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Numerical simulation of CO_2 dispersion from punctures and ruptures of buried high-pressure dense phase pipelines with experimental validation

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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

- The COOLTRANS Research Programme
- Near-field sonic dispersion of carbon dioxide (CO_2) from high pressure pipelines
  - Thermodynamic model
  - Numerical method
  - Venting releases, with validation
  - Puncture releases, with validation
  - Rupture releases, with validation

COOLTRANS Research Programme

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- The electricity and gas global company National Grid's expertise in building and running safe and effective pipeline networks could play a critical role in helping the UK to meet its obligation to cut CO_2 emissions through provision of CO_2 transport services to support deployment of CCS technology.

- National Grid initiated the TRANSport of Liquid CO_2 (COOLTRANS) Research Programme to address knowledge gaps relating to the safe design and operation of onshore high pressure pipelines for transporting liquid CO_2 from industrial emitters to storage sites offshore.
    - **Pragmatic quantified risk assessment (QRA) models**

- As part of this programme, the University of Leeds undertook research into the near-field sonic dispersion of CO_2 from an accidental puncture or rupture of a high-pressure dense phase CO_2 pipeline.
    - **Robust source conditions for use in far-field CFD studies**

Near-field dispersion model

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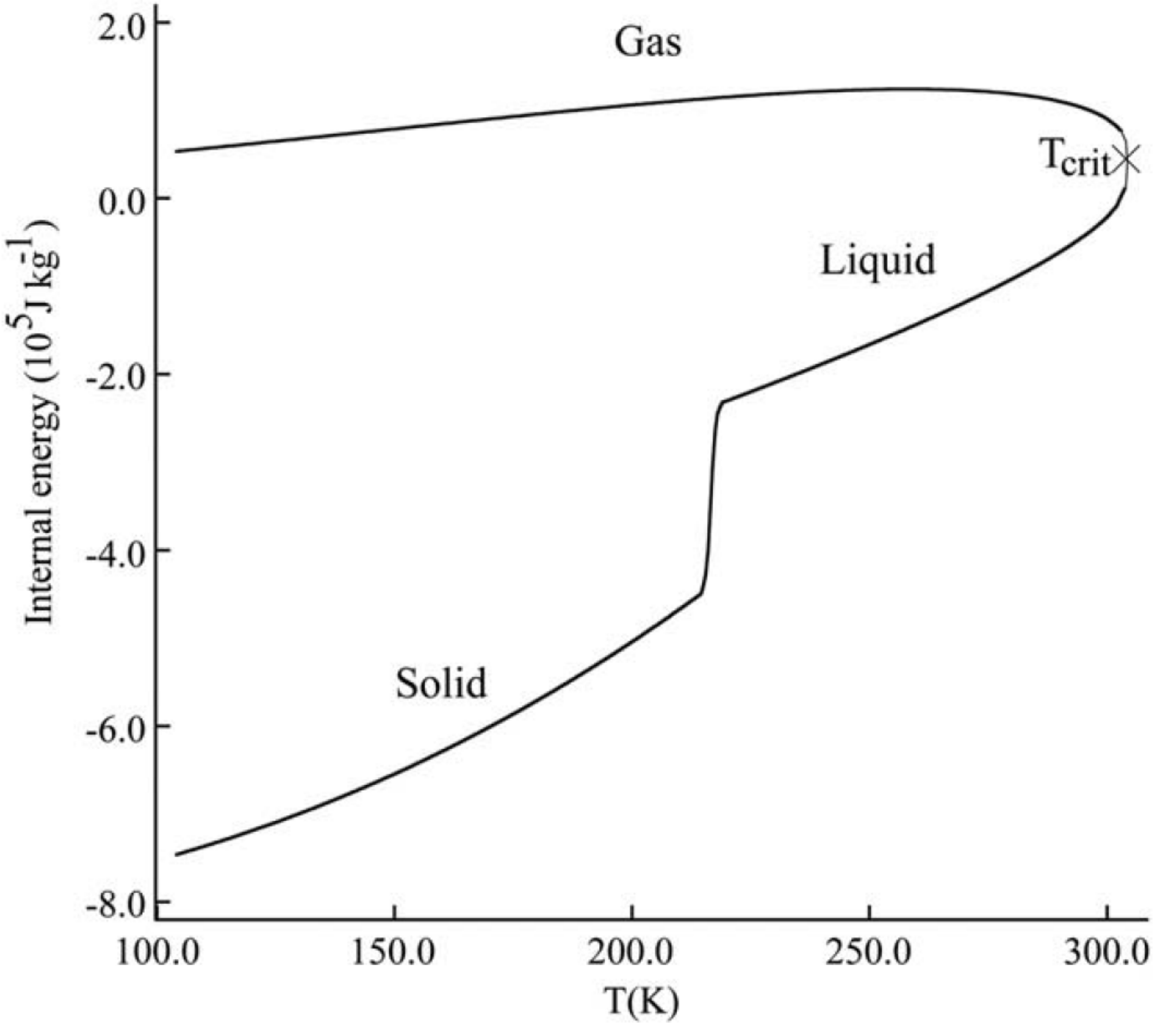
*(Wareing et al. 2013, AIChE Journal **59** 3928-3942)*

- 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 model

- Thermodynamic model (continued):



- Internal energy on the saturation line.
- T_{crit} marks the critical temperature.
- The triple point can be identified by the steep connection between the liquid and solid phases – the latent heat of fusion.

Near-field dispersion model

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- Numerical method:
  - 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 model

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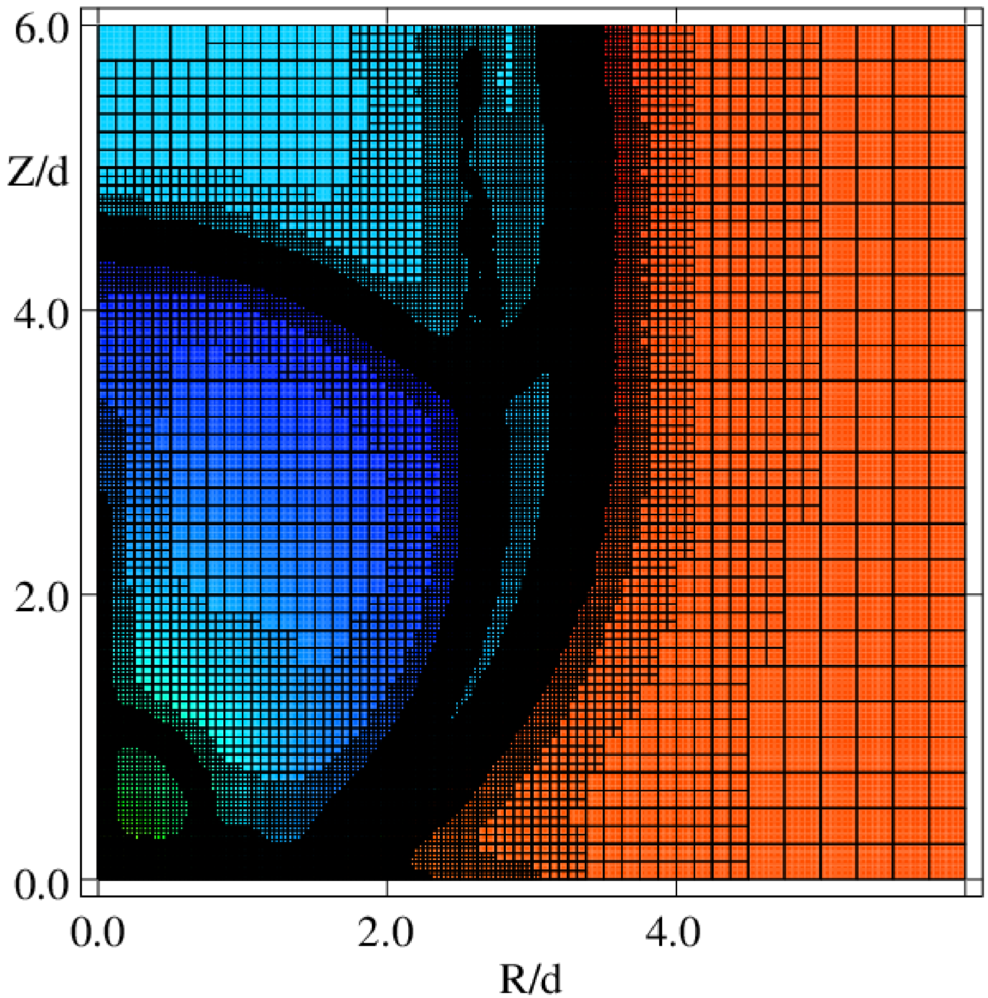
- Numerical method (continued):



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

Note the axis units are in release diameters.

