WHEN TRUST MATTERS

CO_2 Dispersion Joint Industry Project

Introduction and Scoping Workshop: DNV Spadeadam

Dan Allason, Principal Consultant

06 October 2023

Agenda

9:00	Arrival and coffee
9:30	Introduction and review of related research
10:30	Site tour of DNV Spadeadam
12:00	Lunch
13:00	Background and overall project scope
	WP1: Crater experiments
	WP2: Wind tunnel experiments
	WP3: Simple terrain experiments
14:30	Coffee/tea break
14:45	WP4: Complex terrain experiments
	WP5: Modelling
	WP6: Emergency response
	WP7: Venting
	WP0: Management
16:00	Update from ISO TC/265 Committee
16:20	Close

Cannot overrun beyond 16:30 due to onward travel arrangements

Site Tour

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	WP0: Management
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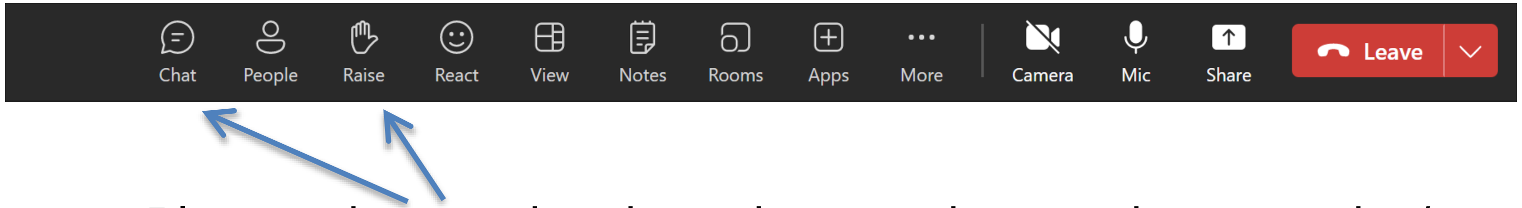
Aims

- To present more detail of each of the work packages
- To allow time for discussion
- To seek feedback on the proposals
  - What pipeline operating conditions are of interest (supercritical, gaseous, liquid?)
  - Is there interest in above-ground pipeline ruptures?
  - What are the highest priorities: e.g., venting or pipeline ruptures?
- To provide you with an estimate of the costs, timescales and next steps



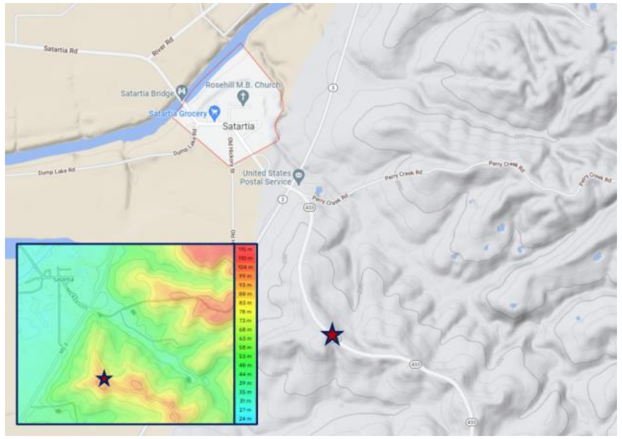
Please raise your hand to ask a question or write a question/comment in the Chat

Background and Overall Project Scope

Background: Satartia CO_2 pipeline incident, 2020

- Failure of Denbury 24-inch CO_2 pipeline near Satartia, Mississippi due to landslide
- Dense CO_2 cloud rolled downhill and engulfed Satartia village, a mile away
- Approximately 200 people evacuated and 45 required hospital treatment
- Communication issues: local emergency responders were not informed by pipeline operator of the rupture and release of CO_2
- Denbury's risk assessment did not identify that a release could affect the nearby village of Satartia

Figure 6: Topographical Map Showing the Delhi Pipeline (Green) and Denbury's Buffer Zone (Red) on Either Side of the Pipeline and the Proximity to Satartia (Blue Star Indicates the Rupture Site)



Terrain map taken from Google Maps and contour map taken from topographic-map.com. Approximate location of release marked by a star.

Image sources: Yazoo County Emergency Management Agency/Rory Doyle for HuffPost and PHMSA
- https://www.huffingtonpost.co.uk/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f
- https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf

CCS safety research over the period 2007-2017

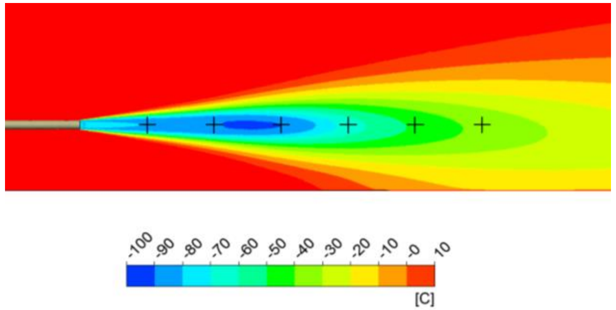
IChemE SYMPOSIUM SERIES NO. 153 © 2007 Crown Copyright

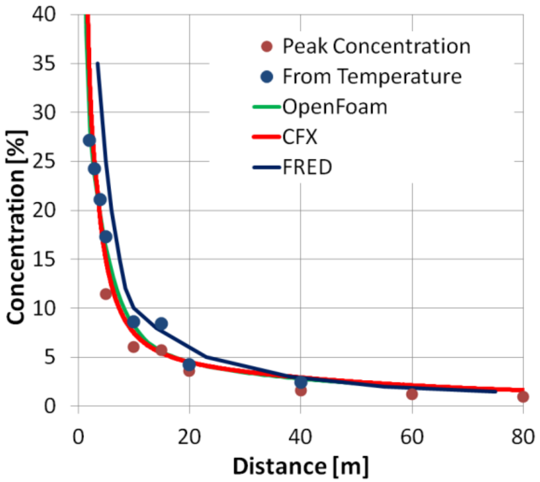
HAZARDS FROM HIGH PRESSURE CARBON DIOXIDE RELEASES DURING CARBON DIOXIDE SEQUESTRATION PROCESSES†

Stephen Connolly[1] and Laurence Cusco[2]

https://www.icheme.org/media/17864/cusco_connolly_2007_hazards_from_co2.pdf

© Image copyright Shell / DNV





- CO2PIPETRANS
- CO2PIPEHAZ
- COOLTRANS
- MATTRAN
- COSHER
- CATO2

RR1121 - Overview of carbon capture and storage (CCS) projects at HSE's Buxton Laboratory

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

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, https://www.icheme.org/media/9162/paper21-hazards-23.pdf

COOLTRANS Research Programme

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 CO_2 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

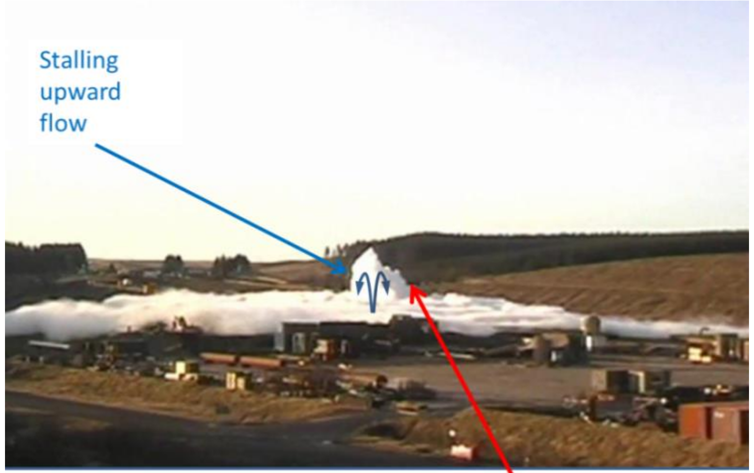
Julian Barnett
National Grid
Solihull, UK

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

by Philip Cleaver[1], Ann Halford[1], Karen Warhurst[1], and Julian Barnett[2]
1 GL Noble Denton, Loughborough, UK
2 National Grid Carbon, Warwick, UK

4th International Forum on the Transportation of CO2 by Pipeline

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



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

Fresh air entrainment possible around plume base

COSHER Joint Industry Project

International Journal of Greenhouse Gas Control 37 (2015) 340–353

COSHER joint industry project: Large scale pipeline rupture tests to study CO_2 release and dispersion

Mohammad Ahmad [a,*], Barbara Lowesmith [a], Gelein De Koeijer [b], Sandra Nilsen [b], Henri Tonda [c], Carlo Spinelli [d], Russell Cooper [e], Sigmund Clausen [f], Renato Mendes [g], Onno Florisson [a]

http://dx.doi.org/10.1016/j.ijggc.2015.04.001

[a] DNV GL, The Netherlands
[b] STATOIL, Norway
[c] TOTAL, France
[d] ENI, Italy
[e] National Grid, UK
[f] GASSCO, Norway
[g] PETROBRAS, Brazil

219 mm (8.6 inch) diameter pipeline ruptured

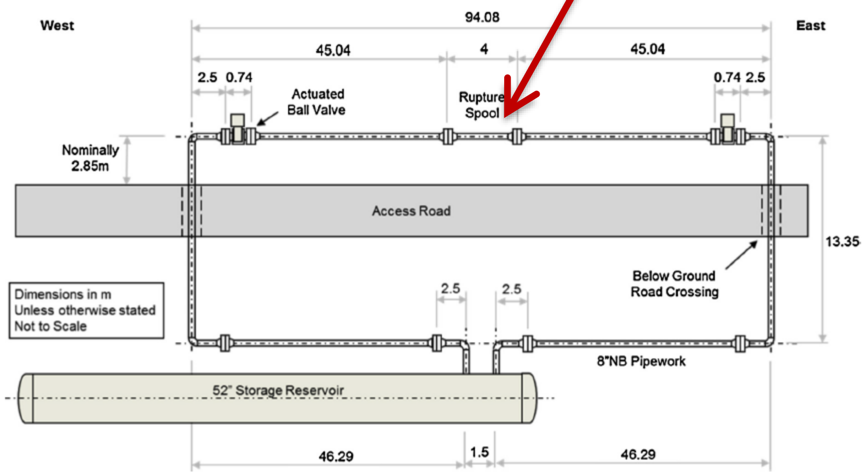


Fig. 1. The pipeline loop (plan view).

