WHEN TRUST MATTERS

SkyLark

CO_2 Dispersion Joint Industry Project

DNV Spadeadam and HSE Science, Engineering and Analysis Division

SkyLark - CO_2 Hazards

Main things to talk about:

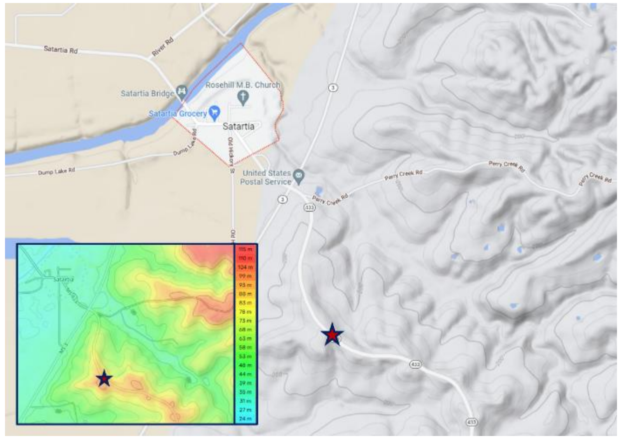
- Why? Motivation
- What do we already know?
- What gaps are there in the knowledge?
- How can we begin to fill the gaps?
- How are we progressing?

Why?

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

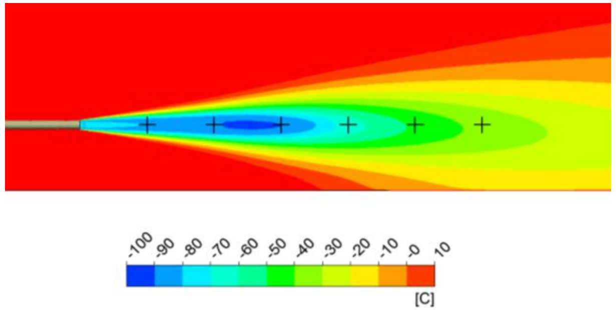
What do we already know?

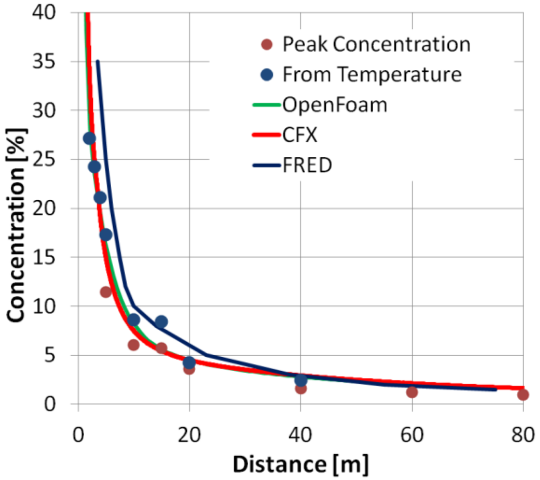
CCS safety research over the period 2007-2017

IChemE SYMPOSIUM SERIES NO. 153

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





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

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

https://webarchive.nationalarchives.gov.uk/ukgwa/20230103152332/https://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

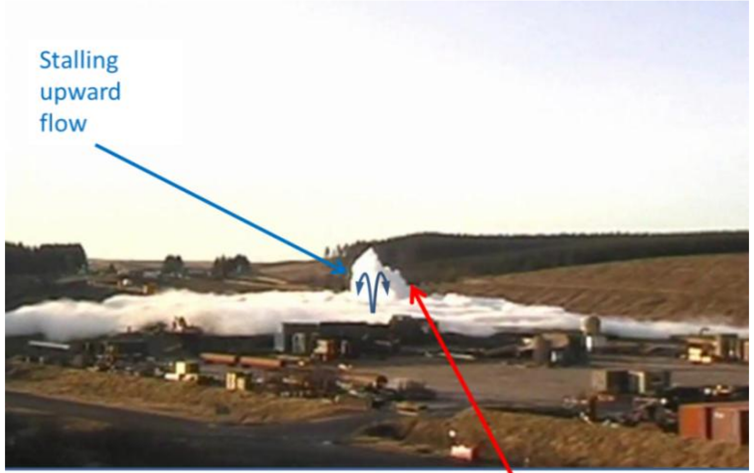
Julian Barnett
National Grid
Solihull, UK

