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Quantitative Failure Consequence Hazard Assessment for Next Generation CO2 Pipelines: The Missing Link

CO_2 Pipelines Good Practice Guidelines

Technical Report

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Executive Summary

This is the report on Workpackage 3.1 of the CO2PIPEHAZ project. It is concerned with the review and refinement of good practice guidelines for risk assessment and decision support tools relating to CO_2 pipelines. The objectives of the report are to:

- Identify and bring together existing good practice guidelines for pressurised CO_2 pipelines, e.g. those being produced in Norway, interim UK HSE guidelines and UK industry guidance (Energy Institute).

- Incorporate the new knowledge gained from this project. For example, for mitigation, emergency valve shut down modelling work will allow the strategic positioning of these valves to minimise release.

- To review, refine and consolidate this information so as to produce refined good practice guidelines based on currently available knowledge.

The structure of the report is to:

- Discuss requirements for decision support (section 2);
- Review existing guidelines for pipelines in general (section 3);
- Review existing guidelines which are specific to CO_2 pipelines (section 4);
- Discuss the contributions that the CO2PIPEHAZ project has made to good practice for decision support (section 5);
- Provide a summary methodology for decision support for CO_2 pipelines (section 6);
- Draw conclusions (section 7); and
- List the references used in the report (section 8).

The guidelines provide a road map identifying the most relevant sources of guidelines including general guidelines for hazardous pipelines, existing guidelines for CO_2 installations and pipelines, and new knowledge produced by CO2PIPEHAZ.

The methodology developed by CO2PIPEHAZ, including numerical outflow calculations and CFD for near-field and far-field dispersion is the most accurate consequence modelling approach. It should be used for any parts of the pipeline with critical hazard ranges and/or risk. Simpler methods, which are much faster to run, should be used to identify potentially critical parts of a pipeline and to carry out sensitivity analysis.

The formation of solid CO_2 deposits and their rate of resublimation remain as significant knowledge gaps.

1. Introduction

Large scale Carbon Capture and Storage (CCS) is an essential part of reducing the impact of global warming, by making significant reductions in greenhouse gas (GHG) emissions from the use of fossil fuels, in particular levels of carbon dioxide, CO_2. With this relatively recent technology, inevitably comes certain risks, the biggest of which is the accidental release from pressurised CO_2 pipelines, which are an integral part of the CCS chain, namely for the transporting of captured CO_2 for subsequent sequestration. A coal-fired power station, consuming 8000 te/day of coal (~1GW power generation), will produce 30 000 te/day of CO_2 to be captured and transported via pressurised pipelines. A very large release of CO_2 has the potential of producing a harmful effect over a significant area, and as such, has potential to significantly affect large numbers of people.

Two key areas that need to be demonstrated to gain public acceptance of CO_2 pipelines are that such mode of transport is safe, and its environmental impact is limited. Key to this is the prior knowledge of the time-dependent release rate, the corresponding fluid phase and the dispersion behaviour of escaping CO_2. Such information is pivotal in governing all the hazards associated with the failure of CO_2 pipelines, including emergency response planning and determining minimum safe distances to populated areas. The CO2PIPEHAZ project undertakes a fundamentally new approach to understanding the hazards presented by CO_2 pipelines based on the development of novel mathematical and computational techniques, challenging chemical engineering concepts and innovative experimentation to:

1. Define optimum level of impurities in the CO_2 stream based on safety, environmental and economic analysis;

2. Develop a computationally efficient multi-phase heterogeneous outflow model for the accurate prediction of the time variant release rate and the physical state of escaping CO_2 following pipeline failure, based on a reliable equation of state for CO_2 and CO_2 mixtures;

3. Develop multi-state dispersion models for predicting the subsequent concentration of the released CO_2 as a function of time and distance from the release, both in terms of a detailed near- and far-field modelling capability;

4. Conduct small and large scale experimental validations of the models developed;

5. Provide a detailed understanding of the hazards presented by CO_2 releases through experimentation and, using the data generated, validate the outflow and dispersion models developed;

6. Embody the understanding and predictive capabilities developed in decision support tools, assessing and improving existing safety, risk assessment methods, tools for CO_2 pipeline application, and producing refined best practice guidelines;

7. Demonstrate the usefulness of the tools developed through their application to possible CO_2 pipeline designs.

The primary focus of the CO2PIPEHAZ project is on onshore pipelines, where the potential proximity to large populations can be a significant risk factor.

This is the report on Workpackage 3.1 of the CO2PIPEHAZ project. It is concerned with the review and refinement of good practice guidelines for risk assessment and decision support tools relating to CO_2 pipelines. The objectives of these good practice guidelines are to:

- Identify and bring together existing good practice guidelines for pressurised CO_2 pipelines, e.g. those being produced in Norway, interim UK HSE guidelines and UK industry guidance (Energy Institute).

- Incorporate the new knowledge gained from this project. For example, for mitigation, emergency valve shut down modelling work will allow the strategic positioning of these valves to minimise release.

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2. Requirements for risk assessment and decision support

Risk assessment can be an input to decisions on many aspects of the design and operation of CO_2 pipelines. The requirements for both risk assessment and decision support will therefore depend on the context of the decision to be made. Some examples include:

- Concept design of a pipeline where a screening level risk assessment may be an input to route determination;

- Detailed design of a pipeline, where risk assessment may be an input to decisions on the need for specific risk reduction measures. The requirements will depend on the specific case and there could be an overview risk assessment, which determines those sections of the pipeline with highest risk. More detailed risk assessment and assessment of risk reduction options might then be applied to specific high risk sections of the pipeline;

- Permitting or other regulatory approval of a pipeline. This might in future require specific risk criteria to be met (as is the case for pipelines conveying hazardous substances in many countries worldwide (Mendes *et al*, 2011)). However, there are no Directives on the safety of pipelines at European level. Although many countries worldwide, including many in Europe, have national legislation on pipelines conveying hazardous substances, carbon dioxide does not meet the definition of a hazardous substance in most cases. However, as major CO_2 pipelines become more prevalent due to the uptake of CCS, it is possible that this position could change;

- Operation of pipelines and/or pipeline networks, where specific risk assessment may be required to inform decisions on risk reduction measures;

- Emergency response plans, which will need to be informed by an understanding of the hazards and hazard ranges.

As a result a range of risk assessment and decision support approaches may be appropriate depending on the context of the decision.

For the risk assessment methodology possible approaches (in roughly increasing order of accuracy) include:

- Qualitative risk assessment (screening approach based on qualitative descriptors of consequence and frequency);

- Consequence based assessment, where the consequences are assessed by modelling and no account is taken of the frequency.

- Semi-quantitative (SQ) risk assessment. This comprises a range of techniques in which the consequences are generally assessed by numerical modelling and the frequency may be assessed at a range of levels from close to qualitative through to quantification by means of historical data or fault tree analysis. The results are usually presented in a risk matrix and there is no attempt to derive cumulative risk from different scenarios.

- Full quantified risk assessment (QRA). This entails quantification of both consequences and frequency and the calculation of measures of risk (individual risk and societal risk) which are cumulated for all scenarios, e.g. individual risk contours and FN curves.

- Specific detailed studies to support particular decisions. The detail of consequence modelling which is possible for general risk assessment (SQ or QRA) is necessarily limited because of the large number of cases which need to be modelled. Usually modelling is limited to integral models (McGillivray *et al*, 2013). For CO_2 pipelines the possibility of using models which include topography has been demonstrated (Lisbona *et al*, 2013). However, when a particular risk issue has been identified it may be appropriate to study the specific issue using more detailed modelling such as CFD. Equally, more detailed studies may also be carried out in terms of the frequency of specific events, for example fault tree analysis and/or estimation of human error probabilities.

A key purpose of risk assessment is to help ensure that adequate safety measures are incorporated into the design and operation. Risk assessment may be an input into the decision of whether a particular risk reduction measure is required. All risk assessment is subject to uncertainties and these need to be considered carefully when the risk assessment results are an input to decision-making. The range of decision support approaches includes the following:

- Application of risk reduction measures required by relevant and appropriate standards or other good practice;

- Consideration of the need to go beyond relevant standards and good practice for risk scenarios and pipeline locations where the risk and/or consequences are high. This may be required if the risk is beyond tolerability criteria, or it may be considered as part of the process of reducing risks as low as reasonably practicable (ALARP). Such a process would involve:
  - Systematic identification of what further risk reduction is possible;
  - Assessment of whether the further risk reduction is required. This might involve:
    - Comparison with tolerability criteria;
    - Qualitative assessment and ranking of risk reduction measures, including factors such as the possibility of risk transfer (the risk being considered is reduced but other risks are increased);
    - Quantitative assessment using cost benefit analysis (CBA).

A key principle is that the decision support methodology, which includes the risk assessment, should be appropriate to the needs of the decision. This includes both the ability to make the decision (higher accuracy may be needed for borderline decisions), and the justification of the decision (greater rigour may be required when the consequences or risks being reduced are high). This is embodied in the UK regulatory principle that the risk assessment should be proportionate to the consequences and risk.

Some examples are:

- Screening level approaches may be appropriate to determine critical sections of a pipeline and during the concept selection stages of the design. More accurate risk assessment, possibly using CFD, may be used to make decisions about high risk sections of the pipeline.

- For pipeline sections with low risk, it may be possible to conclude that the implementation of appropriate design standards is sufficient.

3. Review of general guidelines for hazardous pipeline risk assessment

In this review, the general guidelines for pipelines conveying hazardous fluids are considered first because this gives a necessary context. Such guidelines and legislation are at national level because there is no European directive concerned with hazardous pipelines. Most guidelines and legislation are concerned with natural gas (methane) pipelines but some consider other gases and also hazardous liquid pipelines.

3.1 Risk reduction

3.1.1 Pipeline route selection

Routing the pipeline as far as possible from populations is a key risk reduction measure. Standards such as BS PD8010 Part 1 (BSI, 2004) define a building proximity distance (BPD) and the pipeline cannot be routed closer to existing buildings than this. Other countries use a similar concept of 'setbacks' which define the distance between the pipeline and populations e.g. (Canadian Standards Association, 2004).