Table 2
Summary of the test conditions prior to rupture.

Rig conditions	Test
Overall average gage pressure (MPa)	15.08
Average fluid temperature in reservoir (°C)	13.1
Average wall temperature of reservoir (°C)	14.2
Estimated inventory (tons)	146.8
Atmospheric conditions	
Wind direction (degrees relative to grid N)	261
Wind speed (m s^{-1})	1.9
Ambient temperature (°C)	17.4
Atmospheric pressure (Pa)	99700
Relative humidity (%)	71.5

Max cloud height approx. 60 m

Max visible cloud spread distance approx. 400 m

Fig. 4. The visible cloud at 10 s (top), 30 s and 120 s (bottom) after the rupture.

Recommended Practice, Guidelines and Standards

- DNV
  - "Design and operation of carbon dioxide pipelines" DNV-RP-F104
  - CO2SafePipe JIP https://www.dnv.com/article/design-and-operation-of-co2-pipelines-co2safepipe-240345
- Energy Institute https://www.energyinst.org/
  - "Hazard analysis for onshore and offshore carbon capture installations and pipelines"
  - "Good plant design for offshore and onshore carbon capture installations and pipelines"
- ISO TC/265 https://www.iso.org/committee/648607.html
  - Carbon dioxide capture, transportation, and geological storage

Recommended Practice, Guidelines and Standards

- DNV-RP-F104

In addition to being influenced by the wind, the cold, heavier than air CO_2 stream will spread out sideways, with off-axis ground level concentrations being higher than for a neutrally buoyant or buoyant gas release. Ground topography (e.g. slopes, hollows, valleys, cliffs, streams, ditches, road/rail cuttings and embankments, etc.) and physical objects (e.g. buildings, walls, etc.), as well as wind direction may have a significant influence on the spread and movement of a CO_2 cloud. Care should be taken in identifying topographical features and in the assessment of how they may impact the consequences of a CO_2 release.

In many assessments, empirical integral models should provide acceptable modelling capability, but in areas where the combined effects of topography, buildings, pits, etc. and the heavy gas properties of the released CO_2 may have a significant effect on the exposure of people or livestock, more detailed simulations using advanced dispersion tools (e.g. computational fluid dynamics (CFD)) should be considered.

- Energy Institute “Hazard analysis” draft report 2023

4.3.5 Contribution factors e.g. topography and impingement
Particular scenarios may need to be modelled due to project-specific characteristics. For example, a pipeline route through any terrain which would affect the dispersion of the cloud such as a valley, or heavily urbanised areas, then additional modelling may also be required to understand the dispersion of the cloud. It should be noted that a CO_2 release will likely form a slumping, heavier than air, cloud, hence the need to consider ground topography such as valley, slopes, and hollows.
In many cases, further modelling techniques such as CFD modelling (to evaluate the concentrations in the gaseous cloud) will be needed. Attention should be paid to possible impingent sites near the source of the release (i.e. near the source term) which may reduce the cloud momentum and hence air entrainment into the cloud which will increase the resultant CO_2 concentration in the cloud.

Recommended Practice, Guidelines and Standards

Carbon Dioxide (CO_2) Emergency Response Tactical Guidance Document

Guidelines for Preparedness and Initial Response to a Pipeline Release of Carbon Dioxide (CO_2)

August 2023

American Petroleum Institute | Liquid Energy Pipeline Association | NASFM

https://www.api.org/news-policy-and-issues/news/2023/08/17/api-lepa-publish-co2-pipeline-safety-guide

When the pipeline is in proximity to a nearby HCA, the effect of topography impacting transport must be considered. An overland spread analysis should be performed to determine whether the impact of topography and the dense vapor cloud could affect the nearby HCA. The overland spread analysis should consider worst-case operating conditions, ambient conditions, elevation changes, and topographic features, which would favor the channeling of CO_2 from a release location in the direction of the specific HCA. The Overland Spread Analysis uses site-specific, topographically based CFD modeling to further evaluate the potential hazard distances in these areas.

Simply stated, the atmospheric dispersion plume model will help predict the radius of impact following a pipeline rupture, while the CFD will evaluate the influence of the topographic features to provide the worst-case distance of impact caused by a release. Because CFD modeling requires high levels of computational power, modeling large distances of pipeline is, in most cases, not practical. A recommendation to achieve the highest level of effectiveness is to use the atmospheric dispersion model for the entire pipeline system and use CFD modeling in areas that exhibit significant elevation changes and significant channeling in the direction of an HCA that is within several miles of the pipeline system.

HCA = High Consequence Areas
(defined in 49 CFR195.452)

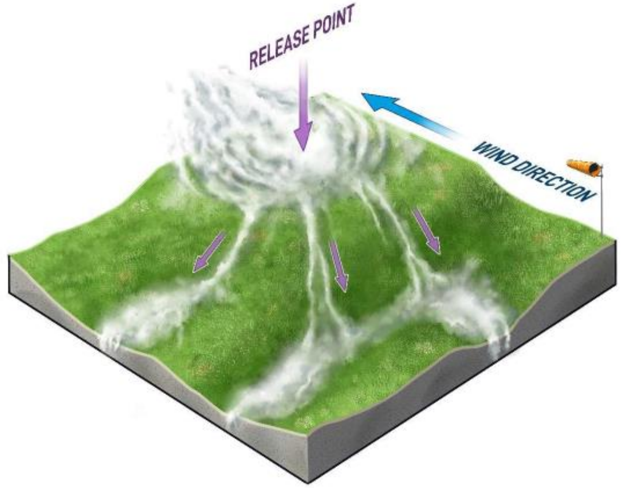
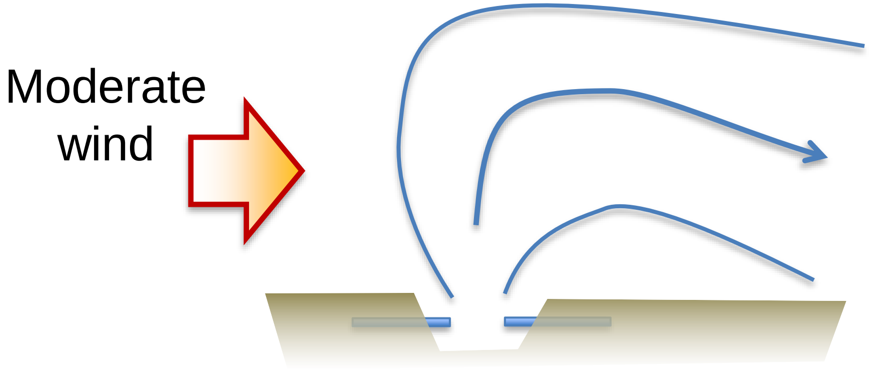


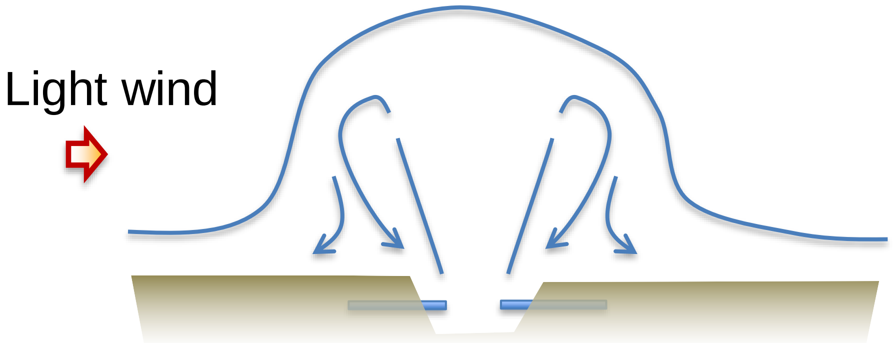
Figure 6—Transport and Dispersion of Released Carbon Dioxide with Topographical Features

Knowledge Gaps

1. Source characteristics from CO_2 pipeline craters



Bent-over plume, no re-entrainment

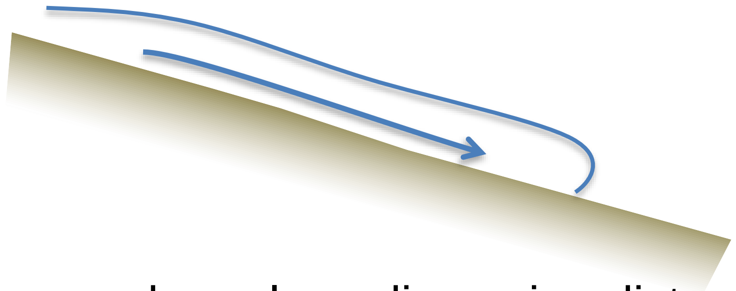


Plume falls onto crater, re-entrainment, blanket

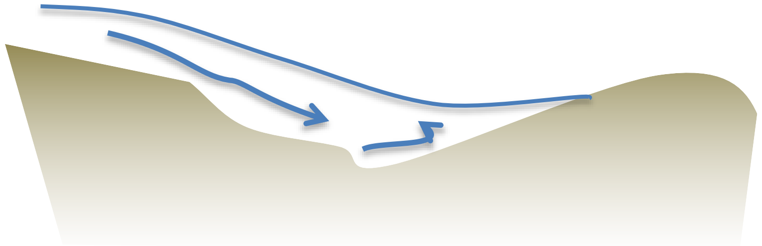
- Questions:
  - Which set of conditions give rise to these two different sources (wind speed, release size etc.)?
  - What are the characteristics of the dispersion source term (composition, flow rate, temperature etc.)?
  - Experimental data is limited to just two COSHER tests (COOLTRANS data is currently unavailable)

Knowledge Gaps

2. Terrain effects on dense clouds



Larger downslope dispersion distances?



