The CO2PipeHaz Good Practice Guidelines for CO_2 pipeline safety

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As part of the challenge to reduce the impact of global warming, pressurised pipelines are considered to be the most practical option for transporting captured CO_2 from fossil fuel power plants for subsequent sequestration. A large release from a pipeline transporting fluids between the capture and injection facilities could have major accident potential due to the toxicity of CO_2 at high concentration. The European CO2PipeHaz project was concerned with the modelling and validation of source terms and dispersion for potential major releases from CO_2 pipelines. This was led by University College London, UCL, (UK) with the other partners being University of Leeds (UK), INERIS (France), GexCon (Norway), Demokritos (Greece), Dalian University of Technology, DUT, (China) and the Health and Safety Laboratory, HSL, (UK).The project's activities included:

- physical properties and thermodynamic modelling of CO_2 with impurities,
- modelling of pipeline release rates, near-field dispersion and far-field dispersion,
- small- and large-scale experimental validation,
- decision support tools including
  - QRA with integral modelling,
  - Possible methods to account for topography in QRA, and
  - The CO2PipeHaz Good Practice Guidelines.

This paper describes the CO2PipeHaz Good Practice Guidelines (GPG) from the decision support tools, including setting them in the context of the project. The GPG include discussion of the decision-making required for CO_2 pipelines, strategies for the use of decision support tools, existing guidelines for the design of hazardous pipelines, existing guidelines for the design of CO_2 pipelines, and the new knowledge developed by the CO2PipeHaz project. An outline strategy is proposed for the use of different methods in decision support. Simpler methods such as QRA incorporating integral modelling should be used for the pipeline as a whole, to screen for pipeline sections with high consequence or risk. The detailed CO2PipeHaz consequence modelling methodology is state-of-the-art and should be considered for application in critically high consequence (or risk) sections of a pipeline.

Keywords: carbon dioxide; pipeline; carbon capture and storage; CCS; QRA; CFD; topography; consequence modelling

Introduction

As part of the challenge to reduce the impact of global warming, pressurised pipelines are considered to be the most practical option for transporting captured CO_2 from fossil fuel power plants to suitable locations for subsequent (geological) sequestration. This has significant implications for Europe given its heavy reliance on large-scale CO_2-producing industries and coal fired power plants for its electricity generation, resulting in the inevitable routing of CO_2 pipelines near populated areas. Two key areas that need to be demonstrated to gain public acceptance of CO_2 pipelines are that such a mode of transportation is safe enough, and the environmental impact in the unlikely event of a pipeline failure is limited. The European CO2PipeHaz project was set up to address knowledge gaps associated with the time-dependent release rate, release physical phase(s) and the dispersion behaviour of the escaping CO_2. Such information is pivotal to quantifying all the hazards associated with the failure of CO_2 pipelines, including emergency response planning and determining the minimum safe distances to populated areas.

The CO2PipeHaz project was led by University College London, UCL, (UK) with the other partners being University of Leeds (UK), INERIS (France), GexCon (Norway), Demokritos (Greece), Dalian University of Technology, DUT, (China) and the Health and Safety Laboratory, HSL, (UK). It focused on the development and validation of mathematical models and decision support tools for the hazard assessment of CO_2 transportation pipelines, which are to be employed as an integral part of the CCS chain. The main objectives were to:

1. Define realistic and optimum levels of impurities in the CO_2 stream based on safety, environmental and economic analysis;
2. Develop a computationally efficient multi-phase 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.

This paper is concerned with the development of decision support tools (objective 6 above). A key part of this was the development of Good Practice Guidelines (GPG) (Wilday, 2013) as a key dissemination output of the project. The paper describes the GPG including:

- the context for decision support in relation to the safety of CO_2 pipelines;
- existing guidance which is relevant to the safety of CO_2 pipelines;
- the relevant new knowledge generated by the CO2PipeHaz project;
- remaining knowledge gaps; and
- summary of good practice for decision support.

Structure of the GPG

There was considerable existing guidance relevant to decision support for the safety of CO_2 pipelines. The GPG do not attempt to be a stand-alone set of guidelines, but instead act as a roadmap to both existing guidance and that generated by the CO2PipeHaz project. The structure of the report is:

- Discussion of the requirements for decision support aimed at the safety of CO_2 pipelines;
- Review of existing guidelines for pipelines in general;
- Review of existing guidelines which are specific to CO_2 pipelines or CO_2 systems in general;
- Discussion of the contributions that the CO2PipeHaz project has made to good practice for decision support;
- A brief summary methodology for decision support for CO_2 pipelines;
- Conclusions, including knowledge gaps.

Context of 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, 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, CO_2 does not meet the definition of a hazardous substance in most cases. However, as high inventory dense phase 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, hazard ranges and the nature of the variation of toxicity with concentration for CO_2.

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, 2014). For CO_2 pipelines the possibility of using models which include topography has been demonstrated (Lisbona, 2014). 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) as appropriate. Equally, more detailed studies may also be carried out in terms of the frequency of specific events, e.g. 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 identified and appropriately 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 consequence and risk assessment is subject to uncertainties and these need to be considered carefully when such 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 being made. 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 of the proportionality of the decision and the methodology 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. For high risk sections, consideration of additional potential risk reduction and a demonstration of ALARP may be required.