Venting: dense phase release

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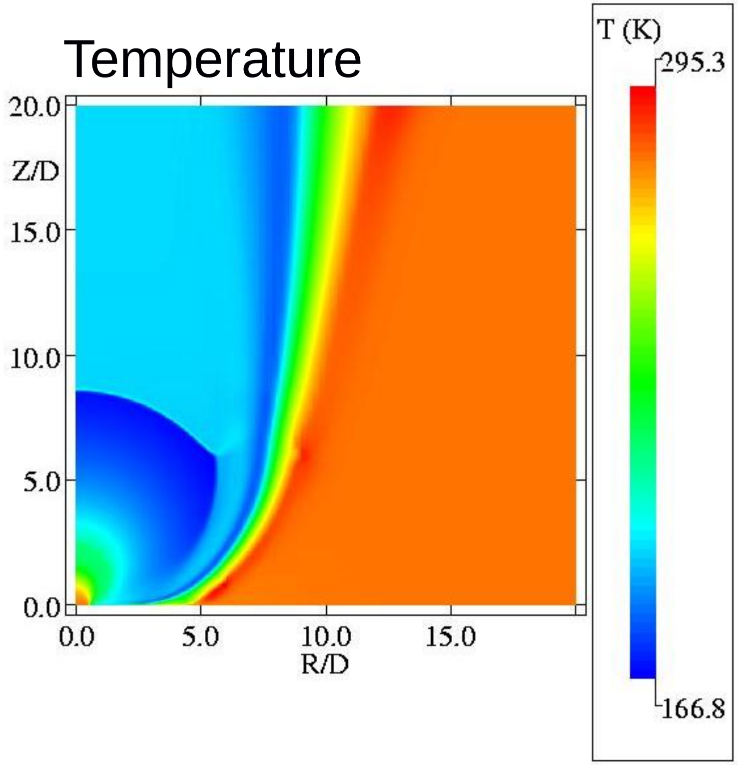
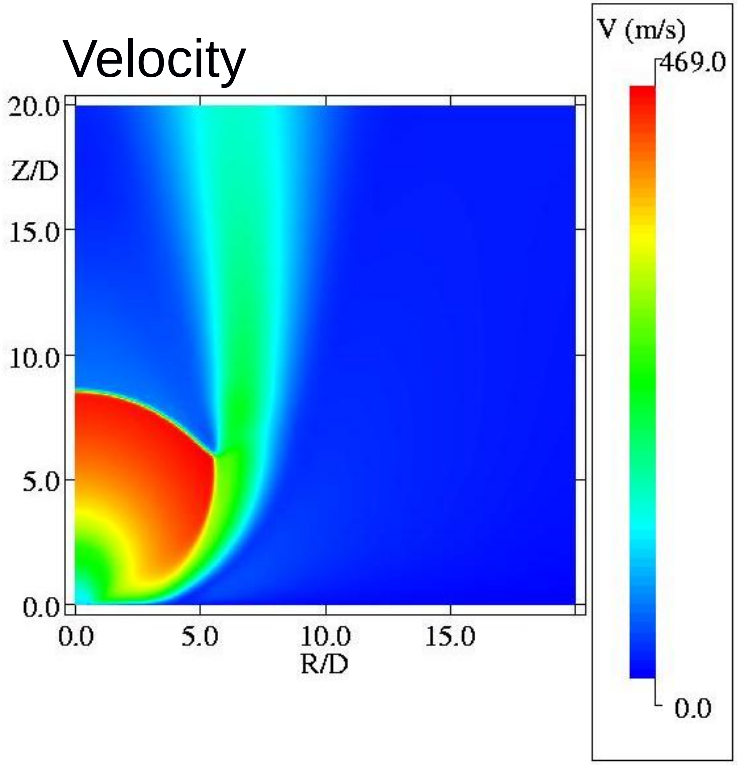
- Dense phase release from a 150bar reservoir through 25mm (D) vent pipe.
- Steady state release conditions achieved by supplying a driving pressure

Temperature



Velocity



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: dense phase release

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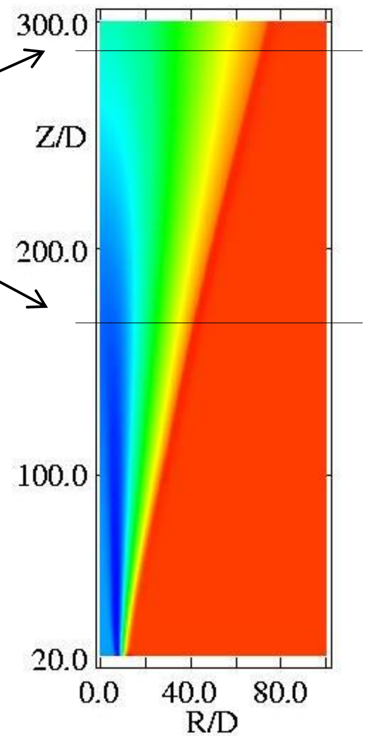
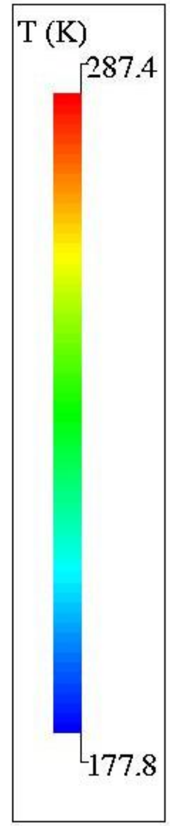
Measuring planes at:

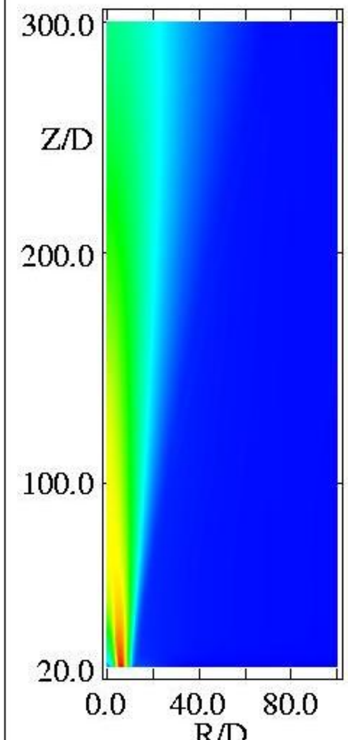
- 4m (165D)
- 7m (288D)

