

Overview of carbon capture and storage (CCS) projects at HSE's Buxton Laboratory

Prepared by the Health and Safety Executive

RR1121

Research Report

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Prepared 2016

First published 2017

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Over the last decade, the UK Government has supported innovation and growth in Carbon Capture and Storage (CCS) technology with the aim of commercial deployment. CCS research across the UK has reduced potential risks by helping to develop a thorough understanding of the operational hazards and by contributing to the design of safe plant and processes.

This report provides an overview of applied scientific work on CCS undertaken at HSE's Buxton Laboratory. The work includes laboratory-scale and field-scale experiments, evaluation of complex dispersion models for dense-phase carbon dioxide releases, development of decision support tools for pipeline risk assessment and publication of best practice guidelines. In particular, work has focussed on assessing the hazards posed by the accidental release of dense-phase carbon dioxide transported by pipeline. The research has been primarily funded by HSE and industry, with support from the European Union.

HSE's scientific work will help reduce both the risks and costs of any future development of industrial-scale CCS by contributing to the assessment and control of risks early in the design and deployment of the technology. The research has contributed to the scientific evidence base that, if CCS is deployed in with UK, will inform HSE policy decisions to ensure that the regulatory framework for pipelines is effective and proportionate to the potential risks associated with CCS.

This report was funded by the Health and Safety Executive (HSE) and describes work funded by HSE, industry, and the European Union. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

Overview of carbon capture and storage (CCS) projects at HSE's Buxton Laboratory

**Dr Simon Gant, Dr Mark Pursell, Alison McGillivray, Jill Wilday,
Dr Mike Wardman and Dr Andrew Newton**

Health and Safety Executive

Harpur Hill

Buxton

Derbyshire SK17 9JN

ACKNOWLEDGEMENTS

The authors are grateful to the following individuals and organisations for their support in the various projects summarised in this report:

- Mike Bilio, Peter Harper, Stephen Connolly, Danny Shuter, Linda Murray and Jim Stancliffe (Health and Safety Executive).
- Simon Coldrick, Laurence Cusco, James Fletcher, Adrian Kelsey, Kevin McNally, Wayne Rattigan, Ju Lynne Saw, David Webber, Rosemary Whitbread (Health and Safety Laboratory)
- Diego Lisbona (AMEC)
- Chris Lea (Lea CFD)
- European Commission, for funding CO₂PipeHaz under the 7th Framework Energy Program (Project Reference: 241346).
- Julian Barnett and Russell Cooper (National Grid)
- Jane Haswell (PIE)
- Philip Cleaver, Henk Witlox, Ann Halford, Karen Warhurst, Aubrey Thyer and Hamish Holt (DNV-GL)
- Chris Dixon (Shell Global Solutions)
- Haroun Mahgerefteh and Sergey Martynov (UCL)
- Solomon Brown (Sheffield University)
- Robert Woolley, Chris Wareing, Mike Fairweather and Sam Falle (University of Leeds)
- Vagesh Narasimhamurthy, Trygve Skjold, Mathieu Ichard, Idar Storvik, Jens Melheim, Lene Saelen and Ole Jacob Taraldset (GexCon)
- Christophe Proust, Didier Jamois and Jerome Hebrard (INERIS)
- Ioannis Economou, Dimitris Tsangaris, Georgios Boulougouris, Nikolaos Diamantonis (NCSR)
- Yong Chun Zhang and Shaoyun Chen (Dalian University of Technology)
- David McManus (Brown Coal Innovation Australia)
- Mike Haines (International Energy Agency, Greenhouse Gas Research and Development Programme)
- Robert Finley and Sallie Greenberg (University of Illinois)
- Scott McDonald (Archer Daniels Midland Company)
- Andy Brown (Progressive Energy)
- Richard Mather (RWE npower)

KEY MESSAGES

- Over the past decade, HSE's Buxton Laboratory¹ has carried out a range of applied research to develop the scientific evidence base needed to understand and manage the potential risks linked to Carbon Capture and Storage (CCS). The research has focussed on the transportation of compressed carbon dioxide (CO₂) by pipeline from its point of capture to the place where it is stored. The research has involved extensive co-operation with industry and other researchers both nationally and internationally.
- This scientific work has produced valuable insights into how releases of CO₂ from pipelines would behave. It has involved a combination of laboratory-scale and field-scale experiments, modelling and other analyses. Research findings have been disseminated through peer-reviewed scientific conference proceedings and journals.
- The research has resulted in good practice guidelines and decision support tools that can assist robust risk assessment and effective risk management by industry and contribute to the safe deployment of CCS.

¹ Formerly known as the Health and Safety Laboratory (HSL)

EXECUTIVE SUMMARY

Carbon Capture and Storage: Background

Carbon Capture and Storage (CCS) is a new technology that is being developed internationally with the aim of reducing carbon dioxide (CO₂) emissions from fossil-fuel energy in order to help tackle climate change. The process of CCS involves the capture of CO₂ produced by burning fossil fuels and its transportation by pipeline to storage in secure geological formations deep underground. Industrial-scale CCS is still in its infancy, both in the UK and worldwide. However, CCS “is widely viewed as a crucial approach to meeting global and national climate change targets”². To enable safe introduction of this innovative technology, it is necessary to understand the potential health and safety risks linked to CCS and how to effectively control them.

Over the past decade, HSE’s Buxton Laboratory has worked in collaboration with industry and other researchers nationally and internationally to identify hazards and understand potential risks relating to CCS. This research has been primarily funded by HSE and industry, with support from the European Union. In particular, work has focused on the potential risks associated with the transportation of compressed (so-called “dense-phase”) CO₂ by pipeline from its point of capture to the place where it is stored. Additionally, research has considered the potential for CCS technologies to help reduce risks associated with existing technologies. For example, investigating whether CO₂ could be mixed with hydrocarbon gases to reduce risks on offshore platforms.

This report summarises all of this wide-ranging work, drawing together its key outputs and outcomes. The report is aimed at technical and scientific specialists involved in CCS development, particularly those working in industry. It shows, through an array of pioneering scientific projects, how HSE has helped to create the conditions for the safe exploitation of CCS.

Scope of the Review

This review of CCS-related work carried out at HSE’s Buxton Laboratory provides a short description of the aims of each scientific project, the methodology, the main findings and the wider impact of the work. It lists the peer-reviewed scientific papers and reports that provide further details of studies. The projects are grouped into three categories:

- **Involvement in major UK and international collaborations:**
 - *CO₂PipeHaz*: This EU Programme brought together experts from the UK, other European countries and China to develop and test mathematical models for assessing the safety of CO₂ pipelines. HSE’s Buxton Laboratory led the work on developing decision support tools for risk assessment and contributed to modelling work on how

² House of Commons Energy and Climate Change Committee (2016) *Future of carbon capture and storage in the UK: Second Report of Session 2015–16. HC692. The Stationary Office Limited: London.*

CO₂ would disperse into the atmosphere in the event of a release. The good practice guidelines and decision support tools are published by the CO₂PipeHaz project³.

- *COOLTRANS*: Led by National Grid, this UK programme focused on issues surrounding the safe routing, design, construction and operation of pipelines used to transport dense-phase CO₂. The involvement of HSE's Buxton Laboratory centred on the issue of CO₂ dispersion.
- *CO2PIPETRANS*: This Joint Industry Project was initiated by safety and sustainability specialists, DNV-GL, and it involved 14 participants including BP, Maersk, Petrobras and Shell. Involvement by HSE scientists and regulatory specialists centred on a technical advisory and steering group role. One of the resulting publications of the project is recommended operating practices for CO₂ pipelines.

- **Projects for Industry:**

- RWE npower engaged HSE's Buxton Laboratory to support a feasibility study on CO₂ capture at one of the company's power stations.
- For the Decatur large-scale demonstration of CO₂ storage in the US, HSE's Buxton Laboratory evaluated and modelled potential CO₂ release scenarios.
- Progressive Energy commissioned HSE's Buxton Laboratory to produce predictions of CO₂ dispersion for CCS hazard analysis, focusing on offshore platforms.
- As part of the International Energy Agency's Greenhouse Gas Research and Development programme, HSE's Buxton Laboratory worked closely with experts from the oil and gas, power generation and other industries on the preparation of safety cases and the planning of emergency procedures for CCS operations.
- For Brown Coal Innovation in Australia, HSE's Buxton Laboratory peer-reviewed a report on CO₂ pipelines.

- **Projects for HSE:**

Over the last ten years, scientific projects have included work on identifying the hazards posed by releases of high-pressure CO₂, analysis of the impact of fluctuations in CO₂ concentrations in CO₂ jets and plumes, and assessment of the flammability of hydrocarbon and CO₂ mixtures.

Outcomes: Illuminating the Issues

- Through a combination of lab-scale and field-scale experiments, modelling work and other analyses, HSE's Buxton Laboratory has shed light on a variety of CCS issues that are key to its safe deployment. Outcomes have included: insights into how CO₂ that is released from pipelines (either intentionally or during an incident) would behave and disperse. This includes the effect of factors such as temperature, humidity, wind speed and local terrain.

³ Wilday A.J. , Saw J.L. (2013) *CO₂ Pipelines Good Practice Guidelines Technical Report*, HSL. Available from: http://www.hsl.gov.uk/media/396859/co2pipehaz_goodpracticeguidelines.pdf accessed 30th June 2016.

- Development, evaluation and validation of mathematical models, for instance for predicting the dispersion of CO₂ releases, including the development of a Model Validation Database for reviewing the capabilities of models focused on CO₂ release and dispersion.
- Development of best practice guidelines and advice for industry on how to assess hazards, how to prepare safety cases and how to plan emergency procedures for CCS operations.
- Development of decision support tools for industry for assessing pipeline risks and for use in the safe design and operation of CCS operations.
- Developing the scientific evidence base that, if CCS is deployed in the UK, will inform HSE policy decisions to ensure that the regulatory framework for pipelines is effective and proportionate to the risks. For instance, this would include decisions on whether CO₂ should be defined as a “dangerous fluid” under the Pipeline Safety Regulations.
- Furthermore, this scientific work has developed new information on the potential use of CCS technologies to reduce hazards associated with existing technologies; for example by combining CO₂ with hydrocarbon gases to produce less flammable mixtures on offshore platforms.

Conclusions: Managing Risks, Enabling Innovation

Collectively, the CCS-related scientific evidence base developed by HSE in collaboration with industry and other researchers, means that the UK is now much better placed to proceed on a sound and secure basis in the event of deployment of CCS technology. Specifically, this work has:

- Pinpointed the potential risks, hazards and broader health and safety issues associated with CCS operations that need to be addressed to enable the safe introduction of any future British CCS industry.
- Provided robust scientific evidence to underpin the realistic assessment of those risks that is critical to enabling them to be effectively controlled.
- Generated greater awareness of what still needs to be done by industry in order to make such risk assessments more robust, and to manage potential risks more effectively.

As a result of its involvement in CCS-related work during the last decade, HSE is now in a strong position to provide constructive support for a future CCS industry, both in the UK and worldwide. HSE is also well-placed to undertake reviews of the Quantitative Risk Assessments that would need to be undertaken by industry as part of the process of building and operating CCS infrastructure.

