
- The gravitational spreading of the plume when in contact with the ground,
- Entrainment of air, including the difference in density of the plume,
- The time variation of the outflow from the crater.

During dispersion, the wind conditions will fluctuate in speed and direction due to atmospheric turbulence. This can cause the plume to meander about a mean position, so that a person near the edge of the plume would experience periods of no exposure interspersed with periods of exposure to the plume. This introduces additional fluctuations into the concentration-time records over and above those introduced by the turbulence within the plume itself. This should be taken into account when evaluating the consequences of the releases. In particular, it is important to consider the 'averaging time' used in the predictions produced by different models.

3.3.4 Slopes and obstacles

The dispersion of a denser than air, ground level plume may be affected by the underlying terrain and by obstacles, such as buildings, embankments or fences, in the path of the plume. Kingston University and the University of Warwick investigated this as part of their programme of work in the COOLTRANS research programme. Their calculations show that the effects of the slopes tend to change the shape and location of the cloud outline, with narrower, but thinner clouds predicted for cases where the wind is blowing across or down a slope. The effect is more pronounced at lower wind speeds. Overall, approximately the same area of ground would be affected in each case, so if there was a uniform population distribution this would lead to little change in the societal risk. However, the results do show that there is potential for the plume to cover the bottom of slopes more than would be expected over flat terrain and so the individual risk in these areas is likely to increase and conversely decrease at the top of any slopes. An order of magnitude estimate of the increase, suggests that the slope could cause an increase in individual risk of about a factor of 3.

3.3.5 Ingress into buildings

Modelling of the ingress of dispersing CO_2 into occupied buildings must be taken into account in the QRA. Being in a building provides a person with protection against an external CO_2 cloud. The protection provided depends upon the net ventilation rate, which will enable the plume material to gradually replace the ambient air inside the building. It is important therefore to be able to model the rate of infiltration of a plume into a building and the resulting accumulation of gas. The ingress and mixing of the plume with the air in a building is driven by the movement caused by temperature differences and the effect of gravity on the denser than air CO_2 plume.

This was investigated by the University of Newcastle as part of the COOLTRANS research programme. Their work suggests that in the cases studied, the enhancement of the ventilation rate due to buoyancy may not be significant with wind speeds in excess of about 1.5 m/s.

Work by the University of Warwick suggested that any buildings close to the location of the release may experience an enhanced inflow of the CO_2 mixture in the early stages as the raised front of any gravity current produced by the releases moves around a building. This effect would be expected to be more pronounced at the lower wind speeds. Similarly, it may be important to consider any tendency for preferential accumulation of the plume in the ground floor of the property. At present, it is recommended that the value assumed for the ventilation rate of a property is not allowed to fall below 1 air change per hour for wind speeds up to 4 m/s and that the rate increases proportionately with the wind speed at greater values of the wind speed.

3.4 Effects of CO_2 on people

The toxic effects of CO_2 on people [13] are summarised in Table 4.

Table 4 Effect of CO_2 concentration on people

CO_2 Concentration in Air (%v/v)	**Exposure**	**Effect on People**
17 – 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death-
>10 – 15	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness.
7 – 10	Few minutes	Unconsciousness, near unconsciousness.
6	1.5 minutes to 1 hour	Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing.
4 – 5	1 – 2 minutes	Hearing and visual disturbances.
3	<16 minutes	Headache, difficult breathing (dyspnea).
2	Several hours	Tremors.

The HSE has developed Dangerous Toxic Loads (DTLs) relating to levels of harm substances pose to people. The DTL describes the exposure conditions, in terms of airborne concentration and duration of exposure, which would produce a particular level of harm in the general population. Two DTLs are defined by the HSE, these being the Specified Level of Toxicity (SLOT) and the Significant Likelihood of Death (SLOD).

The harm level expressed by a given substance in the air is influenced by two factors, the concentration in the air (c) and the duration of exposure (t). Considering firstly, exposure to a steady concentration, a functional relationship between ‘c’ and ‘t’ has been developed by the HSE, such that the end product of this relationship is a constant called the Toxic Load.

For CO_2, the following expressions have been defined by the HSE [14] for the SLOT, DTL and SLOD DLT:

$$\text{SLOT DTL: } 1.5 \times 10^{40} = c^8.t$$
$$\text{SLOD DTL: } 1.5 \times 10^{41} = c^8.t$$

Where c is measured in ppm by volume and t is measured in minutes.

