

Overview of Research on CCUS at HSE Science and Research Centre

Simon Gant

CCSA Technical Working Group meeting 12 August
2020

Research - HSE funded to provide evidence which underpins its policy and regulatory activities
Guidance - freely available to help people comply with health and safety law

Overview

- Initial safety concerns with CCS
- Anecdotal information from incidents
- Research at HSL in period from 2005-2015
- Status of initial safety concerns
- Recent and ongoing work
- Remaining issues

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Initial Safety Concerns

IChemE SYMPOSIUM SERIES NO. 153

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HAZARDS FROM HIGH PRESSURE CARBON DIOXIDE RELEASES DURING CARBON DIOXIDE SEQUESTRATION PROCESSES[†]

Stephen Connolly¹ and Laurence Cusco²

- **Uncertainties:**
 - Dispersion modelling of (liquid/solid + gas) CO₂ jet releases: how does it behave? Can we predict extent of hazardous zones?
 - Implications of severe Joule-Thomson cooling (embrittlement?)
 - Solid CO₂ implications for blowdown (blocking valves?)
 - Solid CO₂ particles scouring and erosion (jet cleaning and cutting)
 - Solid CO₂ deposition as dry-ice bank (prolonged sublimation)
 - Running ductile crack propagation along CO₂ pipelines
 - Equation of state for CO₂ + impurities for flow assurance modelling
 - Corrosion issues

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Anecdotal Information from Incidents

- Onshore well-head blowout in Hungary, 1998
 - 207 bar release of CO₂ and H₂S
 - 5,000 people evacuated, no significant injuries or fatalities
 - Solid CO₂ snow bank 1.5 – 2 metres thick, -30 °C near release point



https://publishing.energyinst.org/_data/assets/file/0006/71394/Guidance-on-HA-for-onshore-CCS-installations-WEB-VERSION.pdf

Anecdotal Information from Incidents

- Proctor and Gamble, Worms, Germany, 1988
 - Catastrophic failure of 30 t vessel storing CO₂ due to over-pressurization
 - Explosion threw vessel 300 m into the river Rhine
 - 3 fatalities, 8 serious injuries
 - Cause: failure of heater in vessel, poor venting, weld failure
 - CO₂ BLEVE

https://publishing.energyinst.org/_data/assets/file/0006/71394/Guidance-on-HA-for-onshore-CCS-installations-WEB-VERSION.pdf

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Scientific Work at HSL from 2005-2015



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HSE: Innovation in Regulation

RR1121 - 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.

Related content

- HSE Buxton Laboratory
- HSE Foresight Centre
- Workplace Health Expert Committee (WHEC)
- Contract opportunities
- Statistics
- Economics of health and safety
- HSE jobs

<http://www.hse.gov.uk/research/rrhtm/rr1121.htm>

Scientific Work at HSL from 2005-2015

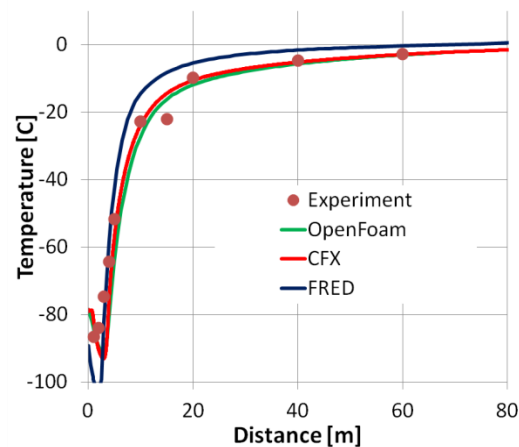
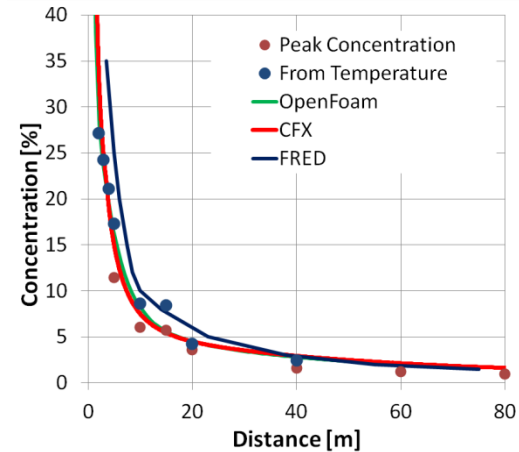
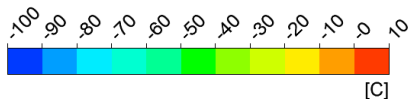
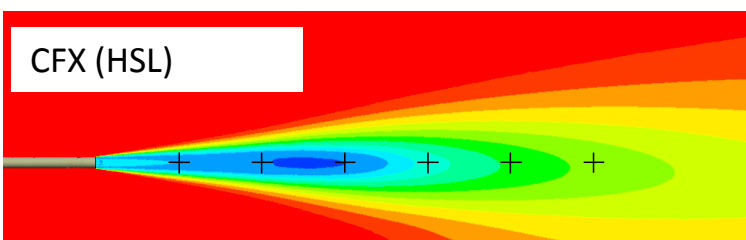
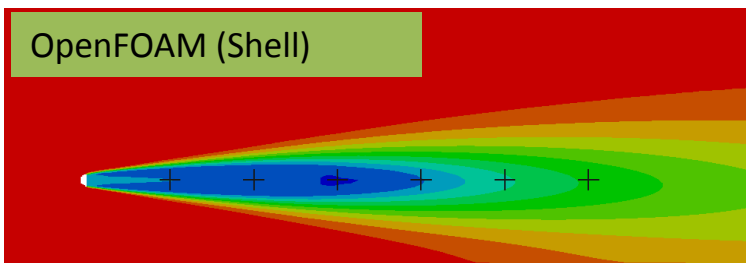
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<http://www.hse.gov.uk/research/rrhtm/rr1121.htm>

Shell experiments at Spadeadam

Images copyright Shell / DNVGL



Dixon C.M., Gant S.E., Obiorah C. and Bilio M. "Validation of dispersion models for high pressure carbon dioxide releases" IChemE Hazards XXIII Conference, Southport, UK, 12-15 November 2012

COOLTRANS

Proceedings of the 2014 10th International Pipeline Conference
IPC2014
September 29 - October 3, 2014, Calgary, Alberta, Canada