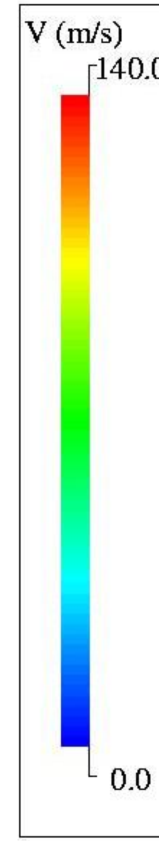
Temperature





Velocity





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

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

Venting: dense phase validation

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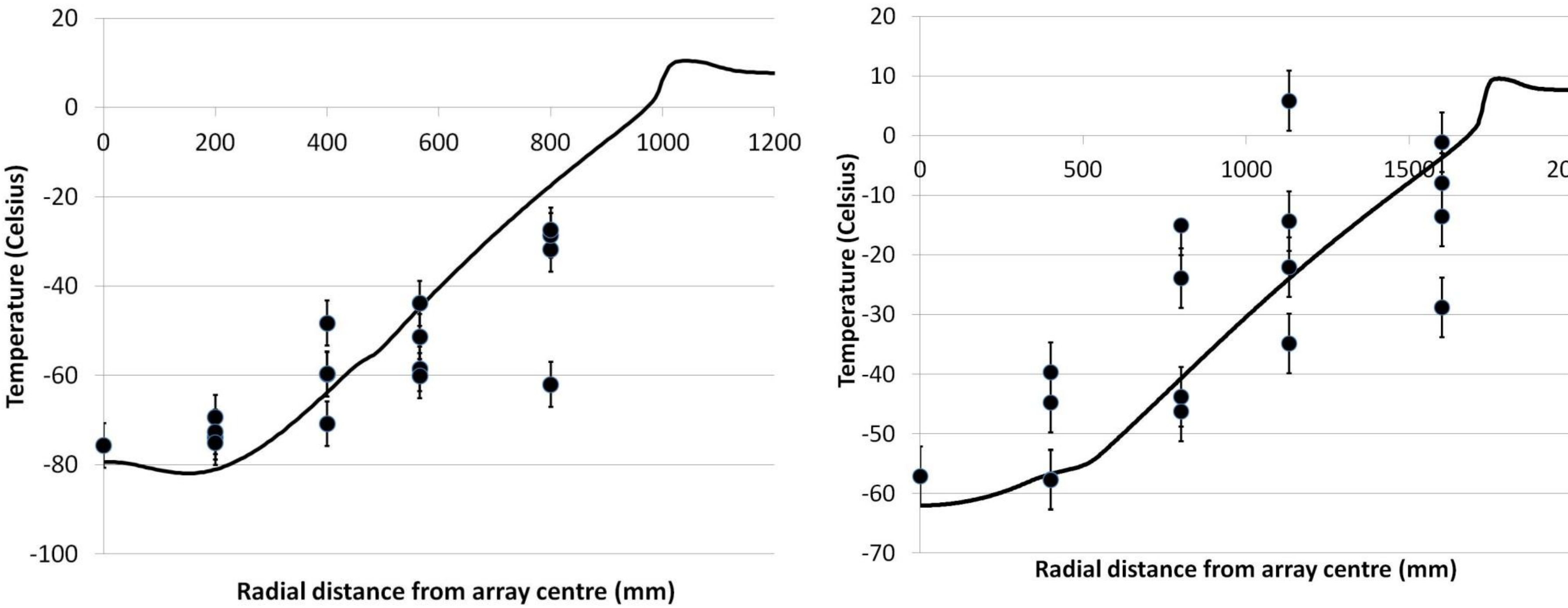
(a) 4m above the vent (b) 7m above the vent



- 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: gas phase release

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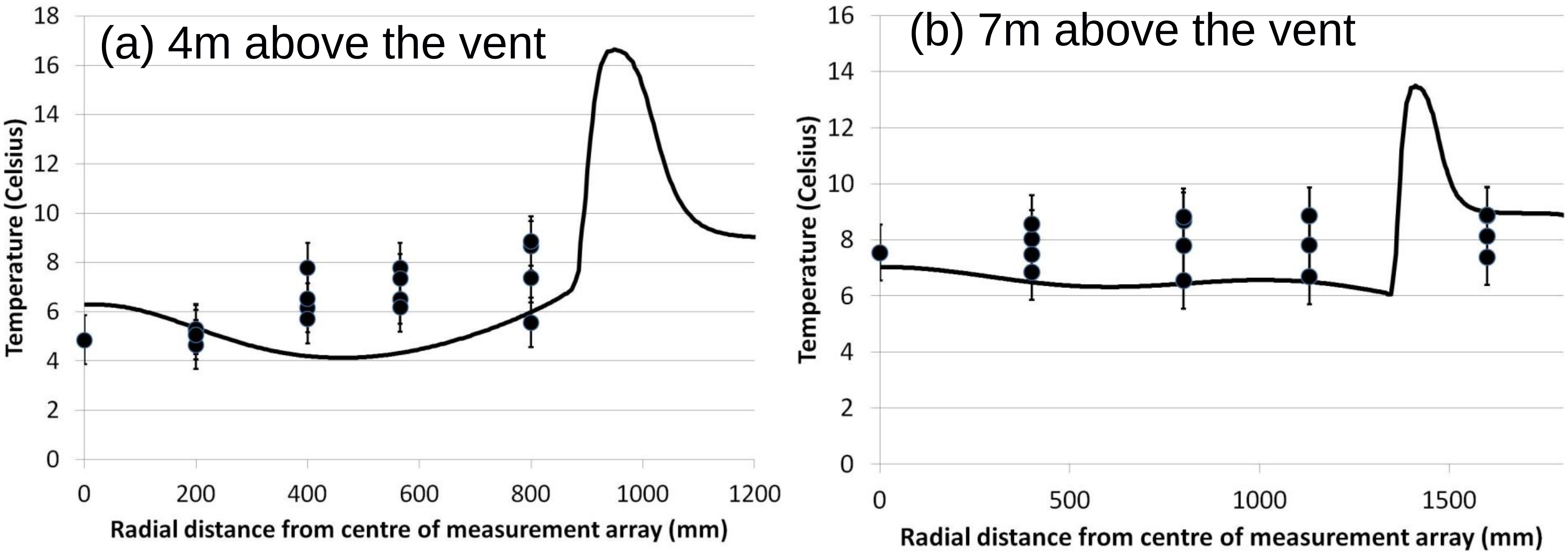
- Gas phase release from a 35bar reservoir through a 25mm vent pipe.
- Steady state release conditions achieved by supplying a driving pressure