As a guide, the SLOD measure corresponds to a toxic load that would cause 50% fatalities amongst an average cross-section of the population and SLOT approximately 1% fatalities. This information can be used to infer what is called a ‘probit’ relationship for exposure to CO_2 in which the value of the toxic load is used to predict the percentage chance of fatality associated with the load (see for example, Lees [15]).

The effects on the population in the vicinity of the pipeline are calculated from the accumulated toxic dose in terms of whether the SLOD or SLOT dose thresholds have been exceeded. The dosage received by persons at specified distances from the pipeline, taking account of daytime and night time and whether the population are indoors or out, are evaluated from the output of the dispersion models. These values determine the likelihood of a person exceeding the SLOT or SLOD thresholds, or the extent of casualties, in terms of the number of people receiving more than the SLOD or SLOT thresholds.

3.4.1 Behaviour of people and escape

CO_2 is odourless and the effects of the gas may not be identified by people subjected to unexpected plumes from a pipeline release. However the release will generate a high noise level plus debris throw which will alert residents, particularly those out of doors, to the failure and allow a response and the potential to escape from the release. Low temperature effects caused by the Joule Thomson effect will cause the releases from the dense phase CO_2 pipelines to be visible, as the water vapour present condenses. This may allow some indication of which way to escape from the plume. In typical UK conditions, the areas of the plume in which people would be vulnerable would be within the visible plume, or expressing this in another way, people outside of the visible plume would be expected to be safe.

For persons indoors the effect of the release will be delayed and for a short duration release, persons indoors may be safe. For a longer duration release involving exposure to higher concentrations of CO_2, sufficient CO_2 may infiltrate and accumulate within a building to make it advantageous to attempt to escape from the building. Whether people would do this is an open question with the answer depending on many factors including the age of the people involved, the time of day, time of year and awareness of the hazards. Because of the above complications of deciding how and when people might attempt escape from indoors, no escape is assumed from any building in the methodology demonstrated within COOLTRANS. Average persons out of doors are expected to respond in some way, e.g. to move downwind, crosswind, or to higher ground however, to allow for uncertainties, for the purposes of the QRA are assumed either to attempt escape at a speed of 2.5 m/s or to remain stationary at their initial position, with a probability of 0.5 assumed for each. Vulnerable persons out of doors are either assumed to remain stationary at their initial location or attempt escape at 1 m/s.

3.5 Development of pragmatic models

The detailed state of the art phase boundary and CFD analyses carried out by the universities involved in the COOLTRANS research programme have enabled the sensitivities in the modelling and prediction of the behaviour of dense phase CO_2 releases to be understood and evaluated. CFD analyses at all stages of the release require considerable run times and it is not possible to analyse the full CO_2 release behaviour in a single CFD analysis.

QRA uses pragmatic models, which apply integral equations to provide thermodynamic solutions for outflow and dispersion, linking the two with an appropriate source model to represent the highly non linear near field expansion behaviour. These models are fast and efficient, but care is required to ensure they adequately represent all the complexities of the process and are able to provide predictions of the hazardous cloud generated by the dispersing CO_2 with reasonable accuracy.

The results of the COOLTRANS research programme have shown that simple pragmatic models can be used to provide reliable predictions of outflow and dispersion of dense phase CO_2 for use in QRA.

3.6 Risk assessment

The ‘risk’ is obtained by combining the casualty probability with the failure frequency and the associated probabilities of each event: wind speed, wind direction, atmospheric stability, day/night residency, proportion out of doors and probability of escape. Where a puncture case is being assessed in addition to a rupture, the risks arising from the two events are added.

3.6.1 Assessment of individual risk

The calculation is carried out to determine the sum from all of the hazards which affect people. Individual risk is normally based on the ‘hypothetical house resident’ assumed to be present 100% of the time and out of doors for 10% of the time in the day and 1% at night. The individual risk is calculated at a range of distances from the pipeline, the variation of individual risk along a line perpendicular to the pipeline is the risk transect. The calculations need to take account of both average and vulnerable people if they are likely to be present near the pipeline.