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]

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

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

219 mm (8.6 inch) diameter pipeline ruptured

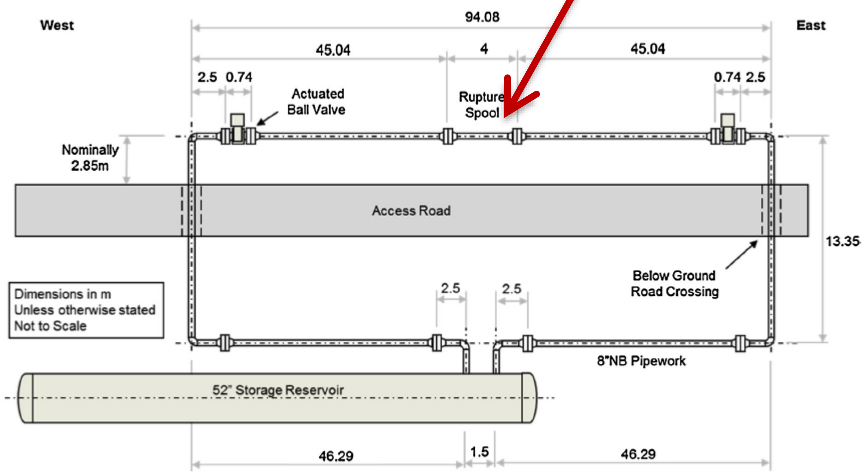


Fig. 1. The pipeline loop (plan view).

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.

COSHER

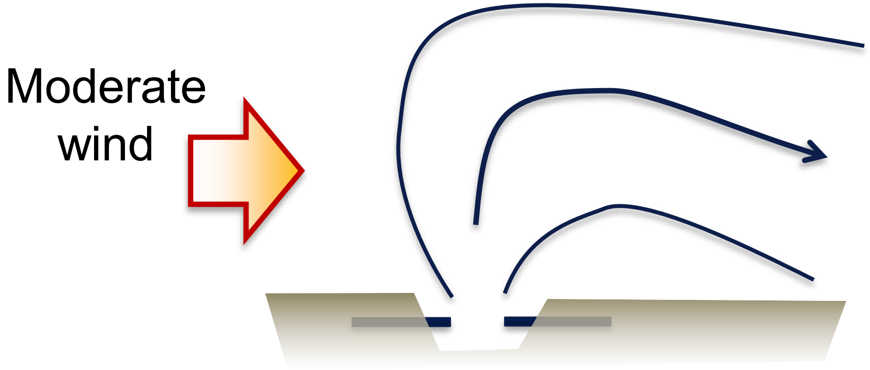
- CO_2 behaves as a dense gas
- Initial plume at release point and vapour slumps to the ground
- Spreads into two shallow valleys either side of the site
- Wind blowing from bottom to top of view
  - Some vapour spreads upwind

Side View

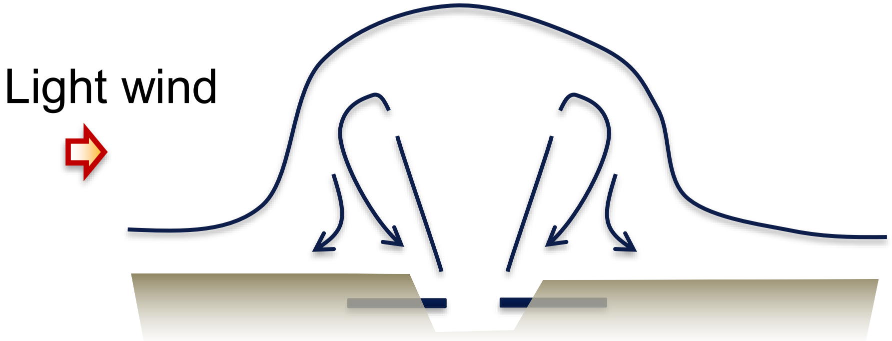
What gaps are there in the knowledge?

