School of Chemical and Process Engineering
FACULTY OF ENGINEERING
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High pressure CO_2 pipelines: 1. CFD simulation of the consequences of puncture and rupture *on land*

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Overview

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Carbon capture and storage, the short term option for reducing CO_2 emissions, is likely to proceed with transportation from source to storage along high-pressure dense phase pipelines

- COOLTRANS Research Programme – already covered.
  - **Pragmatic quantified risk assessment (QRA) models**
  - **Robust source conditions for use in far-field CFD studies**
- Near-field sonic dispersion of carbon dioxide (CO_2) from high pressure pipelines
  - Thermodynamic model and numerical method
  - Venting releases, with validation
  - Puncture releases, with validation
  - Rupture releases, with validation

Complex equation of state

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(*Wareing et al. 2013, AIChE Journal* ***59*** *3928-3942)*

- Thermodynamic model:
  - Near-field dispersion of CO_2 in the gas, liquid and solid phases into dry air.
  - Novel **composite equation of state** for pure CO_2 employing:-
    - the Peng-Robinson equation of state in the **gas phase**;
    - tabulated data derived from the Span & Wagner equation of state for the **liquid phase** and vapour pressure;
    - and NIST/DIPPR data for **the solid phase and latent heat of fusion**.
  - Calculations were undertaken using the Helmholtz free energy in terms of temperature and molar volume, as all other thermodynamic properties can be readily obtained from it.
  - Homogeneous equilibrium model, but a simple sub-model for relaxation to equilibrium is required for the solid phase, as it would appear that the particles are not sufficiently small enough to be in equilibrium.

Near-field dispersion method

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- Method for computational fluid dynamics:-
  - Based on a code first used in astrophysics, now widespread application.
  - Adaptive, finite-volume grid algorithm with 2D or 3D rectangular mesh.
  - Grid adaption achieved successive overlaying of refined layers of computational mesh.
  - Where steep gradients of variable exist, such as at the **Mach shock** in this case, the mesh is more refined. This technique enables the generation of fine grids in regions of high spatial and temporal variation. Conversely, coarser grids are allowed where the flow field is smooth.
  - **Turbulence model**: we employ a standard k-ε model, but since performance is poor for prediction of compressible flows, we include a compressibility correction.
  - Solutions obtained for the time-dependent, density-weighted equations.
  - Efficient, general-purpose shock-capturing, upwind, second-order-accurate Godunov numerical scheme with a HLL Riemann solver.

Near-field dispersion method

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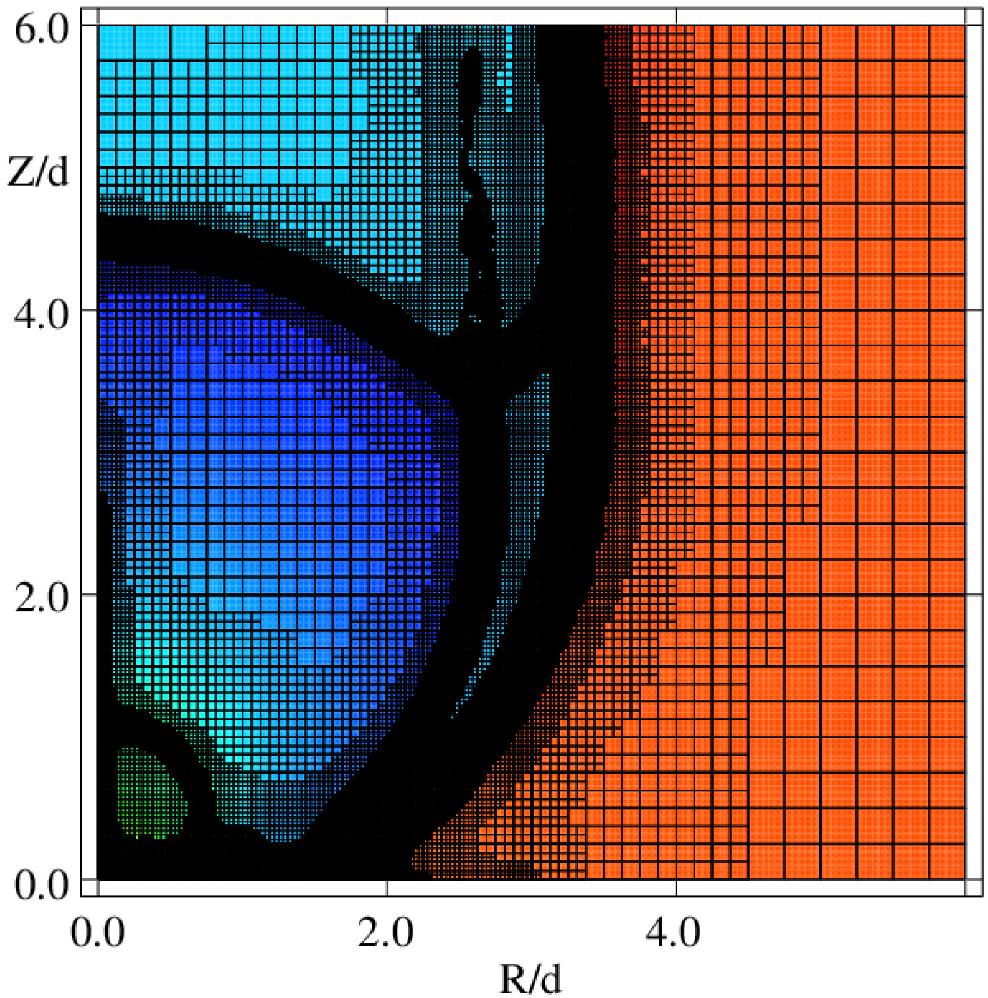
- Numerical method (continued):



- **Very expensive computations**

•**Adaptive meshing** around the Mach shock in a dense high pressure release of CO_2.

Still require hundreds of CPU hours on hundreds of processors

Total: 128x150hrs: **20,000 CPUhrs per case.**

Note the axis units are in release diameters.

Venting: case 1 – liquid phase

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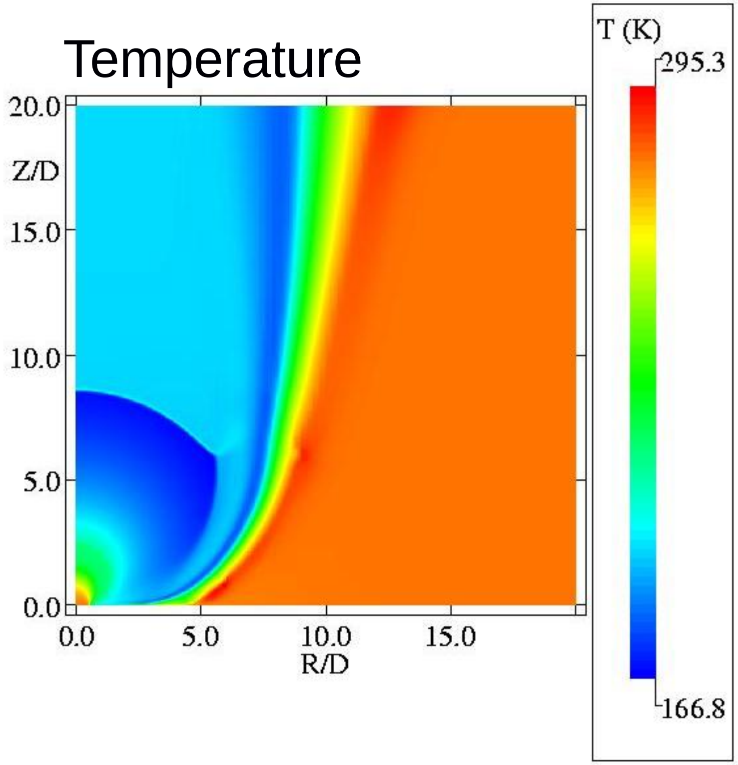
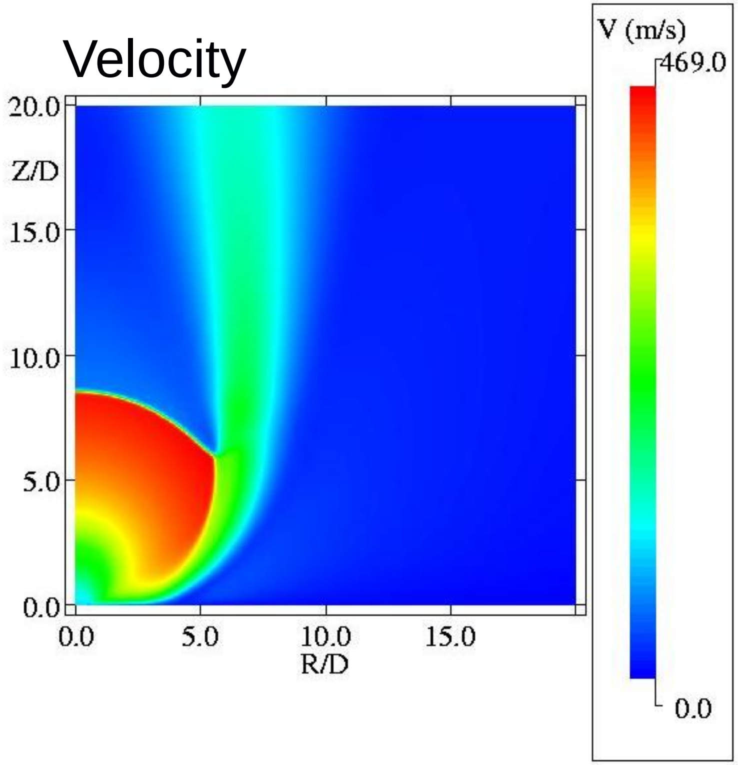
- Dense phase release from a 150bar reservoir through 25mm (D) vent pipe.
- Steady state release conditions achieved by supplying a driving pressure