Relevant existing guidance

General guidelines for hazardous 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.

A range of risk reduction measures would usually be expected, including:

- 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. Land use planning controls help to prevent new buildings from being constructed close to the pipeline once constructed (HSE, 2011).
- 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, 2008) for natural gas pipelines and BS PD 8010-1 (BSI, 2004) for hazardous liquid pipelines. Mendes (2011) indicates that other international countries also cover safety issues in their pipeline design codes. Analysis of pipeline incident data indicates that third party activity (TPA), e.g. inadvertently damaging a pipeline with a mechanical digging machine, dominates pipeline failures for buried pipelines. 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.
- Additional risk reduction measures. These may be part of the general design or considered for high risk sections of pipeline only. Additional potential risk reduction could include:
- Crack arrestors.

- 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.
- Slabbing. Some standards specify the design of slabbing systems, e.g. PD 8010-1. Different regulators and standards allow differing amounts of credit to be taken for slabbing in reducing the failure frequency in a risk assessment.
- Statutory one-call system , e.g. in the Netherlands and some other countries 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.
- Surveillance Frequency – The UK standards IGEM TD/2 (IGEM, 2009) and PD 8010 (BSI, 2009) provide a curve of reduction factors if surveillance is increased, and these also appear to be used in Switzerland (Swissgas, 2010).
- Isolation 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 (Mahgerefteh, 2006).

Risk assessment methodologies are specified in some guidelines, standards and regulations, e.g. the industry standards PD 8010-3 (BSI, 2009) and IGEM/TD/2 (IGEM, 2009) in the UK. Mendes (2011) concluded that there was little agreement in worldwide pipeline risk assessment methodologies with respect to detailed assumptions and societal risk criteria. It would be important to meet the requirements of any regulations or guidelines for the country concerned.

Existing guidelines for CO_2 pipelines and systems

A number of international guidelines are reviewed in the CO2PipeHaz GPG. It was concluded that the guidelines on the design and operation of CO_2 pipelines which have been developed 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. DNV-RP-J202 (DNV, 2010) includes safety features (risk reduction measures) recommended for pipeline design and operation, and is specific to CO_2 pipelines. It also discusses risk assessment and the knowledge gaps in risk assessment for a CO_2 pipeline. 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. 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.

The CO2RISKMAN Guidelines (DNV, 2013) were the output of a 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.

Publications from the Energy Institute (EI, 2010a,b) provide additional detail in some areas. The guidelines on 'Good plant design and operation for onshore carbon capture installations and onshore pipelines' (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 a number of risk reduction measures.

The EI 'Technical guidance for hazard analysis for onshore carbon capture installations and onshore pipelines' (EI, 2010b) specifically addresses the risk assessment requirements for an onshore CO_2 pipeline. A companion document has subsequently been published covering offshore pipelines (EI, 2013). 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, with DNV Phast used as an example:
- Development of source terms for models which are not designed for CO_2.

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

Other recent work

The following relevant work was published after the CO2PipeHaz GPG:

- Sensitivity testing of DNV Phast integral modelling (Gant, 2013):
    i. Use of Gaussian Emulation Machine (GEM) to perform a global sensitivity analysis on Phast's dispersion model for simulating jet releases of dense-phase CO_2. The parameters varied included the reservoir temperature and pressure, orifice size, wind speed, humidity, surface roughness and height of the release. The results produced by GEM showed in some cases that there were some interactions between model input parameters. The results also showed that for the range of conditions tested, as expected the orifice diameter has a far greater impact than any of the other parameters varied. The second-largest effect was from the release height, with a lower release height producing a plume that extends further, due to the reduction in air entrainment.
    ii. Use of CFD software (ANSYS-CFX13) that uses a Lagrangian particle-tracking model to examine the effect of the solid CO_2 particle size on dispersion distance. It was found that the CO_2 particle size has a relatively minor effect in the scenarios considered.

iii. Techniques for uncertainty analysis will be tested using realistic probabilities for wind speed, atmospheric stability etc. based on meteorological data. Further work may also look at model calibration, using experimental datasets.

- Hazard identification. Paltrinieri, (2014) describes two hazard identification (HAZID) approaches which are suitable for CO_2 pipelines. One is a top-town HAZID coupled with specific consideration of changes to standard technology introduced by CO_2 (Wilday, 2011). The second is the new HAZID technique, DyPASI (Dynamic Procedure for Atypical Scenarios Identification), and was used to identify CCS emerging risks and "atypical events" (accident scenarios deviating from normal expectations or worst case scenarios). A worked example was presented for a CO_2 capture plant but the principles are transferable to pipeline CO_2 transport. Suggestions are given as to the best HAZID approach in different situations.

New knowledge produced by CO2PipeHaz

The CO2PipeHaz GPG gives an overview of the main contributions of the project and references sources of further information. These fall into three main areas as described below.