IPC2014-33370

**THE COOLTRANS RESEARCH PROGRAMME – LEARNING FOR THE DESIGN OF
CO₂ PIPELINES**

Julian Barnett
National Grid Carbon
Solihull, UK

Russell Cooper
National Grid Carbon
Solihull, UK

Proceedings of the 2016 11th International Pipeline Conference
IPC2016
September 26-30, 2016, Calgary, Alberta, Canada

IPC2016-64456

**ANALYSIS OF A DENSE PHASE CARBON DIOXIDE FULL-SCALE FRACTURE
PROPAGATION TEST IN 24 INCH DIAMETER PIPE**

Andrew Cosham
Ninth Planet Engineering
Newcastle upon Tyne, UK

David G Jones
Pipeline Integrity Engineers
Newcastle upon Tyne, UK

Keith Armstrong
DNV GL
Spadeadam Test & Research Centre, UK

Daniel Allason
DNV GL
Spadeadam Test & Research Centre, UK

Julian Barnett
National Grid
Solihull, UK

Crater size and its influence on releases of CO₂ from buried pipelines

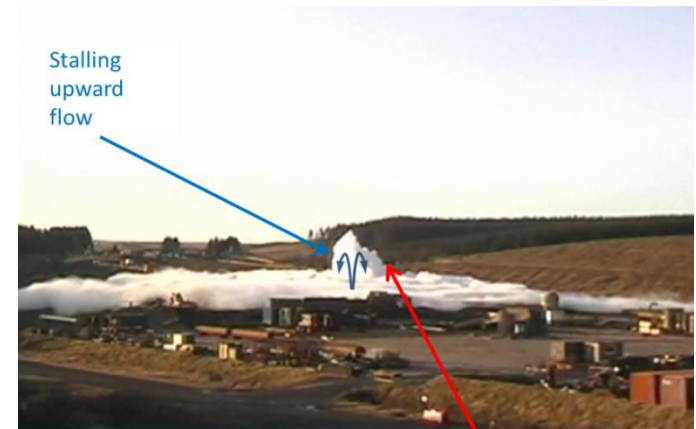
4th International Forum on the Transportation of CO₂ by Pipeline

Hilton Gateshead-Newcastle Hotel, Gateshead, UK
19-20 June, 2013

by Philip Cleaver¹, Ann Halford¹, Karen Warhurst¹, and Julian Barnett²
1 GL Noble Denton, Loughborough, UK
2 National Grid Carbon, Warwick, UK



Fresh air entrainment possible around plume base



Crater is covered by vapour blanket – mixture released previously is drawn into flow

COOLTRANS

Framework for validation of pipeline release and dispersion models for the COOLTRANS research programme

by Simon Gant
Health and Safety Laboratory, Buxton, UK

3rd International Forum on the Transportation of CO₂ by Pipeline

Hilton Gateshead-Newcastle Hotel, Gateshead, UK
20-21 June, 2012



Organized by
Newcastle University
Clarion Technical Conferences
and Tiratsoo Technical
and supported by
The Professional Institute of Pipeline Engineers



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CO₂PipeHaz

CO₂PipeHaz

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

- Jan 2010 – June 2013
- WP1: Accidental Discharge Phenomena
 - WP1.1 CO₂ composition and cost benefit (DUT China/UCL)
 - WP1.2 CO₂ EOS and transport properties (Demokritos)
 - WP1.3 Pipeline decompression model (UCL)
 - WP1.4 Near-field dispersion model (Leeds)
 - WP1.5 Far-field dispersion model (Gexcon/HSL)
- WP2 Experiments
 - WP2.1 Small scale (INERIS)
 - WP2.2 Large scale (DUT, China)
- WP3 Decision support/risk assessment (HSL/INERIS)

CO₂PipeHaz: WP1.5 HSL involvement

1. GIS and CFD integration
 - Transfer of terrain data from GIS into CFD
 - Transfer of concentration predictions from CFD into GIS

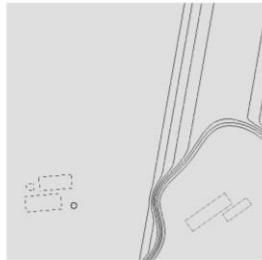
2. Far-Field Dispersion Model Validation
 - Development of two-phase CO₂ dispersion CFX model to benchmark against FLACS
 - Validation using INERIS and Dalian experiments

3. Hypothetical Industrial CO₂ Release
 - Demonstration of CFD and GIS model capabilities using hypothetical industrial CO₂ release scenario

CO₂ PipeHaz: WP1.5 GIS-CFD integration

GIS Topography

General terrain
from map data
~ 2m resolution



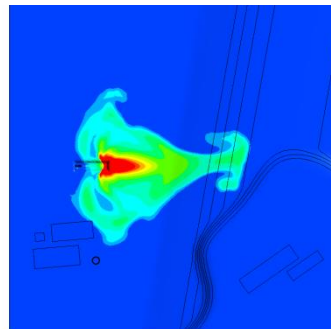
Release Geometry

Detailed near-field
e.g. 3D laser scan
O(mm) resolution



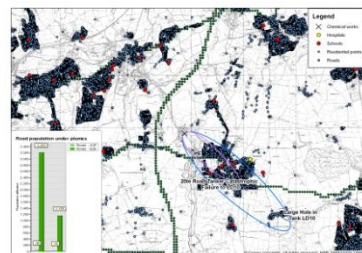
CFD

Vapour concentration
field from dispersion
simulation



GIS

Assess hazard by overlaying vapour
concentration and population density



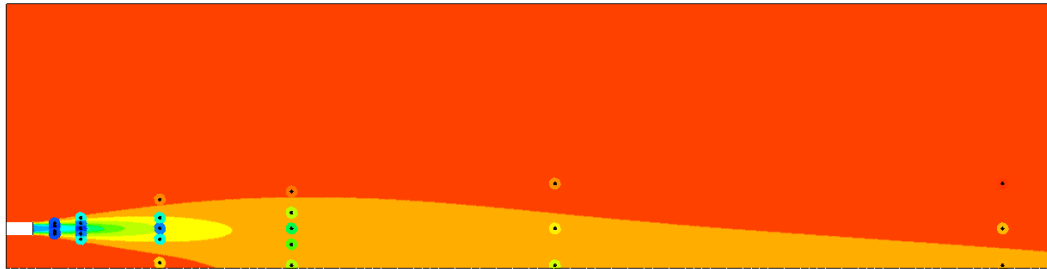
CO₂ PipeHaz: WP1.5 Dispersion Model Validation