Near-field shock containing region: 20D x 20D (0.5m x 0.5m)

Wareing et al., Int. J. Greenhouse Gas Control, ***20****, 254-271 (2014)*

Venting: case 1 – liquid phase

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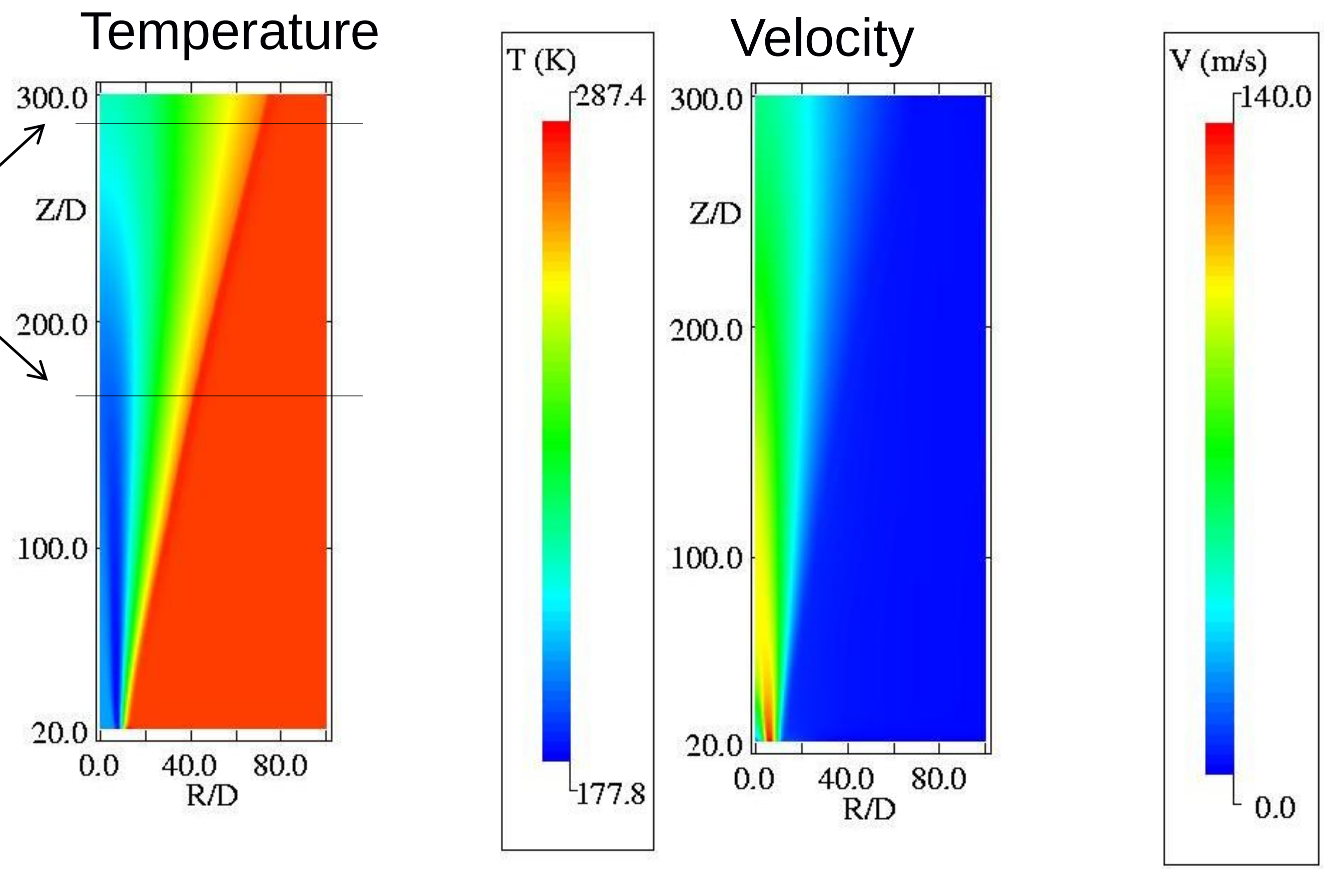
Measuring planes at:

- 4m (165D)
- 7m (288D)



Far-field region up to 300D (7.5m) from the release

*Wareing et al., Int. J. Greenhouse Gas Control, **20**, 254-271 (2014)*

Venting: case 1 - validation

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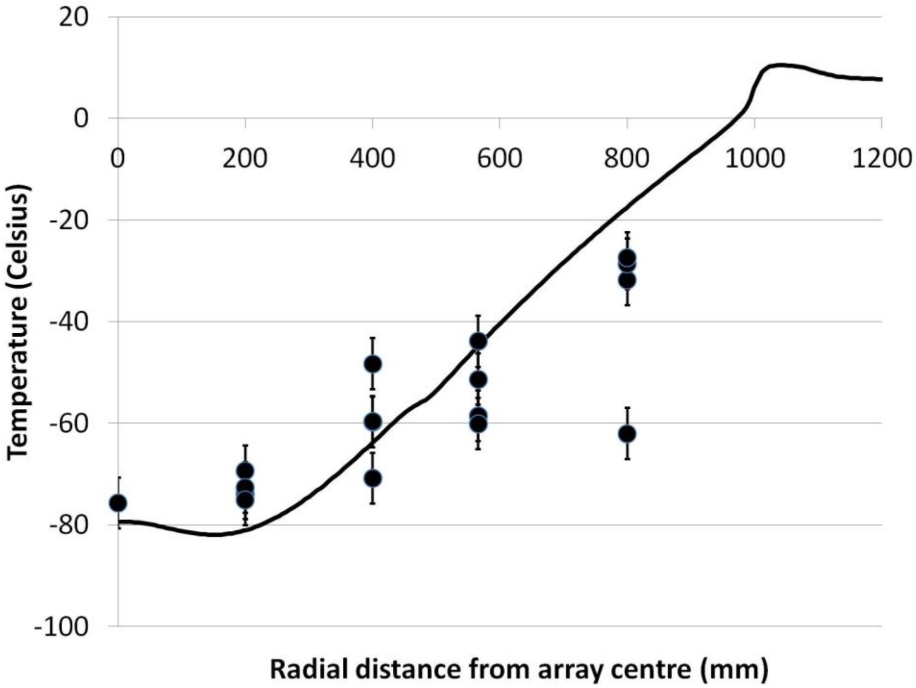
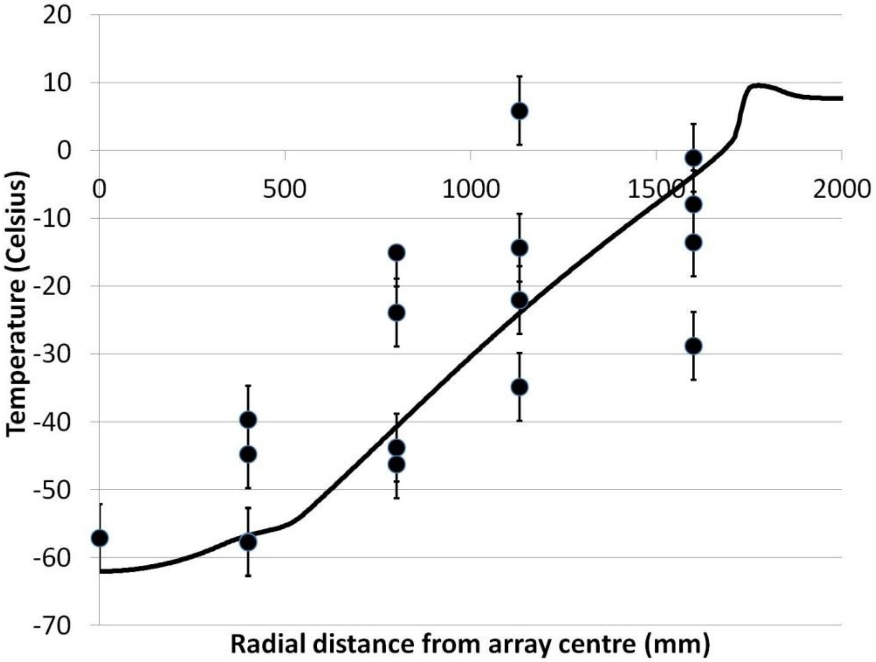
(a) 4m above the vent



(b) 7m above the vent



- **Core temperature prediction in good agreement** with data at 4m and 7m.
- **Predicted jet widths also in good agreement with data.**
- A cross-wind of 2.5 m/s has led to some spread in the data at 7m.