Land use planning controls help to prevent new buildings from being constructed within the BPD. However, the pipeline operator will still periodically survey the pipeline and may use PD 8010 Part 3 (BSI, 2009) to conduct a risk assessment and provide further risk reduction if new buildings are found within the BPD.

3.1.2 Design for pipeline integrity

A number of design codes exist on a national basis for pipelines and cover design of pipelines for adequate initial integrity. For example, those in the UK are IGEM TD1 (IGEM, 2009) for natural gas pipelines and BS PD 8010 (BSI, 2009) for hazardous liquid pipelines. Mendes *et al* (2011) indicate that other international countries also cover safety issues in their pipeline design codes. For example, in the USA (US Congress, 2006), regulation covers the rules for design and operation of pipelines to achieve integrity. More detailed requirements are specified at State rather than Federal level. In the Netherlands the safety issues are written within the law, rather than the design codes.

Analysis of pipeline incident data (see 3.2.1 below) indicates that third party activity (TPA), e.g. inadvertently damaging a pipeline with a mechanical digging machine, dominates pipeline failures. It is possible to select appropriate material of construction, design factor and wall thickness so as to essentially eliminate catastrophic failure scenarios from this cause. In those countries which use structural reliability assessment (SRA) to derive pipeline failure rates (see 3.2.1 below), e.g. UK, Netherlands, there is incentive to use higher wall thickness. Some other countries such as Switzerland take account of increased wall thickness reducing failure frequency using historical failure rate data from EGIG (see 3.2.1 below).

3.1.3 Additional risk reduction measures

Additional potential risk reduction includes:

- Crack arrestors - An issue is whether damage to the pipeline could give rise to a propagating crack. As stated above, this should be avoidable using an appropriate combination of pipeline material properties and wall thickness. An alternative is the installation of 'crack arrestors' at intervals along the pipeline. There is an identified issue about crack propagation for CO_2 pipelines (see 'isolation valves' below).

- Depth of Cover – Burying the pipeline deeper can reduce the risk of failure due to third party activity (TPA). The degree of credit varies between different regulators and standards. The Netherlands have developed a function based on Gasunie data and depths of up to 2 m are considered (Laheij, 2010). HSE in the UK only considers depths up to 1.1 m, and the origins of the factors used appear to be based on British Gas data from the 1980s (Chaplin, 2009). Industry within the UK use a different set of values, as detailed in PD 8010 (BSI, 2009) and IGEM (2009) and these consider depths up to 3 m. Switzerland also uses these factors from the UK industry standards (SwissGas, 2010).

- Slabbing – This is considered in the Netherlands in the BevB Manual (RIVM, 2010) and also by industry in the UK, which both use the values given in PD 8010 and IGEM TD/2. These apply to slabs sized using IGEM TD/1, 6-Impact Protection. Here, a reduction factor of 30 is used for concrete slabs plus warning tapes, where a slab is defined as being 3 m wide and at least 150 mm thick. Western Australia also applies these factors for slabbing (Western Australian Planning Commission, 2007). Switzerland applies a factor of 0.1 for the same scenario (SwissGas, 2010). The UK regulator is currently considering what level of credit to give to slabbing, but is unlikely to adopt the values given in PD 8010 and IGEM TD/2 as they are not convinced that the evidence supports the use of these values.

- Land use – In the Netherlands, agreements about land utilization can lead to reduction factors of between 1.6 and 100 (Laheij, 2010). In Switzerland, if the pipeline does not fall into a "natural danger map" area, then the failure frequencies may be reduced by a factor of 10. The age of the installation is taken into account for material failures, and if the pipeline runs through a site that has been put aside for future redevelopment, then the failure frequencies are increased by a factor of 3.

- Statutory one-call system – In the Netherlands there is a "statutory one-call system" in place, whereby a single phone call can provide information about any buried pipelines in a particular location. This reduces the likelihood of damage by TPA and is assumed in the failure frequencies used in the Netherlands. Stringent supervision of the digging activities can also lead to a reduction factor of 3. One-call systems are also in place in other countries such as Canada (Canadian Standards Association, 2004).

- Surveillance Frequency – The UK standards IGEM TD/2 and PD 8010 provide a curve of reduction factors if surveillance is increased and these appear to be used in Switzerland as well (Swissgas, 2010). The use of this curve is not recognised by the UK regulator, HSE.

- Other reduction factors – The two UK industry publications IGEM TD/2 and PD 8010 Part 3 also include reduction factors for additional liaison visits and for additional high visibility marker posts. These would not be considered by the UK regulator.

- Isolation valves - In the UK the preferred mitigation would be for installation of thicker-walled pipeline rather than additional valves. Isolation may give some mitigation but for flammable events the worst case event has often occurred before isolation can be achieved. Some concerns have been raised in terms of isolation of a CO_2 pipeline being more likely to cause propagation of a failure (Mahgarefteh & Atti, 2006).

3.2 Risk assessment

Mendes *et al* (2011) carried out a survey of pipeline risk assessment methodologies and criteria used by, or required by, different international regulators. A key conclusion was that many different detailed assumptions are in use and there is also a wide range of different risk criteria. Assumptions and methodologies are briefly discussed below which are in use for:

- frequency (failure rates);
- consequence assessment;
- vulnerability assessment;
- risk criteria.

3.2.1 Failure rates

There are two basic approaches to deriving failure rates for pipelines, at the level of risk assessment for regulatory permitting and land-use planning purposes:

- Historical data;
- Structural reliability assessment which uses fracture mechanics models.
- Fault tree analysis tends not to be used but could be appropriate for very specific failure modes and scenarios which may not be captured by historical data.

The most prevalent historical data are collected and provided by EGIG (European Gas Pipeline Incident Data Group) and CONCAWE (CONservation of Clean Air and Water in Europe). Where possible, countries use their own subset of data from these datasets. The UK also uses data from UKOPA (UK Onshore Pipeline Operators' Association) and the Netherlands use some information from their oil operators, which are a subset of CONCAWE. France uses French historical data for natural gas, CONCAWE data (French operators) for liquid hydrocarbons, and EGIG data for flammable or toxic gases.

Structural Reliability Assessment (SRA) models are required in the Netherlands for natural gas pipelines by the use of CAROLA (a dedicated computer programme), but are not used for other substances. For natural gas pipelines, only third party activity (TPA) is considered but, for other substance pipelines, various failure mechanisms are included. In this latter case, the failure rates are based on Dutch historical data.

In the UK, the use of fracture mechanics models for TPA is widely accepted. In PD8010 Part 3, the TPA values quoted are based on an SRA model, although the document states that failure frequencies derived from published operational data sources (EGIG, CONCAWE and UKOPA) may be used as an alternative. The values for the other failure mechanisms are based on historical data from UKOPA. It is expected that all failure mechanisms will be considered and should be representative for the pipeline in question. HSE, the UK regulator, carries out risk assessment to inform land-use planning and uses an SRA model for TPA whilst failure rates for the other mechanisms are based on a mixture of UKOPA, EGIG and CONCAWE data, dependent on the substance under consideration.

It should be emphasized that SRA models derive failure rates specific to the pipeline in question whilst historical data is more generic. An SRA model will consider the wall thickness, diameter, material of construction and operating pressure. Failure rates based on historical data, on the other hand, will include all materials, operating pressures, wall thicknesses and diameters. In some cases, it may be possible to provide a split by either wall thickness or diameter, but this is often very coarse in nature.

Historical data indicate that TPA is the dominating failure rate and that external corrosion and internal corrosion can also be significant.

3.2.2 Consequence assessment

Mendes *et al* (2011) reported a wide variety of assumptions in use for pipeline risk assessment worldwide. However, since most pipeline regulation is concerned with flammable materials conveyed in pipelines, many of the assumptions are not relevant to CO_2. Some that are relevant are briefly discussed below:

- Scenarios modelled. These need to be relevant to the substance conveyed.

- Hole Sizes. It is usual for a QRA to consider a range of hole sizes with associated frequencies. The choice of hole size to represent a particular frequency range was found to vary.

- Crater modelling. The Netherlands is the only country to calculate the crater size and this is done within the CAROLA software (RIVM, 2009), which is their version of PIPESAFE. The UK has taken some account of crater size in the modelling of CO_2 releases (McGillivray & Wilday, 2009).

- Discharge rates – A range of methods are in use to calculate flow rates. Variation was also seen in how the leakage time is calculated.

- Topography – none of the countries surveyed currently consider topography although this is being explored for simplified models in the CO2PIPEHAZ project (Lisbona *et al*, 2013).

- Computational Fluid Dynamics (CFD) – CFD is accepted in appropriate circumstances in the UK and South Korea. It is also allowable in specific circumstances in France where the results have to be reviewed by a third party.

- Weather data – There is variation seen in the type of weather data used including no consideration of weather conditions generic weather conditions defined for all places, and observed weather data from local weather stations.

3.2.3 Vulnerability modelling

This concerns the harm criteria used to determine the level of harm for which criteria have been set and also the estimated number of fatalities for use in societal risk calculations. Again Mendes *et al* (2011) were most concerned with vulnerability modelling for flammable consequences. The following have some relevance to CO_2:

- Level of harm – The level of harm used in assessments is generally based on fatalities. The exceptions to this are the UK, who use a dangerous dose level of harm (roughly equivalent to 1% fatality), and France, who do not model this at all.

- Harm criteria – The Netherlands and South Korea use probits. The UK regulator uses toxic load criteria for 1% and 50% fatality.

- Escape modelling – This is permitted for flammable events in most countries surveyed.

- Population data – Significant variation was seen in the calculation of population data for societal risk calculations. All of the countries that consider societal risk, with the exception of France, take some account of future population variation. Census data is used where possible in Switzerland and France. If this is not available then Internet research and standardized approximations are permitted in Switzerland, whilst France also uses rough estimation and aerial photography combined with mandatory counting rules. The Netherlands start with a national population database and it is up to the competent authorities to ensure the correctness and completeness of the data used. South Korea bases the population on counting the number of houses from aerial photographs. South Korea considers future populations if there is an official plan for any development. The UK does not currently use societal risk for providing land-use planning advice but has a national population database (Lisbona *et al*, 2011) which is used for societal risk calculations.

3.2.4 Risk criteria

The types of criteria which are in use worldwide comprise:

- Hazard or consequence criteria
- Individual risk
- Societal risk
- Risk matrix approaches
- ALARP.