- 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)*

Punctures of a buried pipeline

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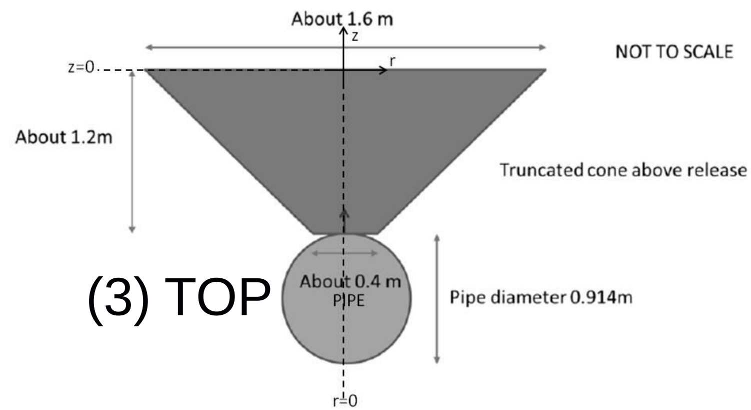
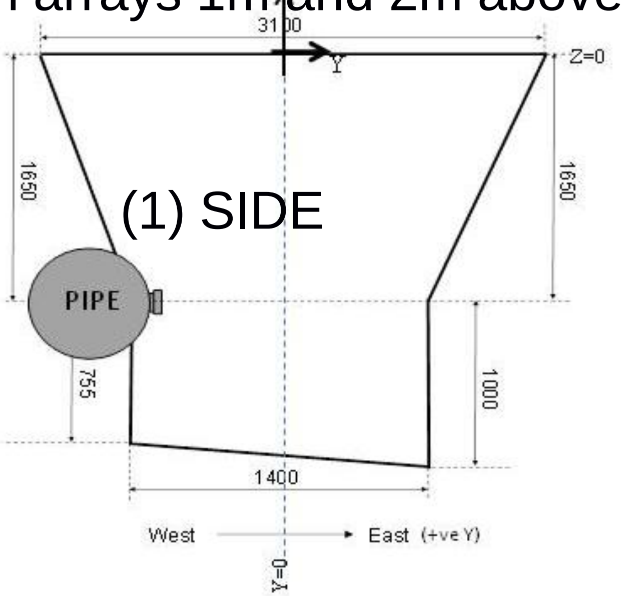
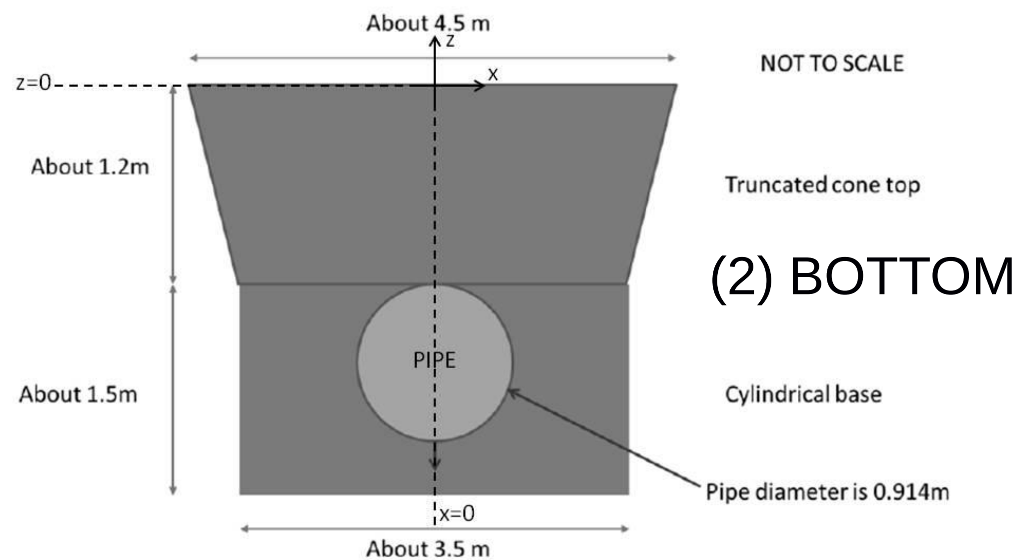
Experimental setup
- 0.9m diameter pipeline.
- Pipeline pressurised to 150bar.
- 25mm diameter circular puncture.
- Preformed craters based on observations of real craters.
- Experimental measurements taken on arrays 1m and 2m above ground level for the side puncture only.







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

Puncture results – side

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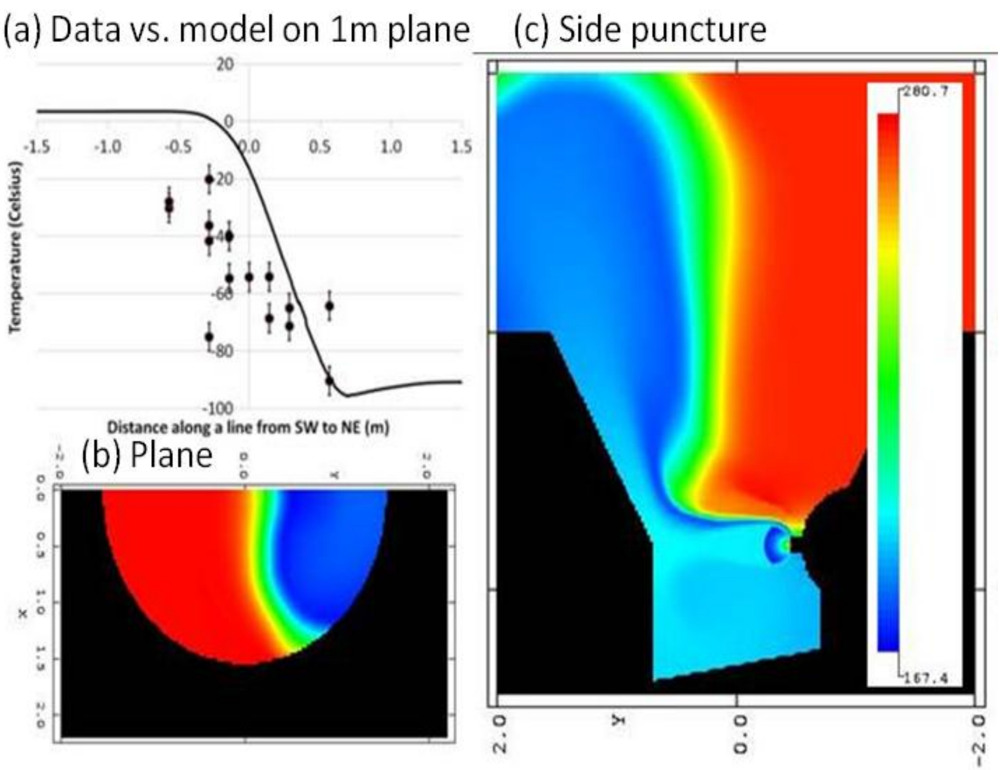
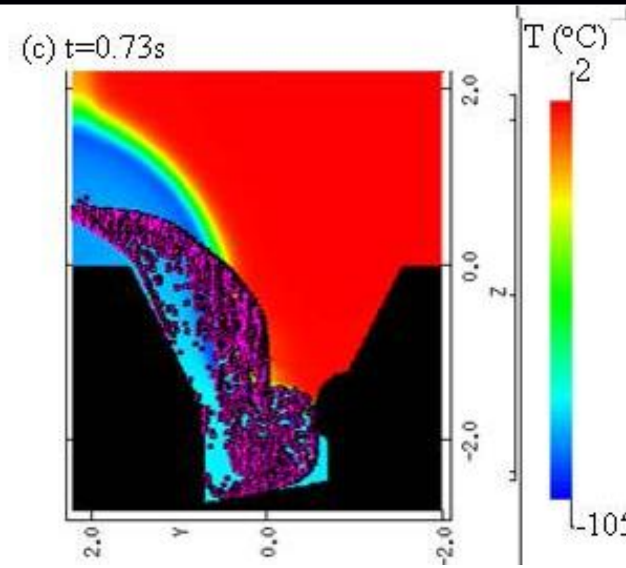
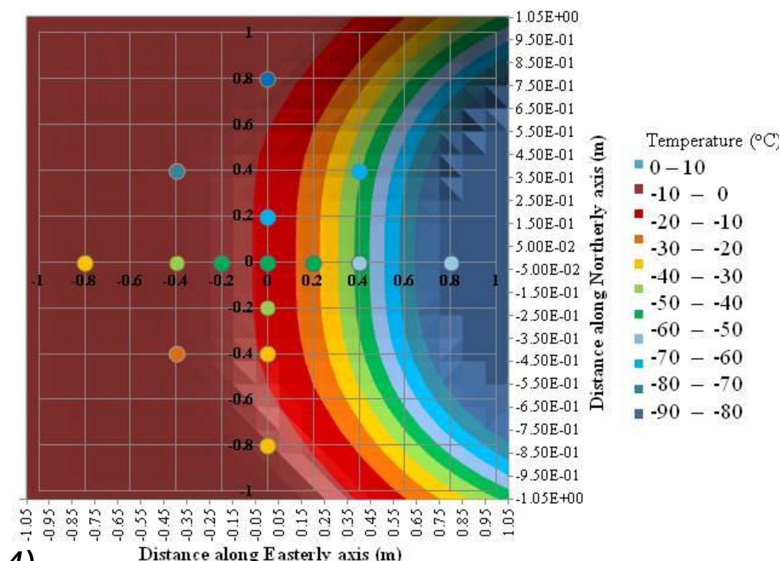
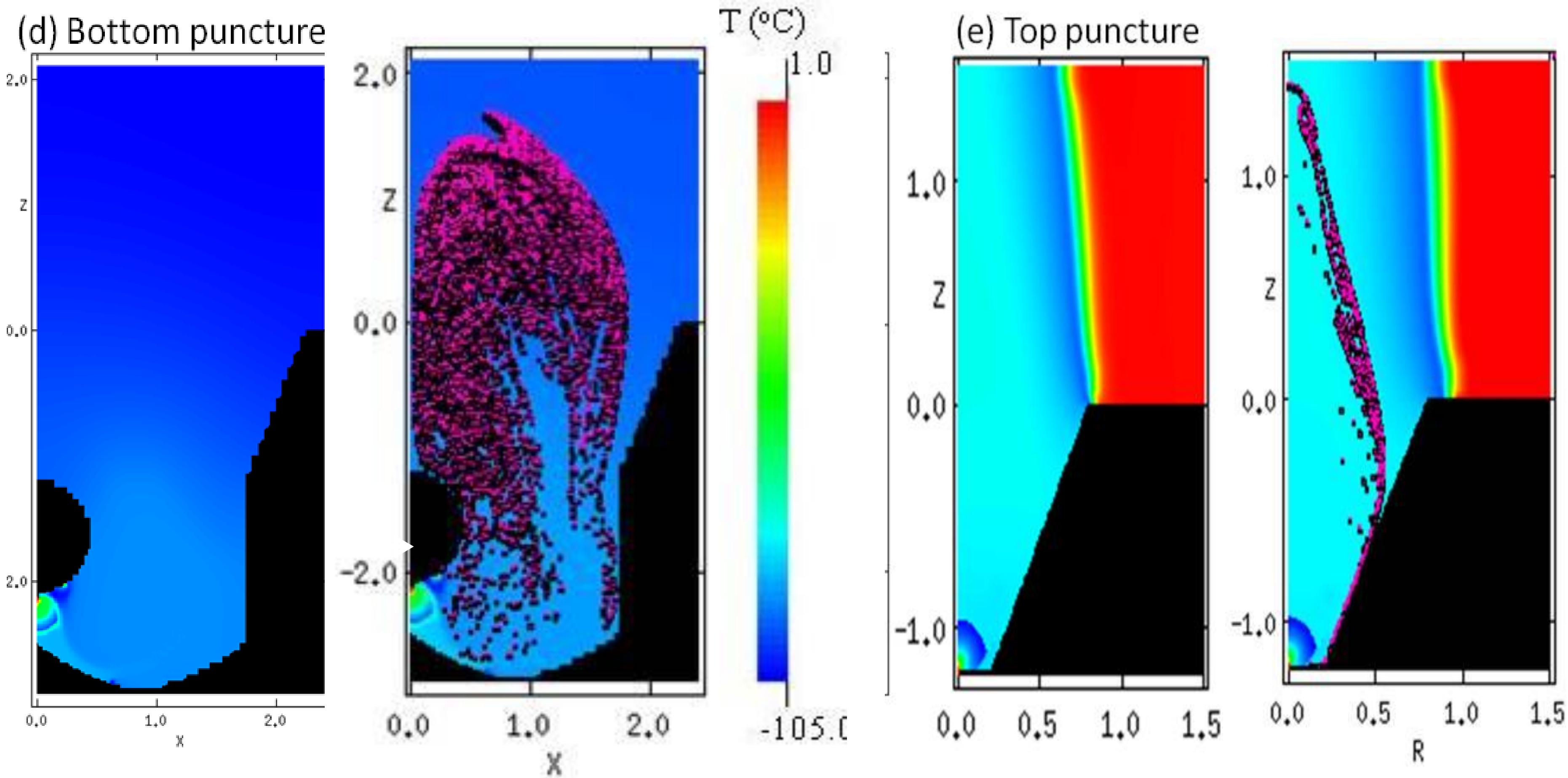