Wareing et al., Int. J. Greenhouse Gas Control, ***20****, 254-271 (2014)*

Venting: case 1 – gas phase

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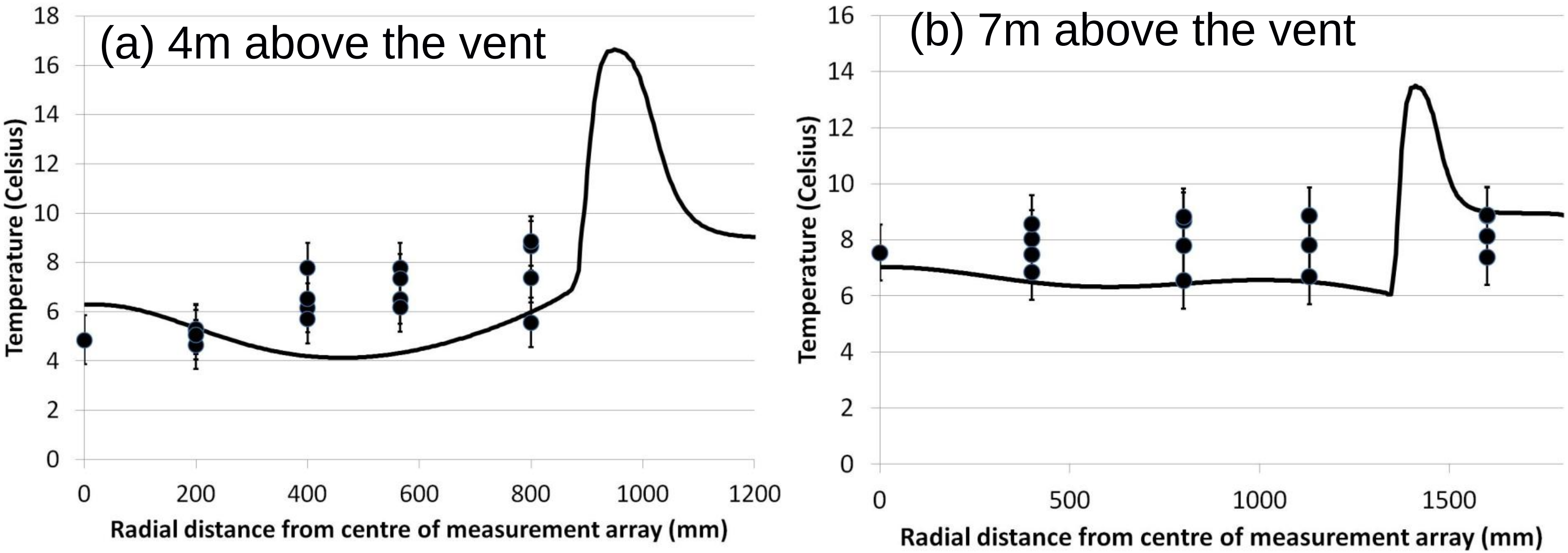
- Gas phase release from a 35bar reservoir through a 25mm vent pipe.
- Steady state release conditions achieved by supplying a driving pressure



Despite the considerably different temperature range observed as compared to the dense phase release, predicted core jet temperatures and widths are again in good agreement with the data on both planes

*Wareing et al., Int. J. Greenhouse Gas Control, **20**, 254-271 (2014)*

Comparison to other datasets

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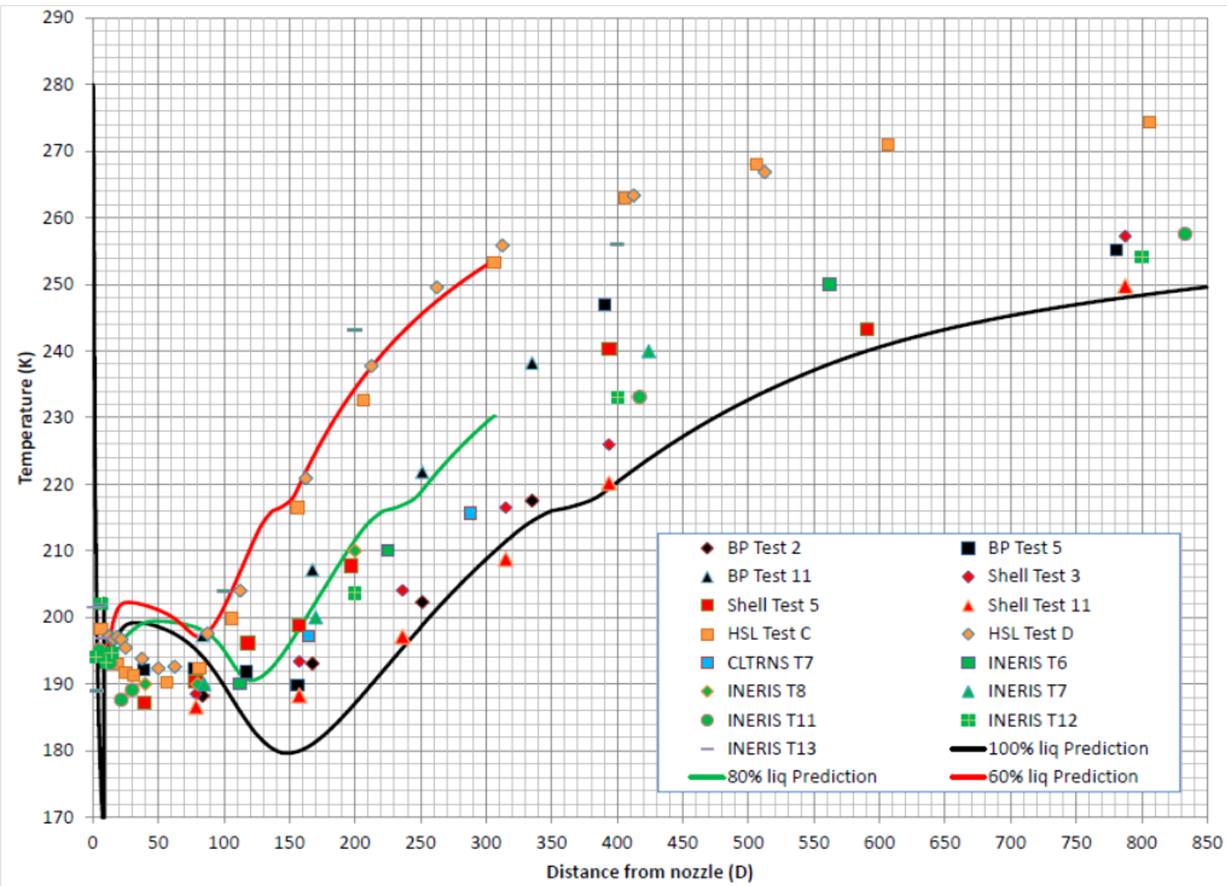
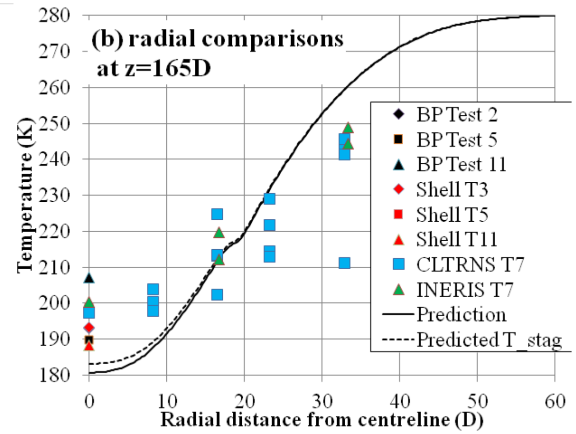
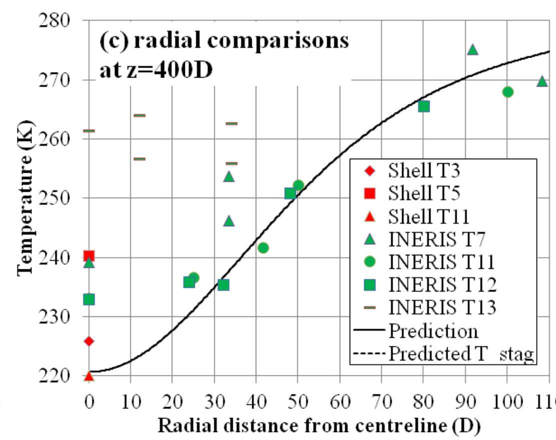
- A comparison between experimental data and numerical prediction along the centreline of the jet and radially at 165D and 400D along the centreline.