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1 INTRODUCTION

The introduction of Carbon Capture and Storage (CCS) would result in carbon dioxide (CO₂) being processed and transported in much greater quantities than it is today. It has been estimated that in order to generate 1 GW of electrical power from a coal-fired power station fitted with CCS will require around 30,000 tonnes/day of CO₂ to be captured and sequestered (Harper, 2011). To transport CO₂ from emitters, such as power stations, to sequestration sites, it is likely that pipelines will be used that will operate with the CO₂ in a dense-phase state, as either a supercritical fluid or liquid, i.e. at a pressure higher than 74 bar (absolute), and a temperature above or below its critical temperature of 31 °C.

As part of the design and risk assessment process for CCS infrastructure, it is necessary to have an understanding of the consequences of an intentional or accidental release of dense-phase CO₂. This is complicated by the somewhat unusual properties of CO₂. At normal atmospheric pressure, when CO₂ gas is cooled below a temperature of -78°C it transforms into a solid (dry ice), whereas other common hazardous substances (e.g. methane, chlorine) are transformed into liquids when cooled. CO₂ also has an unusually high Joule-Thomson coefficient, which means that its temperature decreases significantly when the pressure of CO₂ is rapidly decreased (for example, in an accidental release of CO₂ from a high-pressure pipeline). The toxic effects due to inhalation of CO₂ are also unusual in that they are a highly non-linear function of concentration: doubling the concentration leads to a factor of 256 increase in the dangerous toxic load⁴.

These unusual characteristics of CO₂ present a number of challenges for modelling the consequences of an intentional or accidental release. For example, the fact that CO₂ forms a solid when cooled led to concerns that a leak from a vessel storing dense-phase CO₂ could produce an erosive jet of solid particles, which could potentially impinge on nearby structures and cause knock-on effects (Connolly and Cusco, 2007). Supercritical CO₂ is used commercially for erosion jet cleaning and cutting and so this concern seemed valid.

There were also concerns that a sustained leak of dense-phase CO₂ could produce a solid bank of dry-ice that would take a considerable amount of time to sublime into CO₂ gas and present a different dispersion hazard to a conventional evaporating pool.

In addition to these potential new hazards, there was interest in assessing whether CCS technologies could help to mitigate against existing hazards. For example, HSL was involved in assessing whether CO₂ could be combined with hydrocarbon gases to partially or fully inert the mixture. This was considered as one possible option to reduce risks on offshore platforms handling large quantities of CO₂ and hydrocarbons (Gant *et al.*, 2011a).

These issues and others were examined in various projects undertaken by HSE's Buxton Laboratory which are summarised in this report. The report is organised as follows: work funded solely by the Health and Safety Executive (HSE) is described in the next chapter, which is split into a number of sub-sections describing discrete projects. This is followed by three chapters that describe major collaborative projects: CO₂PipeHaz, COOLTRANS and CO2PIPETRANS. The final chapters describe smaller-scale commercial work that HSE's Buxton Laboratory has undertaken. This includes, for example, the peer review of a report by Sherpa Consulting on dispersion modelling techniques for CO₂ pipelines in Australia. The intention in reviewing these projects is to summarise their aims and objectives, the achievements and impact in each case, and provide references so that the interested reader can find out more about the projects.

⁴ <http://www.hse.gov.uk/chemicals/haztox.htm>, accessed 19 January 2016.

2 HSE RESEARCH PROJECTS

2.1 ASSESSMENT OF THE MAJOR HAZARD POTENTIAL OF CO₂

2.1.1 Background

This section focuses on two studies:

1. The paper presented at the IChemE Hazards XX conference entitled: “Hazards from high pressure carbon dioxide releases during carbon dioxide sequestration processes” by Connolly and Cusco (2007)
2. The HSE report on “Assessment of the major hazard potential of carbon dioxide (CO₂)” by Harper (2011)

2.1.2 Objectives

The purpose of the work by Connolly and Cusco was to identify significant issues and knowledge gaps in assessing the consequences of a release of high-pressure CO₂. Topics covered included: source terms for dispersion modelling, strong cooling effects from pressure reduction and the erosive effects of two phase solid/gas flows. The paper also suggested where improvements could be made.

The purpose of the study by Harper was to present an initial assessment of the hazards resulting from loss of containment from large vessels containing CO₂ and to discuss the major hazard potential associated with such events.

2.1.3 Methodology

Connolly and Cusco presented a review of potential issues relating to CCS and knowledge gaps, including:

- Identification of some technical issues:
 - Lack of pipeline operating experience globally
 - Absence of a source term(s) that accurately describes the release conditions
 - Lack of understanding of the thermodynamic path the CO₂ takes on release
- Consideration of some engineering issues:
 - Scale of thermal cooling from a supercritical CO₂ release
 - Supercritical CO₂ containment
 - Fire and explosion hazard profile changes
 - Toxic contamination effects of supercritical CO₂ release
 - Dry ice “grit blasting” effects
 - CO₂ detection

- Emergency response and temporary refuge integrity

Harper presented a series of dispersion modelling runs that were carried out using the software packages: IRATE (HSE, 2006), DRIFT (Tickle and Carlisle, 2008) and PHAST⁵, to estimate the hazardous distances from various large instantaneous releases of CO₂. The following model inputs were varied:

- CO₂ inventory
- Release pressure and temperature
- Weather conditions (wind, humidity etc.)

The hazardous distances were obtained for the Specified Level of Toxicity (SLOT), which is the HSE Dangerous Toxic Load (DTL) that results in fatalities for 1% of the exposed population⁶.

Harper also reviewed:

- The toxicity of CO₂
- Incidents where CO₂ has been a major contributing factor to the loss of life
- The CCS process
- Use of CO₂ in other industries
- Ongoing research (as of June 2011)

2.1.4 Conclusions

The conclusions of the Connolly and Cusco paper were:

- A lack of pipeline operating experience means there are significant difficulties in accurately identifying the associated hazards. This means that the characteristics of the process and particularly the release behaviour of supercritical CO₂ need to be defined.
- It is essential that source terms are developed to accurately describe the release conditions in order to predict hazard ranges with reasonable confidence.
- In a sudden release of CO₂ from a high pressure reservoir, the thermodynamic path taken by the CO₂ remains uncertain. Phase changes need to be sufficiently well described in consequence models. The points of transition between states (e.g. from dense phase through liquid or solid to gas) must be determined to enable a reasonable estimate of the source term.

The general conclusions of the Harper report were:

- The hazard range for an instantaneous release from storage was predicted to be 50 m to 400 m with large, cold liquid-phase storage producing larger distances
- The hazard range for a continuous release through a 50 mm hole was predicted to be up to 100 m

⁵ <http://www.dnvgl.com/phast-and-safeti>, accessed 3 March 2016.

⁶ See <http://www.hse.gov.uk/chemicals/haztox.htm> (accessed 29 February 2016) for further details.

- Releases from pressurised storage (both refrigerated and ambient temperature) have the potential to create hazard ranges that could create a Major Accident Hazard (MAH)
- As such, the technical evidence suggests that CO₂ has a MAH potential in line with other hazardous substances currently regulated through permissioning regimes

With specific regard to the CO₂ MAH analysis modelling, the following conclusions were drawn:

- There is significant uncertainty in the modelling of instantaneous and continuous releases of CO₂ from storage. A significant amount of research needs to be completed before a suitable model can be developed
- The current HSE instantaneous source term model will need to be updated for CO₂
- While the DNV PHAST 6.6.0 model has been updated to include some improvements to the source term calculations for CO₂, the use of the PHAST/DRIFT model combination suggests that the hazard ranges predicted by PHAST 6.6.0 may not be conservative.

2.1.5 Impact

Stephen Connolly and Laurence Cusco were awarded the IChemE Frank Lees medal in recognition of the contribution made by their paper. The work encouraged the development of significant joint industry funded research projects to address the knowledge gaps that they identified. To date, the Connolly and Cusco paper has been cited 23 times and the Harper work cited 16 times in the literature.

Although the work undertaken by Harper concluded that CO₂ used for CCS has a MAH potential comparable to other hazardous substances currently included in major hazard regulatory regimes, this work was undertaken prior to major research programmes such as COOLTRANS and CO2PIPETRANS (see Sections 4 and 5). In the future, if there is renewed interest in CCS in the UK, any policy decisions made regarding the inclusion of carbon dioxide as a dangerous fluid under the Pipeline Safety Regulations (PSR) would benefit from a review of the findings of these major research programmes.

2.2 COMPARISON OF RISKS FROM CO₂ AND NATURAL GAS PIPELINES

2.2.1 Background

CO₂ is not regulated as a dangerous fluid under the Pipeline Safety Regulations (PSR). However, in their report: “Comparison of hazard ranges from carbon dioxide and natural gas” Moonis and Wilday (2008) recommended further investigation into the possibility of including CO₂ in PSR because of the size of the hazard footprint produced from CO₂ pipelines. They recommended that further analysis in terms of risk be undertaken.

2.2.2 Objectives

The purpose of subsequent work by McGillivray and Wilday (2009) was to determine if CO₂, when used for the purpose of CCS, should be regulated as a “dangerous fluid” under PSR.

2.2.3 Methodology

It was proposed to compare the hazard distances and risks generated by CO₂ against those generated by another substance that is already regulated under PSR. If the results were comparable, this would suggest that CO₂ should be considered for reclassification. In the work of McGillivray and Wilday (2009), the comparison was made against natural gas. Even though CO₂ is toxic and natural gas is flammable, the associated harm criteria can be compared.

The majority of the pipeline input parameters were obtained from Moonis and Wilday (2008) and were applied to the releases of CO₂ and natural gas. Releases of pure vapour were modelled for both cases.

PHAST version 6.53.1 was used to model the CO₂ releases and the subsequent hazard distances were input to HSE's land-use planning software, TPRAM (Toxic Pipeline Risk Assessment Method), for the risk calculation. HSE's pipeline risk assessment tool, MISHAP, was used to obtain the hazard distances and the risks for natural gas for similar scenarios to those used for the CO₂ releases.

2.2.4 Conclusions

The main findings were:

- Distances to a similar level of risk were roughly comparable between CO₂ and natural gas.
- Increasing the fluid pressure increases the distance to a given risk level for both CO₂ and natural gas.
- Modelling was carried out at lower pressures than the likely operating pressure for CO₂ pipelines because (at that time) there was some uncertainty when modelling dense-phase CO₂ and the formation of solids. The hazard ranges and therefore the risks involved were expected to be substantially larger for higher-pressure, dense-phase CO₂ releases.
- On the whole, the work implied that in terms of risk, CO₂ used for CCS has sufficient toxicity to be regulated as a dangerous fluid under PSR.

2.2.5 Impact

This work was published on the HSE website as a Research Report (McGillivray and Wilday, 2009) and presented at the IChemE Hazards Conference in 2009 (Wilday *et al.*, 2009). The HSE report has been cited 16 times in the literature and the conference paper 7 times.