Channelling effects in complex terrain, vapour hold-up in valleys

- Questions:
  – How confident are we in dispersion model predictions for dense-gas dispersion in complex/sloping terrain?
  – Have the dispersion models been validated against reliable experimental data?
  – Do any dispersion models exist that produce results quickly, i.e., within a few seconds (or minute at most) for use in risk assessment and emergency planning/response?

Knowledge Gaps

3. Are emergency responders sufficiently prepared to deal with possible incidents involving large CO_2 releases from CCS infrastructure?
   - Learning points from Satartia incident, e.g., vehicle engines stalling in CO_2-rich atmosphere: difficulties evacuating casualties (could electric vehicles be used?)
   - Similar approach could be adopted to the Jack Rabbit II chlorine dispersion experiments

     Work led by Andy Byrnes at Utah Valley University https://www.uvu.edu/es/jack-rabbit/

Plans for Joint Industry Project

- Work Package 0: Project Management
- Work Package 1: CO_2 pipeline craters and source terms
- Work Package 2: Wind-tunnel experiments
- Work Package 3: Simple terrain dispersion experiments
- Work Package 4: Complex terrain dispersion experiments
- Work Package 5: Model development and validation
- Work Package 6: Emergency response
- Work Package 7: Venting

Plans for Joint Industry Project

- Work Package 0: Project Management – **DNV**
- Work Package 1: CO_2 pipeline craters and source terms – **DNV**
- Work Package 2: Wind-tunnel experiments – **University of Arkansas**
- Work Package 3: Simple terrain dispersion experiments – **DNV**
- Work Package 4: Complex terrain dispersion experiments – **DNV**
- Work Package 5: Model development and validation – **HSE**
- Work Package 6: Emergency response – **NCEC**
- Work Package 7: Venting – **DNV**

with support from the **Met Office** in the DNV field trials

WP1: Crater Experiments

Work Package 1: CO_2 pipeline craters and source terms

- **Aim**: to improve our understanding of source characteristics for CO_2 pipeline releases from craters, using field-scale experiments
- Review existing data for CO_2 pipeline craters, both punctures and ruptures
- Conduct pipeline rupture tests
  - Both gas-phase and dense-phase CO_2
  - 6-inch or 8-inch diameter buried pipelines
  - At least two soil types (e.g., clay/sandy)
  - Assess size/shape of craters produced in soil
  - Construct realistic-shaped metal crater
  - Perform further tests using metal crater with near-field instrumentation
  - Repeat tests in both light and moderate wind speeds

Work Package 1: CO_2 pipeline craters and source terms

- Conduct experiments on both ruptures and smaller holes (punctures) on side, top and/or bottom of pipeline
- Measure CO_2 concentration and temperature at array of points
- Photograph maximum plume height and cloud shape
- Perhaps repeat some tests with restriction in upstream pipe connections to extend the release duration
- Use any system blowdowns to provide useful data on venting

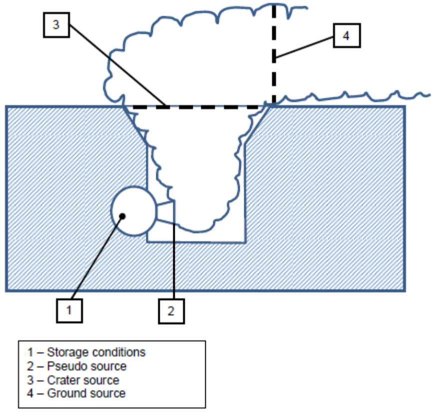


Figure 1 Puncture and crater sources

Work Package 1: CO_2 pipeline craters and source terms

- Outcomes:
  - Validation data for realistic two-phase CO_2 releases (roughly ¼ of full-scale)
  - Some indication of conditions when dense CO_2 jet: 1.) drifts away with the wind, or 2.) falls back onto source and produces vapour blanket
  - Answer practical questions:
    - Do gas-phase pipeline releases give rise to significant concentrations at ground level?
    - Is the cloud visible where it is dangerous?
  - Data for wider-area dispersion model validation (some complex terrain)
- Limitations:
  - Not possible to measure flow velocities nor composition of jet leaving crater
  - Temperature/concentration measurements may be affected by icing
  - Costly to undertake multiple repeated tests in range of conditions
  - Crater model validation based on limited measurements: some uncertainties likely to remain

Work Package 1: Potential Programme

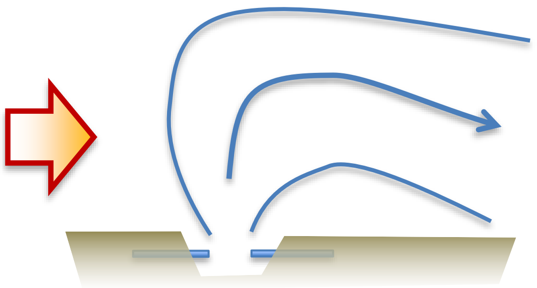
- Baseline testing programme of six 4” rupture tests:
  - 2x dense phase (>100 barg) on flat terrain
  - 1x gaseous phase (~30 barg) on flat terrain
  - 3x dense phase on slopes
- 6 additional rupture tests, varying parameters such as slope, wind, etc
- 6 puncture tests

WP2: Wind Tunnel Experiments

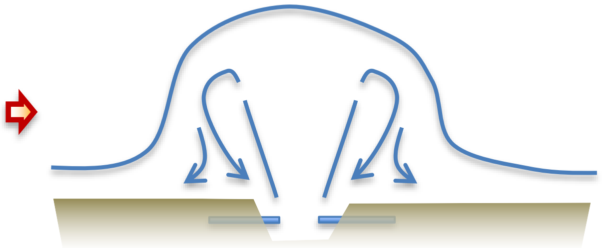
Work Package 2: Wind tunnel studies

- **Aim 1**: to study crater source behaviour across a wide range of carefully-controlled conditions, with detailed measurements, for model development
- Variables: source area, initial jet velocity and density, wind speed
- Measurements: velocity, concentration, flow visualisation
- Answer question: what are the criteria that control when the plume falls back onto the crater, producing re-entrainment and a source blanket?

When is it:

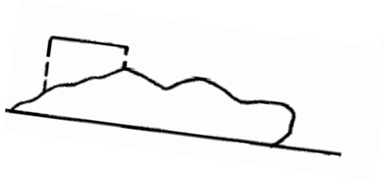


Or ?

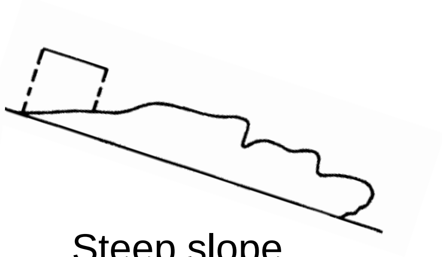


Work Package 2: Wind tunnel studies

- **Aim 2**: to study crater source behaviour in idealized simple and complex terrain, with detailed measurements, for model development, verification, and validation
- Variables: two simple terrain slopes; idealized complex terrain for model verification and validation; terrain orientation with the wind
- Measurements: velocity, concentration, flow visualisation
- Coordinate with DNV for field test conditions
- Answer question: what is the cloud behaviour with complications of terrain?