- Experimental errors of ±5K throughout; error bars omitted for clarity.

Punctures: 3 cases considered

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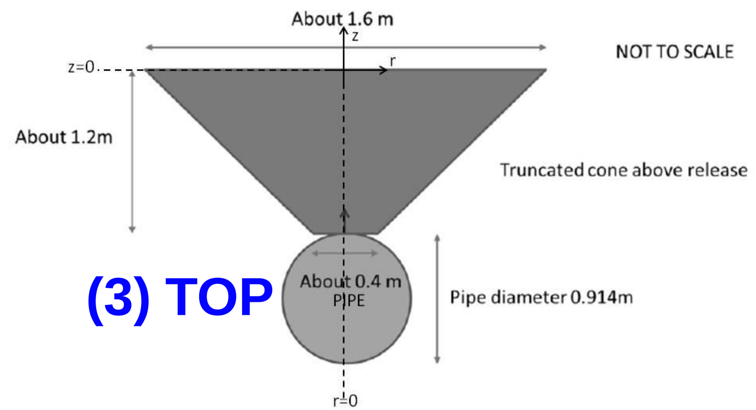
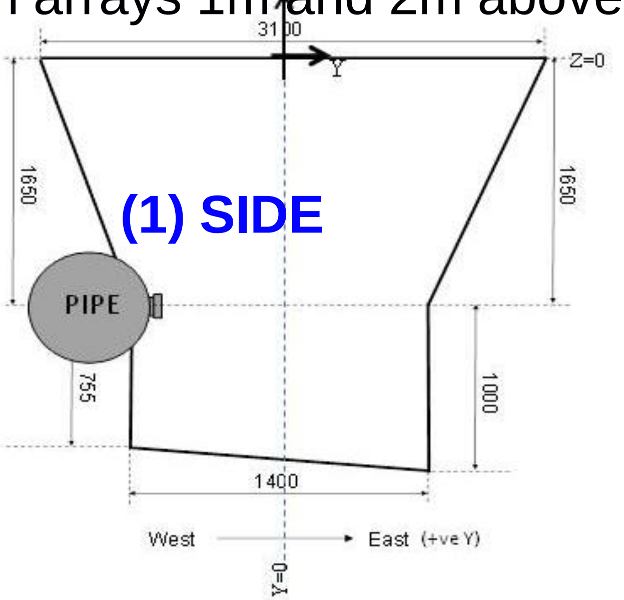
Experimental setup

- **0.9m diameter** pipeline.
- Pipeline **pressurised to 150bar**.
- **25mm** diameter circular **puncture**.
- **Preformed craters** based on observations of real craters.
- Experimental measurements taken on arrays 1m and 2m above ground level for the side puncture only.

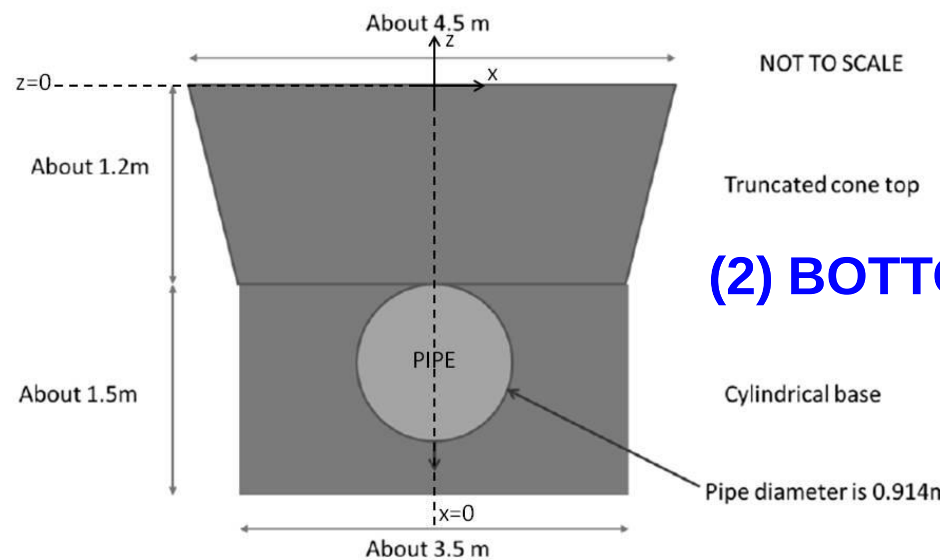
(3) TOP



(1) SIDE



(2) BOTTOM



Wareing et al., Int. J. Greenhouse Gas Control, ***29****, 231-247 (2014)*

Puncture results: Case 1 – side

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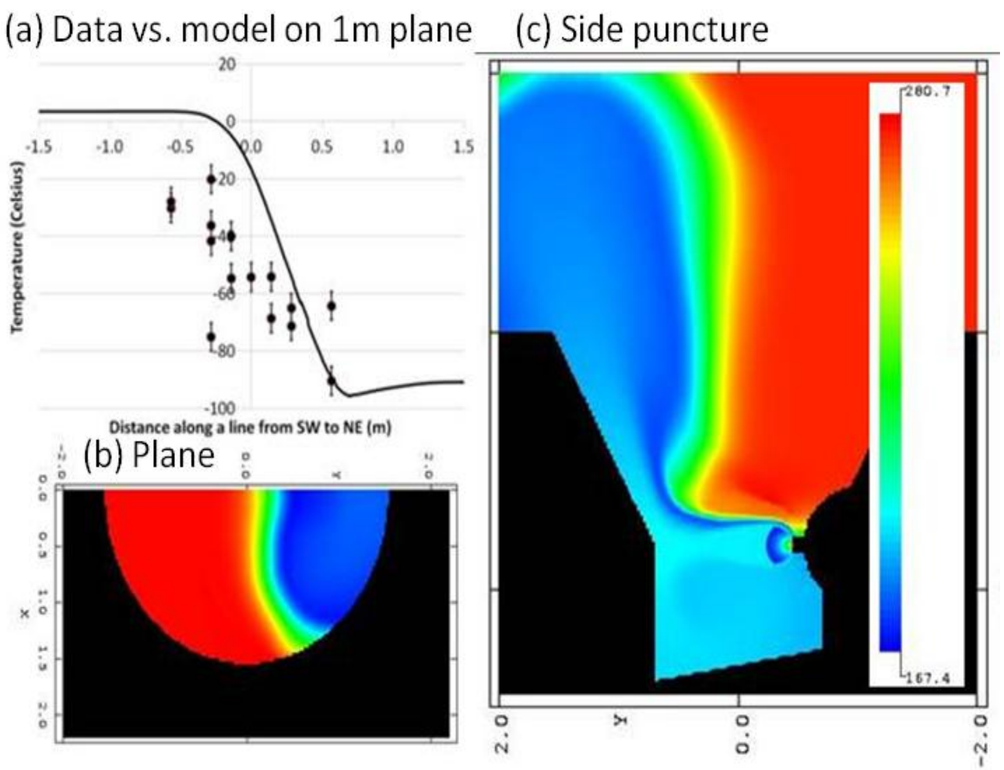