Knowledge Gaps

1. Source characteristics from CO_2 pipeline craters



Bent-over plume, no re-entrainment



Plume falls onto crater, re-entrainment, blanket

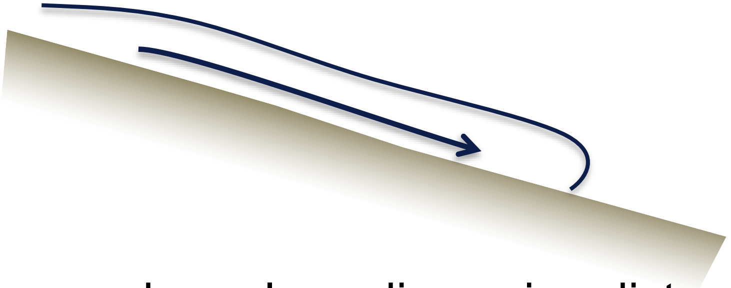
- Questions:
  - Which set of conditions give rise to these two different sources (wind speed, release size etc.)?
  - What are the characteristics of the dispersion source term (composition, flow rate, temperature etc.)?
  - Experimental data is limited to just two COSHER tests (COOLTRANS data is currently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

Work Package 1: CO_2 pipeline craters and source terms

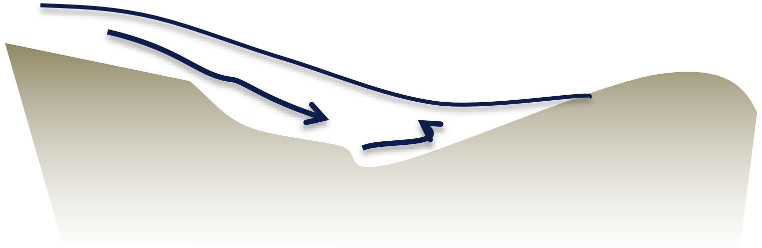
- Conduct experiments on both ruptures and smaller holes (punctures) on side, top and/or bottom of pipeline
- Measure CO_2 concentration and temperature at array of points
- Photograph maximum plume height and cloud shape
- Visibility of interest for emergency response

Knowledge Gaps

2. Terrain effects on dense clouds



Larger downslope dispersion distances?

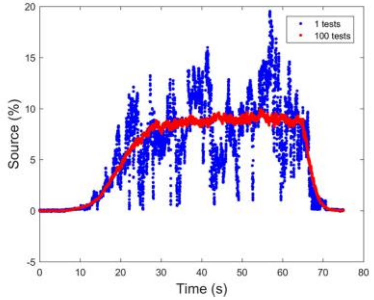


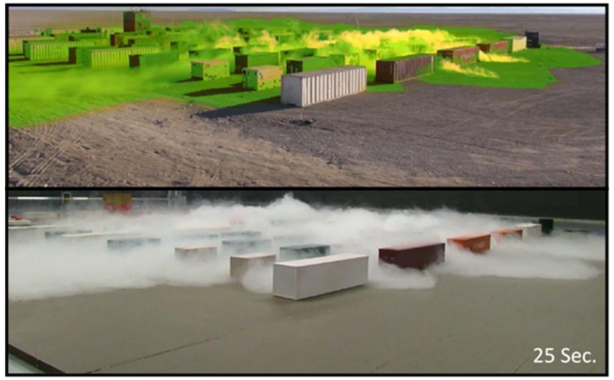
Channelling effects in complex terrain, vapour hold-up in valleys

- 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?