The findings were also summarised in a later paper that was presented at the 10th International Greenhouse Gas Control Technologies (GHGT-10) conference by Shuter *et al.* (2010).

Although the work undertaken by McGillivray and Wilday (2009) concluded that CO₂ used for CCS has sufficient toxicity to be regulated as a dangerous fluid under PSR, this work was undertaken prior to major research programmes such as COOLTRANS and CO2PIPETRANS (see Sections 4 and 5). In the future, if there is renewed interest in CCS in the UK, any policy decisions made regarding the inclusion of carbon dioxide as a dangerous fluid under the Pipeline Safety Regulations (PSR) would benefit from a review of the findings of these major research programmes.

2.3 CONCENTRATION FLUCTUATIONS AND TOXIC LOAD

2.3.1 Background

For potential exposures to toxic substances, the hazard and risk is estimated by HSE on the basis of the DTL⁷. For CO₂, this is calculated from the time-integral of the gas concentration to the power eight. As a consequence of this highly non-linear dependence of the toxic load on the concentration, turbulent concentration fluctuations that occur naturally in jets or plumes of CO₂ may have a significant effect on the calculated hazard ranges. Most dispersion models used for Quantified Risk Assessment (QRA) only provide estimates of the time- or ensemble-averaged concentrations. If only mean concentrations are used to calculate the toxic load, and the effects of concentration fluctuations are ignored, there is a danger that toxic loads and hence hazard ranges will be significantly under-estimated.

2.3.2 Objectives

Gant and Kelsey (2012) carried out work to assess the impact of concentration fluctuations on toxic load in CO₂ jets and plumes. The aim was to understand whether these fluctuations led to a significant increase in the size of the hazardous cloud, as compared to standard approaches where concentration fluctuations were ignored.

2.3.3 Methodology

Gant and Kelsey presented an empirically-based model to assess the impact of concentration fluctuations on CO₂ toxic load in jets. The results from this model were compared to a simpler, pragmatic modification to the standard calculation procedure for CO₂ toxic load that assumed that the concentration fluctuated by a factor of two with a prescribed square-wave variation over time, i.e. that the concentration was twice the mean for half of the time, and zero for the remaining time. The results showed that this simple factor-of-two method provided conservative estimates of the hazard range as defined using HSE's SLOT and Significant Likelihood of Death (SLOD) criteria for CO₂. This finding was useful in that the factor-of-two method can easily be applied with existing dispersion models for QRA. The method described by Gant and Kelsey provided a simple means of accounting for the effect of concentration fluctuations on CO₂ toxic load in unobstructed jets.

A large release of CO₂ from a buried pipeline or vessel is likely to disperse as a dense plume of gas travelling across the ground, rather than as a "free" unobstructed gas jet. The analysis of gas jets by Gant and Kelsey (2012) was not applicable to these dense plume cases. To address this limitation of their analysis, Gant and Kelsey (2012) provided a survey of the relevant literature for dense plumes.

2.3.4 Conclusions

The work by Gant and Kelsey (2012) examined the validity of a simple approach to account for the effect of concentration fluctuations in calculating the toxic load for jet releases of CO₂. The method was demonstrated to provide conservative predictions of the hazard range, in terms of the maximum distance to the SLOT and SLOD.

For low-momentum plumes of dense CO₂ gas, the literature review by Gant and Kelsey (2012) indicated that at present there is insufficient information to come to any definite conclusions as to the effect of concentration fluctuations in these cases. They therefore made recommendations for future work, which included further analysis of existing dense gas dispersion data,

⁷ <http://www.hse.gov.uk/chemicals/haztox.htm>, accessed 19 January 2016.

measurements of concentration fluctuations in large-scale CO₂ release experiments, and numerical simulations.

2.3.5 Impact

The recommendations for further work by Gant and Kelsey may have influenced subsequent work carried out by GL Noble Denton (GLND) in the COOLTRANS Research Programme, discussed in Section 4. In the COOLTRANS field-scale experiments, GLND measured fluctuating gas concentrations in dispersing dense plumes of CO₂ to assess their impact upon the toxic load.

The work by Gant and Kelsey was independently reviewed by Sherpa Consulting in their report on dispersion modelling for CO₂ pipelines in Australia (see Section 6). Based on this analysis, they proposed that hazard distances for dense plumes of CO₂ from pipeline releases be calculated by either halving the value of the Temporary Emergency Exposure Limit (TEEL) concentration or by using the TEEL concentration to calculate the hazard distance and then increasing this distance by 50% to account for the effect of concentration fluctuations.

The paper by Gant and Kelsey has been cited six times in the literature.

2.4 SENSITIVITY ANALYSIS OF CO₂ JET DISPERSION MODELS

2.4.1 Background

Part of the risk assessment process for a CCS facility will involve using consequence models to predict the potential hazards produced by atmospheric releases of CO₂. In many cases, the inputs to the consequence model such as the operating pressure or wind speed are likely to be poorly defined or feature a large degree of variability. It is important to understand how the range of conditions could affect the consequence model predictions and the resulting risk assessment. Modellers often develop an understanding of the important factors in a given situation, but in complex multi-phase flows like dense-phase CO₂ releases, model behaviour can sometimes be counter-intuitive.

Commonly, the behaviour of consequence models is assessed using sensitivity analyses, which involve varying one of the model's inputs from a baseline value to assess its effect on the output. This type of approach in which each of the inputs is varied in isolation from other inputs is called a "one-at-a-time" or "local" sensitivity analysis. It is simple to apply in practice, but has limitations: the results may be sensitive to the choice of baseline case, and there is no information provided on any interactions between multiple variable inputs.

An alternative is to perform a large matrix of calculations in which all of the inputs are varied simultaneously to cover the different combinations of the consequence model inputs across their ranges. This approach, known as "global" sensitivity analysis can identify any interactions between the inputs. It also does not rely upon a "baseline" case that may influence the results. However, as the number of inputs increases, the number of model runs rapidly increases to the point where it becomes prohibitively costly to perform a global sensitivity analysis, because of the computing time needed to carry out the many thousands of runs that are required.

To overcome this problem of the high computational cost, a practical alternative is to create a statistical model (or sophisticated curve fit) to the results from a few hundred consequence model calculations, and then use the statistical model for the sensitivity analysis. A few hundred consequence model calculations typically take a few minutes to run on a laptop using an

integral-type model like PHAST. Statistical models are much faster to run than the underlying consequence model, which typically enables the complete global sensitivity analysis to be performed in less than 30 minutes. These statistical methods have been developed over the last decade and are well-known in the field of environmental hazards modelling (e.g. flooding) but they have yet to become widely used in process safety.

2.4.2 Objectives

The purpose of the study was to perform a global sensitivity analysis on the PHAST dispersion model for simulating jet releases of dense-phase CO₂. The releases studied consisted of above-ground, unconfined, horizontal, steady-state orifice discharges, with orifices ranging in diameter from ½ to 2 inch (12.7 to 50.8 mm), and the liquid CO₂ reservoir maintained at between 100 bar and 150 bar and close to ambient temperatures. These scenarios are relevant in scale to leaks from large diameter above-ground pipes or vessels.

2.4.3 Methodology

The sensitivity analysis was performed using a Gaussian emulator that was constructed from 100 PHAST simulations. The parameters varied include the reservoir temperature and pressure, orifice size, wind speed, humidity, surface roughness and height of the release. The emulator was used to identify the input parameters that had a dominant effect on the dispersion distance of the CO₂ cloud. The whole analysis (including the PHAST simulations) ran on a laptop computer in less than 30 minutes.

2.4.4 Conclusions

The results from the analysis showed that for the range of conditions tested, the orifice diameter had a far greater impact than any of the other parameters varied. The second-largest effect was from the release height. There were interactions between these two model input parameters: when the release was close to the ground, a large orifice produced a much longer plume than when the release was higher, due to the limited entrainment of air near the ground.

The analysis showed that the choice of output quantity was also important: the inputs that had a significant effect on one output had much less effect on a different output. This was demonstrated by the choice of CO₂ concentration for the output of interest. Using a lower CO₂ concentration showed that the dominant input parameter became the wind speed, rather than the orifice diameter or release height.

The study demonstrated that Bayesian analysis of model sensitivity can be conducted rapidly and easily on consequence models such as PHAST. There is the potential for this to become a routine part of hazard assessment.

2.4.5 Impact

The work was presented at the 14th International Symposium on Loss Prevention and Safety Promotion in the Process Industries (Gant *et al.*, 2013a) and published in the Journal for Loss Prevention in the Process Industries (Gant *et al.*, 2013b). The journal paper has since been cited four times in the literature.

Following this work, HSE's Buxton Laboratory has used the same methodology to perform a global sensitivity analysis of LNG pool fires (Kelsey *et al.*, 2014) and HSE's Buxton Laboratory are also actively seeking to engage with other regulators and industry in a Joint Industry Project (JIP) on sensitivity and uncertainty analysis of consequence models used in the

process safety industry. Adrian Kelsey (HSE) gave a presentation on global sensitivity analysis at the DNV-GL PHAST/SAFETI user group meeting in Carlisle on 8-9th October 2014.

As a consequence of the work, HSE's Buxton Laboratory was invited to attend the CREDIBLE Project Team Meeting and Research Showcase in January 2016. The CREDIBLE project⁸ is a Natural Environment Research Council (NERC) funded project on environmental risk, which involves Bristol, Exeter, Oxford and Lancaster Universities, the Met Office, Environment Agency, HR Wallingford, JBA Trust, Risk Management Solutions and Willis Re.

2.5 VALIDATION OF CFD DISPERSION MODELS WITH SHELL

2.5.1 Background

In 2010, Shell commissioned a series of CO₂ release experiments at the DNV-GL Spadeadam test site in Cumbria. The experiments consisted of steady-state horizontal discharges onto an open test pad with a well-defined mass flow rate of liquid CO₂. The test area was well instrumented to provide measurements of temperature and gaseous CO₂ concentration at numerous locations, at distances up to around 80 m from the release orifice. In addition, a more limited set of tests was conducted in which liquid CO₂ was discharged into a steel container.

At that time, the Shell experiments provided probably the best dataset for validating consequence models for dispersion of dense-phase CO₂. The experimental data was not released publicly but a collaborative arrangement was entered into by Shell and HSE's Buxton Laboratory in which both parties independently performed model predictions of the experiments and compared their results to the data. This provided Shell and HSE's Buxton Laboratory with an opportunity to benchmark their models' performance and to have greater scrutiny of the experimental data. The work was published at the IChemE Hazards XXIII conference (Dixon *et al.*, 2012). Some years later, as part of the CO₂PIPETRANS joint industry project⁹, data from the Shell tests was made publicly available.

2.5.2 Objectives

The purpose of the study was to compare predictions from an integral dispersion model and two Computational Fluid Dynamics (CFD) models to experimental data for confined and unconfined jet releases of dense-phase CO₂. For the unconfined cases, the jets consisted of a horizontal discharge through either a ½ inch or 1 inch diameter orifice, with the dense-phase CO₂ reservoir maintained at approximately 150 bar and close to ambient temperature. The confined release involved a ½ inch diameter jet discharging into a largely-enclosed steel container of dimensions 6 × 2 × 2 metres. The releases studied are relevant in scale to leaks from above-ground pipes or vessels.