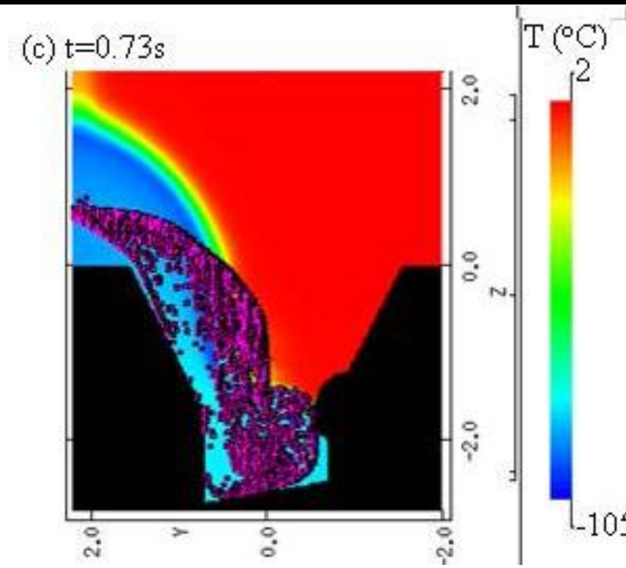

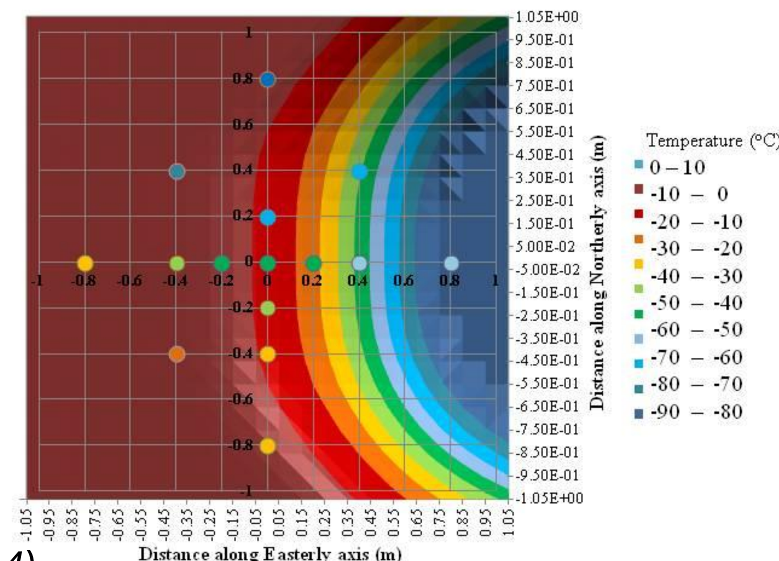

*Wareing et al., Int. J. Greenhouse Gas Control, **29**, 231-247 (2014)*

Cases 2 and 3 – bottom and top

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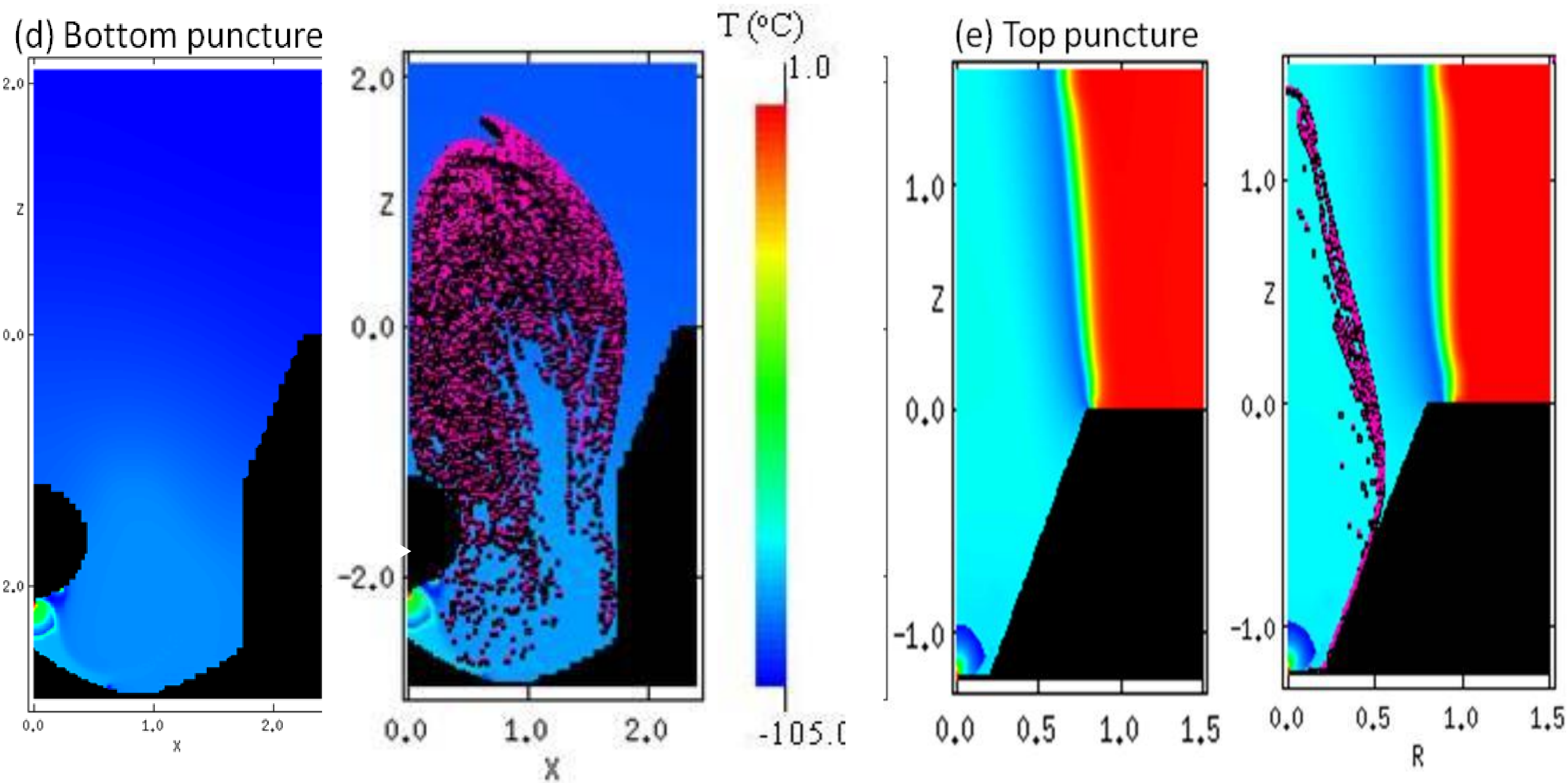

*Wareing et al., Int. J. Greenhouse Gas Control, **29**, 231-247 (2014)*

Ruptures – validation at ¼ scale

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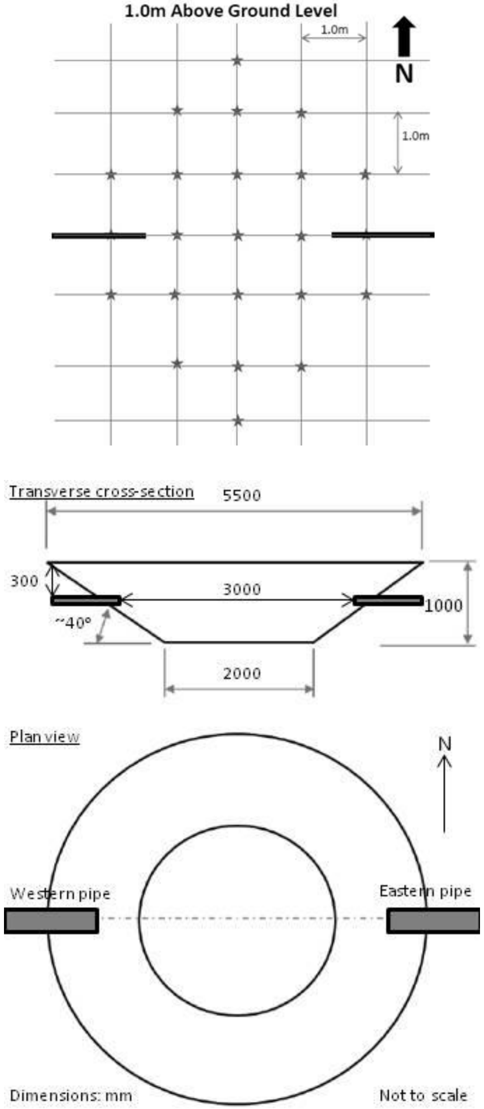
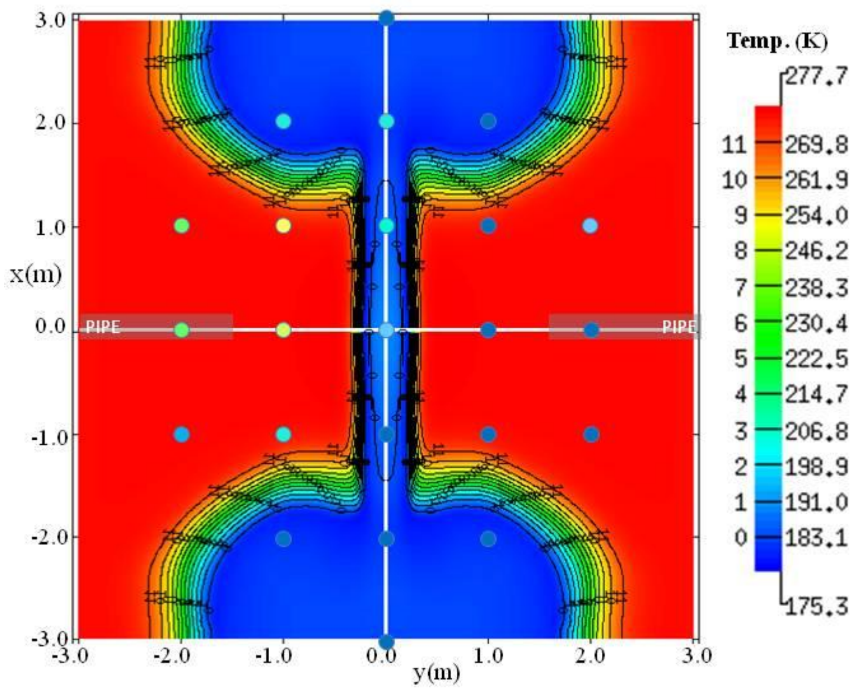
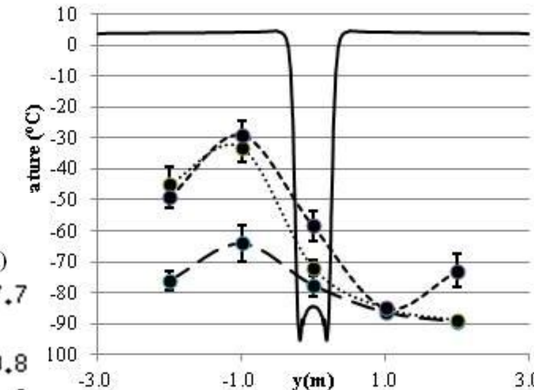