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





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

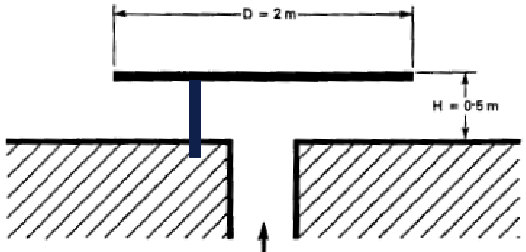


Fig. 22.4 Geometry of ground-level source for continuous release experiments

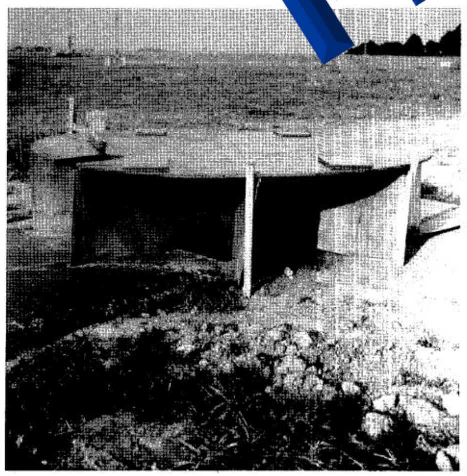
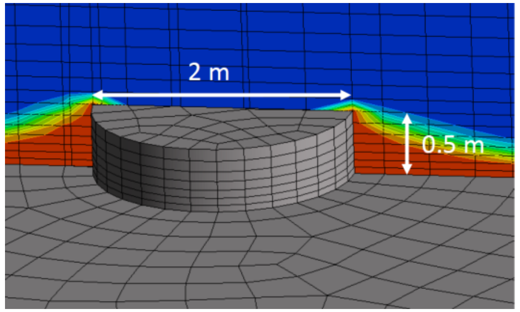
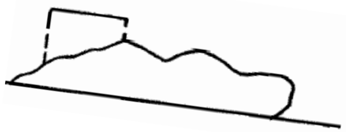


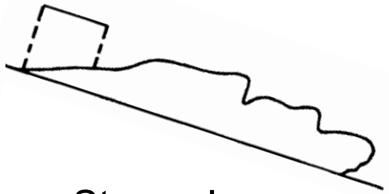
Fig. 22.2 Outlet from the gas supply duct at the release point



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



Shallow slope



Steep slope

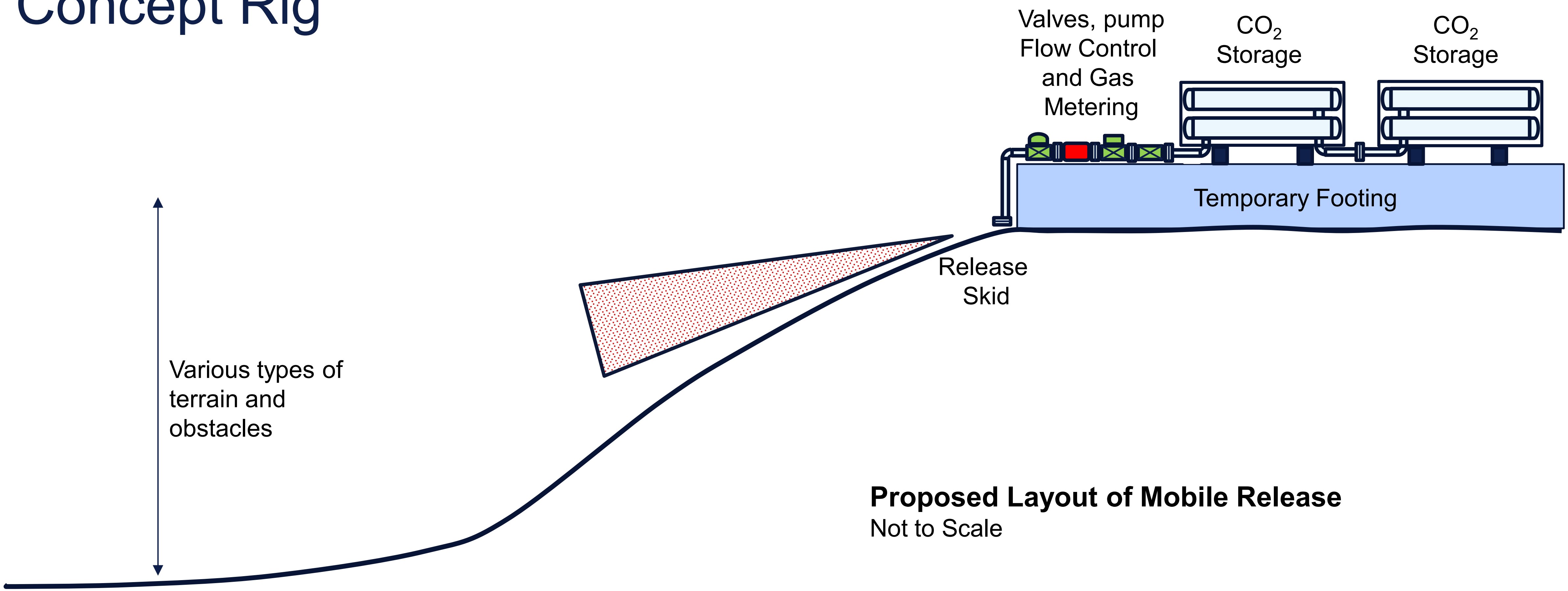
How does dispersion behaviour compare to flat terrain?