- INERIS Test 8 experiment:
 - Orifice diameter 1"
 - Reservoir pressure 77 bar
 - Reservoir temperature 4 °C

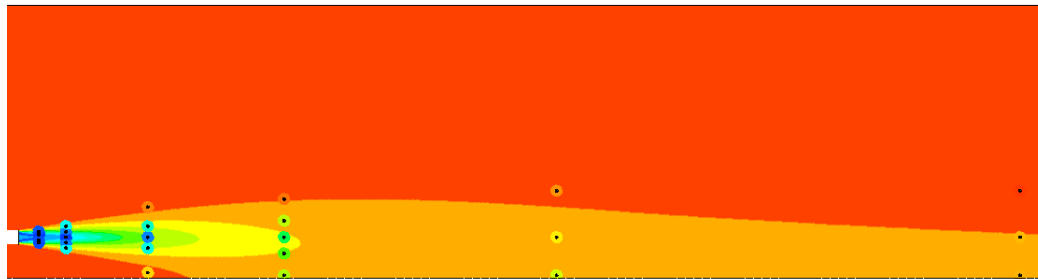


Image courtesy of INERIS

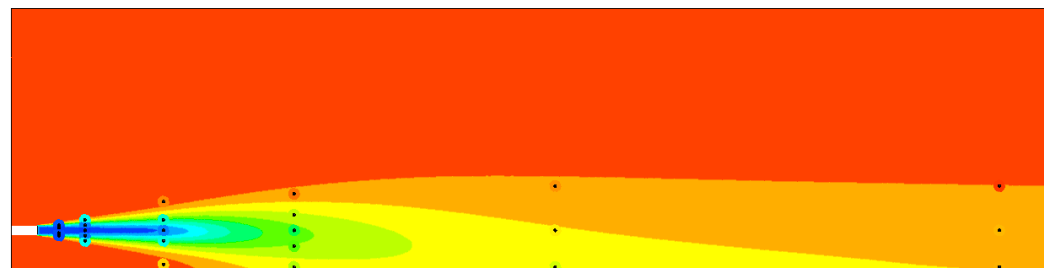
CO₂ PipeHaz: WP1.5 INERIS Test 8



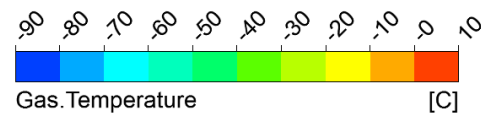
Leeds source 1



Leeds source 2

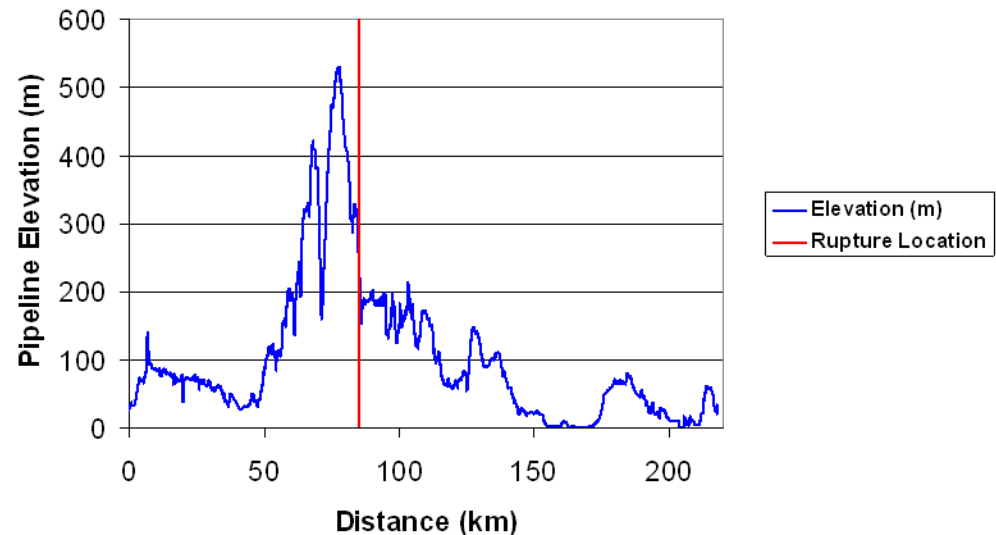


Leeds source 1
averaged with
assumed
turbulence levels

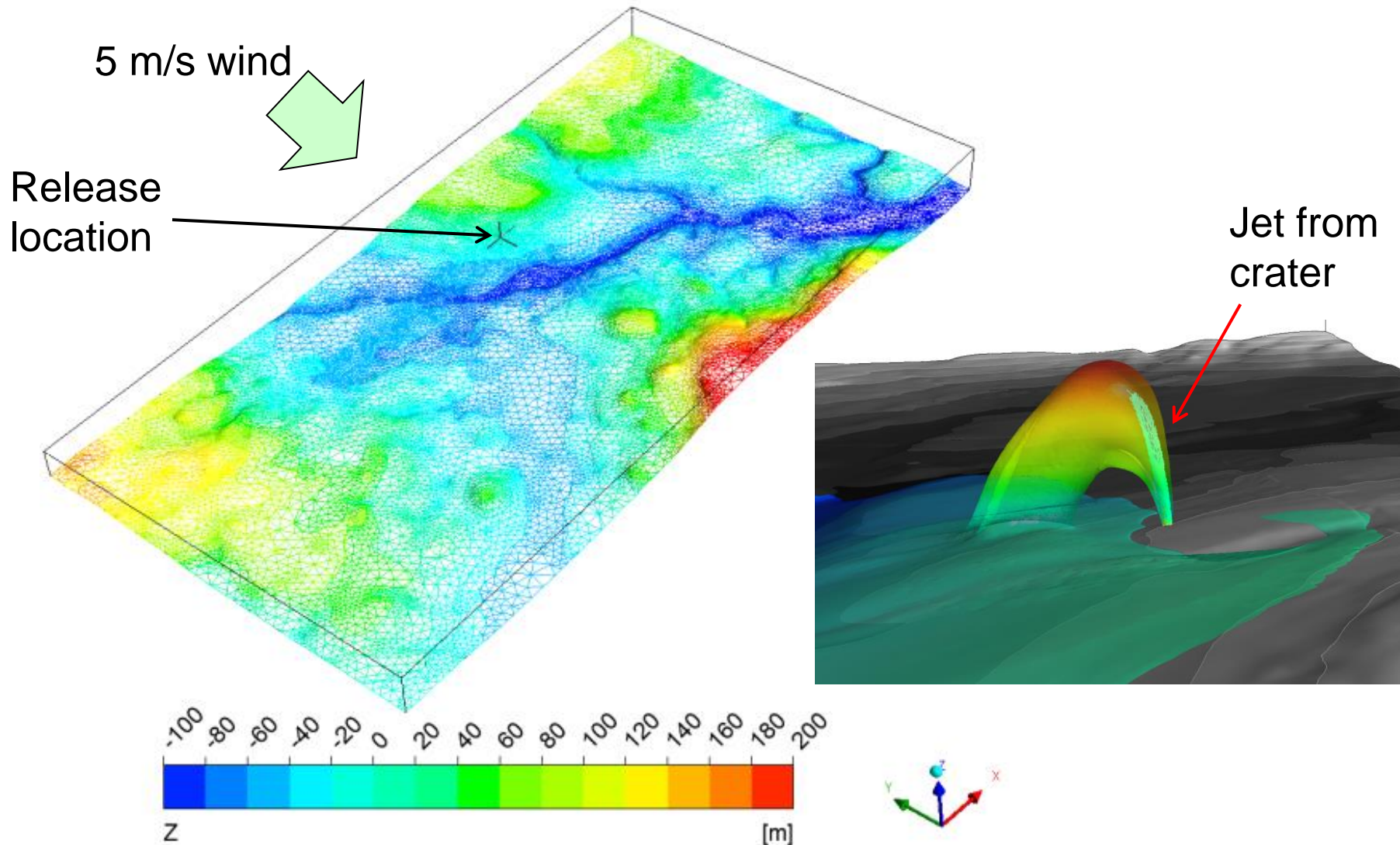


CO₂PipeHaz: WP1.5 “Realistic” release scenario