Pipeline diameter D=0.15m

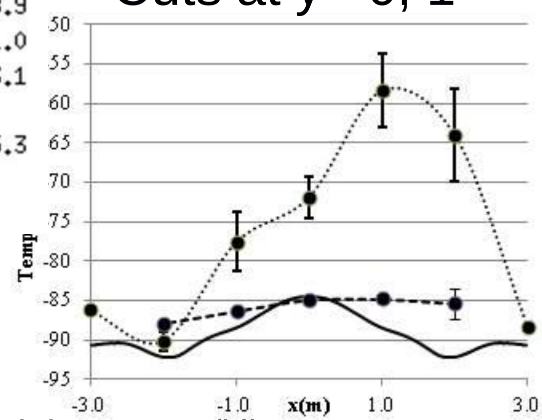
1m above crater





Cuts at x= -1, 0, 1

Cuts at y= 0, 1



Wareing et al., Int. J. Greenhouse Gas Control, doi: 10.1016/j.ijggc.2015.01.020

Rupture of a full-scale buried pipeline

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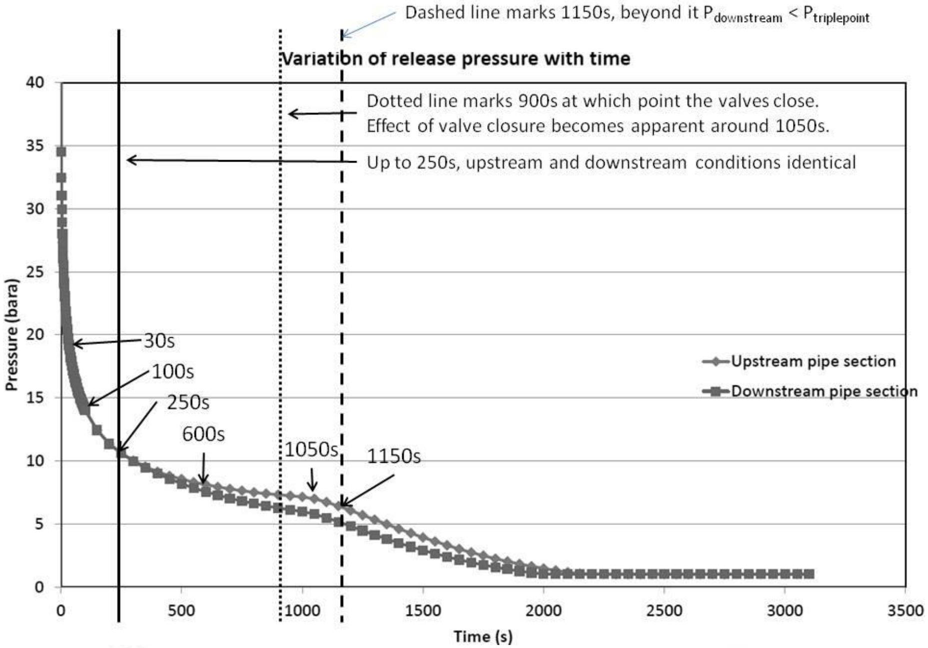
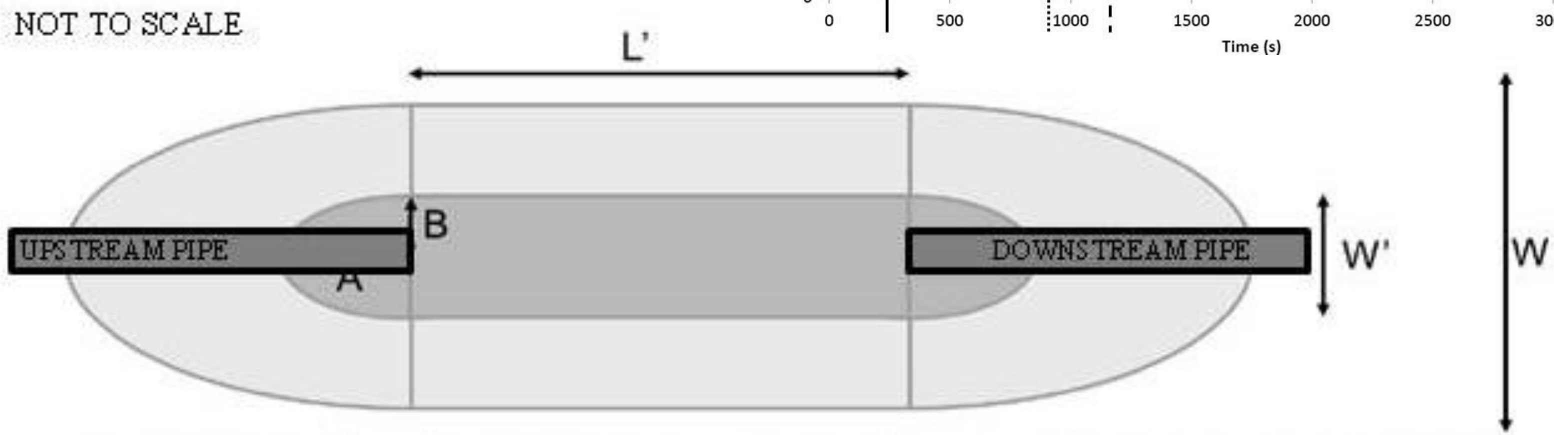
Experimental setup

- **0.6m diameter pipeline**.
- Pipeline pressurised to **150bar**.
- **Preformed craters** based on observations of real craters.
- Experimental measurements on arrays above ground level.





L = crater length, W = crater width, L'=length of flat base, W'=width of flat base,
D = crater depth, θ = wall angle, A = semi-major axis of base ellipse, B = 0.5 W'