These are discussed in more detail below.

Hazard criteria

Switzerland uses hazard criteria to decide whether a safety case, which includes a risk assessment, needs to be submitted (Mendes *et al*, 2011). The inner zone for LUP in the UK is based on hazard criteria (for natural gas pipelines).

Individual risk

The Netherlands, South Korea and the UK (regulator and codes) use an individual risk criterion of 10^{-6} per year (tolerable risk) for the purposes of pipeline siting. In the Netherlands, the distance to the individual risk contour of 10^{-6} per year shall be < 5 m. This criterion is prescribed for vulnerable populations but is a guideline for less vulnerable populations.

In the UK, HSE has the PADHI system (HSE, 2011) for land use planning, which uses three zones to determine what developments can occur. The inner zone is the building proximity distance (BPD) for natural gas, which is defined by the pressure and diameter of the pipeline. The middle zone is defined as the distance to a risk of 10^{-6} per year of a person receiving the HSE Dangerous Dose (roughly equivalent to 1% fatality). The outer zone is the distance to a risk of 0.3×10^{-6} per year of a person receiving the dangerous dose.

The Western Australian Planning Commission (2007) uses risk criteria in terms of individual risk of fatality which are given as:

- A risk level in residential areas of 1×10^{-6} per year or less;
- A risk level in sensitive developments such as hospitals, schools, childcare facilities and aged care housing of 0.5×10^{-6} per year or less; and
- A risk level for commercial developments, including offices, retail centers, showrooms, restaurants and entertainment centers of 5×10^{-6} per year or less.

New South Wales (NSW) Australia (2008) is proposing to use the same criteria, with the addition of:

- A risk level in sporting complexes and active open space of 1×10^{-5} per year or less; and
- A risk level in industrial areas of 5×10^{-5} per year or less.

Societal risk

Mendes at al (2011) showed that a very wide range of societal risk criteria are in use worldwide. Figure 1 shows a selection of criteria from CETESB (Brazilian province of Sao Paulo), the Netherlands, the UK code PD8010 Part 3, Switzerland and NSW Australia.

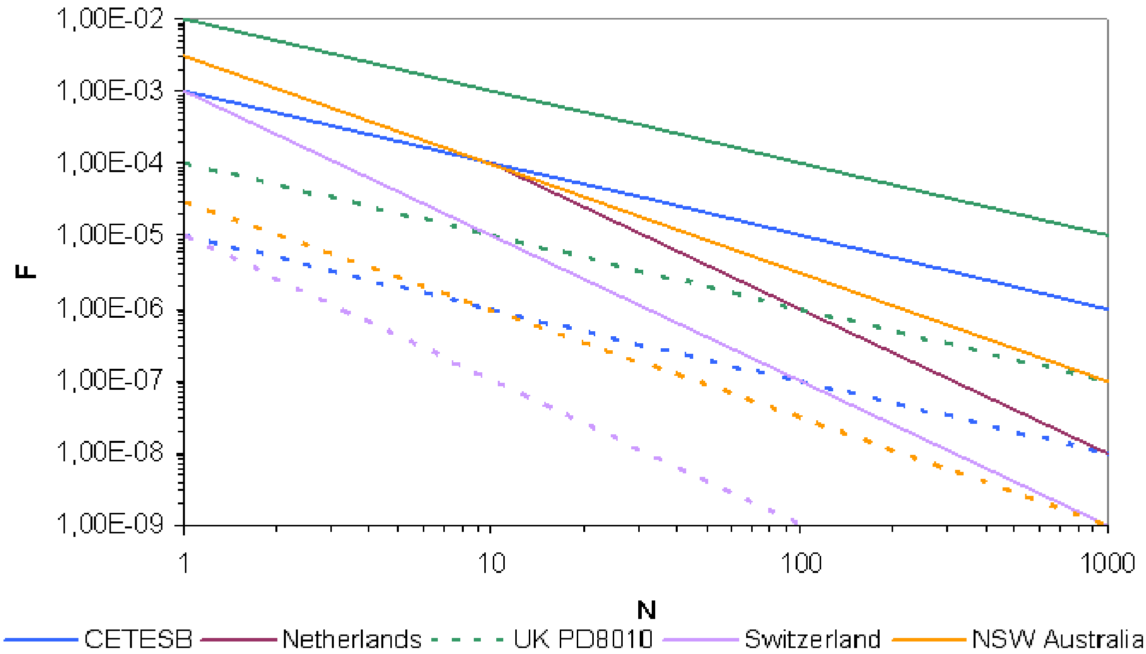

Figure 1. Comparison of international societal risk criteria for pipelines

For each case, an upper (continuous) line is shown above which the risk is deemed unacceptable. For some cases there is a lower (dotted) line, below which the risk is deemed acceptable. The region between these lines is the ALARP region, in which the risk must be shown to have been reduced 'as low as reasonably practicable' in order to be acceptable**.** The Netherlands do not have an ALARP region and so have only a single (continuous) line in Figure 1. PD 8010 gives a single criterion line for the boundary between broadly acceptable risk and an ALARP region (dotted line). However, PD 8010 also describes the position of the boundary with unacceptable risk as being two orders of magnitude higher in frequency. Cut-offs in the criteria are not shown in Figure 1, e.g. the Swiss criteria do not extend below N = 1, and the Netherlands criteria do not extend below N = 10. It can be seen that there are considerable differences in the FN criteria shown in Figure 1. Some countries (Netherlands, NSW Australia, Switzerland) use a slope of more than -1 to take account of the aversion of society to events that kill large numbers of people. The criteria of São Paulo Brazil (fixed sites) and PD 8010 do not include risk aversion.

In France, two risk matrices (probability versus severity) are used, one for Significantly Lethal Effects (SLE) and one for First Lethal Effects (FLE). The two risk matrices are then divided into unacceptable areas and acceptable under certain conditions. The unacceptable areas are different between new pipelines and those already in service.

Switzerland is the only country to consider the cumulative risk from existing pipelines in the right of way (RoW), although France is currently developing such a method, and the code PD8010 Part 3 (UK) requires a cumulative risk assessment for a RoW.

Risk matrix approaches

Risk matrix approaches may be applicable for risk screening, when, for example, considering the risk from pipeline segments closest to populations. Risk matrices are extensively used in the UK by companies for risk assessments of fixed sites under the Seveso Directive and can incorporate approximate tolerability criteria (Middleton & Franks, 2001).

In France, such a risk matrix (Figure 2) is used as part of the GESIP risk assessment methodology for hazardous pipelines. The gravity or severity scale uses two defined harm criteria:

- First lethal effects (FLE) (1% lethality);
- Significant lethal effects (SLE) (5% lethality).

The gravity is the number of people exposed within the effect distance for the above harm criteria. The frequency on the matrix is the cumulative frequency for all relevant events. The methodology is further defined by Descourrière & Chaumette (2010) and by Dupuis (2013).

Gravity (persons)		**Probability (year^{-1})**						
FLE	**SLE**		**5.10^{-7}**	**10^{-6}**	**5.10^{-6}**	**10^{-5}**	**10^{-4}**	**10^{-3}**
>3000	**>300**	*	*					
1000< ≤3000	**100< ≤300**	*	*	*				
300< ≤1000	**30< ≤100**	*	*	*	*			
100< ≤300	**10< ≤30**							
10< ≤100	**1< ≤10**							
≤10	**≤1**							

* *Specific building (public buildings, very high buildings and nuclear facilities)*

Figure 2 : French r*isk matrix defining risk acceptability for hazardous pipelines (source: GESIP guidance document)*

ALARP

ALARP (As Low As Reasonably Practicable) is a feature of most of the individual and societal risk criteria in use for pipelines. In the ALARP region, the risk would be deemed acceptable provided it has been reduced to as low as reasonably practicable. ALARP demonstrations are required by Switzerland and by the UK regulator for safety evaluations supporting the routing of new pipelines. They are not required in the Netherlands (ALARP is assumed to be satisfied if all the standards are followed) or France.

UK guidance (HSE, 2010) indicates that relevant standards and other recognized good practice should be the starting point and should be implemented in any new design. The ALARP principle is used to decide whether additional risk reduction should also be implemented.

In the UK many ALARP demonstrations are qualitative. UK guidance for fixed sites (HSE, 2010b) indicates that an ALARP demonstration consists of systematically identifying what further risk reduction is possible ("What more could I do?") and then assessing and presenting the arguments as to why it is not reasonably practicable ("Why haven't I done it?"). However, in some cases the assessment will lead to the conclusion that further risk reduction is necessary and in any case low cost risk reduction should be done rather than argued about.

In cases where the decision is more finely balanced, a quantified assessment can be carried out using cost benefit analysis. Mendes *et al* (2011) found that the only country to set a value of a statistical life (VOSL) is the UK regulator, where the value was £1.34 million in 2004. In the UK, one way of demonstrating ALARP would be to carry out a cost benefit analysis (CBA) to compare the benefits of reducing the risk (in cost terms) with the cost of doing so. Detailed guidance is provided for carrying out CBA (HSE, 2001).

3.3 Conclusions on general guidelines for hazardous pipelines

1. A considerable body of guidance, including guidelines, industry standards and legislation, exists worldwide and provides decision support for hazardous pipelines. This includes required and potential risk reduction measures; and requirements for risk assessment, risk criteria and the need or otherwise for further risk reduction.

2. In most cases CO_2 is not currently in scope of this body of guidance, but most of the principles are applicable to all but very specific hazards from CO_2.

3. The available guidelines contain areas of commonality and some areas of difference, partly reflecting differences in scope.

4. There is little agreement worldwide on criteria relating to societal risk, nor on the detailed assumptions to be included in any pipeline risk assessment.

4. Review of existing guidelines for CO_2 pipelines

In this section, existing guidelines for CO_2 pipelines, which have relevance to decision support, are reviewed.