2.5.3 Methodology

The integral model used in the study was Shell FRED (Betteridge and Roy, 2010), which adopted a semi-empirical jet model for the momentum-dominated part of the release and a similarity model for the subsequent dense-gas dispersion. FRED also assumed homogeneous equilibrium between the CO₂ vapour phase, i.e. the particles and surrounding vapour shared the same temperature and velocity. Since FRED was primarily designed for hydrocarbon hazards it

⁸ Consortium on Risk in the Environment: Diagnostics, Integration, Benchmarking, Learning and Elicitation (CREDIBLE), <http://www.credible.bris.ac.uk/>, accessed 26 January 2016.

⁹ <https://www.dnvgl.com/oilgas/joint-industry-projects/ongoing-jips/co2pipetrans.html>, accessed 25 January 2015.

did not simulate solid CO₂ (dry ice) particles but, rather, the liquid-vapour line was extrapolated down to atmospheric pressure and the particles were treated as liquid.

The two different CFD dispersion models consisted of one developed by Shell in the OpenFOAM CFD software and another developed by HSE's Buxton Laboratory in the ANSYS-CFX software. The OpenFOAM model assumed homogeneous equilibrium whereas the CFX model used a particle-tracking approach to simulate the sublimating solid CO₂ particles. FRED and the two CFD models each accounted for the latent heat effects associated with humidity and the condensation of water vapour in the cold CO₂ cloud.

2.5.4 Conclusions

For the free-jet releases studied, all three models provided generally good predictions of the concentrations along the centreline of the plume. Plume widths were slightly better predicted by FRED than the two CFD models. At a distance of a few metres downstream from the nozzle, the jet became attached to the ground and the flow exhibited behaviour similar to a wall-jet. The turbulence model used by CFX and OpenFOAM was known to have weaknesses in predicting the spreading rate in this type of flow.

The thermodynamics model employed by FRED and its treatment of solid CO₂ particles led to the post-flash vapour fraction being too low and the temperatures being underpredicted in the near-field of the jet. However, this appeared to have a limited effect on the concentration profiles. It was therefore concluded, for the scale of releases considered, that FRED performed adequately for the purpose for which it was intended, which was providing hazard distances from free-jet releases.

The CFX model used a particle-tracking approach for the solid CO₂ particles with an initial diameter of 5 µm, whilst the OpenFOAM model assumed homogeneous equilibrium between the particles and the surrounding vapour. The results from the two models were found to be remarkably similar, especially considering that CFD models are known to be sensitive to user inputs and the two models in this case were set up independently by different users at Shell and HSE's Buxton Laboratory. The good agreement between the model predictions and the experiments suggested that it was reasonable to assume a small initial CO₂ particle size, for the scale of releases considered in the study. Furthermore, the homogeneous equilibrium assumption appeared to provide an adequate description of the solid CO₂ transport in these cases. For larger-scale releases, such as pipeline full-bore ruptures or catastrophic vessel failures, the size of the CO₂ particles and the validity of the homogeneous equilibrium assumption remained uncertain.

2.5.5 Impact

The results from the study led to a greater understanding of the strengths and weaknesses of dispersion models used by Shell and HSE's Buxton Laboratory. If the Shell CCS project at Peterhead had gone ahead, this would have provided useful information to help review their risk assessment. The conference paper (Dixon *et al.*, 2012) has been cited 14 times in the literature.

2.6 INTEGRAL MODELLING OF CO₂ PIPELINE OUTFLOW AND DISPERSION

2.6.1 Background

At present, there are a number of consequence models available to simulate releases from pipelines containing pressure-liquefied substances. These models predict the behaviour of the

liquid flashing into vapour as the pressure within the pipeline drops, and the dispersion of a two-phase mixture of droplets and vapour. However, for CO₂, as the pressure falls in the pipeline, conditions pass through the triple point, where the gas, liquid and solid phases co-exist. Liquid droplets in the flow will turn into solid dry-ice particles as the conditions pass through the triple point.

2.6.2 Objectives

The aim of this work was to analyse how existing integral models for pipeline outflow and dispersion could be generalised to account for the unusual behaviour of CO₂.

2.6.3 Methodology

A theoretical analysis of homogeneous equilibrium models for two-phase pipeline outflow and dispersion was performed. To account for the phase behaviour of CO₂, the analysis showed that the liquid/solid mole fraction must be discontinuous at the triple point. The solid mole fraction downstream of the triple point is less than the liquid mole fraction just upstream, i.e. some of the liquid solidifies but a small fraction vaporises to make up for the decrease in volume of the solid CO₂. This process is also accompanied by a jump in enthalpy at the transition from liquid to solid.

2.6.4 Conclusions

The main conclusion of the work was that standard homogeneous equilibrium models of pipeline outflow and dispersion could be generalised straightforwardly to the case of CO₂. There are a number of models currently in use for pipeline outflow and dispersion which rely on the assumption of two-phase homogeneous equilibrium. The work showed how these models could be generalised to encompass the three phases of CO₂.

2.6.5 Impact

The analysis was published in the Journal of Loss Prevention in the Process Industries (Webber, 2011) and it has been cited six times in the literature.

The main benefit of this work was that, in the future, if HSE decides to update its pipeline outflow and dispersion models to account for the behaviour of CO₂, the necessary changes and underpinning physics are documented in the peer-reviewed journal paper. In addition, the work enables alternative methods developed by others to be critically reviewed.

2.7 FLAMMABILITY OF HYDROCARBON AND CO₂ MIXTURES

2.7.1 Background

In 2009, a joint experimental and modelling project was initiated at HSE's Buxton Laboratory to study the effect of CO₂ on the flammability of hydrocarbon gas mixtures. There were three main motivations for this work. Firstly, it was foreseen that over the next decade there would be an increased use of CO₂ for Enhanced Oil Recovery (EOR) and CCS in depleted oil and gas fields. As a result, it was thought that hydrocarbon gas streams from these fields could become increasingly contaminated with CO₂, and therefore it would be beneficial to understand how the presence of CO₂ affected flammable hazards. Secondly, it was thought that in some situations, operators of offshore platforms may consider it advantageous to mix CO₂ and hydrocarbon streams to reduce the hazard posed by fires and explosions from unintended releases. Thirdly,

ageing offshore installations in the North Sea were being decommissioned or dismantled at an increasing rate. There had been incidents in which dismantling of poorly-inerted former hydrocarbon processing plant had caused fires and explosions resulting in fatalities. There was therefore an interest in assessing the behaviour of partially-inerted gas mixtures and in disseminating the findings to the oil and gas industry.

2.7.2 Objectives

The aim of the work was to examine the flammability of premixed and non-premixed hydrocarbon and CO₂ gas mixtures.

2.7.3 Methodology

Explosion tests were performed at HSE's Buxton Laboratory using a 20 litre sphere and an 8 m long section of 1.04 m diameter pipeline with premixed CO₂ and propane or methane mixtures in air. The results were compared to previous flammability measurements published in the literature.

The flammability of jets was also examined experimentally using a small-scale test rig in which mixtures of CO₂ and methane were released from a 6 mm diameter pipe at a pressure of 3 barg. The jets were ignited either using a propane blow torch or a spark ignition system. The characteristics of the ignitions using the propane pilot flame were characterised in terms of whether a stable flame was produced or an unstable flame, whether the pilot flame was enhanced by the presence of the gas or whether there was no effect. For the spark ignition tests, multiple ignition attempts were made at various different points in the dispersing jet to map the ignition probability.

In addition to the experimental studies, a detailed literature review was performed on the flammability of gas jets and an empirically-based jet flammability model was developed, based upon work published in the literature. The results from this model were then compared to the ignition probability measurements.

2.7.4 Conclusions

The explosion tests showed that the explosion overpressure decreased as the CO₂ concentration increased, as anticipated. For the 20 litre sphere, it was found that CO₂ concentrations needed to be greater than 15% v/v in the CO₂-methane-air mixture to completely suppress the explosion. These results agreed well with the published flammability measurements in the literature. In the larger-scale explosion tests, no ignition of the gas mixture occurred for a CO₂ concentration of 12% v/v, although the mixture should have been within the flammable range for this case. This result was attributed to incomplete mixing of the gases, which highlighted the fact that poor mixing of the inerting gas needs to be considered when analysing certain fire and explosion events.

The measurements and model predictions of gas jets showed that the ignitable region in a jet of methane containing 20% CO₂ is smaller than that of the equivalent pure methane release, as expected. It was demonstrated that it was possible to ignite the gas jets at points in the flow where the mean concentration was either below the LFL or above the UFL, due to fluctuations in concentrations above or below these mean concentrations. The agreement between the flammability factor predicted by the empirical model and the measured ignition probability was reasonably good in the near-field of the jet but it deteriorated in the far-field further downstream. The model predictions of the flammability factor were higher than those measured in these locations. These differences were attributed mainly to the effect of the wind in the

experiments. The tests were conducted in a walled courtyard that was open to the atmosphere, whereas the model assumed completely quiescent conditions.

The results from gas jet tests with pilot ignition showed that in some situations where a stable flame was not sustained, the fuel present in the CO₂-methane jet still promoted combustion near the pilot flame. In practical terms, this means that if a partially-inerted mixture was released onto a continuous ignition source, such as an on-going hydrocarbon fire, the presence of the partially-inerted gas could potentially increase the severity of the fire.

2.7.5 Impact

The work undertaken in this project was documented in an HSL report (Gant *et al.*, 2011a) and summarised in two conference papers presented at the IChemE Hazards XXII Conference (Pursell *et al.*, 2011; Gant *et al.*, 2011b) and also in a journal paper (Gant *et al.*, 2011c). The journal paper has since been cited three times.

The empirical model that was developed as part of the project to predict the likelihood of flammable gas igniting in a jet was subsequently adapted to model pure CO₂ jets and assess the impact of concentration fluctuations on toxic load (see Section 2.3).

2.8 EXPERIMENTAL WORK AT HSE'S BUXTON LABORATORY

2.8.1 Background

During the period from 2008 to 2010, there was interest in gaining a thorough understanding of the physical processes that occur during an accidental release of CO₂ associated with a CCS transportation network. At around this time, a number of Joint Industry Projects (JIPs) were starting to obtain pertinent data for the development of consequence models for dense-phase CO₂ releases. In response to the requirements of these programmes of work and to provide HSE with a test facility to conduct similar programmes of research, it was proposed to construct a large-scale pipeline depressurisation test facility at HSE's Buxton Laboratory. The facility was to comprise a 150 m section of 6 inch pipe that would allow CO₂ tests to be conducted across a range of dense-phase and supercritical conditions. Funding for the facility was to come initially from HSE with the prospect that the cost would be recouped through the delivery of commercial contracts to industrial research projects.

The development of this facility coincided with the period of economic recession in the UK and it was decided that capital expenditure to fund the facility was a non-core HSE activity. Development of the facility was therefore halted. At about the same time, a similar facility was constructed in the private sector by GL-Noble Denton at Spadeadam.