Ruptures – full scale results

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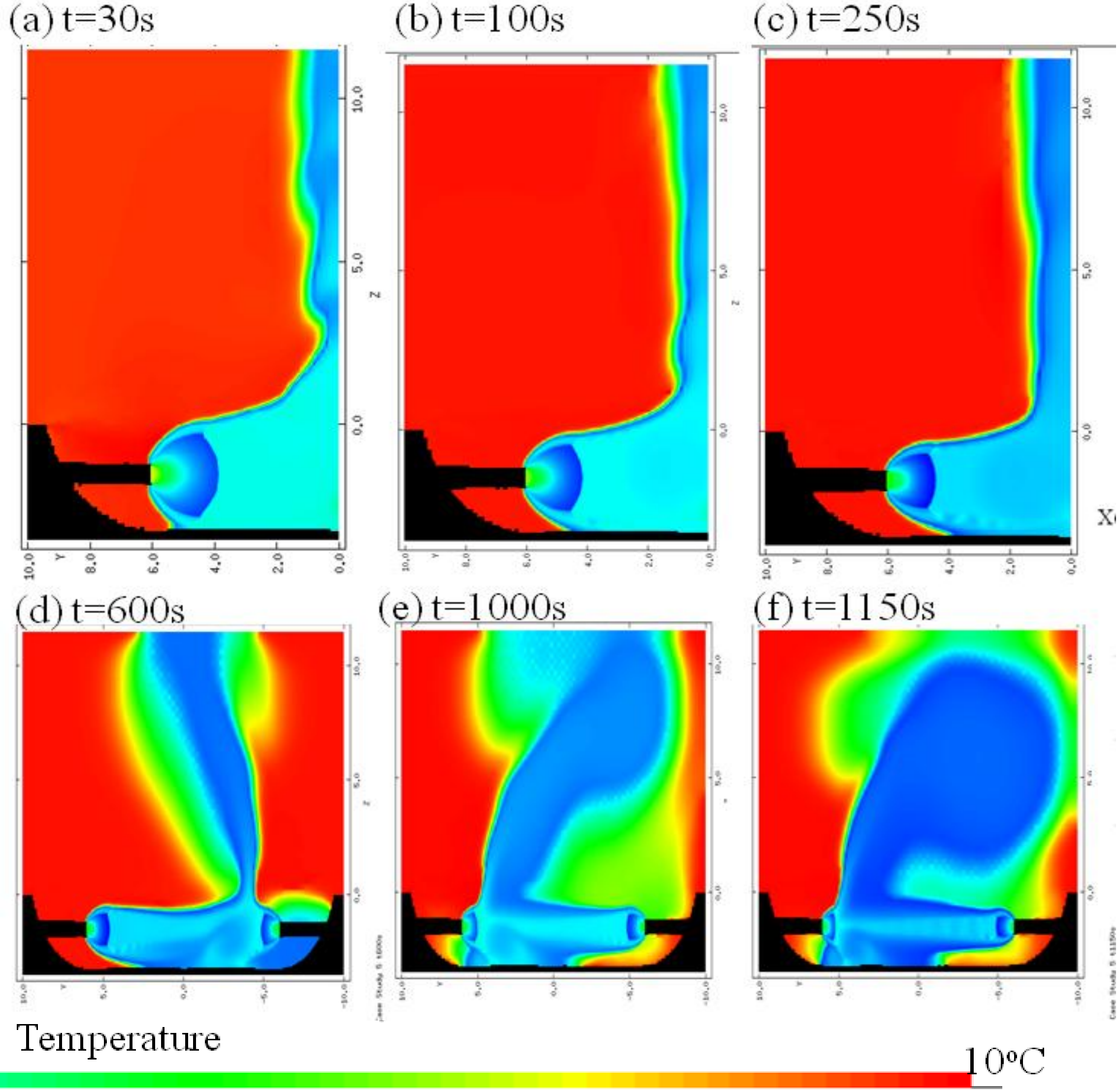
Pipeline diameter, D=0.6 m

COSHER Project (Carbon Dioxide, Safety, Health & Environmental Risk), http://www.cosher.net/en/



Wareing et al., Int. J. Greenhouse Gas Control, doi: 10.1016/j.ijggc.2015.08.020

Ruptures - sensitivity study

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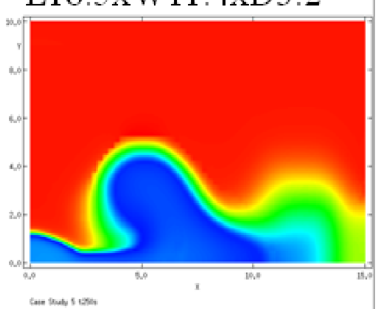
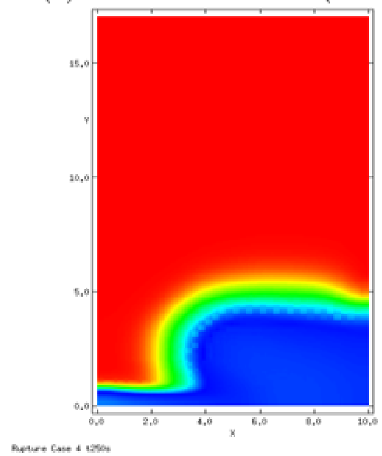
<u>Shape of flow on planes above the crater – top down view</u>

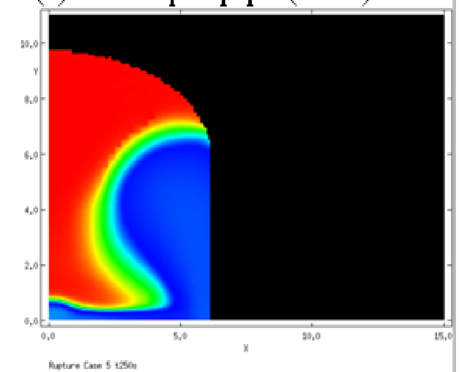
(a) <u>Base Case</u>
12m fracture
1.2m deep pipe
75° wall angle
Aligned pipes
Crater:
L18.5xW11.4xD3.2



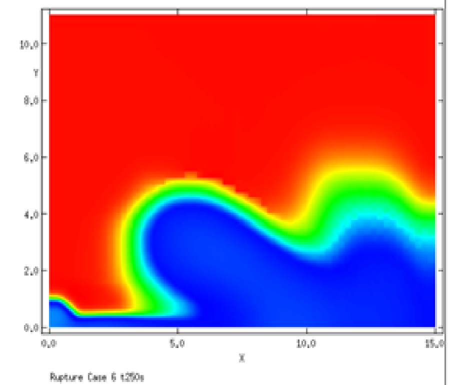
(b)S1- 24m fracture: (L30.5)



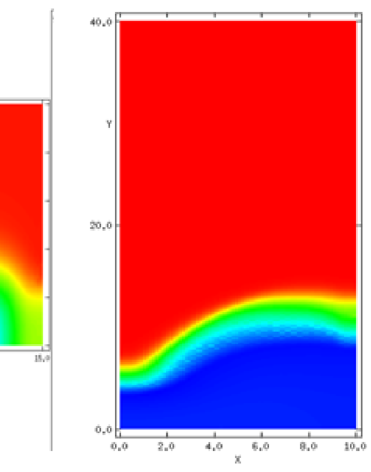
(c)S2- deeper pipe (D4.0)



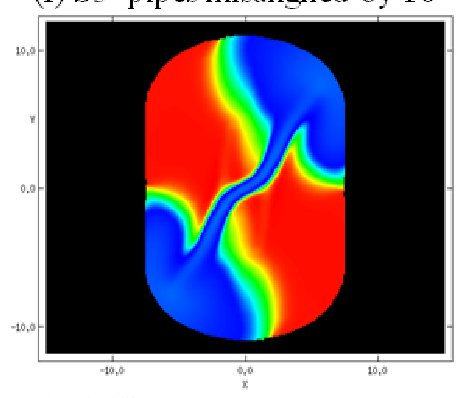
(d)S3- shallower wall (64°)



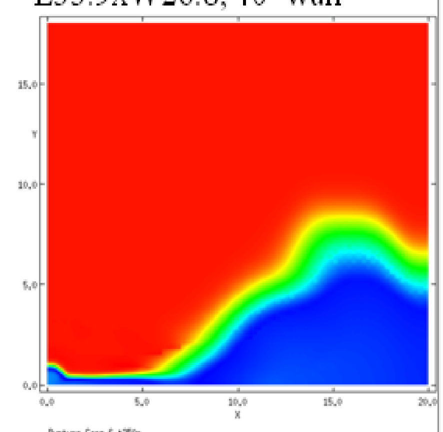
(e)S4- 72m fracture (L78.5)