- Pipeline diameter 36”
- Length 217 km
- Pressure 150 bar
- Temperature 10 °C
- Composition 100% CO₂
- Failure mode Full-bore rupture
- Complex terrain



CO₂PipeHaz: WP1.5 “Realistic” release scenario

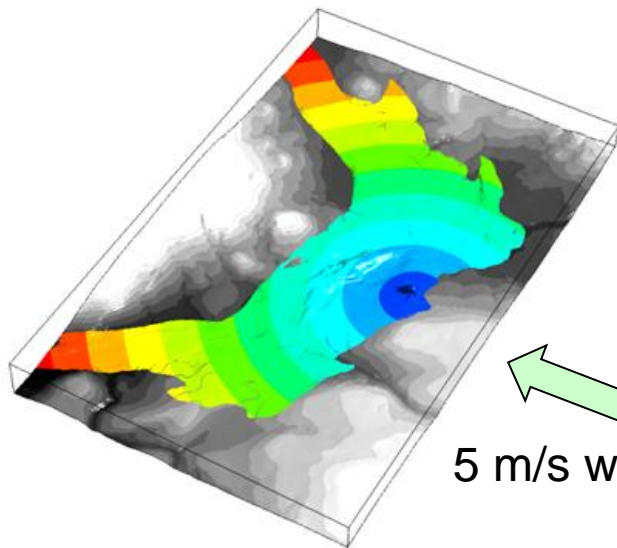


CO₂PipeHaz: WP1.5 “Realistic” release scenario

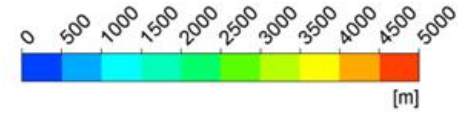
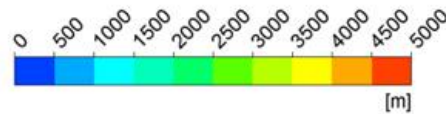
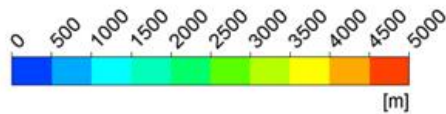
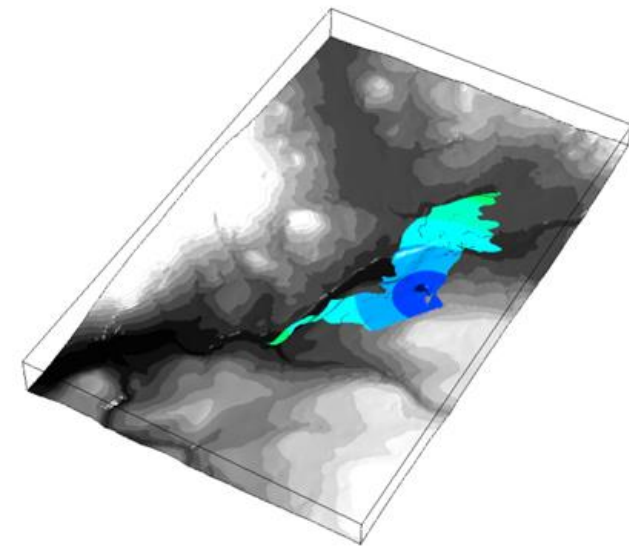
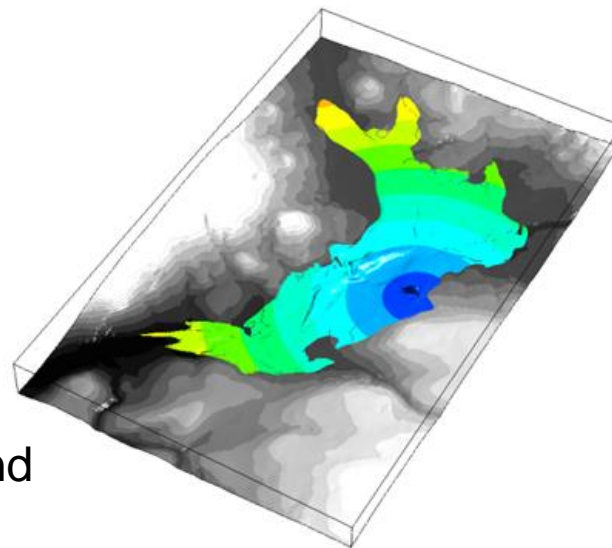
CO₂ Concentration = 1% v/v