Thermodynamic and physical properties models

Impurities in the CO_2 influence the thermodynamic behaviour including the position of the two-phase region and hence the propensity for solid CO_2 to be formed. All of this is important in the calculation of outflow from a pipeline rupture, and the near-field source term for far-field dispersion modelling. These impurities may be substances such as CH_4, N_2, Ar, H_2O, 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. hydrocarbon streams containing high CO_2) and technology employed (e.g. post combustion vs. oxy-fuel vs. integrated gasification combined cycle (IGCC)) and whether the stream has been scrubbed prior to entering the pipeline.

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 a cubic equation of state (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. 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. Further details of work on thermodynamic modelling within CO2PipeHaz can be found in Diamantonis (2011, 2012, 2013).

Improved detailed consequence modelling

The project partners developed a suite of linking models to allow significant improvements in the accuracy of the consequence modelling for potential releases from CO_2 pipelines. The models make use of the improved thermodynamics modelling for impure CO_2 (see Section 5.1). The stages of the modelling comprise:

- Outflow modelling is required as an input to near-field dispersion modelling and as an input to estimation of the potential for propagating failure of a CO_2 pipeline. This includes the development of the Homogeneous Relaxation Model (HRM) (Martynov, 2014) 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. 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. The outflow rate was found to be 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. To model solid CO_2, a three-phase flow model for predicting the transient outflow spanning the dense phase to below the triple point has been developed. 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, 2013).
- Near-field dispersion modelling. 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 (Wareing, 2013), (Woolley, 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 accounts for three phases, 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), corresponding better with experiments carried out to validate some of these models. The particle tracking capability of the near-field model can be used to predict solid deposition, if present.
- Far-field dispersion modelling used computational fluid dynamics (CFD) and methods were developed to import realistic terrain data into the FLACS software. To model the behaviour of solid CO_2 particles formed in the near-field jet, a Lagrangian particle-tracking model for multiphase dispersion has been successfully implemented in FLACS. The model can predict the spatial and temporal evolution of the CO_2 concentration during pipeline release scenarios. The model takes into account the two-way coupling effects between the continuous gas-phase and the dispersed particle-phase, and also particle sublimation and deposition. The validation of both FLACS and CFX models against results from the small-scale

experiments of INERIS and the large-scale experiments of DUT (see Section 5.3) was successfully carried out (Gant, 2014).

Additional experimental data

The CO2PipeHaz project added to the available experimental data for model development and validation:

- 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 50 mm inner diameter-max × 40 m long pipe) was to investigate the flow from a vessel and near-field dispersion. The third experimental programme, a 50 mm × 40 m long pipe, was set up to investigate the transient flowfield during the blow down of a portion of pipe (Woolley, 2012, 2013), (Gant, 2014).
- Complete blowdowns of dense phase CO_2 were performed by DUT in a 40 m long, 50 mm diameter pipe, either through a calibrated orifice or via a full bore section. Pure CO_2 was used in the experiments. Instrumentation included 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 (Martynov, 2014).

Decision support tools

In addition to the CO2PipeHaz GPG, a number of other decision support tools were developed:

- A risk assessment methodology for CO_2 pipelines based on ARAMIS (Dupuis, 2013). ARAMIS is 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 work was concerned with pipeline failure rate data which was identified as a key knowledge gap.
- Detailed guidance for integral consequence modelling of CO_2 pipelines and its use in QRA (McGillivray, 2014). This included CO_2 harm criteria, scenario selection including event tree, failure rates, source term and dispersion modelling, and a worked example.
- QRA 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. 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 be required. As part of CO2PipeHaz, Lisbona (2014) demonstrated that it can be feasible using simplified consequence models which incorporate topography. While such simplified consequence models have limitations in accuracy they are an area of development. Their use gives insight into QRA (using integral modelling) uncertainties resulting from topography.

Remaining knowledge gaps

Key knowledge gaps for risk assessment as a decision support tool are: failure rates for CO_2 pipelines and components, since there is as yet limited operating experience; and the modelling of sublimation of solid CO_2 which has been deposited. As discussed above, solid CO_2 which re-sublimes with low momentum may have potential for channeling due to topography and so might sometimes lead to dominant consequence scenarios. The behavior of solid CO_2 may also be important for emergency response planning.

Summary of good practice for decision support

The following steps summarise a decision support process, using risk assessment and incorporating the results of the CO2PipeHaz project, 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 4.1).
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 4.2).
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 in terms of the context of decision support. A starting point for the risk assessment would be QRA incorporating integral modelling or the simpler ARAMIS approach (Section 5.4).

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).
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 5.4);
   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 full CO2PipeHaz consequence modelling methodology (Section 5.2) to obtain the current state-of-the-art analysis.
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).
8. Periodically review the pipeline, risk assessment and ALARP position, for example to take account of new developments close to the pipeline.

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, 2013) 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 EI (2013) does the same for offshore pipelines. 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).

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.
- 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/near field dispersion 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;

The CO2PipeHaz GPG 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 currently available. 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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