Large scale test programmes were still conducted by various JIPs, but the majority of experimental work was conducted at Spadeadam.

Alongside the proposal for the development of the large-scale test facility at HSE's Buxton Laboratory, HSE commissioned an experimental research programme at HSE's Buxton Laboratory related to accidental releases of CO₂. One of the original aims of this work was to undertake small-scale experiments to support the development of the larger-scale test facility. Following the halt in the development of the large-scale facility, work on the small-scale facility continued, but with a revised set of objectives.

2.8.2 Objectives

The aim of the project was to conduct small-scale experiments to improve the understanding of CO₂ release behaviour and produce data to develop and validate consequence models. Since the tests were conducted on a relatively small scale, it was envisaged that a greater number of tests could be undertaken that would complement the fewer, large-scale tests undertaken by the JIP test programmes.

The specific objectives were to:

1. Examine the near-field expansion region of CO₂ jets for a range of pressures and hole sizes
2. Examine the downstream dispersion behaviour to identify any effects associated with solid CO₂ that may affect the prediction of downstream concentration profiles
3. Examine the influence of ambient atmospheric conditions (temperature and humidity) on the visual appearance (opacity), temperature and concentration of the dispersing plume
4. Conduct CO₂ pipeline depressurisation tests across a range of initial pressure and hole sizes to obtain data on mass release rates and in-pipe temperature and pressure profiles.

2.8.3 Methodology

The test conditions (temperature and pressure) used in the small-scale HSE's Buxton Laboratory tests are compared to those examined in the CO₂PipeHaz, CO₂PIPETRANS, BP DF1 and Shell test programmes in Figure 1. High temperature supercritical release experiments were not considered in the tests performed at HSE's Buxton Laboratory. Two experimental facilities were used: a laboratory-based steady-state release chamber and a small-scale pipeline depressurisation facility, which was constructed specifically for the test programme. In total 95 release experiments were performed, in addition to commissioning work.

2.8.3.1 *Steady-State Release Chamber*

Steady-state releases were conducted in a 4 m long ventilated chamber that allowed experiments to be conducted safely in a controlled environment. The CO₂ was supplied from a pressurised vessel that could deliver saturated liquid CO₂ at pressures up to the critical point (~74 bar). The feed vessel was located on a load cell platform that allowed the mass release rate to be recorded. Pressure sensors in the feed line monitored the upstream flow conditions. The release orifices used were either 2 mm or 4 mm circular holes. Downstream of the release point, an instrument array measured the temperature, concentration and opacity of the plume. Photographic images of the near field were recorded to assess the expansion behaviour. Example images are shown in Figure 2, which demonstrate the difference between gaseous and liquid CO₂ releases. In the left-hand image, the internal high pressure shock structure is visible in the gas jet, whilst in the right-hand image, the presence of liquid or solid CO₂ and condensed water obscures the flow structures.

2.8.3.2 *Pipeline Depressurisation*

The small-scale pipeline depressurisation experiments were performed using a 10 m long shock tube that was constructed from ½ inch diameter tubing. A schematic of the experimental design is given in Figure 3. The shock tube was sub-divided into four sections, each of which was approximately 2.5 m long, with instrumentation for measuring the temperature, pressure and

mass located at the start and end of the shock tube, and between each section. The release end of the tube was either fully open or fitted with a 2 mm, 4 mm or 8 mm orifice. Tests were also performed with insulation applied to the shock tube, to examine the influence of heat transfer effects.

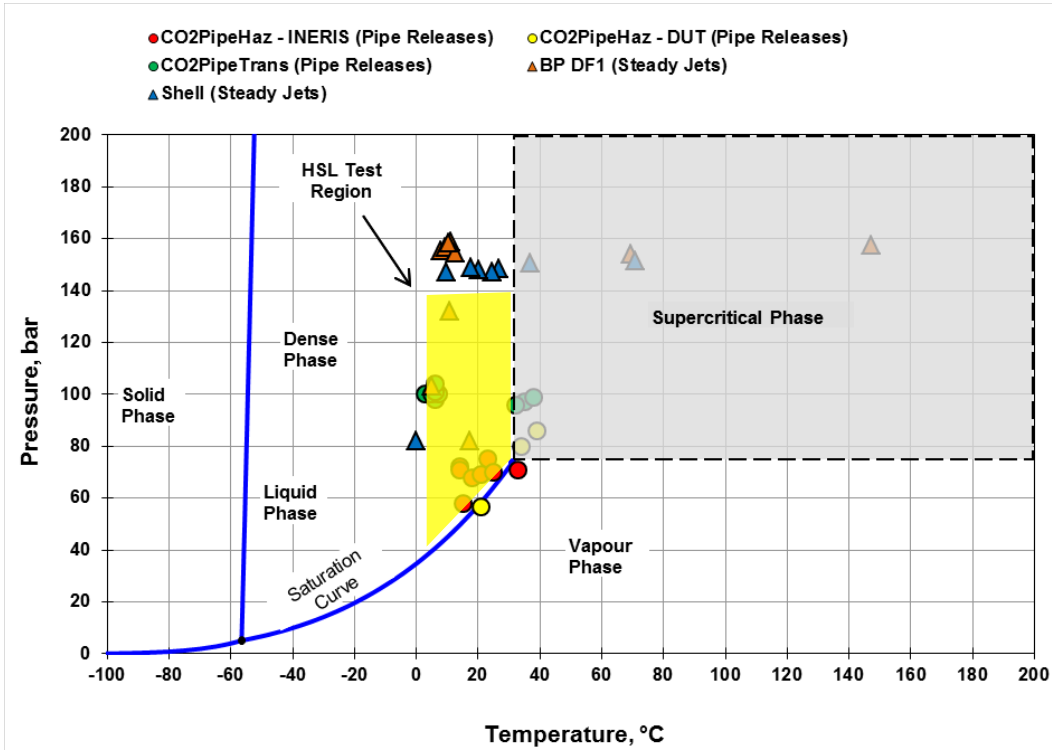


Figure 1 Pressure-temperature CO₂ phase diagram showing the conditions for the HSE's Buxton Laboratory tests (in yellow) and the conditions for various other larger-scale experiments

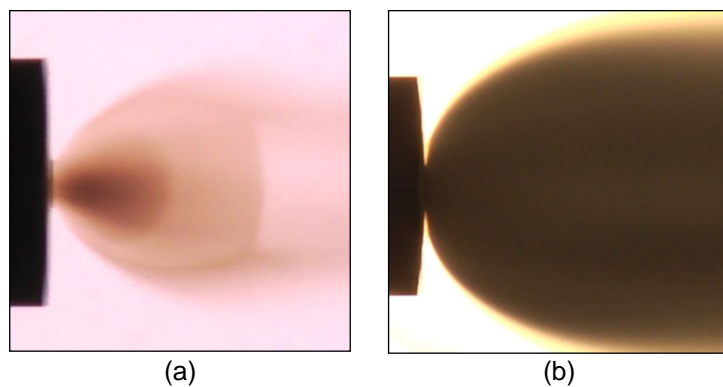
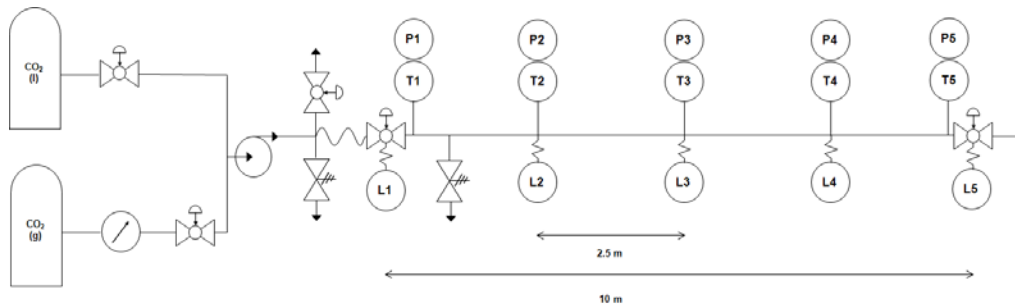


Figure 2 Images of the near-field structure of high-pressure jet releases: a) saturated gaseous CO₂, and b) saturated liquid CO₂



L_i , T_i and P_i denote the location of the load cells, thermocouples and pressure transducers

Figure 3 Schematic of the HSE's Buxton Laboratory CO₂ shock tube test facility

2.8.3.3 Test Programmes

A summary of the experimental tests is given in Table 1.

2.8.4 Conclusions

A wide range of experimental tests were undertaken to produce data relevant for the development and validation of consequence models for the transportation of CO₂. To date, a limited set of model validation tests have been undertaken using PHAST. The final project report is due for completion in April 2016.

2.8.5 Impact

Preliminary results from the work were presented at the IChemE Hazards XXIII conference (Pursell, 2012). Following completion of the project report, it is planned to produce a further journal publication to disseminate the results.

Table 1 Summary of conditions and data collected during CO₂ release experiments

	Release Conditions	Data collected	Model Validation
Expansion size / dispersion source term	<ul style="list-style-type: none"> • Feed Pressure = 26 bar to 57 bar • 13 expts with 2 mm orifice, 11 expts with 4 mm orifice 	<ul style="list-style-type: none"> • Size and position of atmospheric expansion plane determined from video analysis • Mass release rates determined for all tests 	Comparison with consequence modelling tools (PHAST)
Downstream dispersion properties	<ul style="list-style-type: none"> • Feed Pressure = 26 bar to 57 bar • 18 expts with 2 mm orifice, 19 expts w 4 mm orifice, 	<ul style="list-style-type: none"> • Temperature and concentration profile across the jet at locations from 12.5 to 500 diameters from release point • Mass release rates determined for all tests 	Comparison with consequence modelling tools (PHAST)
Visual Hazard Range	<ul style="list-style-type: none"> • Feed Pressure = 55 bar to 75 bar • Humidity = 41% to 72% • 18 expts with 2 mm orifice, (due to release volume 4 mm expts were not possible) 	<ul style="list-style-type: none"> • Centreline measurements of temperature, concentration and opacity • Mass release rates determined for all tests 	
Pipeline Depressurisation	<ul style="list-style-type: none"> • 40 tests with 2, 4, 8, 10 mm hole sizes • Initial Pressure nominally = saturation, 80, 100, 120 and 140 bar • 10 test with pipe insulation 	<ul style="list-style-type: none"> • In pipe measurements of temperature and pressure at 5 locations (pressure at high data capture rate – 100kHz) • High speed mass loss from pipe • Video observation of outflow behaviour 	To be completed

3 CO₂PIPEHAZ

3.1 OBJECTIVES

CO₂PipeHaz¹⁰ was a four-year project funded by the European Commission FP7 Energy programme that ran between December 2009 and December 2013. The aims of the project were to:

1. Define the optimum level of impurities in the CO₂ stream based on safety, environmental and economic analysis
2. Develop a computationally efficient multi-phase heterogeneous outflow model for predicting the time-varying release rate and the physical state of CO₂ from a pipeline release, based on a reliable equation-of-state for pure CO₂ and CO₂ mixtures
3. Develop multi-phase dispersion models for the released CO₂, both in terms of a detailed near- and far-field modelling capability
4. Conduct small- and large-scale experiments to validate the models
5. Improve understanding of the hazards presented by CO₂ releases
6. Embody the understanding and new predictive capabilities developed by the project in decision support tools
7. Demonstrate the usefulness of the tools developed in the project by their application to possible CO₂ pipeline designs

3.2 PARTNERS

There were seven partners in CO₂PipeHaz that each focussed on different topics within the project:

- **University College London, UCL (UK)**
 - Development of a pipeline depressurisation and outflow model for dense-phase CO₂
- **Dalian University of Technology, DUT (China)**
 - Large-scale pipeline depressurisation and dispersion experiments at a test site in China
- **GexCon (Norway)**
 - Far-field dispersion modelling using the CFD model, FLACS
- **L'Institut National de l'Environnement Industriel et des Risques, INERIS (France)**
 - Measurement of material properties and small-scale field experiments on pipeline depressurisation and dispersion
- **National Center for Scientific Research, NCSR, "Demokritos" (Greece)**
 - Development of equations of state for CO₂ mixtures
- **University of Leeds (UK)**
 - Development of a near-field dispersion model
- **HSE's Buxton Laboratory (UK)**
 - CFD dispersion modelling and development of decision support tools

The CO₂PipeHaz project was split into several work packages which each had an overall leader and contributors (Figure 4). HSE's Buxton Laboratory was involved in two work packages:

¹⁰ *Quantitative Failure Consequence Hazard Assessment for Next Generation CO₂ Pipelines: The Missing Link (CO₂PipeHaz)*, <http://www.co2pipehaz.eu>, accessed 27 January 2016.