*Wareing et al., Int. J. Greenhouse Gas Control, **29**, 231-247 (2014)*

Puncture results – bottom and top



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

Ruptures of a buried pipeline

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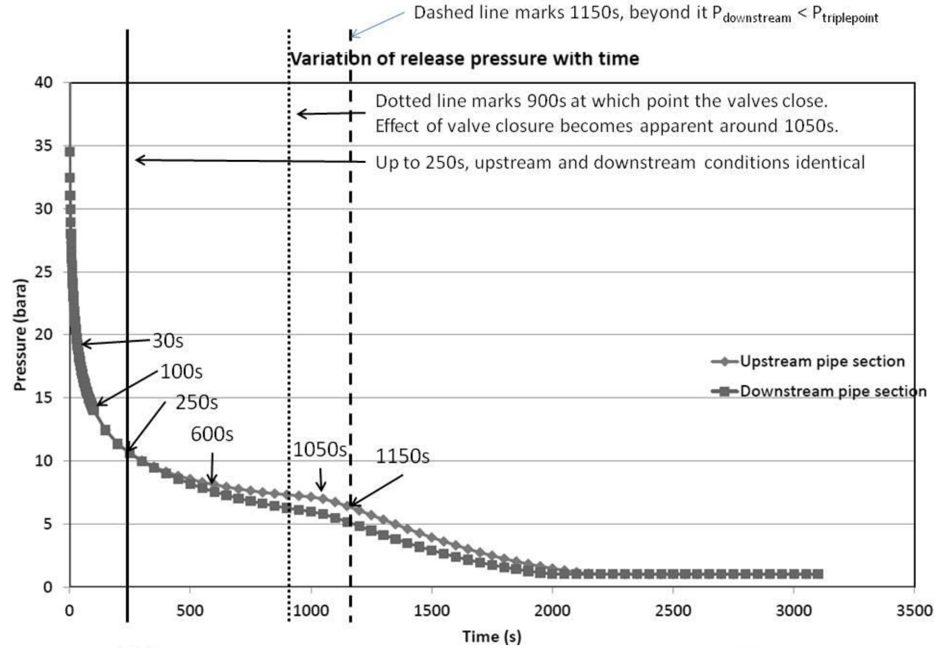
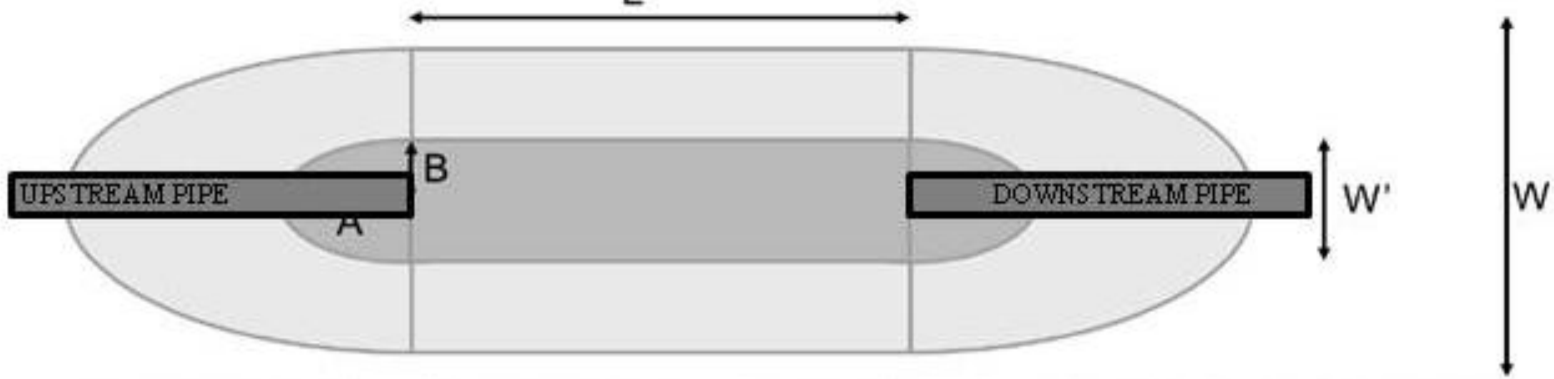
Experimental setup
- 0.6m diameter pipeline.
- Pipeline pressurised to 150bar.
- Preformed craters based on observations of real craters.
- Experimental measurements on arrays above ground level.