The distances to individual risks of 10 chances per million years (cpm), 1 cpm and 0.3 cpm, evaluated with appropriate vulnerability criteria, have been used in assessments of other pipelines to determine the extent of the different LUP zones.

3.6.2 Assessment of societal risk

The calculation of societal risk is required to determine the combined effect of the pipeline on the population in the neighbourhood of the pipeline. The societal risk is usually expressed in the form of an F-N curve, in which the cumulative frequency F with which events that cause more than a certain number of casualties, N, is plotted against N. The curve produced by a standard length of pipeline can be compared with acceptance criteria.

In practice, the basic risk calculation is carried out for a specific section of pipeline, and is concerned with the total harm resulting from each separate incident at that step (variation of wind speed, wind direction, atmospheric stability) and for each population development for the location(s) being assessed. The casualty probability is assessed for all of the population within the hazard range, the numbers of casualties, ‘n’, are assessed and assigned the frequency ‘f’ using the failure frequency of that pipeline step and the probabilities of the other associated variables. Calculations are carried out for each variable which takes a range of values (for example, wind speed, wind direction or residency period), resulting in a number of ‘f-n’ pairs for each step. The calculations are repeated for each equal step along the pipeline for the populated location being assessed. The ‘f-n’ pairs can be combined to give the cumulative F-N curve referred to above and an Expectation Value (EV), often referred to as Potential Lives Lost (PLL) if a probit relationship has been used for the casualty criterion, can be evaluated from this.

3.6.3 Criteria

The acceptability of the calculated risk levels is determined by comparison with available criteria. For any hazard in the UK, the requirements of ALARP apply. For individual risk the guidance in the HSE’s document ‘Reducing Risk, Protecting People’ R2P2 [16], is used to determine that the individual risk is either ‘broadly acceptable’, ‘tolerable if ALARP’ or ‘unacceptable’. The societal risk is compared against the FN curve in PD 8010 P-3 [7]. This is a curve based on the SLOD casualty criterion and on a 1 kilometre pipeline length, but a different casualty criterion can be used, provided that the assessment can be shown to be conservative. For example, comparing a SLOT based assessment with a SLOD based F-N criterion is conservative, as the number of casualties receiving a toxic load of SLOT will exceed those receiving SLOD.

If the F-N curve from the assessment crosses (goes above) the F-N criterion, risk reduction measures must be considered, following the ALARP principle. Where the F-N curve is wholly below the criterion the risks are considered to be in the ‘tolerable is ALARP’ region, however an ALARP demonstration may be required in some cases.

3.7 Risks posed by CO_2 pipelines

The work completed under COOLTRANS has shown that the hazards arising from a drifting toxic CO_2 cloud produce a different shape to the individual risk curves when compared with curves for a flammable fluid, such as natural gas. This is illustrated in Figure 8, where the individual risk values are plotted against the distance along a line perpendicular to the pipeline (the risk transect) for a typical high pressure natural gas pipeline and for a large diameter, thick walled dense phase CO_2 pipeline. Figure 8 shows that the individual risk due to the thermal hazard is higher close to the pipeline, but falls to zero within a limited distance from the pipeline, while the individual risk due to the toxic hazard are lower over the pipeline, but extend a considerable distance from the pipeline.

The differences arise as the thermal hazard distances from a natural gas pipeline are less sensitive to variations in the atmospheric conditions, wind speed and topography than the dispersion distances associated with a drifting cloud of CO_2. The sensitivity produces a ‘long tail’ to the risk transect for CO_2 pipelines. Also, the lower failure frequencies associated with the large diameter, thick walled CO_2 pipelines mean that the individual risk levels are relatively low. As a result, the balance between individual and societal risk is different for CO_2 pipelines, and while the individual risks are low, the potential for exposure to the low risks at an extended distance from the pipelines raises the requirement for societal risk as the hazardous cloud may drift to populations at distances from the pipeline.

Further, the greater distance and longer time period associated with the CO_2 hazard mean that a number of factors may be more significant in modelling the risk, such as the influence of the source conditions and subsequent dispersion from the crater; population factors, including the density of people at larger distances from the pipeline, the time people spend out of doors, escape and shelter assumptions, and the influence of isolation valves along the pipeline.