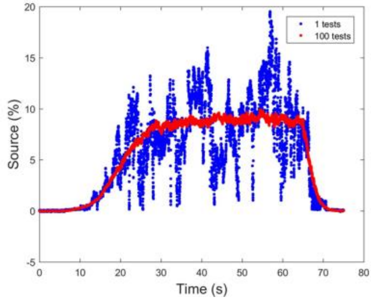
Shallow slope

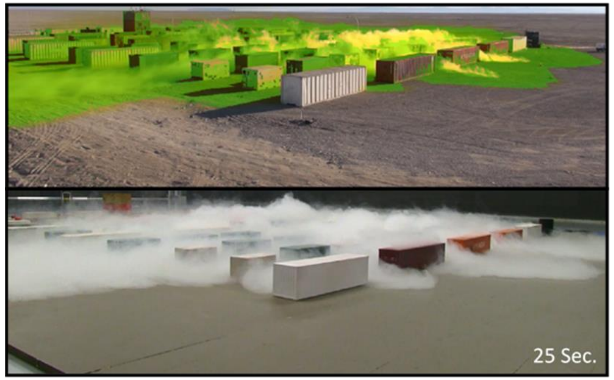


Steep slope

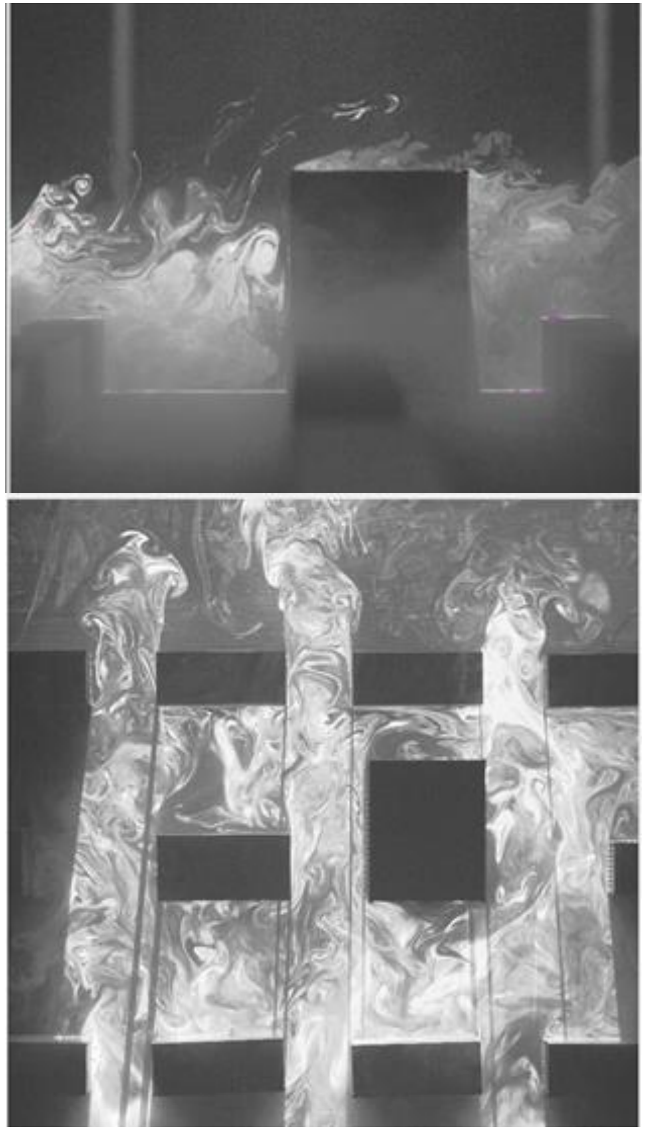
Work Package 2: Wind tunnel studies

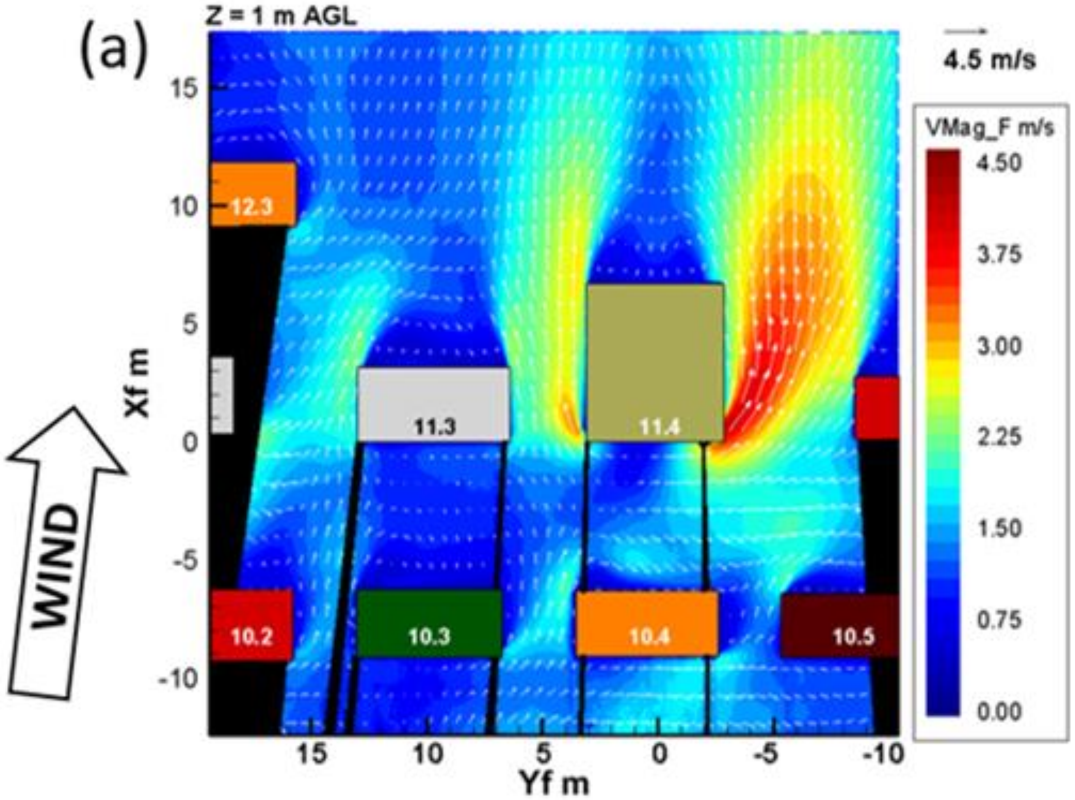
- Chemical Hazards Research Center (CHRC), University of Arkansas
  - Largest ultra-low speed wind tunnel
  - 24 m long working section with a 6 m × 2.1 m cross section
  - Capable of wind speeds as low as 0.3 m/s and still air experiments
  - State of the art instruments for velocity and turbulence (LDV and PIV) and gas concentration (FID, PLIF, PID)
  - Data from CHRC wind tunnel has previously used for:
    - PHMSA/NFPA model evaluation protocol for LNG siting applications
    - DNV Phast model development
    - Jack Rabbit II chlorine trials assessment





PIV Measurements





- Raw PIV images for vertical velocity slice when wind aligned with conex containers and horizontal slice if wind is not aligned.
- Average velocity field in Jack Rabbit II containers.

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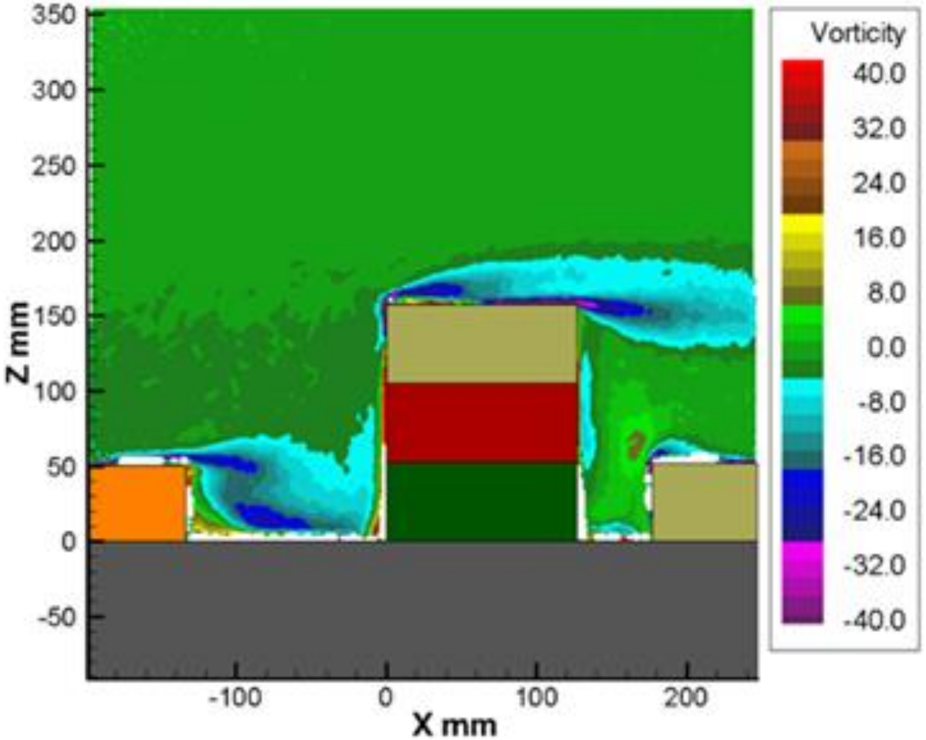
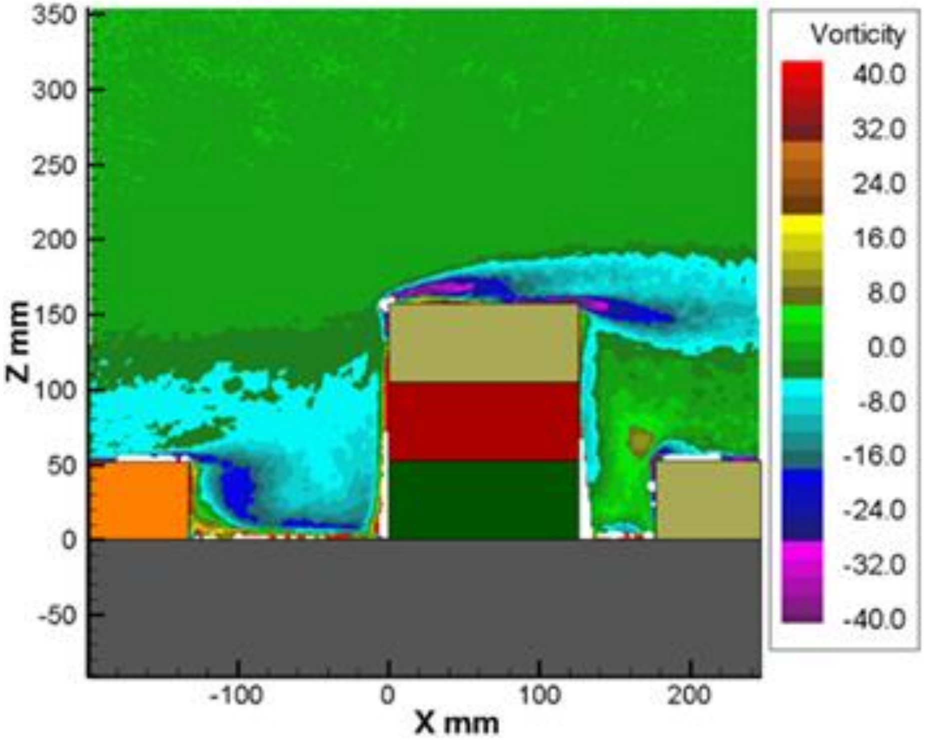
PIV Measurements