CO₂ Concentration = 2% v/v

CO₂ Concentration = 4% v/v



5 m/s wind



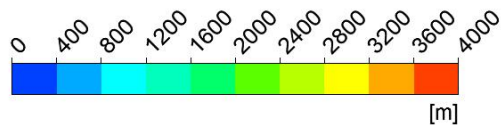
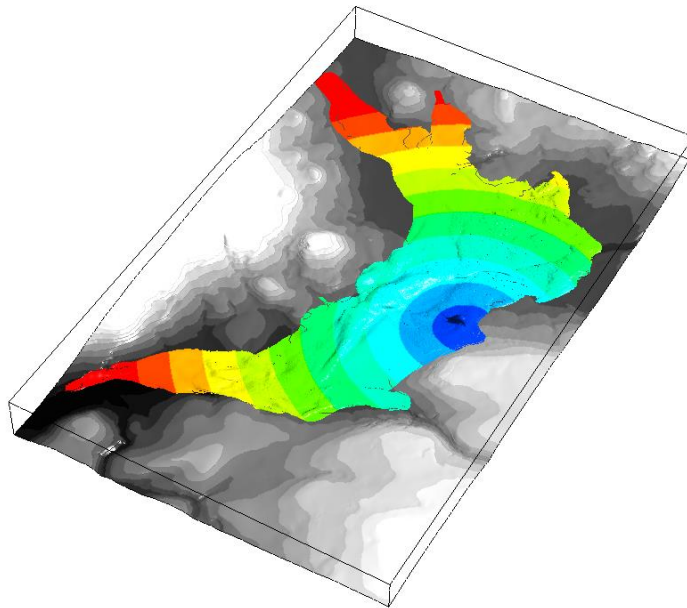
CO₂PipeHaz: WP1.5 “Realistic” release scenario

Cloud visibility

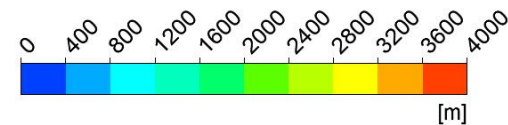
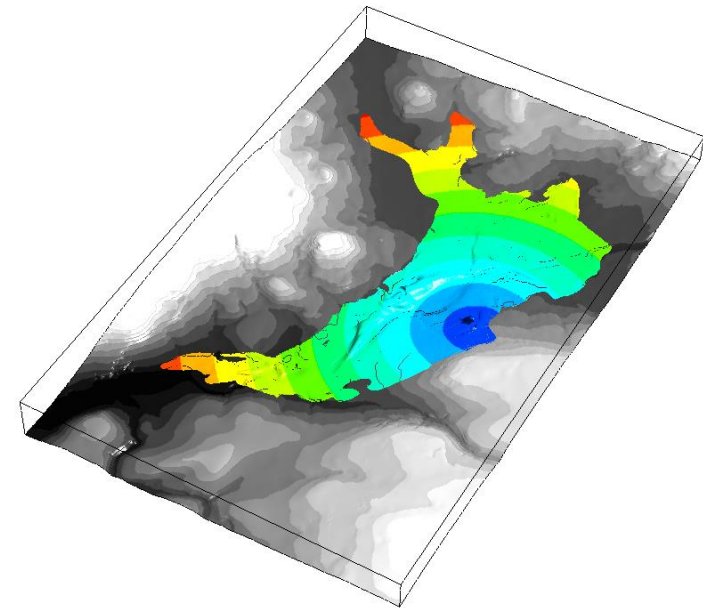
LIQUID WATER CONTENT AND NUMBER OF DROPS PER CUBIC METER IN FOGS AND CLOUDS
(according to Houghton and Radford, 1938)

	Cloud	Fog
Water content (gm/m ³)	0.5 to 1.5	0.05 to 0.25
Number of drops /m ³	50 to 500 × 10 ⁶	1 to 10 × 10 ⁶

Water Droplet Conc = 0.05 g/m³



Water Droplet Conc = 0.5 g/m³



CO₂PipeHaz: WP3 Risk Assessment

- 3.1 Review of existing risk assessment tools for application to CO₂ pipelines
- 3.2 Risk assessment using ARAMIS
- 3.3 Use of integral models
- 3.4 Accounting for topography
- 3.5 Good practice guidelines
- 3.6 Test case using integral models

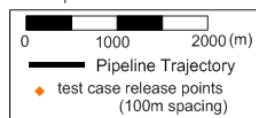
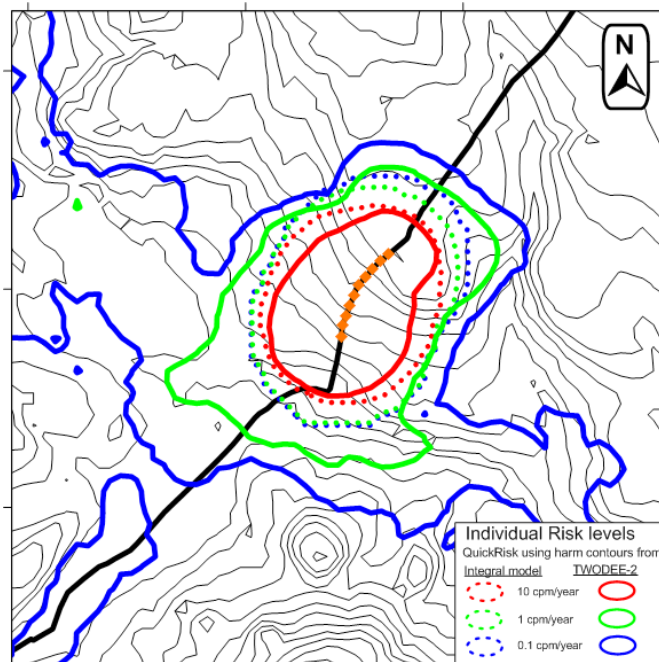
CO₂PipeHaz: WP3.4 Topography

- Review of dense gas dispersion models that account for topography
 - Integral
 - Shallow layer
 - Lagrangian
 - 3D CFD
- Case study using Twodee
- Comparison of shallow-layer and CFD