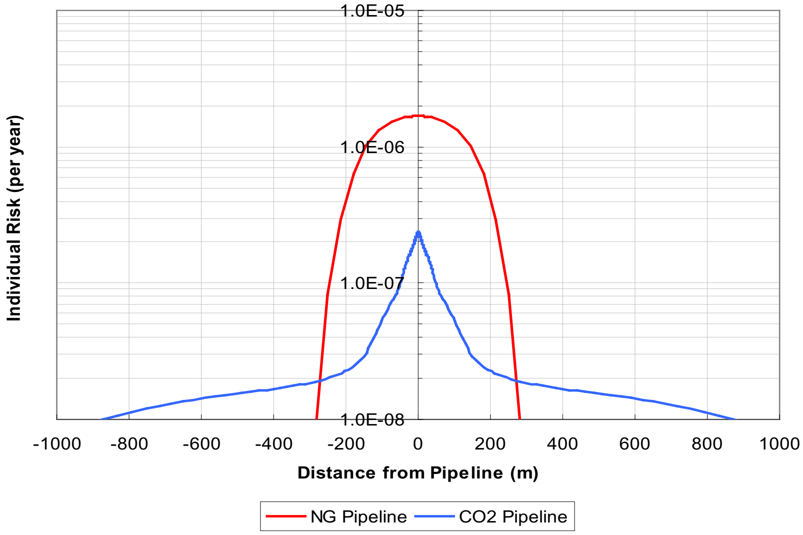


Figure 8. Individual risk transect for natural gas and CO_2 pipelines (ruptures only)

The more fundamental CFD based modelling studies conducted as part of the COOLTRANS research programme have provided the theoretical understanding that is required to address these issues. In parallel, the more practical risk assessment models are being applied to investigate the sensitivity of the results to the above factors and to advise on any modifications required for CO_2 pipelines.

4. Routeing of CO_2 pipelines

4.1 UK design standards – requirements for pipeline routeing

Both IGEM/TD/1 and PD 8010-1 allow the use of individual and societal risk levels calculated using QRA to be used to route pipelines and to carry out site specific risk assessments.

4.2 Requirements for routeing of CO_2 pipelines

The QRA methodology described above has been used to develop a societal risk screening methodology for use in CO_2 pipeline routeing.

The pipeline route selection process defined in the UK pipeline standard and code is based on choosing the most suitable corridor taking into account areas which must be avoided, such as centres of population, historic sites, environmentally, archaeologically or ecologically sensitive sites, difficult terrain and engineering issues related to crossings or unstable ground. When the route corridor has been selected, the location of the pipeline within the corridor then takes account of the numbers and location of any population groups in the vicinity of the pipeline with the aim of minimising the number of people within the hazard zone.

Management of the risk, both individual and societal, is based on a consideration of the separation distance from the pipeline to the nearest occupied building, to provide protection from the more likely events such as small leaks, and a reduction in risk level from larger less credible events; and by limiting the design factor to reduce the likelihood of the more serious failure modes where there are numbers of people at risk.

The proposed Yorkshire and Humber dense phase CO_2 CCS pipelines will operate at higher pressures than natural gas pipelines, and will require increased wall thickness for fracture arrest, and will therefore be thick walled (i.e. greater than or equal to 11.9mm). Pipelines of this wall thickness are resistant to damage, the failure frequency is therefore low and hence the individual risk levels around these pipelines are low. However, as seen earlier, because of the sensitivity of the atmospheric dispersion to variations in wind speed, the low risk levels are likely to decay very slowly beyond about 200 metres from the pipeline. An approach to routeing based on individual risk indicates that only small separation distances between the pipeline and occupied buildings are required, but the maximum hazard distances in the event of a worst case rupture event could be considerably larger.

The QRA process is site specific, time consuming and resource intensive. A screening methodology using generic case assessments based on population densities at different distances from the pipeline in which the F-N curve approaches the criterion curve given in PD 8010-3 [10] has therefore been developed as follows.

Firstly, generic studies have been carried out to investigate how societal risk varies with population density and distance from the pipeline. The situation that is assessed is sketched in Figure 9 below.