4.1 Available guidance on CO_2 pipelines

4.1.1 US Federal Regulations: Transport of Hazardous Liquids by Pipeline. CFR 49 - 195 (US, 1991)

In many countries worldwide, CO_2 pipelines are not currently regulated. The USA and Canada have historically transported CO_2 by pipeline for use in enhanced oil recovery (EOR). In the USA, CO_2 pipelines are classified by the Office of Pipeline Safety of the United States Department of Transportation as Highly Volatile/Low Hazard and Low Risk. The Code of Federal Regulations, Part 195: Transport of Hazardous Liquids by Pipeline (US, 1991) specifically covers issues relating to the transportation of hazardous liquid or carbon dioxide. The regulations listed in Part 195 are comprehensive and represent US pipeline industry best practice. US federal pipeline safety regulations are framed to ensure safety in design, construction, inspection, testing, operation and maintenance of pipelines. In addition, they set out procedures for administering pipeline safety programmes and incident response plans. Similar regulations are in place in Canada.

Note: Within the scope of these regulations 'carbon dioxide' means a fluid consisting of more than 90 percent carbon dioxide molecules compressed to a supercritical state. However, although these regulations only apply to CO_2 in the supercritical phase, they are a good reference source on which to build upon in developing regulatory regimes for the transportation of CO_2 by pipeline. It is unclear why these regulations are limited to supercritical CO_2 and do not deal with dense phase CO_2.

4.1.2 US CCS Guidelines - Guidelines for CO_2 Capture, Transport, and Storage (WRI, 2008)

The World Resources Institute (WRI, 2008) has produced 'Guidelines for Carbon Capture and Transport'. The main guidelines relevant to pipelines are outlined below.

Transport Guideline 1: Recommended Guidelines for Pipeline Design and Operation

a. CO_2 pipeline design specifications should be fit-for-purpose and consistent with the projected concentrations of co-constituents, particularly water, hydrogen sulfide (H_2S), oxygen, hydrocarbons, and mercury.

b. Existing industry experience and regulations for pipeline design and operation should be applied to future CCS projects.

Transport Guideline 2: Recommended Guidelines for Pipeline Safety and Integrity

a. Operators should follow the existing Occupational Safety and Health Administration (OSHA) standards for safe handling of CO_2.

b. Plants operating small in-plant pipelines should consider adopting Office of Pipeline Safety (OPS) regulations as a minimum for best practice.

c. Pipelines located in vulnerable areas (populated, ecologically sensitive, or seismically active areas) require extra due diligence by operators to ensure safe pipeline operations. Options for increasing due diligence include decreased spacing of mainline valves, greater depths of burial, and increased frequency of pipeline integrity assessments and monitoring for leaks.

d. If the pipeline is designed to handle H_2S, operators should adopt appropriate protection for handling and exposure.

Transport Guideline 3: Recommended Guidelines for Siting CO_2 Pipelines

a. Considering the extent of CO_2 pipeline needs for large-scale CCS, a more efficient means of regulating the siting of interstate CO_2 pipelines should be considered at the federal level, based on consultation with states, industry, and other stakeholders.

b. As a broader CO_2 pipeline infrastructure develops, regulators should consider allowing CO_2 pipeline developers to take advantage of current state condemnation statutes and regulations that will facilitate right-of-way acquisition negotiation.
Note: Site topography is an important issue, which has not been mentioned here.

Transport Guideline 4: Recommended Guidelines for Pipeline Access and Tariff Regulation

a. The federal government should consult with industry and states to evaluate a model for setting rates and access for interstate CO_2 pipelines. Such action would facilitate the growth of an interstate CO_2 pipeline network.

4.1.3 HSE, Interim guidance on conveying CO2 in pipelines in connection with carbon capture, storage and sequestration projects

The UK HSE (2008) published interim guidance on its website pending the development of standards specific to CO_2 pipelines. This requires the designers of CCS and sequestration projects involving the transport of CO2 in pipelines:

- to understand the hazards and the mechanisms, consequences and probabilities of pipeline failures;
- to take part in research initiatives; and
- to give a health and safety demonstration as if CO_2 were classified as a 'dangerous fluid' under the UK Pipelines Safety Regulations (PSR) and (for offshore installations) as if all relevant offshore regulations applied, in order to satisfy the requirements of the Health and Safety at Work etc Act 1974.

Relevant standards for pipelines in general are identified but it is stated that they do not address specific issues for transport of CO_2.

4.1.4 Safety in Carbon Dioxide Capture, Transport and Storage, IEA Greenhouse Gas R&D Programme (IEAGHG, 2009)

This report by IEAGHG (International Energy Agency Greenhouse Gas R&D Programme) presents hazard identification for the whole CCS chain of capture, transport and injection into storage. It includes transportation by pipeline. It is therefore a source of potential accident scenarios which require consideration. In addition it provides high level bow-tie diagrams which identify a number of possible risk reduction measures (safety barriers) which can be considered as part of a decision-making process.

Hazards relevant to CO_2 pipelines include:

- Potential for releases to form low level CO_2 clouds with risk of fatality to exposed individuals;
- Increased risk of running pipeline fractures;
- Potential for components within intelligent pigs to explode when depressurized;
- Human factors issues in the management of CO_2 pipeline networks;
- Potential for rapid corrosion failure if free water enters the pipeline;
- Potential for small leaks to escalate due to corrosion or by causing ice formation under the pipeline;
- Incomplete coverage when advanced pipeline leak detection systems are deployed.

4.1.5 Comparison of risks from carbon dioxide and natural gas pipelines

This report (McGillivray & Wilday, 2009) is a UK HSE research report and presents risk assessment for a CO_2 pipeline in order to compare with the risks from natural gas pipelines and draw conclusions about whether there is a technical case for CO_2 pipelines to be regulated under the UK Pipeline Safety Regulations. Its main interest is that it provides a tentative methodology for risk assessment of CO_2 pipelines which is consistent with methodologies used to give land-use planning advice for pipelines conveying toxic substances in the UK. The methodology addresses:

- Harm criteria
- Event tree
- Tentative frequency data
- Modelling using Phast using tentative source term assumptions.

The methodology was one of the inputs to CO2PIPEHAZ work on risk assessment using integral models which is further discussed in section 5.3 below.

4.1.6 DNV-RP-J202, Design and Operation of CO_2 Pipelines (DNV, 2010)

This recommended practice standard (DNV, 2010) includes safety features (risk reduction measures) recommended for pipeline design and operation and specific to CO_2 pipelines. It also discusses risk assessment and the knowledge gaps in risk assessment for a CO_2 pipeline.

Its objective is to provide guidance on safe and reliable design, construction and operation of pipelines intended for large scale transportation of CO_2 to meet the requirements given in referenced pipeline standards. It is the first comprehensive standard for CO_2 pipelines for CCS worldwide but it also highlights a number of gaps in knowledge, particularly with respect to consequence modelling source terms within risk assessment.

DNV-RP-J202 provides the most detailed guidance currently available on the safe design and operation of CO_2 pipelines. It discusses the design and use of a number of potential risk reduction measures and provides guidance on the considerations involved in their selection, especially in cases where knowledge gaps remain. The standard addresses many of the knowledge gaps previously identified by DNV (2007) and Oosterkamp and Ramsen (2008). It proposes that external hazards to CO_2 pipelines (including third party activity (TPA) and external corrosion) can largely be addressed by measures in existing standards for hydrocarbon pipelines, whilst internal hazards are specific to CO_2. Potential risk reduction measures which are discussed include:

- Overpressure protection;
- Water content specification, dewatering and control of water content;
- Prevention of hydrate formation;
- Pipeline layout including block valves, check valves (non-return valves), pigging stations and vent stations;
- Pipeline routing;
- Materials and pipeline design;
- Wall thickness design;
- Control of running ductile fracture;
- Control of fatigue;
- Construction; pre-commissioning and commissioning;
- Integrity management system;
- Operational controls;
- Inspection, monitoring and testing;
- Re-qualification of existing pipelines for CO_2 service.

Risk assessment is discussed as a decision support tool and some knowledge gaps are highlighted, including validated models for running ductile fracture and modelling of the dispersion of releases of CO_2 (aspects which are addressed by CO2PIPEHAZ). The guidance provided on risk assessment is high level. Sources of failure rates are briefly discussed. The UK SLOD and SLOT harm criteria are recommended for major hazards risk assessment purposes.

4.1.7 Stream composition of CO2 in pipeline (typical impurity levels)

One of the technical challenges being looked at in the CO2PIPEHAZ Project is the definition of the "optimum level of impurities" in the CO_2 stream based on safety, environmental and economic analysis; and the possible (synergistic) impact of these impurities on the physical release/ source terms/ thermodynamics/ consequence modelling of an accidental release. Whilst a significant volume of (experimental and modelling) work has been, and is being conducted on the release of pure CO_2, in reality a release is likely to contain impurities which are inherent to CO_2 streams from the various carbon capture processes/ technologies. These impurities may be substances such as CH_4, N_2, Ar, H_20, SO_x, H_2S, CO, glycol *etc*., contained at varying concentrations, depending on the CO_2 source (i.e. coal-fired vs. natural gas-fired power plants vs. industrial processes vs. natural sources vs. HC-streams containing high CO_2) and technology employed (e.g. post combustion vs. oxy-fuel vs. IGCC) and whether the stream has been scrubbed prior to entering the pipeline.

A technical note by DNV (Brown, 2011) presents the typical range of substances or compounds that may be present in a CO_2 pipeline and summarises the maximum potential concentration of each component (not necessarily existing simultaneously in any one single stream), for the different types of CO_2 source and carbon capture technology and processes involved. The potential impact of these impurities on a large scale release and the large degree of uncertainty will need addressing so as to improve confidence in models being developed. Some of these are addressed in the CO2PIPETRANS Project.

4.1.8 Energy Institute, Good plant design and operation for onshore carbon capture installations and onshore pipelines (EI, 2010a)

This guide (EI, 2010a) gives recommendations for design and operation of capture plant and onshore pipelines. A key source of the guidance was the industrial gases sector, which has some relevance but often involves CO_2 at different conditions and at a different (smaller) scale of operation. One chapter is devoted to pipeline design and operation and provides information on risk reduction measures including those relating to:

- CO_2 compositions and properties;
- Pipeline design standards;
- Fracture propagation control;
- Blowdown;
- Pigging;
- Block valve location;
- Emergency shutdown valves;
- Routing and topography;
- Materials selection;
- Construction;
- Flow measurement;
- Start-up and shut-down;
- Operational issues.