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 – base case results

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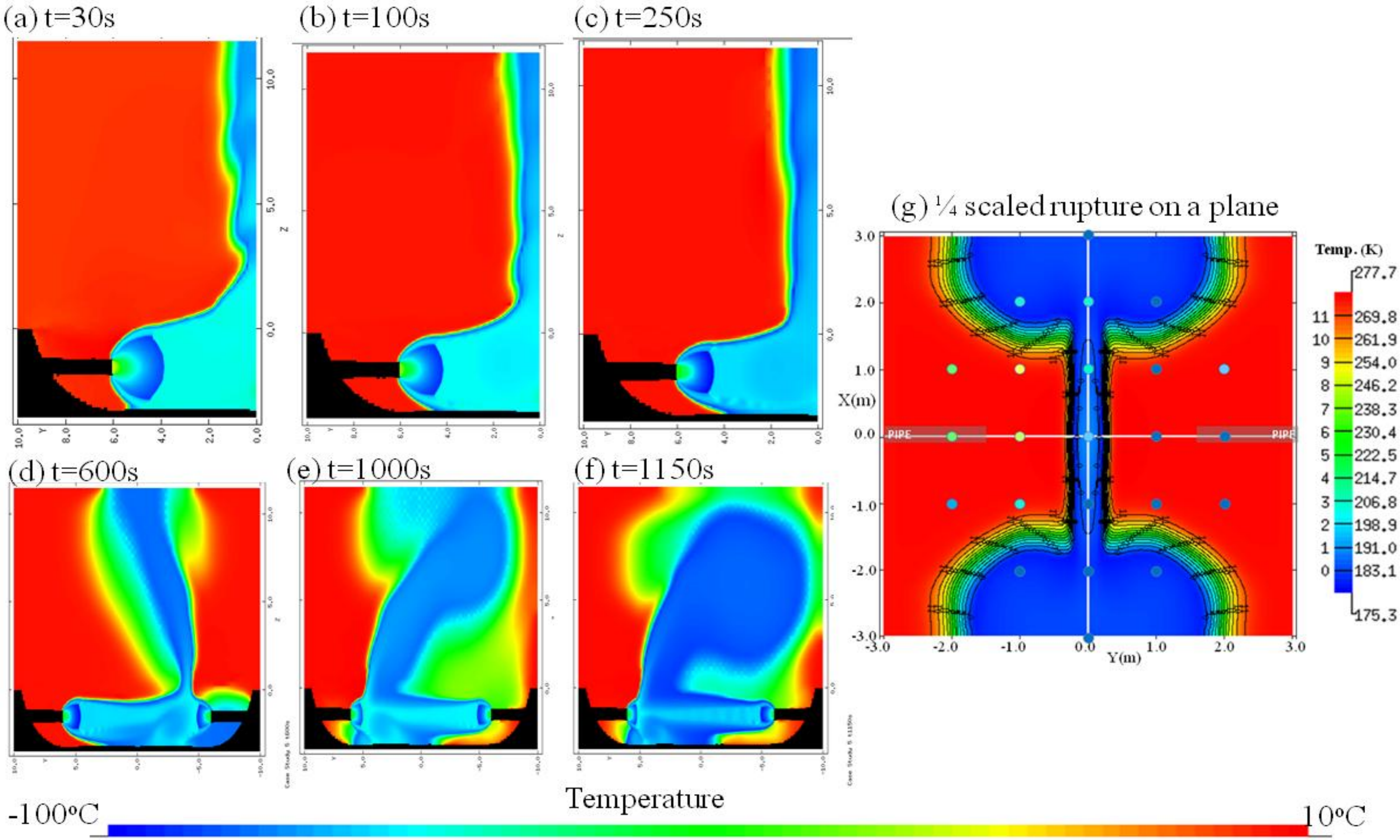

*Wareing et al., Int. J. Greenhouse Gas Control, **submitted***

Ruptures - sensitivity study

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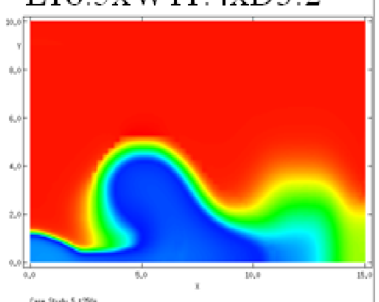
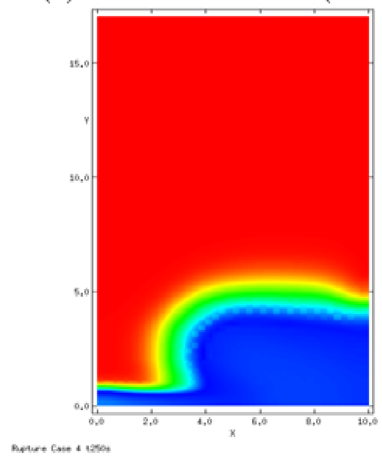
Shape of flow on planes above the crater – top down view

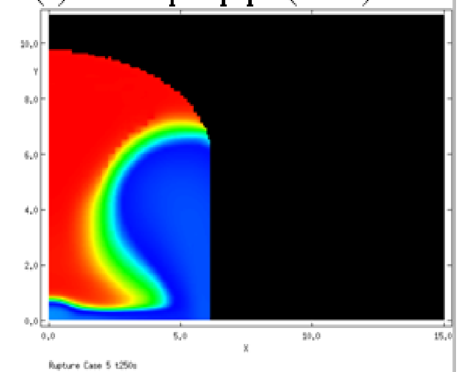
(a) Base Case
12m fracture
1.2m deep pipe
75° wall angle
Aligned pipes
Crater:
L18.5xW11.4xD3.2



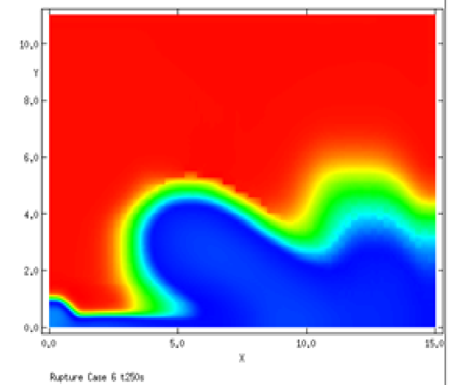
(b)S1- 24m fracture: (L30.5)



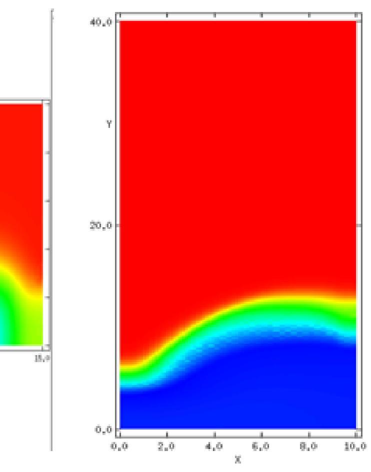
(c)S2- deeper pipe (D4.0)



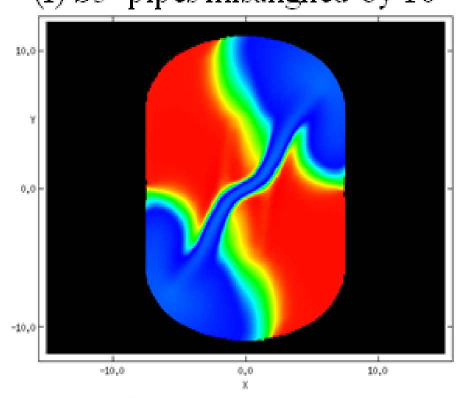
(d)S3- shallower wall (64°)