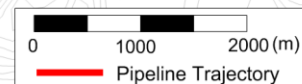
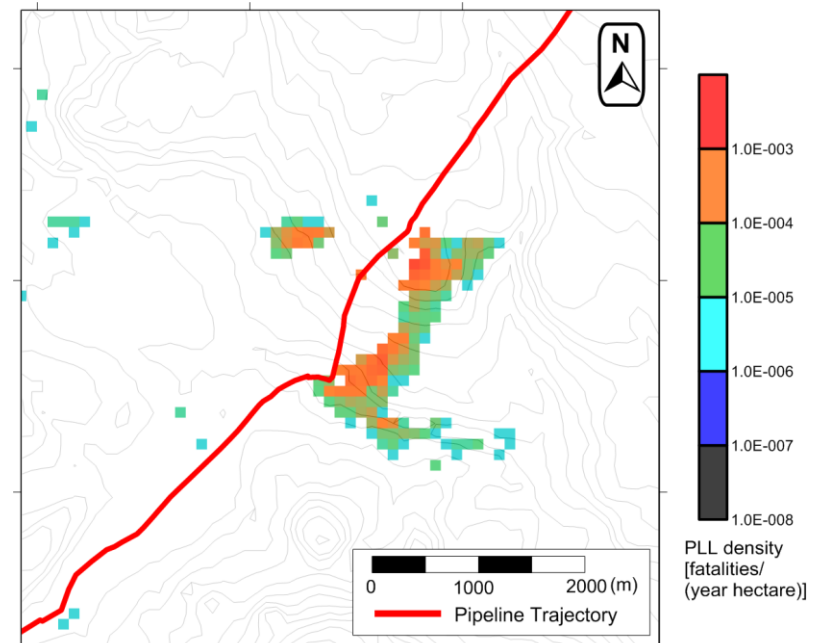
CO₂PipeHaz: WP3.4 Case study using Twodee

- Releases modelled using Risk Twodee at 100 m intervals along pipeline
- D5, F2 weather, wind rose with 5° resolution
- Day/nighttime population from National Population Database (NPD)