4.1.9 Energy Institute, Technical guidance for hazard analysis for onshore carbon capture installations and onshore pipelines (EI, 2010b)

This document (EI, 2010b) specifically addresses the risk assessment requirements for an onshore CO_2 pipeline. A companion document is in preparation covering offshore pipelines.

The guidance concentrates mainly on QRA using integral dispersion models although the need for CFD in some specific situations is mentioned briefly. Topics covered include:

- Failure scenarios;
- Pipeline failure rates (mostly based on data for non-CO_2 pipelines, with uncertainty for CO_2 pipelines raised due to the small current sample size);
- Use of integral models for consequence assessment:
- Development of source terms for models which are not designed for CO_2;
- Use of the CO_2 modelling option in DNV Phast;
- Derivation of harm criteria from the UK HSE SLOD and SLOT criteria;
- Possible impact of impurities;
- Criteria for risk acceptability;
- What can be done to eliminate or reduce risk;
- Worked example;
- Comments on aspects not covered, including site-specific source terms, low momentum releases and sublimation from solid CO_2.

The need for dispersion models to be validated for CO_2 is also discussed, including brief comments on the limited experimental data that were available at the time of publication.

4.1.10 DNV, CO2RISKMAN Guidelines (DNV, 2013)

These guidelines (DNV, 2013) were the output of the CO2RISKMAN joint industry project and are concerned with risk management including risk assessment for the whole CCS chain from capture to storage. It is in four separate documents (Levels 1 to 4) which present information in increasing detail. Both levels 3 and 4 provide significant technical detail. A unique focus of these guidelines is on the CO_2 stream and the need for risk management to be integrated throughout the CCS chain of capture, pipeline, injection and storage. For example, the CO_2 composition resulting from the capture process has fundamental impact on the risks in the downstream parts of the chain, including pipeline corrosion.

Level 3 of the guidelines covers aspects which are generic to all parts of the CCS chain, including:

- Overview of major accident hazard management;
- CO_2 properties and behaviour;
- CO_2 hazard management;
- CO_2 generic hazards;
- Hazard identification;

- Generic bow-tie diagram.

Level 4 contains sections on both onshore and submarine (offshore) pipelines. Both sections cover:

- Hazard identification. Detailed checklists for CO_2 hazards, causes/ failure modes, potential escalation and consequences to people, structures and environment;
- Scenario selection. The importance of considering topography and any features that could remove momentum from the release are highlighted;
- Frequency analysis (discussion of possible sources of data);
- Consequence analysis. Requirements are stated including the need for models to be fit for purpose, in very generic terms, without proposing specific solutions;
- Managing risk to an acceptable level. Considerable detail is provided in terms of CO_2-specific checklists for inherent safety, likelihood reduction; consequence reduction; and prevention/ control/ mitigation of escalation;
- Chain integration (examples of pertinent considerations).

The guidelines appear to be particularly helpful and detailed in the identification of risk management features and strategies. In terms of risk assessment, they tend to identify the issues that need to be addressed without providing detailed help in how to address them. The need for CFD modelling, where appropriate, is highlighted.

4.2 Experimental data and validation of consequence models

Many of the guidelines reviewed highlight the lack of experimental data for model validation (and model development). A number of experimental release studies have taken place at the GL Denton Spadeadam research site in the UK, funded by industry and by projects such as COOLTRANS (Allason *et al*, 2012) and CO2PIPETRANS Witlox *et al* (2011) and (2012)). Most of the data are not available to those not involved in the projects. Furthermore, most of the experimental studies have aimed at providing data for validation of the broad results of consequence models, rather than necessarily understanding and inputting to the modelling of the relevant physical processes.

While there appear to be currently no guidelines that address the issue of the extent of validation of models, it is the subject of a number of literature papers. These include:

- Witlox *et al* (2009, 2012) – validation of DNV Phast integral model
- Dixon *et al* (2012) – validation of Shell FRED and two CFD modelling approaches
- Dixon and Hasson (2007) - calculating the release and dispersion of gaseous, liquid and supercritical CO_2.

Pursell (2012) discusses initial small-scale work aimed at understanding physical processes involved in CO_2 releases.

Little work appears to have been carried out on deposition of solid CO_2 and the rates of its re-sublimation.

4.3 Conclusions of review of existing guidelines on CO_2 pipelines

1. Guidelines on the design and operation of CO_2 pipelines have been developed and are of a good quality considering the relative infancy and lack of practical experience of the technology.

2. The more recent guidelines (DNV, 2013, 2010) are currently the most comprehensive and those from the Energy Institute (2010a,b) provide additional detail in some areas.

3. Guidelines on major accident risk management including possible risk reduction measures and strategies are covered in some detail by the DNV (2013) CO2RISKMAN guidelines.

4. Guidelines on the details of carrying out risk assessment are less available. The DNV (2013, 2010) guidance is very high level and goal-setting on these matters. EI (2010b) provides more details, with worked examples, for modelling CO_2 releases from onshore pipelines and analogous guidance for offshore pipelines is expected. These mainly use DNV Phast and guidance on the use of CFD or other models is not covered in any detail.

5. Many of the guidelines reviewed highlight the lack of experimental data for model validation (and for model development).

5. Good practice for decision support developed by CO2PIPEHAZ

5.1 Scope of risk assessment

5.1.1 Introduction

Most of the guidance reviewed in section 4 uses risk assessment as a decision support tool. As already discussed in section 2, the risk assessment needs to be fit for purpose. This depends on:

- the type(s) of decision(s) to be made;
- their importance; and
- the difficulty in making them.

It is expected that decisions will be about:

- Design of the pipeline;
- Routing of the pipeline;
- Any further risk reductions required due to high risk, over and above those required in existing standards and good practice guidance.

It would be expected that more resource be put into decision-making (and the associated risk assessment) where the decisions are important due to, for example, the potential for large hazard ranges and substantial interaction with populations. Also where they are difficult, for example because the uncertainty in the risk assessment could change the decision. Greater accuracy may be possible by means of CFD modelling and/or accounting for the local effects of topography, for example. However, such risk assessment methodologies require substantially greater resources than integral modelling. CFD is very location-specific and not suitable for wholesale incorporation into quantified risk assessment (QRA) because of the very high resource requirements of carrying out separate CFD calculations at different points along the pipeline. However it could sometimes be appropriate for specific high hazard/risk points in a pipeline.

5.1.2 Event tree

Figure 3 (a) and (b) shows a generic event tree for CO_2 pipelines that has been developed within CO2PIPEHAZ. The event tree assumes that weather can be adequately modeled by two weather conditions D5 (Pasquill stability category D with a wind speed of 5 m/s) and F2 (Pasquill stability category F with a wind speed of 2 m/s). This is based on UK assumptions and is likely to be adequate for much of Europe, but could be revised to reflect local conditions.

A key consideration is whether the release would impact in the near field on the crater or any other local structures or topography and thereby lose significant momentum. If so, the possibility of using CFD rather than integral modelling needs to be considered. Also, if there is significant topography in the far field then the possibility of accounting for it should be considered. It is likely to have most effect on those scenarios with very low momentum, particularly the re-sublimation of deposited solid CO_2.

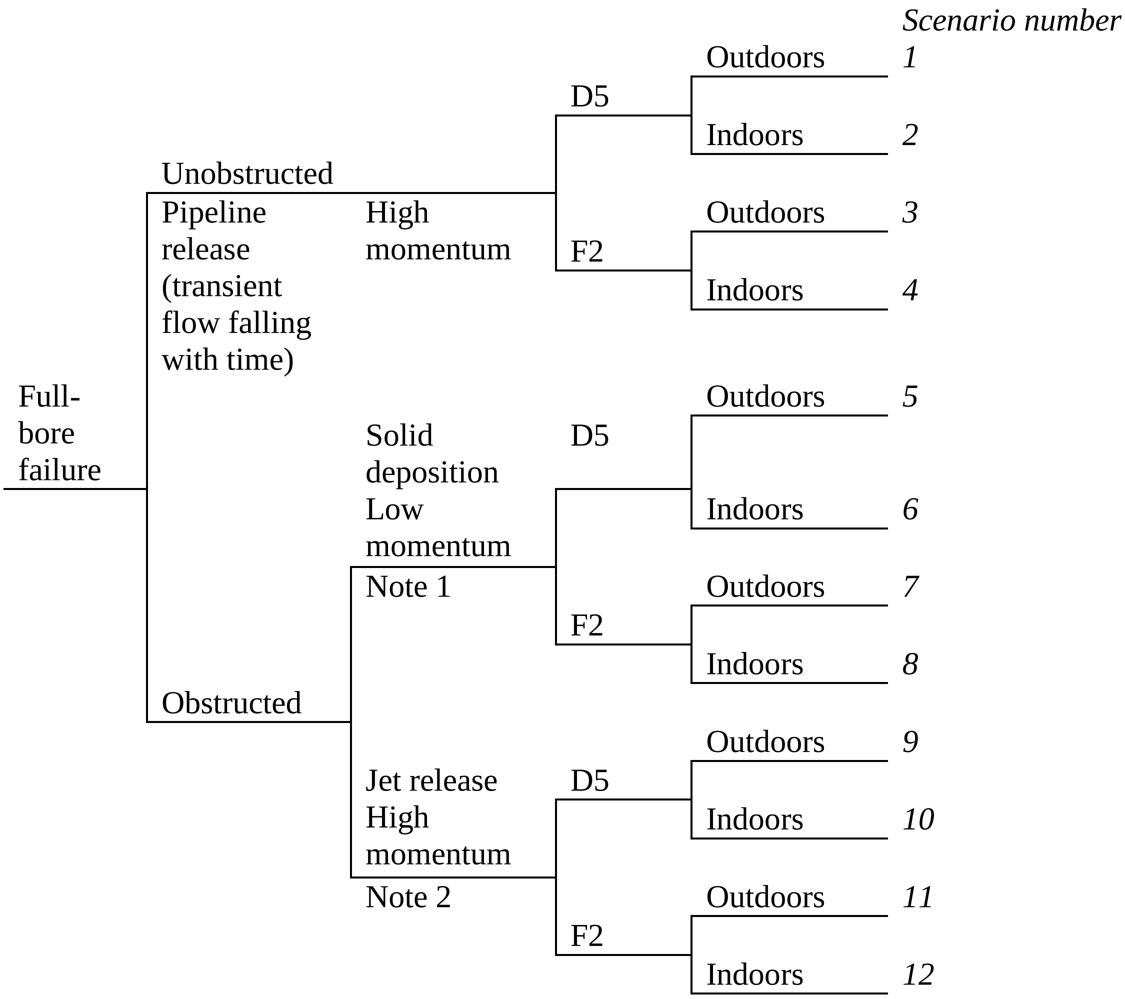

Figure 3(a): Event tree for full bore failure of pipeline

Notes for Table 3(a) and (b)

1. Percentage of CO_2 deposited as solid will need to be estimated. Likely to be less than the percentage of solid produced. Sublimation rate will also have to be estimated. Methodologies for these are currently knowledge gaps.
2. Flow rate needs to take account of deposited solid (see note 1). CFD and experimental evidence suggests that the jet loses little momentum from impact with crater walls. If there are other relevant topography/ local structures then a low momentum release may need to be considered instead, with location-specific modelling.
3. Flow rate needs to take account of deposited solid (see note 1).