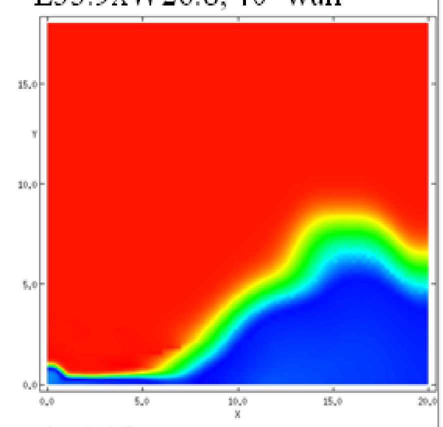
(e)S4- 72m fracture (L78.5)



(f) S5- pipes misaligned by 10°



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



Temperature

*Wareing et al., Int. J. Greenhouse Gas Control, **submitted***

Ruptures – validation at ¼ scale

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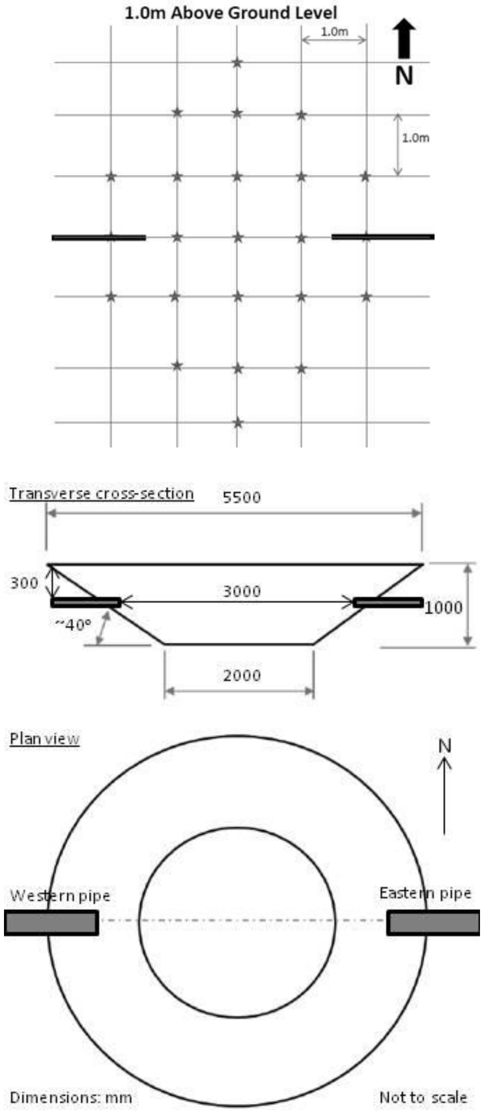
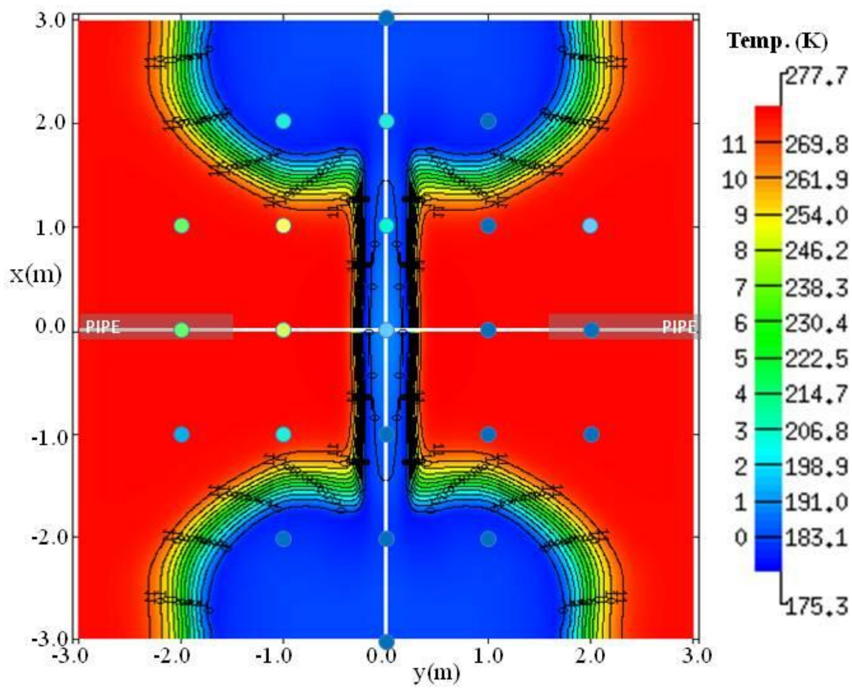
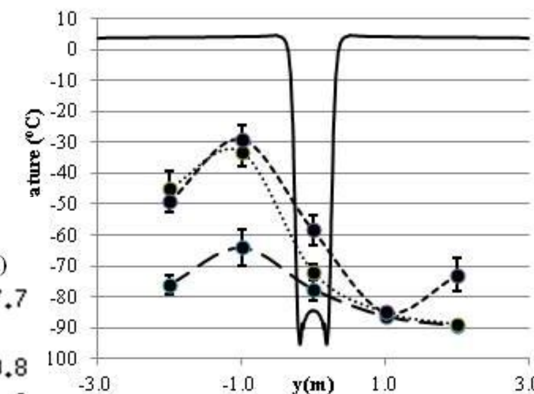


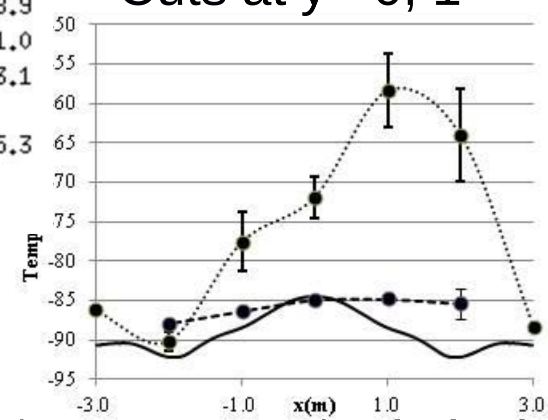
1m above crater





Cuts at x= -1, 0, 1

Cuts at y= 0, 1



Wareing et al., Int. J. Greenhouse Gas Control, ***submitted***

Ruptures - integrated flow

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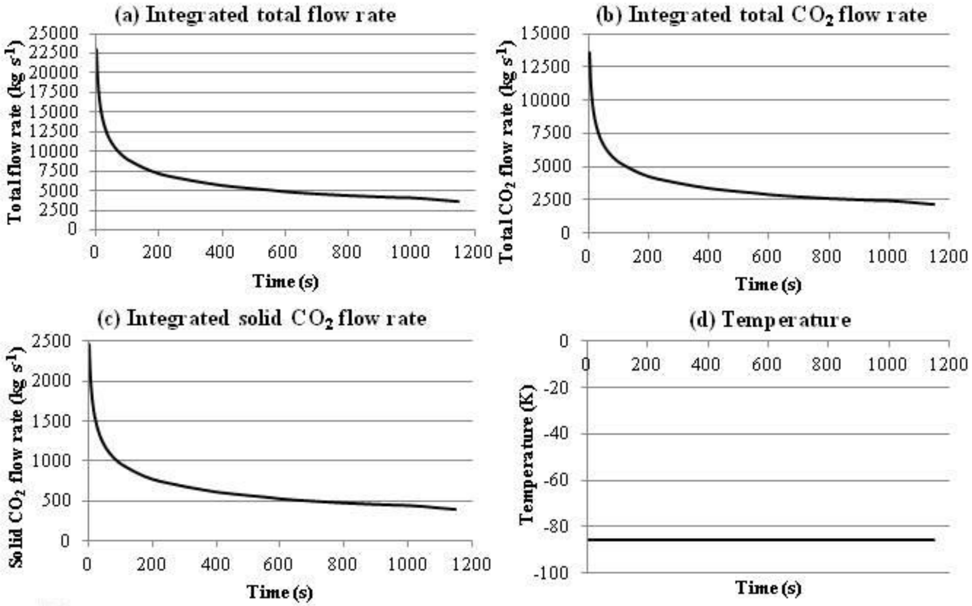