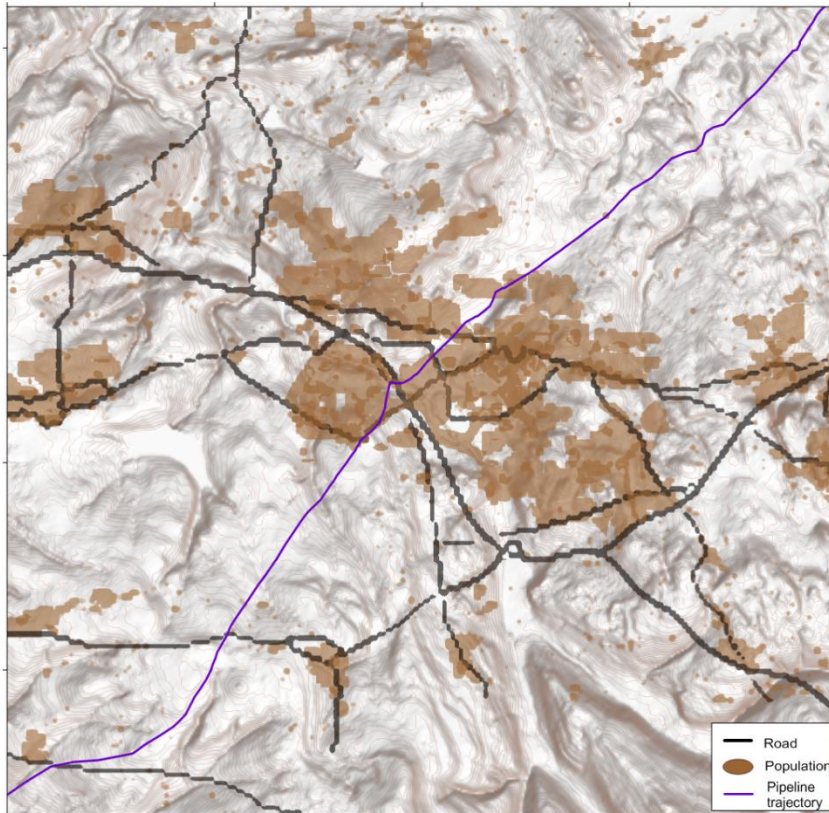
Individual risk



Potential loss of life



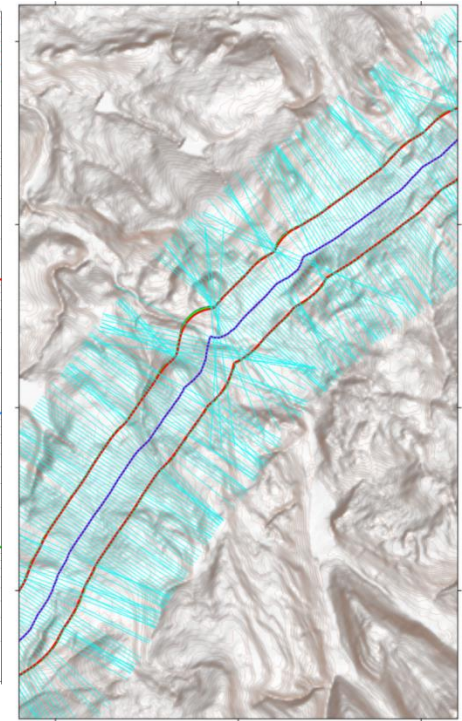
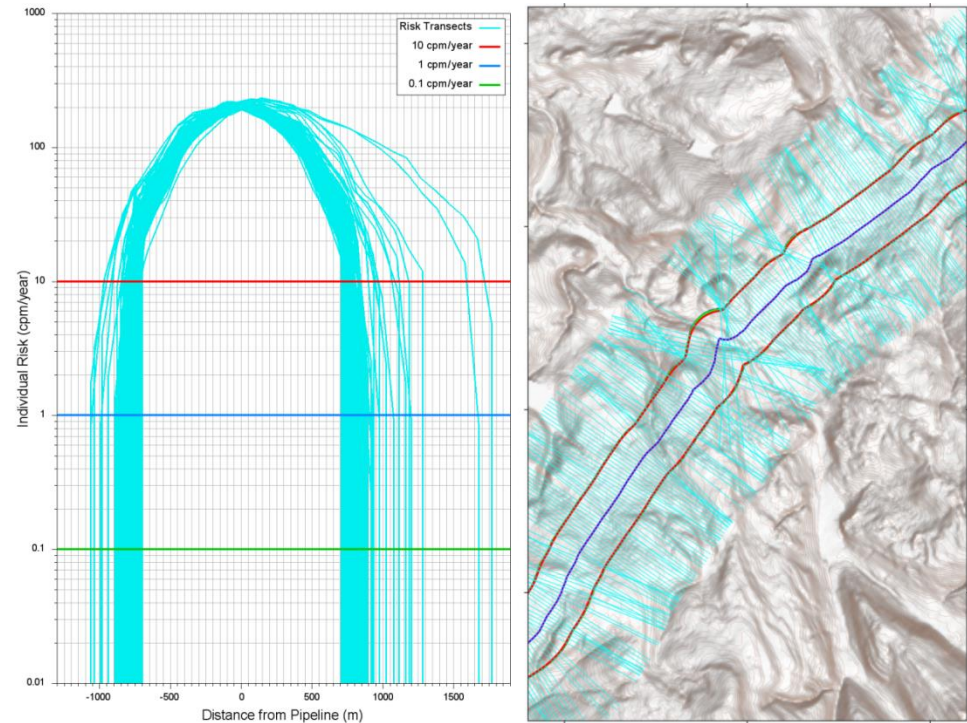
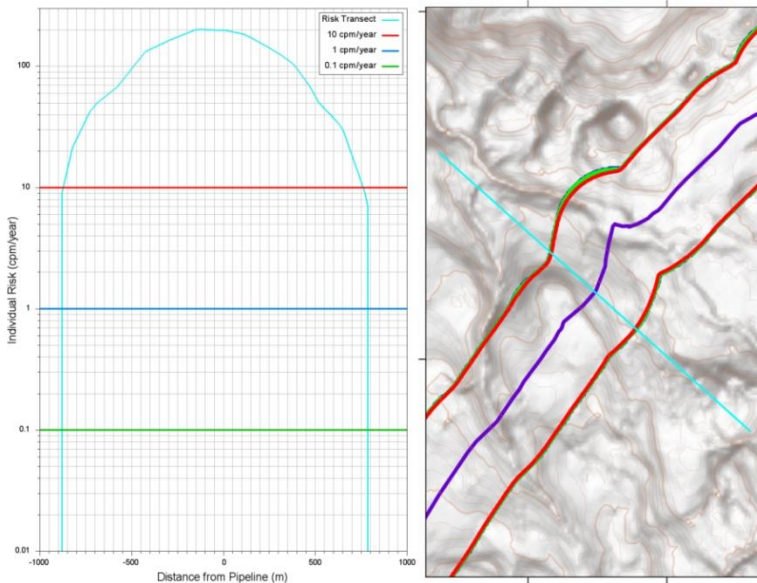
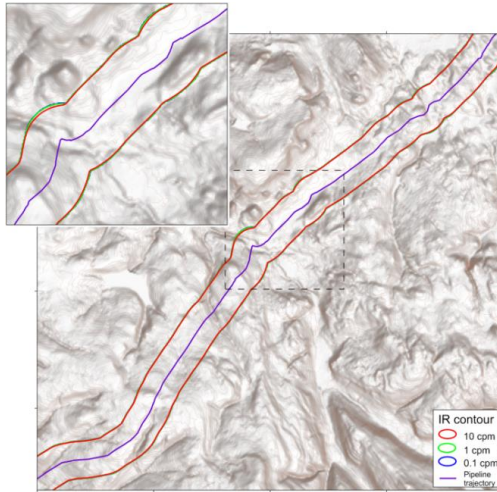
CO₂PipeHaz: WP3.6 Test case using integral model



- Population
 - National Population Database
 - Residential layers (Night time and Daytime), workplaces
 - Schools, Hospitals, Roads (average, peak flow)
- Scenarios & failure rates from integral models report
- 30km Pipeline route
- Weather data

CO₂PipeHaz: WP3.6 Test case using integral model

- IR contours
- Risk transects
- Multiple risk transects



CO2PipeHaz: Summary of outputs

- **WP1**: “An integrated, multi-scale modelling approach for the simulation of dispersion from accidental CO₂ **pipeline releases in realistic terrain**”, Woolley et al., in preparation for IJGGC
- **WP1**: Far-field dispersion **model validation** paper – in progress
- **WP3** “A risk assessment methodology for high pressure CO₂ pipelines using **integral consequence modelling**”, McGillivray, Saw, Lisbona, Wardman and Bilio, Submitted to PSEP journal
- **WP3** "Risk assessment methodology for high-pressure CO2 pipelines **incorporating topography**", Lisbona, McGillivray, Saw, Gant, Bilio and Wardman, Submitted to PSEP Journal
- Other project outputs: <http://www.co2pipehaz.eu>

Scientific Work at HSL from 2005-2015

Several large EU, UK Government and industry-funded projects:

- CO2PipeHaz
 - <http://co2pipehaz.eu/>
- MATTRAN
 - <https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/G061955/1>
- COOLTRANS
 - Cosham *et al.* (2016) “Analysis of a dense phase carbon dioxide full-scale fracture propagation test in 24 inch diameter pipeline” <http://dx.doi.org/10.1115/IPC2016-64456>
 - Cooper R. and Barnett J. (2014) “Pipelines for transporting CO₂ in the UK” <https://doi.org/10.1016/j.egypro.2014.11.264>
- COSHER
 - Ahmad *et al.* (2015) “COSHER joint industry project: Large scale pipeline rupture tests to study CO₂ release and dispersion” <https://doi.org/10.1016/j.ijggc.2015.04.001>
- CO2PIPETRANS
 - <https://www.dnvgl.com/oilgas/joint-industry-projects/ongoing-jips/co2pipetrans.html>

Scientific Work at HSL from 2005-2015



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Related content

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- Remaining issues

Status of Initial Safety Concerns

- Dispersion modelling of (liquid/solid + gas) CO₂ jet releases: how does it behave? Can we predict extent of hazardous zones?
 - Two-phase CO₂ jets can be predicted well
 - Experimental data for concentration and temperatures
 - CO₂ pipeline crater source model published by DNVGL
 - Industrial dispersion models like Phast have been validated
 - Pipeline release-rate models: some uncertainties with initial expansion of liquid phase and limited data available?
- Implications of severe Joule Thomson cooling (embrittlement?)
 - Needs to be taken into account for blowdown
 - Requires appropriate choice of materials

Status of Initial Safety Concerns

- Solid CO₂ implications for blowdown (blocking valves?)
 - Needs to be taken into account in vent design
 - Vent from lower liquid space, not vapour space to prevent dry ice forming in vessel
- Solid CO₂ particles scouring and erosion (jet cleaning and cutting)
 - BP tests did not show significant issues (available in CO2PipeTrans)
- Solid CO₂ deposition as dry-ice bank (prolonged sublimation)
 - Shell tests showed you needed confinement and/or long release durations to produce significant amounts of dry ice