Leaks are likely to be small enough that impact with the crater wall will remove significant momentum (unless a large leak approaches the release rate of a guillotine fracture). Cautious best estimate approach would be to model as a downwards impacting jet for integral modelling.

4. For a small leak the quantity of solid deposited is likely to be very low and can probably be ignored.

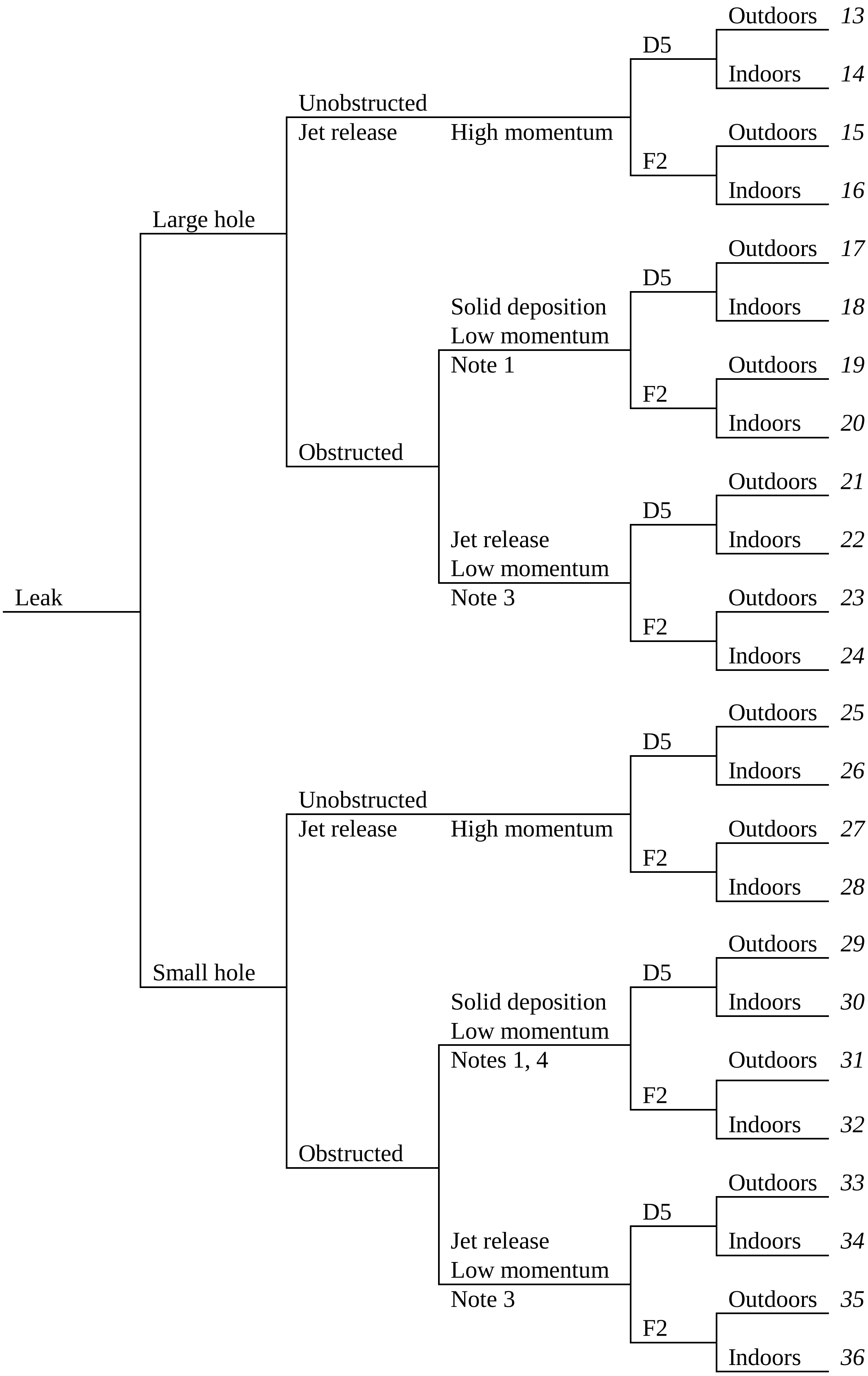

Figure 3(b): Event tree for leaks from pipeline

McGillivray *et al* (2013) reviewed experimental evidence for CO_2 solid deposition and subsequent resublimation. Little deposition was observed in experimental studies designed to study the behaviour of pressurized pipeline releases. However, the duration of these releases may not have been long enough to cause sufficient cooling of the local environment. Deposition was observed in the accidental release at Nagylengyel, Hungary in 1998 from an EOR injection well and in some simple experiments by Mazzoldi *et al* (2008).

The event tree shows different scenarios for 'indoors' and 'outdoors'. These refer to the need to model effects on populations who are located either indoors or outdoors.

The following modelling and risk assessment approaches should be considered:

- Integral modelling and QRA (see 5.2 below) is potentially suitable for all scenarios in which location-specific consequence modelling is not necessary. This could include scenarios 1-4, 9-16, 21-28 and 33-36.

- QRA with simplified consideration of topography (see 5.3 below) could be used for all scenarios in the event tree but this would be very resource intensive. It is most likely to make a significant difference for those events with low momentum, particularly re-sublimation of deposited solid CO_2, i.e. scenarios 5-8 and 17-20.

- Location-specific consequence modelling using CFD may be necessary for locations where structures or topography could cause significant changes to the source term (see Sections 5.4 to 5.7 below). This will be particularly so where there is the possibility of effects impacting on populations. This could apply to scenarios 5-12, 17-24 and 29-36. It would be too resource intensive to apply QRA to such cases but specific modelling for high risk locations as an aid to determining necessary risk reduction may be appropriate.

5.2 Risk assessment based on ARAMIS

Dupuis (2013) developed a methodology for CO_2 pipelines based on ARAMIS. ARAMIS was a risk assessment methodology developed for Seveso II sites and, as such, did not include pipelines within its scope. The ARAMIS methodology has been extended to pipelines. Much of the report is concerned with pipeline failure rate data which was identified as a key knowledge gap. The report covers:

- Necessary adaptations to ARAMIS methodology
- Structure of the CO_2 pipeline risk assessment using ARAMIS
- Qualitative risk analysis (development of failure scenarios)
- Estimation of intensity and hazard effect distances
- Estimation of probability (failure frequencies)
- Risk acceptance criteria
- Risk reducing measures

5.3 Guidance on risk assessment using integral modelling

McGillivray *et al* (2013) provide detailed guidance for integral consequence modelling of CO_2 pipelines and its use in QRA. The report is a CO2PIPEHAZ deliverable and includes:

- **CO_2 harm criteria**. Toxic load, probit and concentration criteria are discussed for CO_2. The point is also made that CO_2 harm is relatively insensitive to exposure duration. The effects of toxic impurities on harm criteria are discussed. Harm criteria for blast overpressure are also included.
- **Selection of scenarios to be modeled**. The event tree in Figure 3 is discussed together with selection of hole sizes and treatment of both non-impinging and impinging jets. Difficulties in modelling CO_2 sublimation are discussed and this is identified as a knowledge gap.
- **Failure rates.** An extensive review is provided of pipeline failure rate data and methods which have applicability to CO_2 pipelines. This review is more recent and more detailed than those in existing CO_2 pipeline guidelines such as Energy Institute (2010) and DNV (2013) (see section 4 above). Failure modes applicable to CO_2 are discussed. Tentative recommendations about pipeline failure rates are made.
- **Source term and dispersion models**. A number of integral dispersion models are reviewed along with comments about their source term modelling capabilities and/or requirements. Comments on applicability to CO_2 are provided.
- **Worked example**. A worked example is provided showing all stages of the QRA for a test case pipeline. DNV PHAST is used as the integral dispersion model for this test case.

5.4 Guidance on risk assessment incorporating topography

The topography local to a pipeline release can potentially be significant for CO_2 pipelines because a release gives rise to a cold, heavier than air gas cloud. The event tree in 5.1 above suggests that it may be most significant when jet momentum is low, and particularly for re-sublimation of deposited solid CO_2. Local topography, such as a valley, has potential to channel a CO_2 cloud towards populations, even when they are not located in the direction of the prevailing wind.

QRA incorporating topography has in the past been considered infeasible because of the very large number of location-specific consequence modelling calculations which would need to be performed. As part of the CO2PIPEHAZ project, Lisbona *et al* (2013) demonstrated that it can be feasible using simplified consequence models which incorporate topography. This report:

- Reviews available consequence models which can take account of topography;
- Presents a detailed worked example case study which uses the TWODEE-2 shallow layer model to incorporate topography within a QRA (note however that the review suggests that TWODEE-2 may not be the best model to use);
- Details are given within the worked example of a methodology for obtaining topography data in suitable form from that available in GIS format.

A comparison between the methodology developed by CO2PIPEHAZ (including numerical outflow calculations and CFD for near-field and far-field dispersion) with shallow layer dispersion modelling for a release from a pipeline including topography has shown deficiencies in the shallow layer model used.