Base case

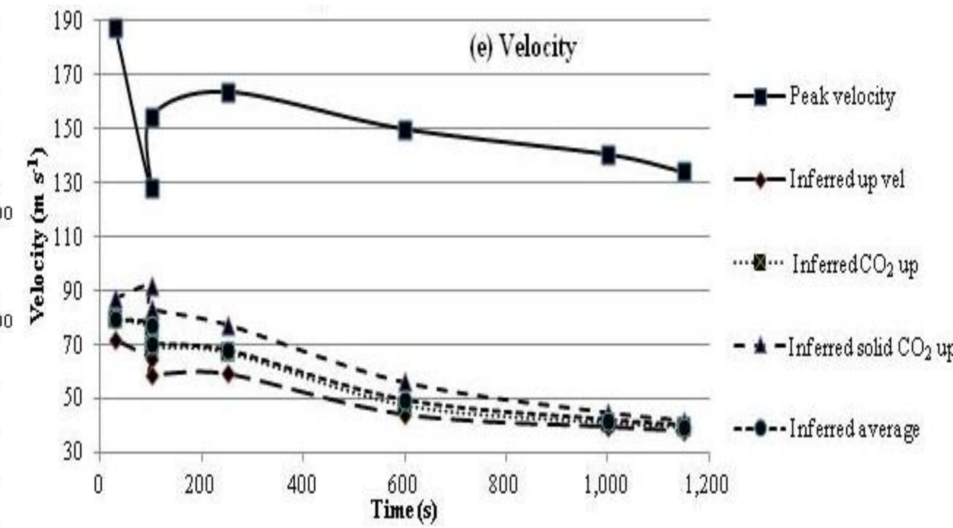

Table 2. Integrated flux comparisons for the base case and sensitivity studies.

Sensitivity studies

#	Description	Plane height	CO_2 fraction	Solid fraction of CO_2 fraction	Average velocity	Peak velocity	Temperature
	Base case	2m	62%	18%	60 m s^{-1}	164 m s^{-1}	189 K
S1	24m fracture	2m	52%	13%	62 m s^{-1}	148 m s^{-1}	187 K
S2	Deeper pipe	0m	62%	18%	73 m s^{-1}		188 K
S3	64° wall angle	2m	55%	15%	50 m s^{-1}		188 K
S4	72m fracture	6m	42%	6%	17 m s^{-1}	30 m s^{-1}	186 K
S5	Misaligned pipes	0m	63%	19%	43 m s^{-1}	140 m s^{-1}	188 K
S6	Sandy soil	1m	54%	15%	54 m s^{-1}		188 K

Wareing et al., Int. J. Greenhouse Gas Control, ***submitted***

Ruptures – solid deposition

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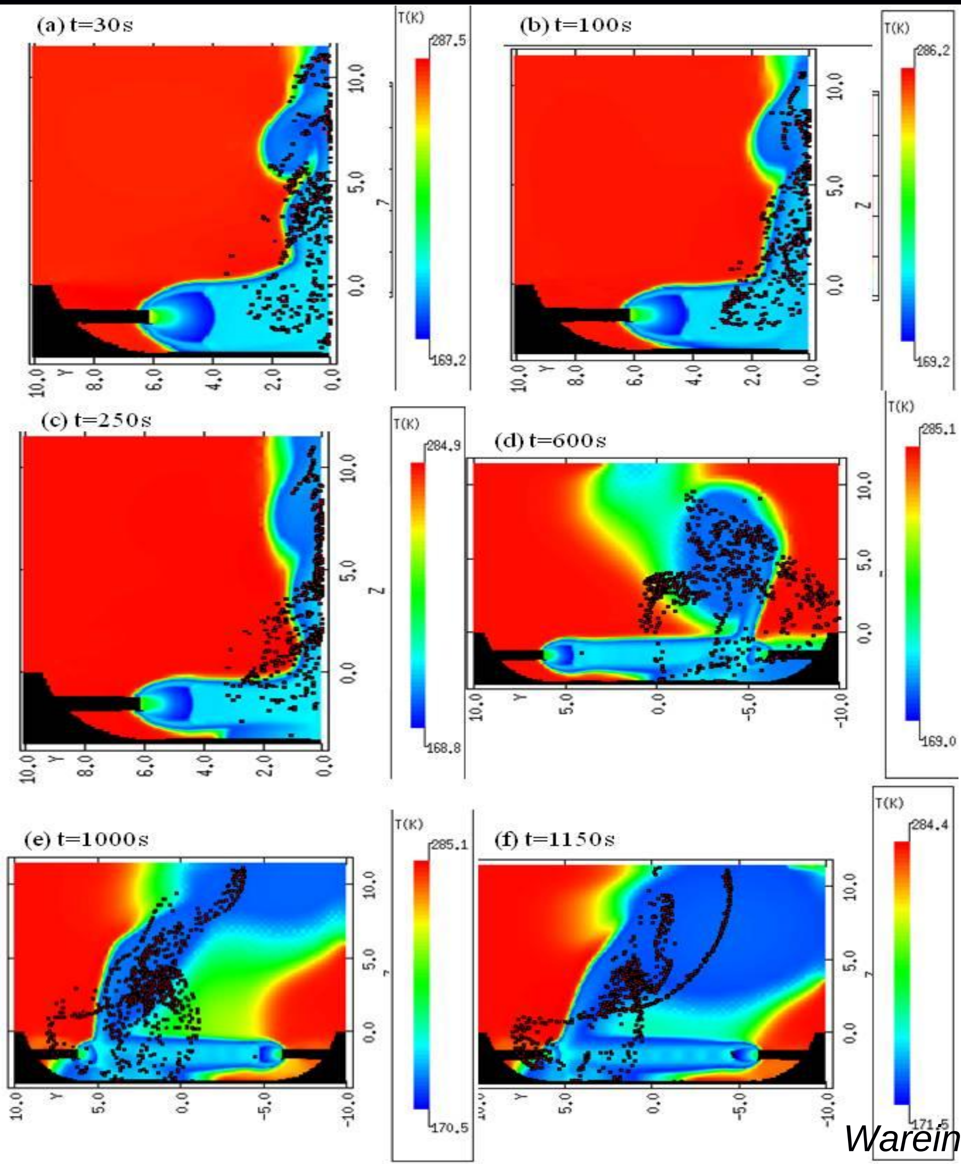

- Lagrangian particle tracking
- Initial conditions based on measurements of particle behaviour in laboratory-scale experiments (Wareing et al. AIP Conference Proc. **1558** 98 (2013))
- Peak deposition rate of 1%
- Equates to 14,000 kg of solid CO_2 over the first 1150s of a full scale rupture
- Covers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

Wareing et al., Int. J. Greenhouse Gas Control, ***submitted***

Conclusions

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- Novel dispersion model covering the necessary range of pressures (0.01 to 150 bar) and temperatures (160K to 310K or -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, testing different equations of state.
  - Improved (Reynolds-stress) turbulence model and comparisons.
  - Extended comparisons of available datasets (from CO2PIPETRANS, COOLTRANS, CO2PIPEHAZ. CO2QUEST)
  - Improved understanding of particle evolution to be applied.

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)
Rupture releases: Wareing et al., Int. J. Greenhouse Gas Control, *submitted*
Particle-laden CO_2 jets: Wareing et al., AIP Conference Proceedings, **1558**, 98 (2013)