- WP1.5: Far-field dispersion modelling (led by GexCon)
- WP3: Risk assessment (led by HSE's Buxton Laboratory and involving INERIS)

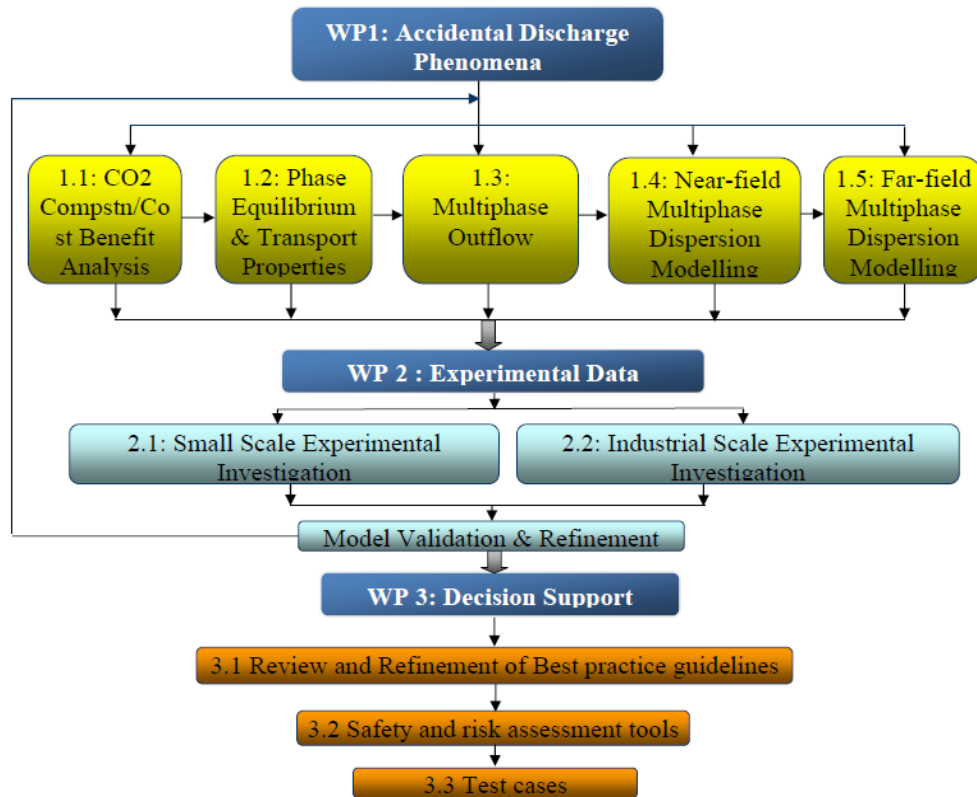


Figure 4 CO₂PipeHaz work activity flow diagram

3.3 DISPERSION MODELLING

3.3.1 Objectives

The primary aim of Work Package 1.5 was to develop and validate multi-phase far-field dispersion models for dense-phase CO₂ releases and to present results for a demonstration test case involving the rupture of a hypothetical 217 km long 36-inch diameter dense-phase CO₂ pipeline. A secondary aim was to assess the strengths and weaknesses of coupling sophisticated models for pipeline outflow, near-field dispersion and far-field dispersion.

3.3.2 Methodology

Two different CFD dispersion models were developed to model far-field dispersion of CO₂: one developed by GexCon using their commercial CFD package, FLACS, and another developed by HSE's Buxton Laboratory using the ANSYS-CFX software. The model developed by HSE's Buxton Laboratory was the same as that used previously for the work described in Section 2.5. Both GexCon and HSE's Buxton Laboratory used a Lagrangian particle-tracking approach to model the presence of solid CO₂ particles in the dispersing plumes. Source conditions were taken from a sophisticated near-field CFD model developed by the University of Leeds that simulated the multi-phase, compressible flow in the expansion region of the CO₂ jet. Different

methods to interface the near- and far-field models were investigated. For comparison purposes, HSE's Buxton Laboratory also performed a limited set of simulations using the PHAST integral dispersion model.

The CFD models were validated by comparing their predictions to measurement data obtained in small-scale experiments by INERIS and large-scale experiments by DUT. The small-scale experiments consisted of a 2 m³ vessel fitted with a short pipe, from which CO₂ was discharged into the atmosphere through either a 6 mm or 25 mm diameter orifice. The large-scale experiments consisted of a 260 m long section of pipeline with an internal diameter of 0.233 m.

3.3.3 Results

Overall, the predicted concentrations from the various models were in reasonable agreement with the measurements in the INERIS tests, but generally in poorer agreement than had been reported previously for similar dispersion models in other dense-phase CO₂ release experiments. In the first INERIS experiment that was examined, all of the models consistently over-predicted the CO₂ concentrations by between 3% and 7% v/v. As a result, the distance from the release point to where the CO₂ concentration fell below the Immediately Dangerous to Life and Health (IDLH)¹¹ value of 4% v/v was over-predicted by a factor of two.

In the second INERIS experiment with a larger orifice, a wide range of predictions were obtained using the different models. The ANSYS-CFX model was sensitive to the way in which the source conditions were specified. The FLACS model showed significant sensitivity to the initial solid CO₂ particle size, whereas the ANSYS-CFX model showed no sensitivity within the range of particle sizes tested. FLACS consistently predicted concentrations of between 3% v/v and 7% v/v higher than ANSYS-CFX, despite both models using the same inlet profiles and particle size, and both being based on Lagrangian particle tracking. The cause of this may be related to differences in the resolution of the CO₂ jet source and the computational grid, but further work is needed to investigate this. PHAST produced similar results to the ANSYS-CFX model.

Dispersion model predictions for the demonstration case involving a 217 km long pipeline (with no experimental data) demonstrated that it was feasible to use CFD models to predict the dispersion of CO₂ over complex terrain. However, CFD models are unlikely to be used on a routine basis for risk assessment of CO₂ pipelines, since the computer run times were of the order of days to weeks for just a single CFD simulation. Instead, integral dispersion models are more likely to be used for routine calculations. The demonstration case showed that if a particularly complex scenario needed to be investigated, such as one where there are large obstacles or significant terrain effects, then it was possible to examine these effects using CFD models.

3.4 DECISION SUPPORT

3.4.1 Objectives

The aim of Work Package 3 on Decision Support (led by HSE's Buxton Laboratory) was to incorporate the improved understanding from the other CO₂PipeHaz work packages on pipeline outflow and dispersion, as well as current knowledge and good practice, into decision support tools, and to demonstrate the usefulness of such tools.

¹¹ <http://www.cdc.gov/niosh/idlh/124389.html>, accessed 27 January 2016.

3.4.2 Methodology and Results

The development of the decision tools was split into six parts:

1. Review of applicability of existing risk assessment methods to CO₂ pipelines and recommendations for safety and risk assessment tools
2. Development of a methodology for CO₂ risk assessment using the ARAMIS approach. ARAMIS is a risk assessment methodology developed for Seveso II sites and, as such, it did not include pipelines within its scope. The ARAMIS methodology was extended to model pipelines. Much of the work was concerned with pipeline failure rate data, which was identified as a key knowledge gap.
3. Development of a methodology for CO₂ risk assessment incorporating integral models. This included CO₂ harm criteria, scenario selection including event tree, failure rates, source term and dispersion modelling, and a worked example.
4. Development of a methodology for short-cut risk assessments for CO₂ incorporating topography. The topography local to a CO₂ pipeline release can potentially be significant because a heavier-than-air gas cloud will be produced. Local topography, such as a valley, has the potential to channel a CO₂ cloud towards populations, even when they are not located in the direction of the prevailing wind. QRA incorporating topography has been considered infeasible in the past because a very large number of location-specific consequence modelling calculations would be required. As part of CO₂PipeHaz, it was demonstrated that it is feasible to account for topography within a QRA using a simplified consequence model.
5. Development of Good Practice Guidelines (GPG) from the decision support tools. The GPG included discussion of the decision-making required for CO₂ pipelines, strategies for the use of decision support tools, existing guidelines for the design of pipelines and the new knowledge developed by the CO₂PipeHaz project. An outline strategy was proposed for the use of different methods in decision support. It was recommended that 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 using state-of-the-art consequence models could be considered for application to critical high-consequence (or high-risk) sections of a pipeline.
6. Test case results for a screening methodology proposed by the CO₂PipeHaz GPG.

Separate reports were produced for each of the six parts of the Decision Support work described above.

3.5 CONCLUSIONS

The contribution of HSE's Buxton Laboratory to the CO₂PipeHaz project led to improved understanding of the strengths and weaknesses of CFD models for simulating far-field dispersion of multi-phase CO₂ releases (which could also be applied to other dense-gas dispersion applications). New models were developed and tested against the experimental data that were produced by other partners during the project. It was demonstrated that, in principle, CFD models could be used to predict the dispersion of CO₂ over complex terrain.

As leaders of the Work Package on Decision Support Tools, HSE's Buxton Laboratory identified and consolidated existing good practice guidelines on CO₂ pipelines to produce

refined good practice guidelines. Relevant and existing risk assessment methods and tools were reviewed, and a gap analysis was undertaken. An integrated consequence assessment methodology was developed, using new knowledge generated from other CO₂PipeHaz Work Packages to fill the gaps in current methodologies, and to permit the development of a risk assessment methodology using integral consequence-modelling. Additionally, short-cut risk assessment methodologies were developed. Overall, this work package delivered a range of decision support tools for use in the safe design and operation of CCS systems.