5.5 Guidance on weather modelling in CFD

In far-field dispersion of carbon dioxide (CO_2), the spread of asphyxiating gas is mainly determined by the wind condition and the interaction between the ambient air and CO_2. When using computational fluid dynamics (CFD), different wind conditions can be represented by modifying the boundary conditions at the inflow: changes in velocity, temperature and turbulence parameters can be specified as a function of height above ground. In addition, surface roughness and surface heat fluxes can be defined for solid surfaces inside the computational domain. The time-dependent flow can then be calculated by solving the governing equations in three dimensions.

Melheim *et al* (2013) modified the wind models for stable and unstable atmospheric boundary layers for use in the CFD code FLACS. The most important improvements were implementation of a density (temperature) profile for the inflow boundaries and automatic calculation of the sensible heat flux from the ground based on the Monin-Obukhov length scale. The Monin-Obukhov length scale is a widely used measure of atmospheric stability.

5.6 Improvements to outflow modelling

Mahgarefteh *et al* (2013) provides detail on work carried out as part of CO2PIPEHAZ on improving outflow modelling. These can be used as an input to source terms for CFD and as an input to estimation of the potential for propagating failure of a CO2 pipeline. This includes the development of the Homogeneous Relaxation Model (HRM) to take into account delayed phase transition, a three-phase flow model to take into account solid formation due to expansion-induced cooling below the triple point, as well as Linking of the HRM outflow model to Physical Properties Library data.

5.6.1 The development of Homogenous Relaxation Model (HRM)

The results of both small and large-scale experiments conducted by the partners, INERIS and DUT (see Section 5.9)_ have indicated the limitations of the Homogeneous Equilibrium Model (HEM) in simulating outflow following dense phase CO_2 pipeline rupture. This is primarily due to the presence of phase-slip and delayed liquid/vapour phase transition during the rapid depressurisation process both of which are not accounted for in HEM. In the case of punctures, visual observation of the in-pipe flow profiles by INERIS has indicated the prevalence of both phenomena. However, in the case of full bore rupture, only delayed phase transition has been found to be prevalent. As part of WP2, a Homogeneous Relaxation Model (HRM) accounting for delayed phase transition has been developed (Brown *et al* (2013b)). In the case of pure CO_2 the HRM has been found to produce improved predictions of the pipeline decompression and discharge rates as compared to the HEM.

5.6.2 Modelling solid release

Pipeline rupture tests conducted as part of the CO2PIPEHAZ project have indicated release temperatures as low as -80°C. Formation of any solid CO_2 because of the expansion induced cooling below the triple point conditions (5.7 bar, -56.8°C) during the depressurisation process will significantly alter the CO_2 hazard profile, and hence must be accounted for.

A three-phase flow model for predicting the transient outflow spanning the dense phase to below the triple point has been developed by UCL (University College London) (Martynov *et al* (2013c)). Depending on the prevailing temperature and pressure, the model is capable of accounting for the solid, vapour and liquid phases, in isolation, in pairs or simultaneously. The choked flow conditions at the rupture plane are modelled through maximisation of the mass flux with respect to pressure, and solids mass fraction at the triple point (Martynov *et al* (2013b)). The pertinent solid/vapour/liquid phase equilibrium data are predicted through the development of an extended Peng-Robinson equation of state (Martynov *et al* (2013)).

5.6.3 Linking of the outflow model to Physical Properties Library data

The quality of the equation of state (EoS) employed has been found to have a profound impact on the reliability of the predicted outflow data. Brown *et al* (2013a) found that the outflow rate is highly sensitive to the composition during the early stages of depressurisation, where the effect of the impurities on phase equilibrium has a significant impact on the outflow, which could influence the results of the far-field dispersion modelling. They conducted preliminary tests on short pipes that indicate that the predicted outflow rate is sensitive to the choice of EoS, but this has yet to be confirmed for full scale pipelines many km long.

The outflow model developed has been linked to the Physical Properties Library developed by NCSR "Demokritos" which enables the use of various equations of state for CO_2 and its impurities, including H_2S, N_2, H_2O, O_2 and CH_4 (Mahgerefteh *et al* (2013a)). The various EoS include the highly accurate PC-SAFT EoS (see 5.9 below) which has been shown to produce improved predictions of phase equilibrium data for CO_2 and its mixtures as compared to the Cubic EoS (Mahgerefteh *et al* (2013a)).

5.6.4 Applicability of PIPETECH

The applicability of PIPETECH for modelling CO2 pipeline releases is considered to be as follows:

i) Gas phase pure CO_2 and CO_2 mixtures.
PipeTech (HEM) is suitable for both full bore rupture (FBR) and punctures in terms of predicting mass outflow and depressurisation rates.

ii) Dense phase pure CO_2 and CO_2 mixtures.
Outflow rate
For FBR, PipeTech is suitable for modelling outflow rate for both pure CO_2 and its mixtures in the early stages of depressurisation (Brown et al, 2013c). Improved results are however obtainable using the HERM (Brown et al, 2013b). However, during the

latter stages of depressurisation where phase stratification becomes significant neither PipeTech (HEM) nor the HERM are appropriate.

For leaks, PipeTech's performance depends on the ratio of the puncture to pipe diameter. If the ratio is small, i.e. the pipe acts like a large vessel (Magharefteh et al, 2012c) where no significant depressurisation takes place within the bulk of the fluid (as would be the case for long pipelines (>1 km)). Results of vessel blowdown tests through a short punctured pipe conducted by the partner INERIS (Proust et al, 2013) show that PipeTech produces reasonable predictions of the discharge rate. However, in cases where the ratio of the puncture to pipe diameter is sufficiently large where phase transition occurs within the bulk of the decompressing fluid PipeTech is not expected to be reliable.

Depressurisation
Based on comparison with shock tube test data (Mahgerefteh *et al* (2012), (2012b), Collard (2013)), PipeTech produces good predictions of depressurisation rates for both gas and to a good degree, dense phase CO_2 in the presence of impurities. As such, PipeTech seems to be appropriate for providing the input for determining whether ductile fracture propagation will occur. PipeTech has recently been coupled with an empirically based fracture model (Mahgerefteh (2012b)), to produce fracture propagation data such as crack velocity and crack arrest length.

5.7 Advances in source term modelling

The potential CO_2 release scenarios can include both above-ground and crater releases, including punctures and ruptures. Defining 'source term' as the input conditions to a far-field dispersion model, directly relates to the results from the near-field model.

With respect to the near-field dispersion, a three-phase, accurate composite equation of state for the relevant temperature range, that can predict multi-phase conditions accurately post Mach-shock was developed and validated by University of Leeds (UoL), as part of the CO2PIPEHAZ project [Wareing *et al* (2013a,b), Fairweather *et al* (2011), Woolley *et al* (2012, 2013)]. This provides accurate input conditions for far-field dispersion models that cannot accurately predict the supersonic shock and thermo-physical conditions in the near-field, and are relevant for use with both phenomenological/ integral and CFD dispersion models.

The near-field model developed is three-phase accurate. Accounting for the latent heat of fusion and accurate sub-triple-point-temperature behaviour, it produces far less solid than previous approaches (e.g. extending Peng-Robinson below the triple point, using PRSV, PRSV2, etc.). The particle tracking capability of the near-field model can be used to predict solid deposition, if present.

The advanced thermodynamics models provided by DEMOKRITOS' software package (see Section 5.8) has led to improvements in the source term results, particularly in the case of mixtures of CO_2 and impurities. A similar level of performance can be seen between UoL's EoS and DEMOKRITOS' developments for pure CO_2. However, the developments with respect to impure CO_2 are unique, and are an improvement over using pure-component models.

5.8 Development of a new software tool for thermodynamic modelling of CO_2 mixtures

Integral and CFD models for CO_2 pipeline releases depend heavily on accurate physical property models. Molecular thermodynamic models for the prediction of primary and derivative thermodynamic properties, transport properties and phase equilibria of CO_2 and its mixtures with gases were developed by DEMOKRITOS, as part of the CO2PIPEHAZ project. A software package was developed to support the new models and calculations, to calculate properties such as density, compressibility, free energies (Helmholtz, Gibbs), heat capacities, enthalpy, entropy, diffusivity, Joule-Thomson coefficient, vapour-liquid and liquid-liquid equilibria. The models incorporated in the software include cubic EoS (Peng-Robinson) and higher order EoS based on the Statistical Associating Fluid Theory (SAFT and PC-SAFT). A database with binary interaction parameters was also developed.

Release calculations were performed to compare outflow and near-field model results using standard cubic and advanced EoS and some deviations between different models were identified by Diamantonis *et al* (2013d). Predictions from advanced EoS were found to be marginally more accurate over predictions from cubic EoS. In terms of release calculations, the accuracy between cubic and higher order EoS was comparable.

The new models have developed the state of the art significantly, by providing a unified well validated tool for the calculation of a range of properties of interest for chemical process design. Executable files are available upon request from DEMOKRITOS Greece, for academic research purposes. Further details of work on thermodynamic modelling within CO2PIPEHAZ can be found in Diamantonis and Economou (2011, 2012) Diamantonis *et al* (2011, 2012a,b,c,d, 2013) Boulougouris *et al* (2013) and Tsangaris *et al* (2013).

5.9 New experimental data

Three small and mid-scale experimental programmes were carried out at INERIS as part of CO2PIPEHAZ. The small-scale (1 litre) experiments were to obtain characteristic points in the Mollier diagram for CO_2-impurities mixtures. The larger-scale (2 m^3 vessel connected to a 2” inner diameter-max × 40 m long pipe) was to investigate the flow from a vessel and near-field dispersion. The third experimental programme, a 2’’× 40 metre long pipe, was set up to investigate the transient flowfield during the blow down of a portion of pipe (Proust et al, 2013). In addition, large scale experiments were carried out at DUT.

5.9.1 Phase equilibrium device

In order to provide the CO2PIPEHAZ consortium with thermodynamic and transport data of CO_2 and impurities mixture to feed into simulation codes, a novel experimental system was designed to allow simultaneous measurements of a range of parameters. Equilibrium two-phase behaviour, viscosity and thermal conductibility are of primary interest.