Before Release



During Release

Wind Tunnel Model of Jack Rabbit II

Jack Rabbit II

Trial 4

7.5-Ton Chlorine Release

September 01, 2015

High Definition Camera 04

CHRC Wind Tunnel

Trial 4

Camera 4

Work Package 2: Wind tunnel studies

- Outcomes:
  - Comprehensive dataset of vertical dense-gas releases from craters
  - Comprehensive dataset of dense-gas releases from craters in idealized simple and complex terrain
  - Criteria that define the set of conditions when CO_2 jet on flat terrain

    1.) drifts away with the wind, or

    2.) falls back onto source and produces vapour blanket

    Using scaling rules to explain how results apply to full-scale pipeline punctures and ruptures
  - Measurements of flow rates and concentrations that can be used to develop models
  - Visualisation of complex flow behaviour
- Limitations:
  - No two-phase flow and temperature effects associated with dry-ice and water vapour condensation that are features of real CO_2 releases

WP3: Simple Terrain Experiments

Work Package 3: Simple sloping terrain dispersion exps

- **Aim**: to conduct dense-gas dispersion experiments on “simple” uniform sloping terrain to provide data to validate dispersion models
- Idealised gaseous CO_2 source configuration to produce radially-spreading cloud, using a circular outlet similar to the Thorney Island dispersion trials
  - Avoid modelling uncertainties associated with two-phase CO_2 release from crater
- Main focus of experiments is to understand effect of slope on dense gas behaviour

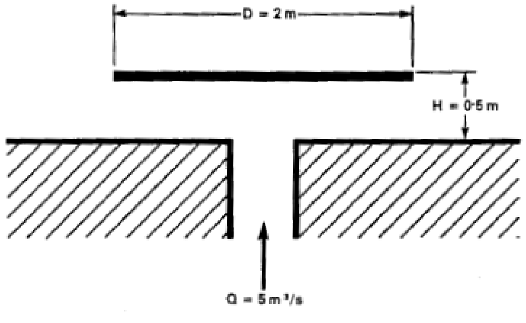
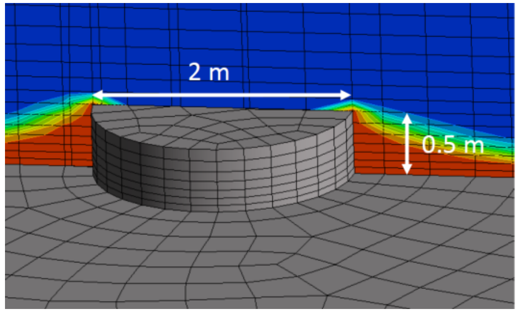
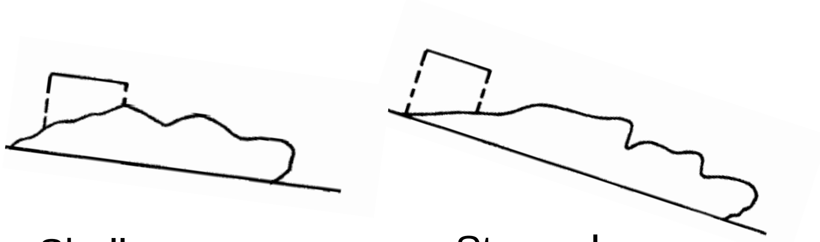


Fig.22.4 Geometry of ground-level source for continuous release experiments


Fig. 22.2 Outlet from the gas supply duct at the release point





Shallow slope

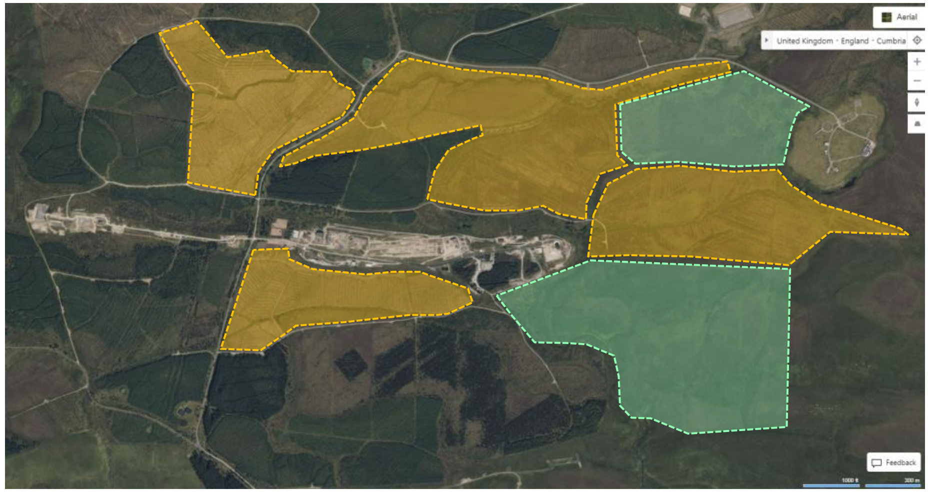
Steep slope

How does dispersion behaviour compare to flat terrain?

McQuaid & Roebuck (1985) Thorney Island
https://admlc.com/thorney-island/
CFD modelling
https://doi.org/10.1504/IJEP.2018.093026

Work Package 3: Simple sloping terrain dispersion exps

- Identify suitable, deforested ‘smooth’ slopes at Spadeadam
- Trials support provided by Met Office
  - Meteorological instrumentation and numerical weather predictions
- Undertake tests on several days with different meteorological conditions
  - Different wind speeds, and different wind directions relative to slope direction



Met Office

DNV

WP3: Simple slopes

  - Site 1 shallow slope, Site 2 steep slope (2 options) – will look to build slopes depending on scale (earthworks)
  - Calm, moderate, strong winds (3 options)
  - Small release, bigger release (2 options)
  - Wind direction aligned downslope, lateral, upslope (3 options)
- For all combinations: $2 \times 3 \times 2 \times 3 = 36$ trials
- Not all combinations may be achievable given variability in weather conditions
- Aim to undertake a minimum of 20 trials
  - Weather dependence important here

Work Package 3: Simple sloping terrain dispersion exps

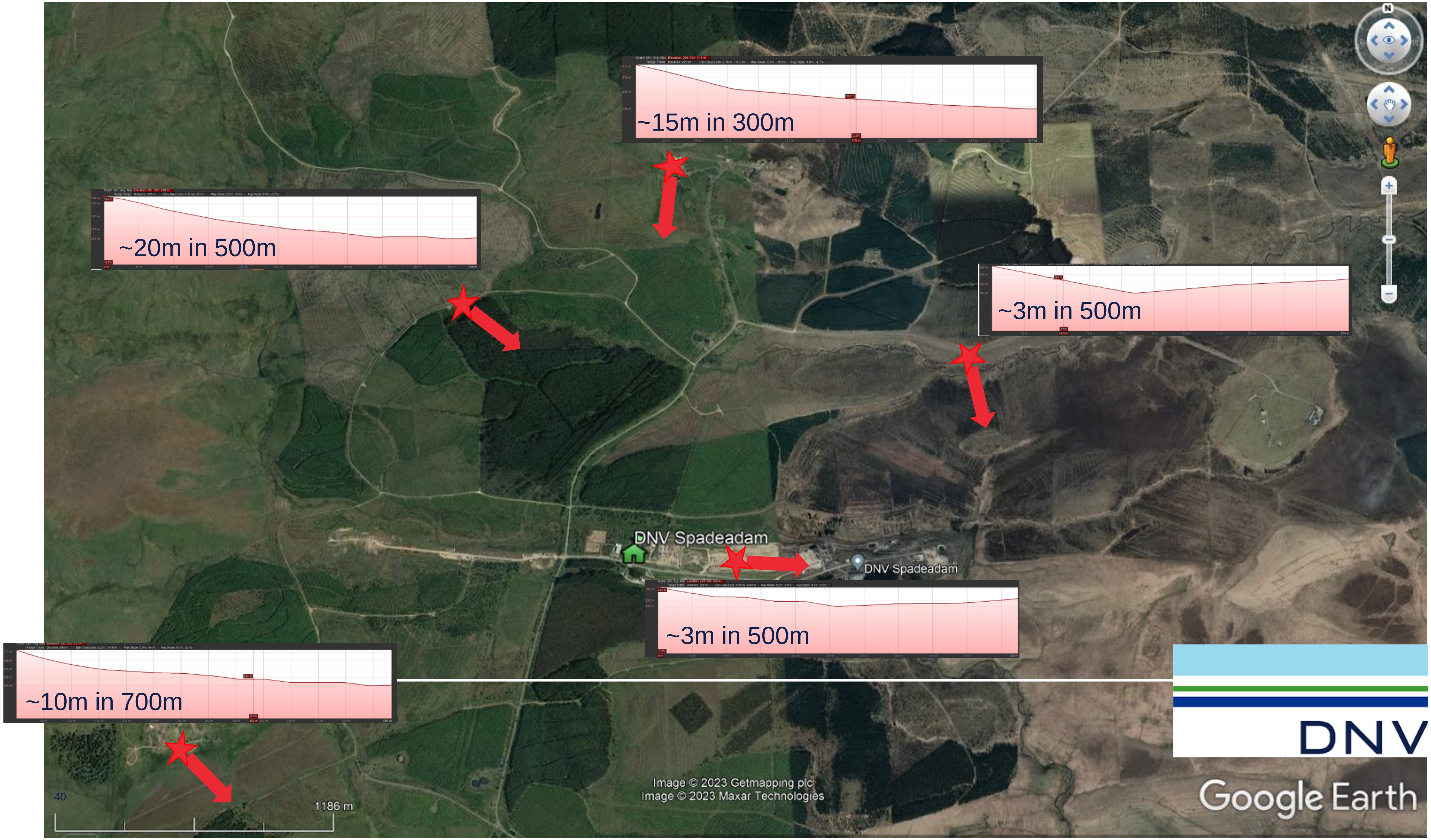
- Outcomes:
  - Data from multiple repeated tests for CO_2 releases on simple slopes
  - Combinations of wind direction versus slope direction, wind speed and release rate, including calm conditions like in Satartia incident
  - Sufficient trials to enable scaling rules or correlations to be developed for morphing flat terrain model predictions to account for slopes
  - Well-defined source conditions for validating dispersion models (fewer uncertainties)