Status of Initial Safety Concerns

- Running ductile crack propagation along CO₂ pipelines
 - COOLTRANS and CATO2 experiments showed that standard Battelle two-curve method is unreliable and non-conservative in selecting appropriate pipeline toughness
 - White-Rose National Grid pipeline design based on full-scale pipeline rupture tests in COOLTRANS
 - Only an issue for dense-phase CO₂ pipelines (i.e. with operating pressure in excess of 100 bar)

Status of Initial Safety Concerns

- Equation of state for CO₂ + impurities for flow assurance modelling
 - Need to make allowances in operational envelope for effect of impurities in bubble point and dew point
 - Consider changes in elevation and changes in temperature following compression
 - Consider process upsets/shutdown and potential for impurities to come out of solution (hydrogen embrittlement)
 - Mainly an issue for dense-phase CO₂ pipeline design
 - Max pressure for gas-phase CO₂ pipelines around 34 barg
 - See <https://www.icheme.org/membership/communities/special-interest-groups/clean-energy/event-archive/>

Status of Initial Safety Concerns

- Corrosion issues
 - Largely an issue of controlling water content (drying to < 50 ppm)
 - Polymeric protective coatings not recommended for dense-phase pipelines (see DNVGL guidance)
 - Important to consider what to do in case of process upset (e.g. CO₂ composition outside specification)

Overview

- Initial safety concerns with CCS
- Anecdotal information from incidents
- Research at HSL in period from 2005-2015
- Status of initial safety concerns
- Recent and ongoing work
- Remaining issues

Recent and Ongoing Work

- Role of Local Transmission Systems (LTS) in the Decarbonisation Pathway
 - Commercial work undertaken for SGN by HSE Science Division (Adam Bannister, Zoe Chaplin, Simon Gant, Catherine Spriggs)
 - 280-page long report on issues to consider when repurposing LTS for hydrogen or CO₂ transport
 - Literature review
 - Risk assessment
 - Materials-related issues for pipeline design

Repurposing the LTS – Gap Analysis

Key areas of interest for LTS

- Crack arrest in gas phase
- CO2 pipelines not studied

Key areas

- Gas phase up to 35 bar
- Dense phase above 75 bar (subject to contaminants)
- MOP for LTS for CO₂ 35bar

Materials Issues

- Corrosion
- Fracture propagation

Repurpose for CO₂

Repurpose for H₂

Materials issues

- Embrittlement
- Increased in fatigue crack growth rate

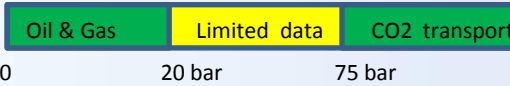
Key areas

- Road crossings, ground movement, pressure cycling
- Concerns over catastrophic failure

Key areas of interest for LTS

- Need to understand tolerable level of material property degradation

Materials Literature CO₂ – test data



Materials literature review - CO₂

Extensive literature available on corrosion, key issues

1. Level of NO_x, SO_x, H₂O have huge effect on corrosion
2. Limited data on corrosion performance 20- 50 bar
3. Gas phase at higher pressures = more condensation = more corrosion

Conclusions

CO₂ – need dry gas (could be expensive)

Hydrogen – need to undertake Fitness for Service Assessment (BS7910)

- Good quality pipeline data needed on pipeline toughness
- Compare critical flaw size and predicted fatigue life compared with NG service

Materials literature review – hydrogen

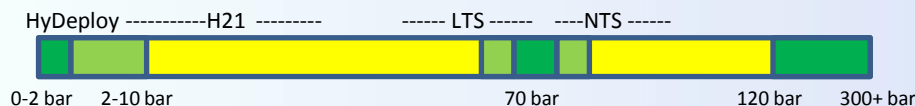
Extensive historical testing conducted on steels

1. Fatigue crack growth rate ↑
2. Fracture toughness ↓ independent of % h₂?
1. Elongation ↓
2. Yield Strength ◊
3. Ultimate Tensile Strength ◊
4. Charpy & Drop Weight Tear Tests (pipeline cert tests – need revisiting)

+ Possible benefit of trace elements O₂ and CO

- Inhibit hydrogen uptake at crack tip due to local oxidation
- Limited but consistent data available
- Needs further data if used to inform basis of safety

Materials literature review hydrogen – test data



Risk Calculations

1. Validation to proposed pressure
2. Assess population along route
3. Failure rate calculations (need to be modified for H₂ and CO₂)
4. Assess ignition probability (needs to be modified for H₂)
5. Apply substance factors (needs to be modified for CO₂)
6. Assess Event Tree (needs to be revisited for CO₂ acknowledging that CO₂ is denser than air)
7. Understand topographical effects for CO₂

Important but out of scope

1. Ability to detect critical flaw size / inspection intervals
2. Operation of components
3. Hazardous areas
4. Procedures
5. Training & competence
6. Flow rates etc.

Recent and Ongoing Work

- Energy Institute
 - Workshops on 7 October 2019 and 27 January 2020
 - Several proposed future projects:
 - Flow assurance and modelling - Develop equation of state (EOS) for CCS fluids (CCS2001)
 - Pipeline design and operation- Repurposing of pipelines and new pipelines design to transport CO₂ (CCS2002)
 - Pipeline design and operation- Running ductile failure and fracture propagation (CCS2003)
 - Failure of subsea CO₂ pipeline (CCS2004)
 - Revision of Energy Institute Guidelines on Carbon Capture and Storage (CCS2005)

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Remaining Issues

- Pipeline design
 - Develop model for running ductile crack propagation along CO₂ pipelines to help specify material toughness and/or crack arresters?
 - Understanding corrosion regimes in non-dry CO₂ streams from different sources?
- Pipeline risk assessment
 - Pipeline failure rates: need for modifications to fracture mechanics model?
 - Toxic risk methodology: sublimating solids need to be taken into account for dense-phase pipelines?
 - Modelling terrain effects on dispersion?

Remaining Issues

- Ship transport?
 - Poor understanding of CO₂ releases onto water, no experimental data available
- What lessons have been learnt from recent experience?
 - Lessons learnt from CO₂ incidents
 - Operational experience, e.g. Boundary Dam, Sleipner
- Current status of industrial/academic research on CCUS safety?
 - HSE has not been engaged with CCUS community since 2015, but some research has been ongoing



Thank you

Sincere thanks to Shell, National Grid, DNVGL, INERIS and the Energy Institute for permission to use images, and thanks to Adam Bannister, Mike Wardman and Catherine Spriggs (HSE) for useful contributions to these slides.

The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.