The principle and main relevant mathematical equations are presented in Proust *et al* (2010). A small adiabatic calorimeter containing a known quantity of mixture is slowly discharged via a straight smooth duct. The remaining mass of mixture is controlled at each time step, alongside its temperatures and pressures. The cooling of the calorimeter is measured to derive the enthalpy exchange. The temperature and pressure difference along the duct (for which the outer wall is kept at a constant temperature) is measured. Theoretically, the viscosity and thermal conductibility of the mixture can be extracted from these measurements.

5.9.2 Dispersion of a large leakage of CO_2 into the atmosphere.

In order to perform the experiments to measure the dispersion of a large leak, a 2 m^3 vessel was connected to a 2" inner diameter (6 to 9 m) pipe. Calibrated orifices were used ranging from 6 mm to full bore (50 mm). The mass flowrate was measured directly by continuously weighing the vessel, the internal temperatures and pressures were also measured. The temperature and pressures were measured in the nearfield to investigate the expansion zone. At larger distances, the repartition of the CO_2 in the plume and temperature/ densities were estimated. Present data suggest that a significant portion of CO_2 is solidified in the expansion zone but this "cryo freezing" process seems so fast such that only very small particles could form, explaining why no large accumulation of dry ice forms, whatever the release conditions. The mixing in the cloud is reasonably adiabatic, enabling a significant reduction of the temperature so that body forces appear and seem to be significant even at low flowrates.

5.9.3 Experimental investigation of high velocity flow through a long pipe

Complete blowdowns of dense CO_2 were performed by DUT in a 40 m long, 2'' diameter pipe, either through calibrated orifice or via the full bore section. Pure CO_2 was used in the experiments. Attempts were also made to prepare "impure" CO_2 through the addition of nitrogen, but it proved impossible to produce a homogeneous "impure" mixture inside the pipe. Valuable results were however obtained due to the comprehensive instrumentation including pressure and temperature measurements along the pipe, observation and instrumentation of the near-field plume and observation of the fluid behaviour inside the pipe, through a transparent section. Significant findings worth noting include:

- The flow inside the pipe is far from being homogeneous (corresponding with the HEM models) but is highly stratified, with the liquid phase at the bottom and the vapour at the top
- The outflow pattern depends significantly on this behaviour;
- A slow propagating "rarefaction wave" is propagating and depressurises the pipe. It is followed by a "shock wave" which might result from a flash vaporisation of the CO_2.

The present findings are curbed by the limitations in the instrumentation, especially the Kulite transducers, which proved relatively inaccurate. In addition, it was not possible to investigate the potential influence of impurities. Further improvements to the current experimental configuration would allow better data to be obtained.

5.10 Conclusions on the contribution to good practice from CO2PIPEHAZ

1. An event tree has been defined together with outline guidance on the types of risk assessment which will be appropriate for difference branches of the event tree.

2. Detailed guidance has been produced on the use of integral modelling for QRA of CO_2 pipelines.

3. Detailed guidance has been produced on how local topography can be incorporated into QRA of CO_2 pipelines.

4. Guidance has been provided on appropriate weather modelling for CFD modelling of releases from CO_2 pipelines.

5. Improvements have been made to outflow modelling. This can be used as an input to source terms for CFD or integral modelling and as an input to estimation of the potential for propagating failure of a CO_2 pipeline.

6. Detailed source term models have been developed for releases from CO_2 pipelines. A software tool has been developed which allows thermodynamic modelling and estimation of physical properties for CO_2 pipelines which contain impure CO_2.

7. The methodology developed by CO2PIPEHAZ, including numerical outflow calculations and CFD for near-field and far-field dispersion, is the most accurate consequence modelling approach. It should be used for any parts of the pipeline with critical hazard ranges and/or risk. Simpler methods, which are much faster to run, should be used to identify potentially critical parts of a pipeline and to carry out sensitivity analysis.

8. New experimental datasets have been produced which extend the range of data available for the development and validation of models. Use has been made of the new data for model development and validation within the CO2PIPEHAZ project.

9. There are remaining knowledge gaps in terms of risk assessment, in particular:
    a. The formation of CO_2 solids and modelling of their sublimation rates;
    b. Failure rates, which will require substantial future operating experience to confirm;

c. Influence of thermodynamic EoS on CO_2 mixture outflow rates for full-scale pipelines.

6. Summary of good practice for decision support for CO_2 pipelines

1. Although CO_2 is generally not regulated in terms of hazardous pipeline design and operation, CO_2 still has major hazard potential. It is good practice to design and operate the pipeline as if relevant regulations are applied. This also serves to 'future-proof' the pipeline as it is possible that national and/or international regulation could follow as CCS projects become more prevalent worldwide.
2. Implement the requirements of local legislation and regulations regarding the pipeline, risk reduction measures and risk assessment methodologies and criteria as a minimum. (A brief review of typical requirements is given in section 3).
3. Design using appropriate codes, but with due regard for the specific properties and hazards of CO_2. This will imply providing a basic level of risk reduction as required by the codes, supplemented by guidelines specific to CO_2 pipelines such as DNV RP J202 (DNV, 2010), CO2RISKMAN (DNV, 2013) and/or EI (2010a). (See section 3.)
4. Carry out risk assessment of the pipeline for the purposes of:
    a. Route selection;
    b. Identification of any stretches of the pipeline with particularly high hazards and/or risks and/or uncertainty in the estimation of hazards and risks.

    (See section 2).
5. There may be the need for multiple separate risk assessments at different stages of the design process and to re-validate operation. The scope of the specific risk assessment should be determined (see sections 2 and 5.1);
6. For such stretches with high hazard/ risk/ uncertainty, carry out additional studies as appropriate, e.g.:
    a. QRA using integral modelling if risk assessment has so far been only by a screening methodology (see section 5.3);
    b. Specific hazard and/or risk assessment taking account of topography (section 5.4) or other local conditions in areas of high hazard or risk. This could include the use of CFD (sections 5.5 – 5.8) or QRA using more simplified consequence analysis techniques which account for topography (section 5.4). (These techniques could help to reduce uncertainty);
7. For areas where high hazard/ risk remains, consider further risk reduction to reduce the risk 'as low as reasonably practicable' (ALARP) (see section 3.2.4).
8. Periodically review the pipeline, risk assessment and ALARP position, for example to take account of new developments close to the pipeline.

7. Conclusions

There is a range of requirements for decision support during the design and operation of CO_2 pipelines.

A considerable body of guidance, including guidelines, industry standards and legislation, exists worldwide and provides decision support for hazardous pipelines. This includes required and potential risk reduction measures; and requirements for risk assessment, risk criteria and the need or otherwise for further risk reduction. In most cases CO_2 is not currently in scope of this body of guidance, but most of the principles are applicable to all but very specific hazards from CO_2. The available guidelines contain areas of commonality and some areas of difference, partly reflecting differences in scope. There is little agreement worldwide on criteria relating to societal risk, nor on the detailed assumptions to be included in any pipeline risk assessment.

Guidelines on the design and operation of CO_2 pipelines have been developed and are of a good quality considering the relative infancy and lack of practical experience of the technology. The more recent guidelines (DNV, 2013, 2010) are currently the most comprehensive and those from the Energy Institute (2010a,b) provide additional detail in some areas. Guidelines on major accident risk management including possible risk reduction measures and strategies are covered in some detail by the DNV (2013) CO2RISKMAN guidelines.

Guidelines on the details of carrying out risk assessment for CO_2 pipelines are less available. The DNV (2013, 2010) guidance is very high level and goal-setting on these matters. EI (2010b) provides more details, with worked examples, for modelling CO_2 releases from onshore pipelines and analogous guidance for offshore pipelines is expected. These mainly use DNV Phast and guidance on the use of CFD or other models is not covered in any detail. Many of the guidelines reviewed highlight the lack of experimental data for model validation (and for model development).

Specificities of CO2 pipelines have been addressed in the methodologies developed by CO2PIPEHAZ. The CO2PIPEHAZ project has extended guidance on good practice for decision support for CO_2 pipelines in a number of areas:

- An outline summary has been produced which suggests the most appropriate source of guidance for different aspects of decision support, including risk assessment.
- An event tree has been defined together with outline guidance on the types of risk assessment which will be appropriate for difference branches of the event tree.
- Detailed guidance has been produced on the use of integral modelling for QRA of CO_2 pipelines.
- Detailed guidance has been produced on how local topography can be incorporated into QRA of CO_2 pipelines.
- Guidance has been provided on appropriate weather modelling for CFD modelling of releases from CO_2 pipelines.

- Improvements have been made to outflow modelling. This can be used as an input to source terms for CFD or integral modelling and as an input to estimation of the potential for propagating failure of a CO_2 pipeline.
- Detailed source term models have been developed for releases from CO_2 pipelines.
- A software tool has been developed which allows thermodynamic modelling and estimation of physical properties for CO_2 pipelines which contain impure CO_2.
- New experimental datasets have been produced which extend the range of data available for the development and validation of models. Use has been made of the new data for model development and validation within the CO2PIPEHAZ project.

There are remaining knowledge gaps in terms of risk assessment, in particular:

- The formation of solid CO_2 deposits and modelling of their sublimation rates;
- Failure rates, which will require substantial future operating experience to confirm;
- Influence of thermodynamic EoS on CO_2 mixture outflow rates for full-scale pipelines.

This good practice guidelines report provide a road map identifying the most relevant sources of guidelines including general guidelines for hazardous pipelines, existing guidelines for CO_2 installations and pipelines, and new knowledge produced by CO2PIPEHAZ.

There are significant uncertainties in integral consequence modelling compared with numerical modelling. This is mainly due to the thermodynamic equations of state used, especially for mixtures; all CCS uses impure CO_2.

Whilst integral modelling could be used for screening and sensitivity analysis, where there are potentially heightened hazards/ risks in particular sections of the pipeline, or if a particular risk issue has been identified, specific runs should be carried out using more detailed modelling or the full CO2PIPEHAZ methodology. The methodology developed by CO2PIPEHAZ, including numerical outflow calculations and CFD for near-field and far-field dispersion is the most accurate consequence modelling approach. It should be used for any parts of the pipeline with critical hazard ranges and/or risk. Simpler methods, which are much faster to run, should be used to identify potentially critical parts of a pipeline and to carry out sensitivity analysis.

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