- Limitations:
  - No two-phase flow and temperature effects associated with dry-ice and water vapour condensation that are features of real CO_2 releases

WP4: Complex Terrain Experiments

Work Package 4: Complex Terrain Dispersion Exps

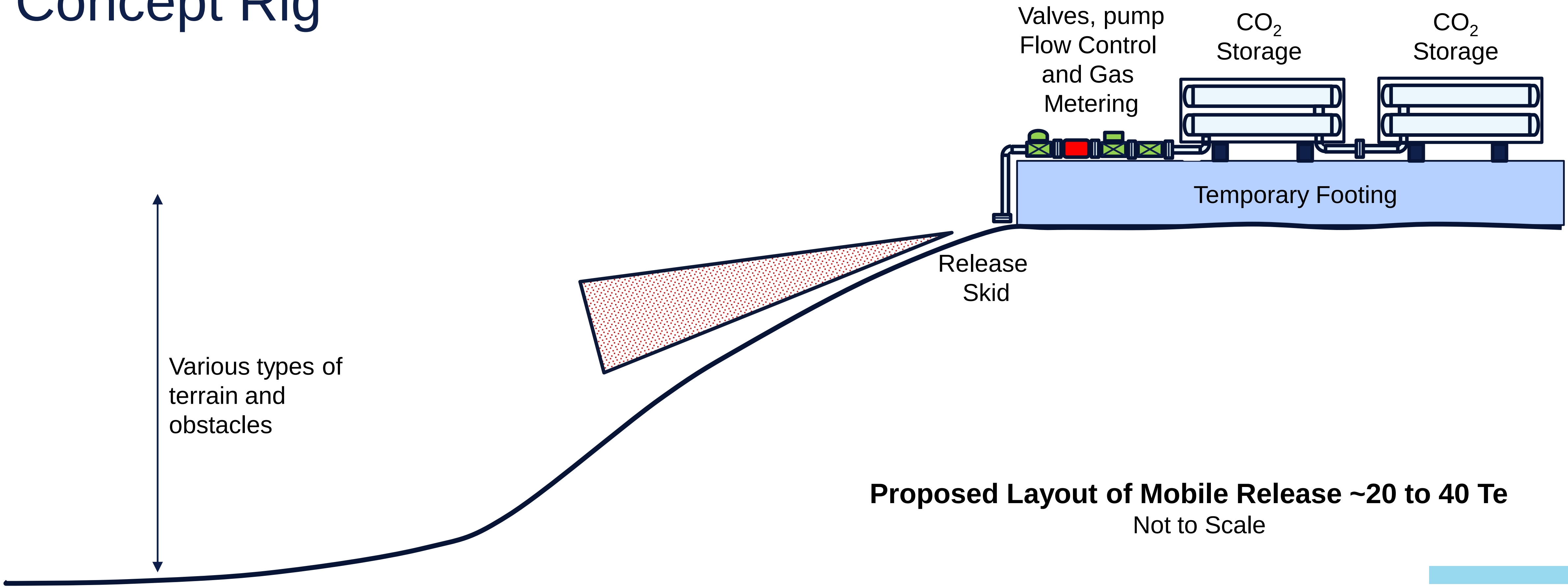
- **Aim**: to conduct series of CO_2 release experiments with complex terrain including valleys, hills, obstacles, changing roughness, buildings etc.
- DNV Spadeadam ideally suited to these tests, with multiple possible release locations and large exclusion distances
- Proposed to use mobile rig with 20 – 40 tonne CO_2 capacity with option to use preformed craters
- More challenging configurations for dispersion modelling
- Aim to answer practical questions:
  - How long does CO_2 persist in depressions?
  - What is the effect of obstacles (trees, hedgerows, buildings)?


~15m in 300m
~20m in 500m
~3m in 500m
DNV Spadeadam
DNV Spadeadam
~3m in 500m
~10m in 700m
Image © 2023 Getmapping plc
Image © 2023 Maxar Technologies
1186 m
Google Earth

DNV

Work Package 4: Complex Terrain Dispersion Exps

Concept Rig



Proposed Layout of Mobile Release ~20 to 40 Te
Not to Scale

Work Package 4: Complex terrain dispersion exps

- Outcomes:
  - Data for CO_2 releases on complex terrain for model validation, with valleys, hills, vegetation and obstacles
  - Dense-phase CO_2 with associated two-phase and temperature effects
  - Provide more challenging test of dispersion models in realistic scenarios
  - Provide further data on whether clouds are visible where they are dangerous
  - Tests could include toxic refuges and emergency responder’s equipment?
- Limitations:
  - Mobile rig will involve smaller CO_2 inventories than Work Package 1 crater tests, which will take place at a fixed location at Spadeadam
  - Model validation may encounter more uncertainties, e.g., characterising porosity of vegetation

Met Office

DNV

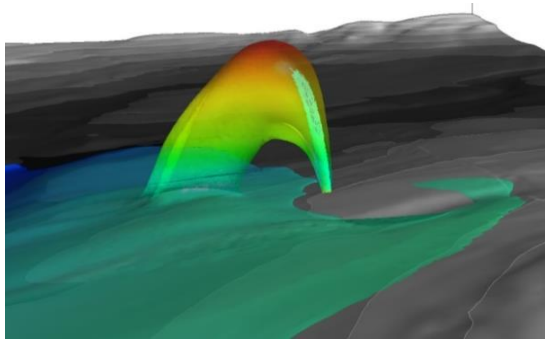
WP5: Modelling

PROTECTING PEOPLE AND PLACES HSE

Work Package 5: Model development and validation

- **Aim**: to develop, test and validate dispersion models that can be used for CO_2 pipeline risk assessment, permitting studies and emergency planning/response
- Open, collaborative and supportive approach, like in Jack Rabbit projects
- Welcome input from government labs, industry, academia and consultants
- Encourage research groups who are developing rapid dispersion models (e.g., Texas A&M, Leeds University) to participate, to inform future commercial software development

- Aim to test spectrum of models, e.g., correlations, Gaussian puff, shallow layer, machine learning, CFD
- Modellers given access to data in return for sharing results and collaborating
- Requests to join project approved by project steering committee
- Modelling exercises coordinated by HSE



Work Package 5: Model development and validation

Activities:

1. Prepare for field trials
   - Run simulations to predict what will happen and to help position sensor array
2. Analyse field trial measurement data
   - Work with DNV and Met Office to check data and summarise it for model validation purposes
   - E.g., define single wind speed and direction (with uncertainty) for each trial
3. Coordinate model validation exercise
   - “Blind” or “a priori” tests – without access to measurement data
   - “A posteriori” tests – with knowledge of data
4. Collaborate with modelling teams: examine capabilities and limitations of different modelling approaches, discuss possible refinements of models, run sensitivity tests
5. Dissemination: jointly publish findings
   - Shared first with project partners, then later externally

RESEARCH AND GUIDANCE FROM HSE

Summary of results from the Jack Rabbit III international model inter-comparison exercise on Desert Tortoise and FLADIS

Simon Gant[1] , Joseph Chang[2], Sun McMasters[3], Ray Jablonski[3], Helen Mearns[3], Shannon Fox[3], Ron Meris[4], Scott Bradley[4], Sean Miner[4], Matthew King[4], Steven Hanna[5], Thomas Mazzola[6], Tom Spicer[7], Rory Hetherington[1], Alison McGillivray[1], Adrian Kelsey[1], Harvey Tucker[1], Graham Tickle[8], Oscar Björnham[9], Bertrand Carissimo[10], Luciano Fabbri[11], Maureen Wood[11], Karim Habib[12], Mike Harper[13], Frank Hart[13], Thomas Vik[14], Anders Helgeland[14], Joel Howard[15], Veronica Bowman[15], Daniel Silk[15], Lorenzo Mauri[16], Shona Mackie[16], Andreas Mack[16], Jean-Marc Lacome[17], Stephen Puttick[18], Adeel Ibrahim[18], Derek Miller[19], Seshu Dharmavaram[19], Amy Shen[19], Alyssa Cunningham[20], Desiree Beverley[20], Matthew O'Neal[20], Laurent Verdier[21], Stéphane Burkhart[21], Chris Dixon[22]