(f) S5- pipes misaligned by 10°



(g)S6- larger sandy crater
L33.9xW26.8, 40° wall



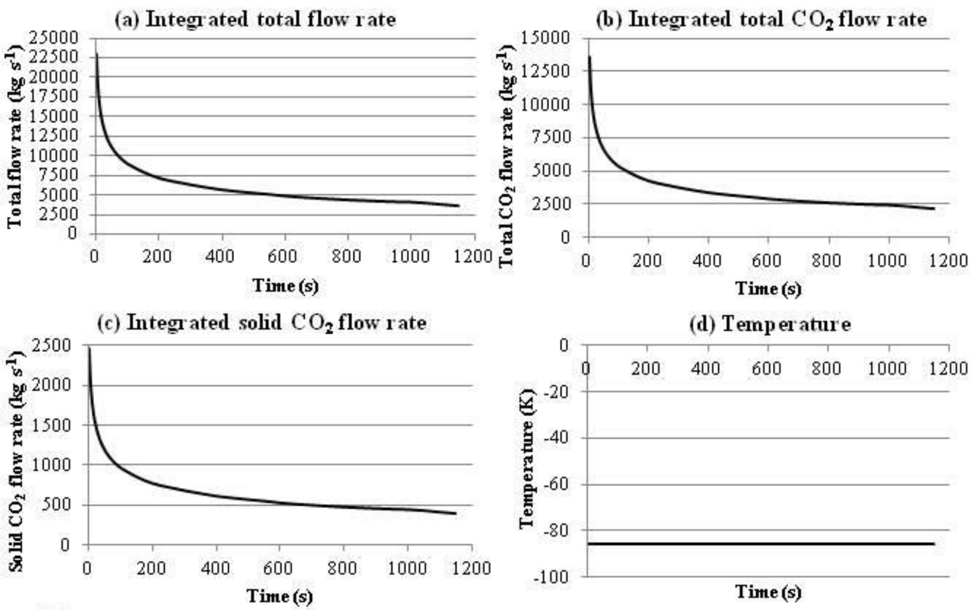
Temperature

12°C

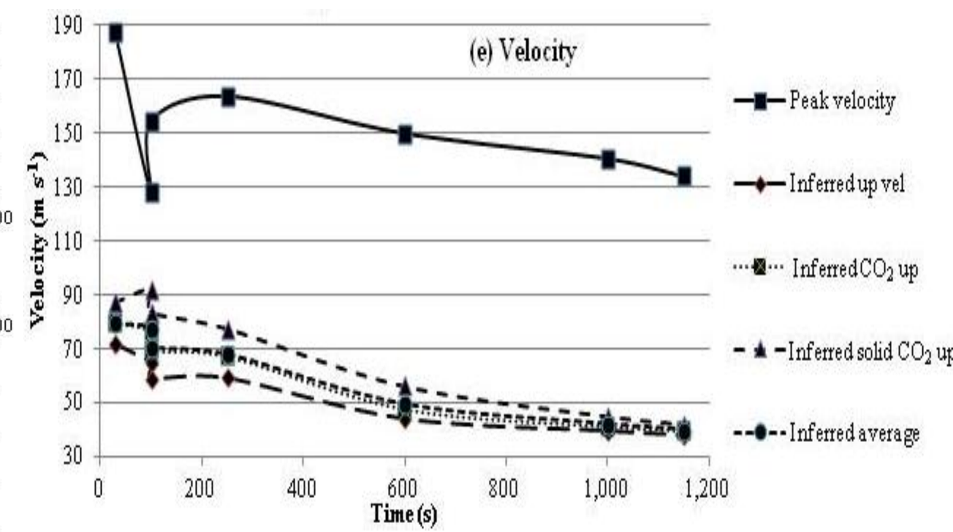
-100°C

Wareing et al., Int. J. Greenhouse Gas Control, doi: 10.1016/j.ijggc.2015.08.020

Ruptures - integrated flow



Base case



Development of an integrated flow model allows far-field models to concentrate on topological and other far-field flow questions, avoiding the need to model the computationally expensive near-field

Ruptures – solid deposition

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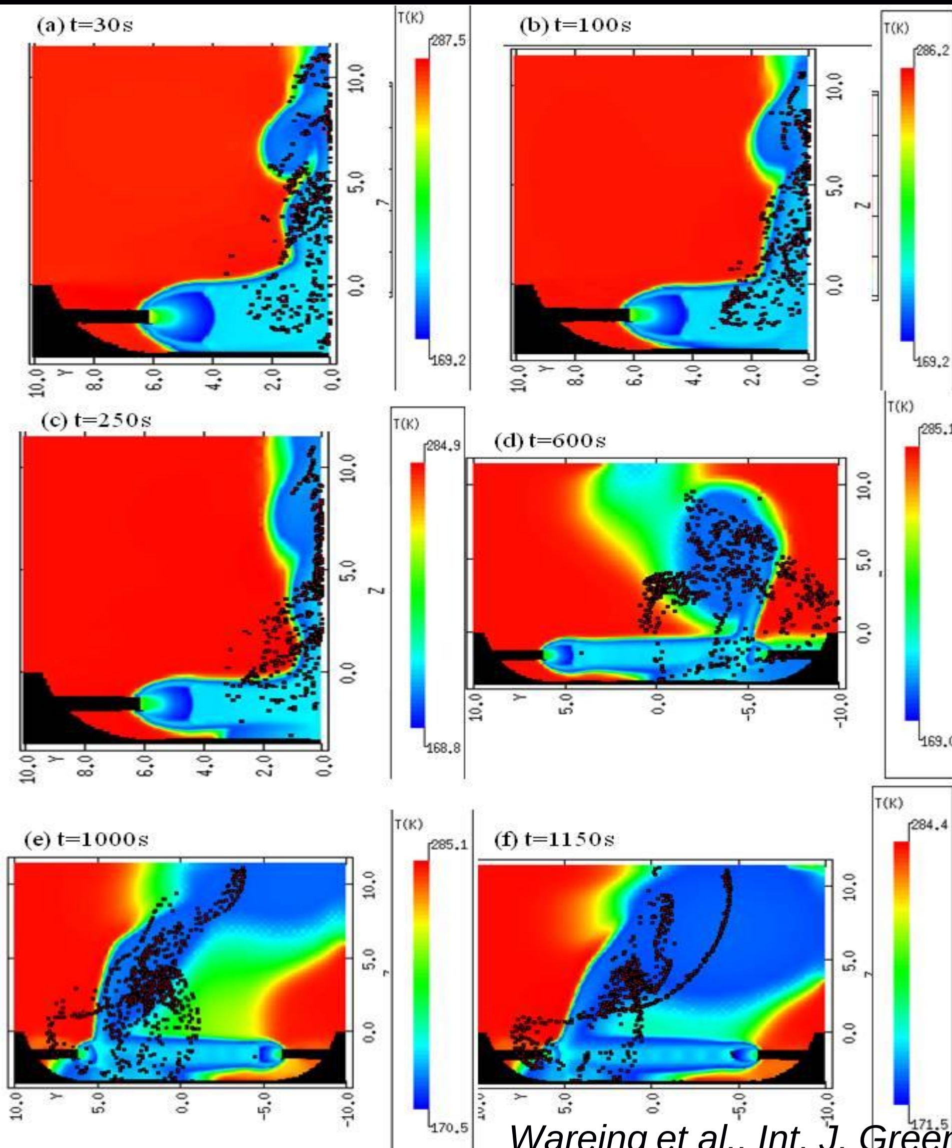

- **Dumping of solid CO_2 occurs**

- Lagrangian particle tracking
- Initial conditions based on measurements of particle behaviour in laboratory-scale experiments (Wareing et al. AIP Conference Proc. **1558** 98 (2013))
- Peak deposition rate of 1%
- Equates to 14,000 kg of solid CO_2 over the first 1150s of a full scale rupture
- Covers the crater base to a depth of 0.4m

Wareing et al., Int. J. Greenhouse Gas Control, doi: 10.1016/j.ijggc.2015.08.020

Conclusions

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- Novel dispersion model covering the **necessary range of pressures (0.01 to 150 bar) and temperatures (-115^{o}C to 35^{o}C)** in accidental releases of CO_2 from high pressure pipelines.
- Venting, puncture and rupture results presented, with accompanying validation for all three scenarios.
- Sensitivity study presented examining the effect of crater variations.

- Future work
  - Impurities in the CO_2 stream and improved thermodynamics.
  - Improved turbulence models.
  - Improved understanding of particle evolution to be applied.

Next: **2. Application to underwater pipelines...**

Thank you for listening

Any questions or comments?

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Thanks to **National Grid Carbon Ltd,** a non-regulated, independent subsidiary of National Grid, created to develop carbon dioxide transportation infrastructure in the UK. National Grid is an international electricity and gas company and one of the largest investor-owned energy companies in the world. National Grid initiated the COOLTRANS research programme as part of the Don Valley CCS Project in order to address knowledge gaps relating to the safe design and operation of onshore pipelines for transporting dense phase CO2 from industrial emitters in the UK to storage sites offshore.

References

Equation of state: Wareing et al., AIChE Journal, **59**, 3928-3942 (2013)
Venting releases: Wareing et al., Int. J. Greenhouse Gas Control, **20**, 254-271 (2014)
Puncture releases: Wareing et al., Int. J. Greenhouse Gas Control, **29**, 231-247 (2014)
¼-scale rupture: Wareing et al., Int. J. Greenhouse Gas Control,doi:10.1016/j.ijggc.2015.01.020
Full-scale rupture: Wareing et al., Int. J. Greenhouse Gas Control,doi:10.1016/j.ijggc.2015.08.020
Particle-laden CO_2 jets: Wareing et al., AIP Conference Proceedings, **1558**, 98 (2013)