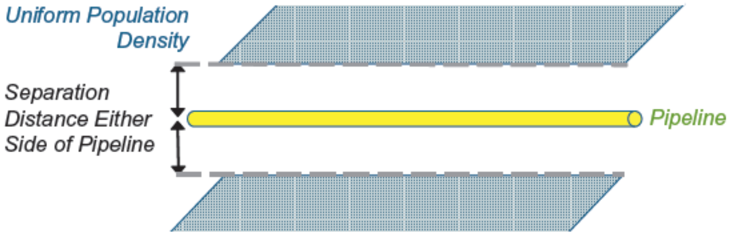


Figure 9 Generic societal risk assessment case

The analysis is carried out for different separation distances and population densities on either one side or both sides of the pipeline. The predicted number of casualties is evaluated and F-N curves are produced. The results are analysed to present the expectation value of the potential number of casualties per year plotted against the separation distance assumed (in metres), as shown in Figure 10 below, for a representative natural gas pipeline operating at 85 barg and a dense phase CO_2 pipeline example. The curves are plotted in the figure below for three different representative values of population density beyond the separation distance.

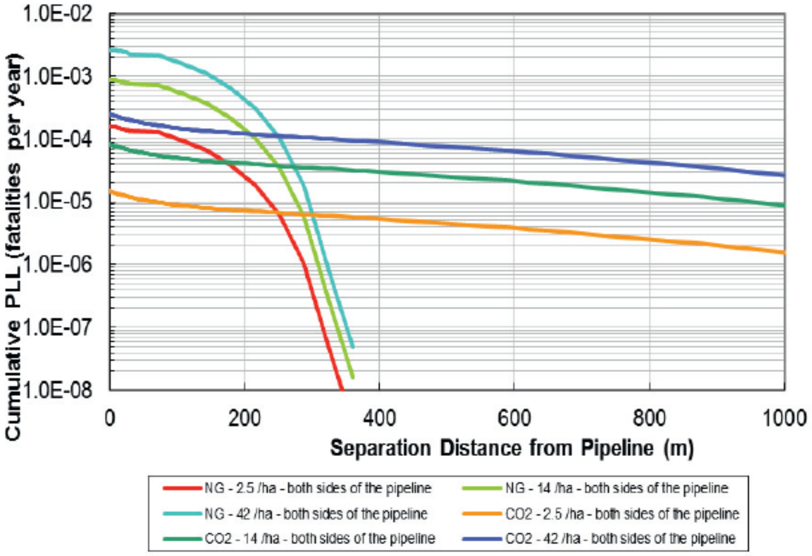


Figure 10. Variation in expected value of the number of casualties per year with distance to the pipeline for different population densities

Figure 10 shows that there is the potential for a significant expectation value and hence a large number of casualties to occur at quite large separation distances from a CO_2 pipeline, and confirms the requirements for societal risk analysis. The curves in Figure 11 show the calculated limiting value of the uniform population density which, if sited uniformly, either on one side or both sides of a pipeline beyond a given separation distance, produces an F-N curve that is guaranteed to meet the PD 8010-3 F-N criterion.

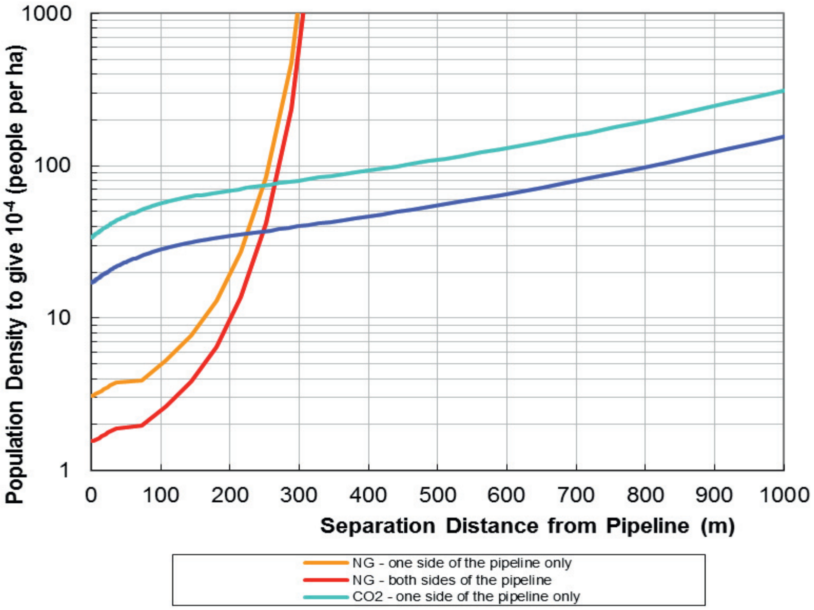


Figure 11. Population density required to give the limiting PD 8010-3 expectation value for a given distance from the pipeline

The screening methodology is based on three defined population types:

1. Villages - population density up to 10 persons/hectare averaged over the region of interest.
2. Suburban development - population density approximately 30 persons/hectare.
3. Inner city/urban areas of terraced housing/high rise flats - population density approximately 60 persons/hectare.