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)?

Work Package 4: Complex Terrain Dispersion Exps

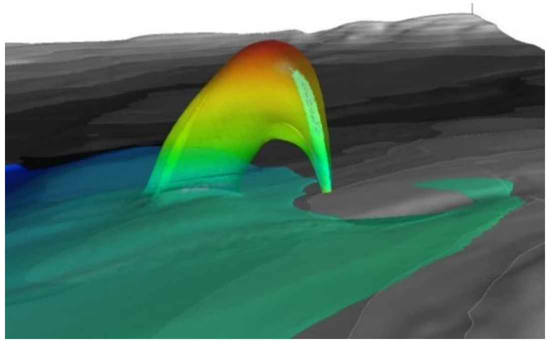
Concept Rig



Proposed Layout of Mobile Release
Not to Scale

Work Package 5: Model evaluation and validation

- **Aim**: to evaluate, 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



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/

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 CO2 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.

WP 7 Venting

4. How will operators manage their venting operations?

- 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, valve types – there is a need to be close to operational requirements.
  - Some reports of blowdown systems struggling with solid CO_2 formation

How can we fill the gaps?

Project Skylark

Transportation of carbon dioxide forms an important element of any accelerated decarbonisation initiative. Repurposed and new-build capture, transportation and storage infrastructure will be required and **must** be delivered safely.

Identify the Challenges

Challenge 1: Source characteristics from CO_2 pipeline craters

Challenge 2: Terrain effects on dense clouds

Challenge 3: Emergency Response

Challenge 4: Operational Issues (venting)

Address the Challenges

WP0 - Project Management

Coordination of the JIP throughout its ~3 year duration.

WP1 - CO_2 Pipeline Craters and Source Terms

Large scale experiments involving gaseous and dense-phase buried pipeline ruptures to assess crater formation and generation of different source terms.

WP2 - Wind Tunnel Experiments

Reduced-scale experiments at University of Arkansas to investigate crater sources and complex terrain effects for a wide range of precisely controlled atmospheric conditions.

WP3 - Simple Terrain Dispersion Experiments

Well-defined large-scale releases of CO_2 onto simple slopes of varying inclination in one plane with dispersion measurements.

WP4 - Complex Terrain Dispersion Experiments

Large, dense phase releases of CO_2 onto complex terrain including multi-planar slopes (valleys, hills, obstacles) with dispersion measurements.

WP5 - Model Evaluation

HSE SD will coordinate a series of model validation exercises using the experimental data generated in this project. The aim is to encourage the development of a variety of tools of differing complexity to enable robust pipeline risk assessment, permitting studies and emergency planning and response.

WP6 - Emergency Response

Led by Ricardo's NCEC, this work package will engage with emergency responders to make best use of the CO_2 dispersion trials. Development of training materials and best-practices for emergency response will be developed with the learning from the experiments and critical pieces of equipment will be tested for their operability in emergency scenarios.

WP7 - Venting

Near full-scale venting experiments will be conducted alongside other work packages to assess the dispersion behaviour and measure temperatures.

How are we progressing?