3.6 IMPACT

The FLACS and PHAST models evaluated as part of the CO₂PipeHaz project are widely used by the process safety industry. The work undertaken in this project provides valuable insight into the performance of these models for simulating multi-phase CO₂ releases, which may assist in future assessments of CCS siting studies.

The work undertaken as part of CO₂PipeHaz was cited widely in the Sherpa Consulting report on CO₂ Pipelines in Australia (see Section 6).

Findings were published in CO₂PipeHaz project reports¹², in conference papers (Mahgerefteh *et al.*, 2011; 2013; Wilday *et al.*, 2014; Woolley *et al.*, 2014) and in journal papers (Gant *et al.*, 2014; Lisbona *et al.*, 2014; McGillivray *et al.*, 2014). According to the journal's usage report, the Gant *et al.* (2014) paper has been viewed 1,867 times up until the present time (January 2016), although to date it has only been cited in two published studies.

¹² See <http://www.co2pipehaz.eu> (accessed 27 January 2016) and Wilday and Saw (2013).

4 COOLTRANS

4.1 BACKGROUND

The COOLTRANS research programme was a four year (2011–2015) project led by National Grid to identify, address and resolve key issues relating to the safe routing, design, construction and operation of onshore pipelines transporting dense-phase CO₂ (Barnett and Cooper, 2014). The project provided the underpinning scientific evidence base to support National Grid's development of a pipeline network in the Humber and North Yorkshire areas of the UK. COOLTRANS included a range of academic, experimental and applied research studies and the results of the research have been extensively published in peer reviewed journals to share the knowledge with the technical community.

The research programme involved a series of large-scale pipeline release experiments supported by modelling work, experiments to assess the ecological impact of CO₂ emissions from pipelines, development of a new risk assessment framework and public consultation. The experimental work on pipeline releases was particularly rigorous and it provided probably the best dataset for model validation of all the various JIPs on CO₂ pipelines.

HSE's Buxton Laboratory contributed to the project by developing a structured process for evaluating dispersion models using the COOLTRANS experimental data and providing general oversight on the dispersion related aspects of the project. The work of HSE's Buxton Laboratory was supported solely by HSE, outside of the main COOLTRANS funding.

4.2 PARTNERS

The COOLTRANS research programme included a range of UK academic partners due to either their knowledge of CO₂ or their specialist knowledge in a particular area of interest, and various specialist companies that each focussed on different topics. Many of the partners were also involved in CO₂PipeHaz (see Section 3):

- **Nottingham University**
 - Experimental measurement of the phase boundary for pure CO₂ and CO₂ mixtures, comparison of experimental data with phase boundary models and review of current equations of state
 - Field studies to determine the effect of CO₂ leaks on vegetation and crops
- **University College London (UCL)**
 - Dense-phase CO₂ pipeline depressurisation modelling, for the purposes of fracture propagation and dispersion analysis, including the effect of emergency shutdown valves
- **Leeds University**
 - Near-field dispersion modelling, including analysis of flow inside craters
 - Laboratory-scale experiments to measure CO₂ particle sizes in jets
- **Kingston/Warwick University**
 - Far-field dispersion modelling, including analysis of the effect of terrain
- **Manchester University (Tyndall Centre)**
 - Public perception of risk from CO₂ pipelines, including use of focus groups along proposed pipeline routes
- **Newcastle University**
 - Development of CO₂ pipeline failure frequency model
 - Analysis of pipeline risk assessment methodology

- Assessment of applicability of fracture mechanics models to thick walled pipelines
- Hydraulic analysis studies
- **GL Noble Denton (now DNV-GL)**
 - Full-scale experimental test programme (including puncture, rupture tests, vent and fracture propagation tests)
 - Assistance in developing validation database for dispersion models
 - Development of a crater model for dense-phase CO₂ releases from buried pipelines
 - Development of a CO₂ pipeline risk assessment methodology
- **Atkins**
 - Development of fracture control methodology for pipelines transporting dense-phase CO₂ with impurities
- **Pipeline Integrity Engineers (PIE)/HH Risk**
 - Project management, management of technical interfaces and technical support
 - Support to development of the CO₂ pipeline failure frequency model and risk assessment methodology
- **Penspen Integrity**
 - Support to the design and specification of full-scale test requirements
- **HSE's Buxton Laboratory**
 - Development of model evaluation protocol for dispersion models
 - Dispersion simulations using PHAST

4.3 OBJECTIVES

The principal aim of HSE's Buxton Laboratory's contribution to the COOLTRANS research programme was to develop a Model Evaluation Protocol (MEP) for release and dispersion of CO₂ from pipelines. The purpose of the MEP was to provide a structured process for reviewing the capabilities and limitations of these models. This would be beneficial to both pipeline operators seeking to use appropriate consequence modelling tools and regulatory authorities in assessing pipeline QRAs.

4.4 MODEL EVALUATION PROTOCOL (MEP)

The framework of the MEP was presented at the Third International Forum on Transportation of CO₂ by Pipeline (Gant, 2012). Its structure followed that of the MEP developed previously by HSL for Liquefied Natural Gas (LNG) dispersion models, which is currently used by the Pipelines and Hazardous Materials Safety Administration (PHMSA) in the USA to approve models for use in LNG siting studies (Ivings *et al.*, 2008). The MEP was split into the following five elements:

- Context definition
- Scientific assessment
- Verification
- Validation
- Sensitivity analysis

The first of these elements involved the definition of the set of operating conditions and credible release scenarios that were to be simulated, together with identification of potential models. The

second step of scientific assessment involved an examination of the underpinning physics of the models to discern whether they are suitable for the relevant release scenario. Verification involved ensuring that the model equations were implemented in the computer software correctly (i.e. code quality assurance). Validation involved assessing model performance against experimental data and the final element of sensitivity analysis involved simulations with a range of different model input parameters to understand the effect of uncertainties in the physical and modelled conditions.

The key output from HSE's Buxton Laboratory's work was the Model Validation Database (MVD), which provided a set of processed experimental data necessary to validate models. HSE's Buxton Laboratory worked with DNV-GL and National Grid to develop the MVD, which consisted of an Excel spreadsheet and accompanying report. The spreadsheet included experimental data from vertical and horizontal above-ground jet releases of gaseous and dense-phase CO₂, and other dense-phase CO₂ releases from buried pipeline punctures and full-bore ruptures. The spreadsheet provided details of the input conditions to configure models to simulate each of the experiments as well as the dispersion measurements. For the buried pipeline puncture and rupture cases, the input conditions were specified at several locations: within the pipeline, at a downstream location within the crater where the CO₂ had expanded to reach atmospheric pressure, and at a further downstream location at the exit from the crater. These multiple source conditions enable users of the MVD to test different approximations for the source conditions within their dispersion models.

To date, only one model has been tested against the COOLTRANS MEP: the FROST integral dispersion model developed by GL Noble Denton (now DNV-GL). At the time of writing (February 2016) work is also still in progress to fully document HSE's Buxton Laboratory's work. The Model Validation Database spreadsheet and report are both complete, but these are confidential National Grid documents¹³. A joint journal paper by HSE's Buxton Laboratory, DNV-GL and National Grid describing the database and the results from FROST is due to be produced in Summer/Autumn 2016.

4.5 CONCLUSIONS

The main contribution from HSE's Buxton Laboratory's involvement in the COOLTRANS research programme was a Model Validation Database (MVD) and the framework of a Model Evaluation Protocol (MEP) for CO₂ pipeline release and dispersion models. These deliverables provided a means of reviewing the capabilities and limitations of pipeline discharge and dispersion models, using high quality data from the large-scale COOLTRANS experiments. The work enabled pipeline operators and regulatory authorities to assess the accuracy of models that may be used within QRAs.

4.6 IMPACT

If industrial-scale CCS is developed in the UK, the COOLTRANS MEP and MVD will provide a valuable way of assessing the capabilities and limitations of consequence models.

¹³ For permission to access these documents, please contact: Russell Cooper (russell.d.cooper@nationalgrid.com), Julian Barnett (julian.barnett@nationalgrid.com).

5 CO2PIPETRANS

5.1 BACKGROUND

DNV (now DNV-GL) initiated the CO2PIPETRANS JIP in 2008. The first phase of the project involved a review of the current technology “state of the art” for CO₂ pipelines and a gap-analysis. The outcome from Phase 1 was the publication of recommended practice for the operation of CO₂ pipelines (DNV, 2010). In undertaking that work, several knowledge gaps were identified and a second phase of the JIP was conceived and funded through the joint industry group. Phase 2 of the CO2PIPETRANS JIP involved the three work packages described in Section 5.3 below. The end point of Phase 2 will be an updated version of the DNV-GL recommended practice report.

5.2 PARTICIPANTS

- Arcelor Mittal
- BP
- Shell DN
- Endesa
- ENI
- EON Ruhrgas
- Gassco
- Gassnova
- HSE
- Petroleum Safety Authority Norway
- Maersk Oil
- Petrobras
- V&M Deutschland
- Vattenfall.

5.3 METHODOLOGY

5.3.1 Work Package 1 - Dense phase CO₂ release model validation data

The objective of the first work package was to make available to the public information and data from experimental work to assist the development and validation of robust dense-phase CO₂ depressurisation, release, and dispersion models. Data collected during two programmes of medium scale CO₂ release experiments previously conducted by BP and by Shell were made publicly-available by the JIP in addition to further data from experiments funded by the CO2PIPETRANS JIP:

- BP - CO₂ discharge data
- Shell - CO₂ discharge data
- CO2PIPETRANS JIP - depressurisation tests on a CO₂ pipeline
- CO2PIPETRANS JIP - discharge data for large diameter CO₂ releases

5.3.2 Work Package 2 - Fracture arrest

The second work package looked to develop recommendations for specifying pipe minimum toughness requirements for preventing fracture propagation in operating CO₂ pipelines. This was to be achieved by conducting large-scale pipeline fracture tests.

5.3.3 Work Package 3 - Corrosion

The third work package focussed on determining the corrosion mechanism and the corrosion rate in dense-phase CO₂ pipelines for various amounts of impurities such as oxygen (O₂), oxides of sulphur and nitrogen (SO_x and NO_x), and hydrogen sulphide (H₂S). Experiments were performed both with and without a free water phase. The aim of the work was to determine a safe operation window of mixture conditions.

5.4 JIP PROGRESS

As of February 2016, the majority of tasks have been completed across the JIP Work Packages.

- WP1 is complete and data arising from the experiments have been reviewed internally by DNV-GL and released.
- WP2 is awaiting the completion of a series of large-scale pipeline rupture, crack arrest tests. These are being undertaken in conjunction with the SARCO2B JIP at the CSM test facility in Sardinia, Italy. The tests are expected to be completed in 2016.
- WP3 is complete and an interim update on the recommended practice has been issued through a journal publication (Brown *et al.*, 2014).

5.5 HSE INVOLVEMENT

HSE has been involved in CO₂PIPETRANS through participation in the JIP Steering Committee and the WP1 Technical Advisory Committee. This has involved attending committee meetings, conducting critical reviews of the test programme specifications and reviewing the technical output from test programmes.