[1]Health and Safety Executive (HSE), [2]RAND Corporation, [3]Chemical Security Analysis Center (CSAC), Department of Homeland Security (DHS), [4]Defense Threat Reduction Agency (DTRA), [5]Hanna Consultants, Inc., [6]Systems Planning and Analysis, Inc. (SPA), [7]University of Arkansas, [8]GT Science and Software, [9]Swedish Defence Research Agency (FOI), [10]EDF/Ecole des Ponts, [11]European Joint Research Centre (JRC), [12]Bundesanstalt für Materialforschung und -prüfung (BAM), [13]DNV, Stockport, [14]Norwegian Defence Research Establishment (FFI), [15]Defence Science and Technology Laboratory (DSTL), [16]Gexcon, [17]Institut National de l'Environnement Industriel et des Risques (INERIS), [18]Syngenta, [19]Air Products, [20]Naval Surface Warfare Center (NSWC), [21]Direction Générale de l'Armement (DGA), [22]Shell

21st International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

27-30 September 2022

Participants in the JRIII Initial Modeling Exercise

#	Organization	Model	Model Type				Desert Tortoise			FLADIS		
			Empirical nomogram/ Gaussian plume	Integral	Gaussian Puff/ Lagrangian	CFD	1	2	4	9	16	24
1	Air Products, USA	VentJet		■			■	■	■	■	■	■
2	BAM, Germany	AUSTAL			■		■	■	■	■	■	■
3		VDI	■				■	■	■	■	■	■
4	DGA, France	PHAST v8.6		■			■	■	■	■	■	■
5		Code-Saturne v6.0				■				■	■	■
6	DNV, UK	PHAST v8.61		■			■	■	■	■	■	■
7	DSTL, UK	HPAC v6.5			■		■	■	■	■	■	■
8	DTRA, ABQ, USA	HPAC v6.7			■		■	■	■	■	■	■
9	DTRA, Fort Belvoir, USA	HPAC			■		■	■	■	■	■	■
10	EDF/Ecole des Ponts, France	Code-Saturne v7.0				■					■	
11		Crunch v3.1		■			■	■	■			
12	Equinor, Norway	PHAST v8.6		■			■	■	■	■	■	■
13	FFI, Norway	ARGOS v9.10			■		■	■	■	■	■	■
14	FOI, Sweden	PUMA			■		■	■	■	■	■	■
15	Gexcon, Netherlands	EFFECTS v11.4		■			■	■	■	■	■	■
16	Gexcon, Norway	FLACS				■	■	■	■	■	■	■
17	GT Science & Software	DRIFT v3.7.19		■			■	■	■	■	■	■
18	Hanna Consultants, USA	Britter & McQuaid WB	■				■	■	■			
19		Gaussian plume model	■							■	■	■
20	HSE, UK	DRIFT v3.7.12		■			■	■	■	■	■	■
21		PHAST v8.4		■			■	■	■	■	■	■
22	INERIS, France	FDS v6.7				■				■	■	■
23	JRC, Italy	ADAM v3.0		■			■	■	■	■	■	■
24	NSWC, USA	RAILCAR-ALOHA		■			■	■	■	■	■	■
25	Shell, UK	FRED 2022		■			■	■	■	■	■	■
26	Syngenta, UK	PHAST v8.61		■			■	■	■	■	■	■

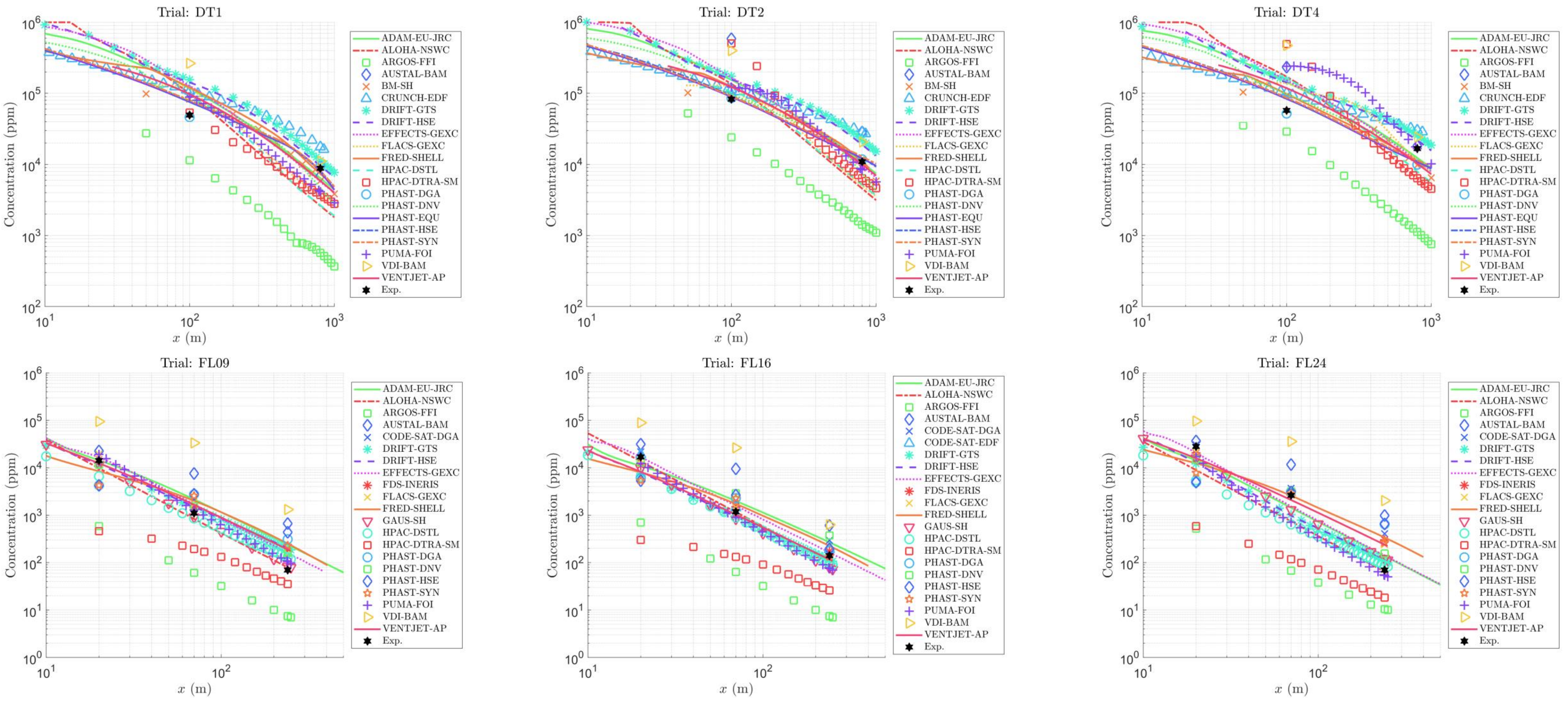
RESEARCH AND GUIDANCE FROM HSE

Modeling Inputs

		DT1	DT2	DT4	FLADIS9	FLADIS16	FLADIS24
Orifice diameter	m	0.081[a]	0.0945	0.0945	0.0063	0.004	0.0063
Release height	m	0.79	0.79	0.79	1.5	1.5	1.5
Exit temperature	°C	21.5	20.1	24.1	13.7	17.1	9.45
Exit pressure[b]	bara	10.1	11.2	11.8	6.93[c]	7.98[c]	5.70[c]
	barg	9.22	10.3	10.9	5.91	6.96	4.69
Release rate	kg/s	80.0[d]	117[e]	108[f]	0.40	0.27	0.46
Release duration	s	126	255	381	900	1200[g]	600
Site average wind speed	m/s	7.42	5.76	4.51[h]	6.1[i]	4.4	4.9[j]
at reference height	m	2	2	2	10	10	10
Friction velocity	m/s	0.442	0.339	0.286	0.44	0.41	0.405
Surface roughness	m	0.003	0.003	0.003	0.04	0.04	0.04
Monin-Obukhov length	m	92.7	94.7	45.2	348	138	-77
Pasquill stability class	-	D	D	D-E[k]	D	D-E	C-D[l]
Ambient temperature	°C	28.8	30.4	32.4	15.5	16.5	17.5
at reference height	m	0.82	0.82	0.82	1.5	1.5	1.5
Ambient pressure	bar	0.909	0.910	0.903	1.020	1.020	1.013
Relative humidity	%	13.2	17.5	21.3	86	62	53.6
Averaging time for mean values	s	80	160	300	600	600	400

- All trials involved horizontal releases of pressure-liquefied ammonia over flat, unobstructed terrain
- Data taken primarily from SMEDIS database (https://admlc.com/smedis-dataset)
- Cross-checks carried out with other information sources
  - Modelers Data Archive
  - REDIPHEM
  - Original data reports, e.g. Goldwire *et al*. (1985)
  - Notes provided to explain choice of values

All Model Results



Work Package 5: Model development and validation

- Outcomes:
  - Optimised design of field trials, using modelling to inform scope and parameters of the experimental programme
  - Detailed scrutiny of measurement data from the experimental work packages
  - Understand strengths and weaknesses of different modelling approaches
  - Potential to see development of new rapid dispersion modelling approaches
  - Findings could be useful to inform understanding of dispersion behaviour of other dense gases, e.g., LNG, LPG/propane, chlorine, ammonia

- Non-disclosure agreement:
  - Modellers asked to sign agreement not to disclose measurement data to external organisations outside the project for a defined period