Each population type is assigned a maximum expectation value equal to one third of that allowed by the PD 8010-3 F-N criterion. Curves similar to those shown in Figure 11 are used to define the distances at which the calculated expectation value exceeds the limiting value for cities (60 persons per hectare), suburban development (30 persons per hectare) and villages (10 persons per hectare). The pipeline route is selected so that its separation distance to villages, urban areas and city areas is greater than these calculated distances. The multi-distance approach is useful for CO_2 pipelines, it avoids the excessive caution that would be imposed by having to apply the overly cautious city type values to every case, and avoids an over optimistic approach based on low individual risk like values which do not take account of developments beyond this distance.

This approach allows the route of the pipeline to be specified taking into account the numbers and location of any population groups in the vicinity of the pipeline with the aim of minimising the number of people within the hazard zone.

5. Application of routeing and design principles to CO_2 pipelines

The routeing and design principles specified in UK pipeline standard IGEM/TD/1 and code of practice PD 8010-

1 require the application of a separation distance between the pipeline and the nearest occupied building, and the definition of a route corridor of four times this distance either side of the pipeline within which the population density is calculated. The area is then classified according to the population density, and the pipeline design factor set to 0.72 for 'R' type/Class 1 areas, and 0.3 (or 0.5 if the wall thickness is equal to or greater than 19.1mm) in 'S' type/Class 2 areas.

The application of the design requirements to CO_2 pipelines is complicated by the lack of a simple, consistent value of the Q factor for use in calculation of the separation distance for a range of pipeline sizes and pressures. Further, the wall thickness of the proposed high pressure dense phase CO_2 CCS pipelines results in a low individual risk, such that there is no 1×10^{-5} cpm individual risk level, so there is no equivalent means of defining a separation distance.

Following assessment of detailed QRA studies carried out by DNV GL for National Grid, an 'inner zone' equal to the larger of the distances to the 0.3×10^{-6} cpm individual risk level or ¼ of the allowable societal risk distance to a population density equivalent to a village (i.e. approximately 10 persons per hectare) was proposed. Where developments occur within this distance, the pipeline design factor is reduced to 0.3, or 0.5 where the pipeline wall thickness is equal to or greater than 19.1mm. In addition, pipe installed at all road, rail, river or canal crossings shall have a design factor of 0.3 or 0.5 for wall thickness equal to or greater than 19.1mm, and this pipe shall be extended to a distance of 3 metres beyond the highway or railway boundary (or 3 metres beyond any drainage ditches adjacent to the boundary).

The results of the application of the methodology described above has been checked for actual distributions of population and have found to provide cautious guidance which clearly meets the level of safety which is implicit in routeing and design principles in the UK pipeline standard IGEM/TD/1 and code of practice PD 8010-1 whilst demonstrating conformity to the ALARP requirements for compliance with PSR 96.

6. Conclusions

The principles specified in the standard IGEM/TD/1 and code of practice PD 8010-1 for the safe routeing and design of high pressure hazardous pipelines in the UK have been presented, and a proposed extension of these requirements to CO_2 pipelines through the use of research findings has been explained.

The extension of the principles to CO_2 pipelines has involved the development of a comprehensive QRA methodology for CO_2 pipelines, which takes account of the toxic hazards of CO_2 and its behaviour as a heavy gas as it disperses as well as the location of population. The QRA methodology for CO_2 pipelines has been presented, and its application in establishing the safe route for a dense phase CO_2 pipeline explained.

Because of the relatively slow decay of the calculated risk with distance from a pipeline, the QRA methodology is based on societal risk, and its application has resulted in recommendations for different separation distances to different types of developments. This is preferred to either an overly cautious approach, based on assuming a maximum population distribution or an optimistic approach based solely on individual risk.

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