The HSE involvement has also included small-scale experimental work at HSE's Buxton Laboratory to investigate whether the design of the release nozzle used in the CO₂PIPETRANS pipeline depressurisation experiments affected the expansion behaviour and the discharge rate. There was uncertainty as to whether the flow restriction would create a back-pressure that would retard the flow through the expansion region. The experiments showed that, while the nozzle design did affect the size and shape of the expansion region immediately downstream from the release orifice, this would not affect the expansion behaviour. The findings from the experimental work were submitted to the JIP in an HSL report (Pursell, 2012b).

5.6 IMPACT

The JIP has released a significant volume of data that has been made available to the wider scientific and engineering community. The DNV recommended practices set an initial technical safety standard for CO₂ pipeline design and development (DNV, 2010).

6 SHERPA CONSULTING REPORT ON CO₂ PIPELINES

In 2015, HSL were contracted by Brown Coal Innovation Australia to provide an independent peer review of a report on CO₂ pipelines (Sherpa Consulting, 2015) prior to its publication.

Many of the projects discussed in the current report (CO₂PipeHaz, CO₂PIPETRANS etc.) were reviewed in the Sherpa Consulting report and guidelines developed by HSL were adopted in some places. For example, the report recommended the use of SLOT and SLOD criteria developed by HSE for defining the extent of consultation distances in land-use planning applications.

Contributors to the report included Hanna Consultants, Environ Australia (Ramboll Environ) and Brown Coal Innovation Australia. The 193-page document provided a comprehensive review of current Australian and global pipeline design standards for CO₂ transport, analysis of the state-of-the-art of CO₂ dispersion models and best practice guidelines.

7 IEA GHG REPORT

7.1 BACKGROUND

In 2009, HSE's Buxton Laboratory conducted a study for the International Energy Agency Greenhouse Gas (IEA GHG) Research and Development Programme on safety issues of above-ground CCS systems. The work focussed on preparing safety cases and planning emergency procedures for CCS projects. A generic CCS system was examined, which included a power station fitted with a CO₂ capture plant and transport of the CO₂ by pipeline to an onshore or offshore injection site.

7.2 OBJECTIVES

The objectives of the project were to study the safety of all surface facilities, excluding the risks associated with underground reservoirs or the below-ground sections of wells.

7.3 METHODOLOGY

The study began by collecting information in the form of flow schemes, material balances and layouts as well as safety information on CO₂ and other materials, such as absorption solvents. When this was completed, a group of experts drawn from the oil and gas, power, pipeline and industrial gas industries were assembled and complemented by staff from HSE and the IEA GHG Research and Development Programme. HSE's Buxton Laboratory lead the group through a series of four structured hazard analysis sessions with the aim of identifying all possible causes of hazards and means of their mitigation. The results of the Hazard Identification (HAZID) were documented and used to construct Bow Tie diagrams. The work and its findings were presented in a report (IEA GHG, 2009).

7.4 CONCLUSIONS

The extensive hazard analysis performed during this study did not find any fundamental safety issues which could not be fully managed, although some new considerations were identified. Nevertheless there are numerous hazards associated with CCS surface operations which will have to be addressed if the industry is to develop without incident.

The CCS industry is in its infancy and as such is starting with a clean record. However, it was acknowledged that there have been a number of fatalities due to the use of CO₂ in other industry sectors over the years. Sharing information and expertise is expected to contribute significantly to safety in the industry in its early years. Additional efforts and mechanisms to ensure that this exchange occurs were deemed to be beneficial.

The report made a number of general recommendations:

- The hazard lists and Bow Tie diagrams produced by the project should be used as an input to hazard identification and design studies for CCS projects.
- Work should continue to develop design standards for CCS and to resolve knowledge gaps that have been identified.
- Particular attention should be paid to layout and interface issues when CCS is retrofitted into existing power stations. Control system compatibility and ergonomic studies should be considered.

- Training and competency issues should be considered at the outset of a project, including setting competency and training requirements for key staff and providing a hazardous substances training module for all staff destined to work on a new CCS plant.
- An international CCS system incident database should be set up with free access to all.
- An emergency response plan should be developed, particularly for incidents involving major loss of containment of CO₂.

Areas where further research and development was needed were identified:

- Consequence modelling of CO₂ releases, particularly the development of source terms.
- Pipeline failure criteria and validation of models for predicting conditions under which a running failure (propagating crack) could occur.
- Understanding the propensity of dense-phase CO₂ to dissolve heavy metals and other toxic or radioactive contaminants from rock formations. Experience from enhanced oil recovery is limited to a relatively small number of reservoirs.
- Design and operational standards for CO₂ pipelines and other equipment are still in development. Issues include suitable CO₂ specification (particularly water content); avoidance of hydrate formation; suitable non-metallic materials for seals etc.; suitable design and operating regime for intelligent pigs; and flow modelling of CO₂ with impurities, which may affect leak detection systems.
- Various aspects of emergency response planning.

8 DECATUR PROJECT

8.1 BACKGROUND

In the period 2007-2017, a large-scale demonstration of CO₂ sequestration is being undertaken in the USA, known as the “Illinois Basin – Decatur Project” (IBDP). The project involves the injection of approximately 1 million metric tonnes of CO₂ produced by a corn-to-ethanol plant into a subterranean saline-water bearing reservoir located in Decatur, Illinois. The work is being led by the Midwest Geologic Sequestration Consortium (MGSC) partnering with Archer Daniels Midland Company (ADM), Schlumberger Carbon Services and other subcontractors.

The keys aims of IBDP are to investigate:

- CO₂ injectivity, volumetric storage capacity and efficiency of the saline reservoir
- Integrity of seals used to contain the CO₂ in the subsurface
- Pre-injection characterisation and injection process monitoring
- Post-injection monitoring to understand the fate of the CO₂.

The CO₂ has been delivered to the injection site via a 2 km long, 6-inch diameter, carbon steel pipeline. The operating conditions of the pipeline were variable but the pressure ranged from 97 barg to 134 barg and the temperature between 15 °C and 49 °C.

The wellhead is located just over 800 m from the ethanol plant and the total depth of the well was 2206 m. The injected CO₂ was more than 99% pure and in either a supercritical or liquid state, depending on the operating conditions.

The MGSC, working under the umbrella of University of Illinois, contracted HSL to provide support in the Decatur project.

8.2 OBJECTIVES

HSL were contracted to evaluate and model potential release scenarios at the Decatur site to aid in the risk management process.

9 PROGRESSIVE ENERGY PROJECT

9.1 BACKGROUND

In 2009, HSE's Buxton Laboratory was contracted by Progressive Energy to produce a set of CO₂ dispersion model predictions to support the development of an Energy Institute technical guidance document on hazard analysis of CCS on offshore platforms.

9.2 OBJECTIVES

The aim of the work was to obtain dispersion model predictions for a set of nine scenarios defined by Progressive Energy. The scenarios included:

- Releases from different locations on the platform's vertical riser pipeline
- Releases from a large diameter long pipeline located on the seabed
- Releases from an instrument line into an enclosed space.

9.3 METHODOLOGY

The scenarios involving holes in the vertical riser pipeline were modelled as a hole in a vessel using PHAST. Full-bore rupture of the vertical riser was modelled using the long pipeline model in PHAST.

For holes in the pipeline on the seabed, the long pipeline model in PHAST was used to provide the discharge conditions. The released CO₂ was assumed to rise to the surface and form a "pool" source, using the method described by Spouge (1999) to determine its diameter.

PHAST cannot model dispersion within an enclosed space. For these releases, the relevant equations for the build-up of gas were taken from the PHAST documentation and used to determine the concentration after 30 minutes. The concentration was then compared against suitable harm criteria to estimate the potential harm to personnel.

9.4 CONCLUSIONS

Overall, the majority of the release scenarios chosen indicated that they have the potential to cause harm either to persons on the platform deck or to those at sea level, such as those in support or rescue vessels.

9.5 IMPACT

This work carried out by HSE's Buxton Laboratory was reproduced in the Energy Institute report "Hazard analysis for offshore carbon capture platforms and offshore pipelines" (Energy Institute, 2013).

10 RWE-NPOWER PROJECT

10.1 BACKGROUND

In 2012, RWE-npower contracted HSL to produce dispersion model predictions to support a feasibility study for CO₂ capture at one of its power stations.

10.2 OBJECTIVES

The objectives of the work were to:

- Produce dispersion modelling results for eight predefined mixture streams at various temperatures and pressures.
- Present profiles of concentration versus distance for various gases at a range of elevations for each mixture scenario.

10.3 METHODOLOGY

RWE-npower provided the flow rates and HSL used PHAST version 6.7 to obtain the dispersion results.

10.4 CONCLUSIONS

The results were reported to RWE-npower (McGillivray, 2012b), and HSL were not required to evaluate these results further.

11 CONCLUSIONS

This report has summarised the research and assessment work conducted over the last decade by HSE's Buxton Laboratory to investigate many of the potential health and safety issues relating to CCS. In particular, the work has focussed on assessing the hazards posed by the transportation of dense-phase CO₂ by pipeline. This has included laboratory-scale and field-scale experiments, development and evaluation of complex dispersion models for multi-phase CO₂ releases, development of decision support tools for pipeline risk assessment and publication of best practice guidelines.

As a result of this work, HSE is in a strong position to review QRAs and provide support to the development of industrial-scale CCS. Even though much of HSE's work has only recently been published, it is already widely used and cited by others.

The early work undertaken by HSE's Buxton Laboratory to inform policy decisions on how to regulate pipelines transporting carbon dioxide was completed before major research programmes were initiated. In the future, if there is renewed interest in CCS in the UK, any policy decisions made regarding the inclusion of CO₂ as a dangerous fluid under the Pipeline Safety Regulations (PSR) would benefit from a review of the findings of these major research programmes, such as COOLTRANS and CO2PIPETRANS.

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Overview of carbon capture and storage (CCS) projects at HSE's Buxton Laboratory

Over the last decade, the UK Government has supported innovation and growth in Carbon Capture and Storage (CCS) technology with the aim of commercial deployment. CCS research across the UK has reduced potential risks by helping to develop a thorough understanding of the operational hazards and by contributing to the design of safe plant and processes.

This report provides an overview of applied scientific work on CCS undertaken at HSE's Buxton Laboratory. The work includes laboratory-scale and field-scale experiments, evaluation of complex dispersion models for dense-phase carbon dioxide releases, development of decision support tools for pipeline risk assessment and publication of best practice guidelines. In particular, work has focussed on assessing the hazards posed by the accidental release of dense-phase carbon dioxide transported by pipeline. The research has been primarily funded by HSE and industry, with support from the European Union.

HSE's scientific work will help reduce both the risks and costs of any future development of industrial-scale CCS by contributing to the assessment and control of risks early in the design and deployment of the technology. The research has contributed to the scientific evidence base that, if CCS is deployed in with UK, will inform HSE policy decisions to ensure that the regulatory framework for pipelines is effective and proportionate to the potential risks associated with CCS.

This report was funded by the Health and Safety Executive (HSE) and describes work funded by HSE, industry, and the European Union. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.