WP6: Emergency Response

NCEC RICARDO

Work Package 6: Emergency response

- **Aim**: to engage with emergency responders and make best use of the CO_2 dispersion trials: help to prepare responders to deal with possible CO_2 release incidents
- Identify knowledge gaps in emergency response, working with Hazmat teams, Fire and Rescue Services and other emergency responders
- Test gas sensors, breathing apparatus, PPE etc. used by responders in the trials?
- Test vehicles can be used to evacuate casualties? (learning from Satartia incident)
- Opportunity for emergency responders to witness trials and review video footage as learning and training exercise
- Work package led by UK National Chemical Emergency Centre (NCEC) part of Ricardo



Examples of emergency responders involvement in the Jack Rabbit II project https://www.uvu.edu/es/jack-rabbit/

Work Package 6: Emergency response

- National Chemical Emergency Centre (NCEC) - Ricardo
  - Established in 1973 by the UK Government to provide emergency response support to incidents involving chemicals & dangerous goods
  - Provides 24/7 emergency response helpline staffed by specialists that provide technical support in dealing with incidents safely, minimising wider impacts and risk to people, the environment, assets and reputation
  - Helpline service operates internationally, with approx 8,000 calls per year
  - Strong links with UK hazardous materials teams and Fire and Rescue Services
  - Annual Hazmat conference (now in 15th year) brings together hazmat professionals, emergency responders, chemical safety experts: presentations, case-studies, practical hands-on workshops. Attendees from fire and rescue, police, airports, ambulance, MOD, chemical industry, regulators and the Met Office

Work Package 6: Emergency response

Activities:

- Collaborate with relevant Cat 1 & 2 response organisations to form working group
- Develop training package for working group to ensure all responders are aware of previous incidents and lessons learned
- Identify knowledge gaps in responders, ensuring relevant data is captured during trials
- Identify appropriate equipment for use during response to large scale CO_2 incidents
- Design operational, tactical, and strategic level training materials (inc. theoretical and scenario based) to be used by relevant response teams in preparation phase
- Design and deliver a large scale, multi-agency exercise to assess response teams
- Facilitate the development of standard operating procedures & operational guidance
- Work collaboratively with National Ambulance Unit & the Association of Amb Chief Execs, National Fire Chief's Council and National Police Chief's Council representatives to ensure learning is embedded in *all* relevant areas.

Work Package 6: Emergency response

- Outcomes:
  - Improved knowledge and awareness of emergency response to CO_2 incidents
  - Development of a training programme for emergency responders and testing of equipment to ensure it is fit for purpose
  - Public reassurance that in the (highly unlikely) event of a significant large CO_2 release, the emergency services are well prepared and equipped to deal with the incident
  - National standard operating procedures and guidance for managing a large-scale incident involving a CO2 release.

WP7: Venting

WP7: Venting

- At the CCSA meeting on 31 August, several organisations raised the issue of venting and the need for experimental data to validate dispersion model predictions
- Some data exists from COOLTRANS, but this is not publicly available
- Aim to assess if Froude/Richardson number correlations used to define jet/plume behaviour are valid
- Assess if specific vent designs could give rise to harmful concentrations downwind, near ground level
- Input from sponsors sought on defining range of conditions to be tested experimentally: vent diameter, temperature, pressure
- Is there interest in testing certain valve designs, following reports of some blowdown valves blocking in the open position due to solid CO_2?

WP7: Venting

- DNV costings are based on:
  - Two vent diameters (up to 2” NB diameter pipes)
  - Dense, supercritical and gaseous CO_2
  - Repeated tests on three days (low, moderate and high wind speeds)
- All combinations: 2 × 3 × 3 = 12 trials
- Conducted alongside other work packages whilst rigs are available in CO_2 service
- Measurements of:
  - Outflow rate, vent conditions (pressure / temperature)
  - CO_2 concentrations near ground level
  - Plume Temperature
  - Normal, thermal and high-speed videography

WP0: Project Management

WP0: Project Management

- **Project delivery team**
  - **DNV Spadeadam (experiments)**: Dan Allason, Rob Crewe, Keith Armstrong
  - **DNV (modelling and analysis):** Ann Halford, Karen Warhurst, Mike Harper, Jan Stene and Gabriele Ferrara
  - **HSE**: Simon Gant and Rory Hetherington
  - **University of Arkansas**: Tom Spicer
  - **NCEC**: Ed Sullivan
  - **Met Office**: Matt Hort and Frances Beckett
  - **External adviser**: Steven Hanna

- **Technical steering group**
  - Representative from each of the project sponsors (or their appointed technical consultant)

- **Modellers working group**
  - Representative from each of the modelling teams contributing and analysing results

WP0: Project Management: Rough budgets

WP	Title	Duration / Comment	Responsible
WP0	Project Management	3 Years	DNV
WP1	CO_2 Pipeline Craters and Source Terms	6 months in existing rig	DNV
WP2	Wind-tunnel Experiments	3 Years	UoA
WP3	Simple Terrain Dispersion Experiments	3 months in modified WP1 rig	DNV
WP4	Complex Terrain Dispersion Experiments	9 months in new rig	DNV
WP5	Model Development and Validation	3 Years	HSE
WP6	Emergency Response	Alongside WP1, WP3 and WP4	NCEC
WP7	Venting	At various times during WP1, WP3, WP4	DNV

- **~18 months of experimentation, weather dependence could extend this!**
- **Experimentation likely to be able to start late 2024, possibly into 2025. Rig builds may be able to be conducted in advance of this.**

WP0: Project Management

- **Summary of costs (approx. estimate, non-binding)**
  - **DNV**
  - **HSE**
  - **University of Arkansas**
  - **NCEC**
  - **Met Office**
  - **External adviser (Steven Hanna, etc.)**

- **~ £10M Budget**

No. Sponsors	Ticket Price (after DESNZ)	Per Year for 3 Years
4	£1.25M	£416k
5	£1.0M	£333k
6	£1.0M	£333k
7	£0.71M	£238k
8	£0.63M	£208k
9	£0.56M	£185k
10	£0.5M	£167k

- **Department of Energy Security and Net Zero (UK Government) contribution**: circa £5m
- **Ideal ten sponsors:** £0.5m per sponsor (spread over 3 years)
- **Potential consortium sponsors and US Government:** discussions welcomed

WP0: Project Management

- **Next steps**
  - All of the organisations participating on today's meeting will be sent a follow-up email with a form to complete asking:
    - Is your organisation willing to fund the project?
    - Would your organisation like to participate in the modelling exercises?
  - Timeline to respond: within one month
  - Aiming for contracts to be agreed and signed within six months
- **Benefits of sponsorship**
  - Membership of the technical steering committee
  - Opportunity to influence prioritisation and scope of trials
  - Full access to experimental data
  - Full access to model inter-comparison exercises and discussions

Input from ISO TC/265 Standards Committee

Standards by ISO/TC 265

Carbon dioxide capture, transportation, and geological storage

Filter : ☑ Published ☐ Under development ☐ Withdrawn ☐ Deleted

Search in the list

Standard and/or project under the direct responsibility of ISO/TC 265 Secretariat (0) ↑	Stage	ICS
ISO/TR 27912:2016 Carbon dioxide capture — Carbon dioxide capture systems, technologies and processes	60.60	13.020.40
ISO 27913:2016 Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems	90.92	13.020.40
ISO 27914:2017 Carbon dioxide capture, transportation and geological storage — Geological storage	90.92	13.020.40
ISO/TR 27915:2017 Carbon dioxide capture, transportation and geological storage — Quantification and verification	60.60	13.020.40
ISO 27916:2019 Carbon dioxide capture, transportation and geological storage — Carbon dioxide storage using enhanced oil recovery (CO2-EOR)	60.60	13.020.40
ISO 27917:2017 Carbon dioxide capture, transportation and geological storage — Vocabulary — Cross cutting terms	90.60	01.040.13 13.020.40
ISO/TR 27918:2018 Lifecycle risk management for integrated CCS projects	60.60	13.020.40
ISO 27919-1:2018 Carbon dioxide capture — Part 1: Performance evaluation methods for post-combustion CO2 capture integrated with a power plant	90.20	13.020.40
ISO 27919-2:2021 Carbon dioxide capture — Part 2: Evaluation procedure to assure and maintain stable performance of post-combustion CO 2 capture plant integrated with a power plant	60.60	13.020.40
ISO/TR 27921:2020 Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO2 stream composition	60.60	13.020.40
ISO/TR 27922:2021 Carbon dioxide capture — Overview of carbon dioxide capture technologies in the cement industry	60.60	13.020.40
ISO/TR 27923:2022 Carbon dioxide capture, transportation and geological storage — Injection operations, infrastructure and monitoring	60.60	13.020.40
ISO/TR 27925:2023 Carbon dioxide capture, transportation and geological storage — Cross cutting issues — Flow assurance	60.60	13.020.40

https://www.iso.org/committee/648607.html

Concluding remarks

Dispersion field trials: naming conventions

<u>Historical trials</u>

- **Avocet**: LNG
- **Burro**: LNG
- **Coyote**: LNG
- **Desert Tortoise**: Ammonia
- **Eagle**: nitrogen tetroxide
- **Falcon**: LNG
- **Goldfish**: hydrogen fluoride
- **Kit fox**: carbon dioxide
- **Jack Rabbit**: chlorine and ammonia
- **Red Squirrel**: ammonia

Proposed name for these experiments:

the Skylark CO_2 trials

https://www.birdguides.com/gallery/birds/alauda-arvensis/1003602/

Thank you

- If you have further questions/comments, please do not hesitate to get in touch:
  - simon.gant@hse.gov.uk
  - daniel.allason@dnv.com (the correct email this time!)

- Opportunity to discuss further at PHMSA Pipeline Safety R&D Forum

  https://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=166

  31 October – 1 November, Arlington, Virginia, USA

www.dnv.com