WP1: Rupture Experiments

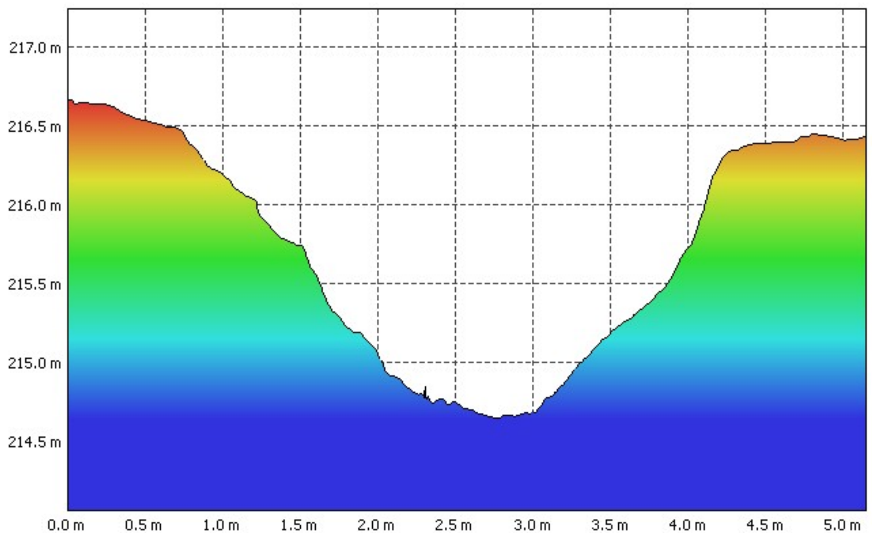
Work Package 1 – Testing Progress

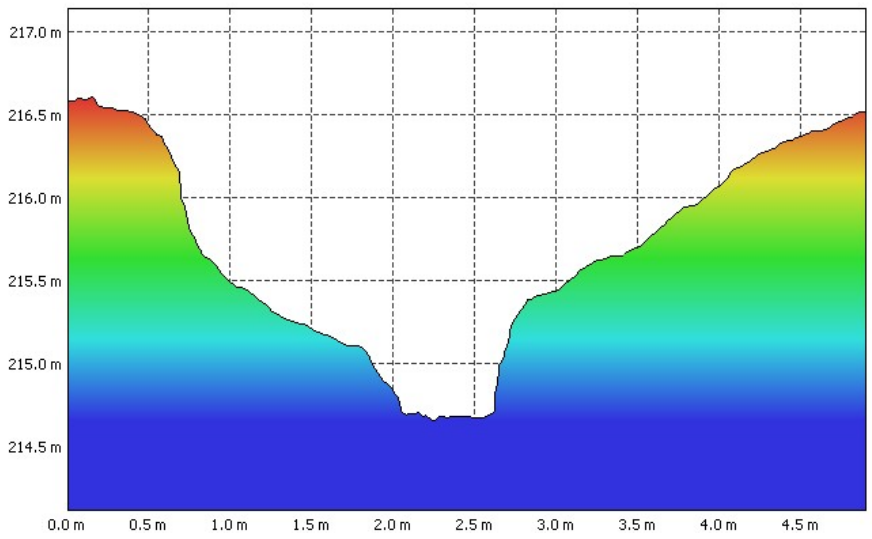
Experiment ID	Completion Date	Type	Orientation	Initial Condition	Comment	Notes
1-01	20/03/2026	4" Rupture	Double ended, east-west	150barg, ambient temperature	Changes in ambient wind condition	Completed in 4-5 m/s wind with axial cut
1-02		4" Rupture				Complete in low wind with axial cut (COSHER style)
1-03	10/06/2026	4" Rupture				Completed in low wind with circumferential cuts
1-04	13/04/2026	4" Rupture		Saturation conditions - Reservoir to be hydraulically full	Open crater from previous test(s), changes in ambient condition	Open crater, saturation condition into 1-09 crater, use for low wind speed opportunity
1-05		4" Rupture				Open crater, saturation condition into 1-02 crater, different wind condition
1-06	23/06/2026	4" Rupture				Open crater, saturation condition into 1-03 crater, different wind condition
1-07	24/04/2026	4" Rupture		~40barg, ambient temperature	Gas Phase	Perform with circumferential cuts (Needs to be repeated)
1-08		4" Rupture			Open crater from previous test, changes in ambient condition	Instead of restriction, use lower start pressure (requirement of reservoir minimum temperature)
1-09	31/03/2026	4" Rupture		150barg, ambient temperature	Condition to match one of Experiment 1-1 to 1-4 but with complete cut-away of ruptured section. Investigate difference in source term, crater formation etc.	Completed in 4-5 m/s wind
1-10		4" Rupture			Changes in ambient wind condition	Complete in <5m/s wind with axial cut (COSHER Style) and sandy backfill
1-11						Complete in <5m/s wind with circumferential cuts

WP1 Test Highlights

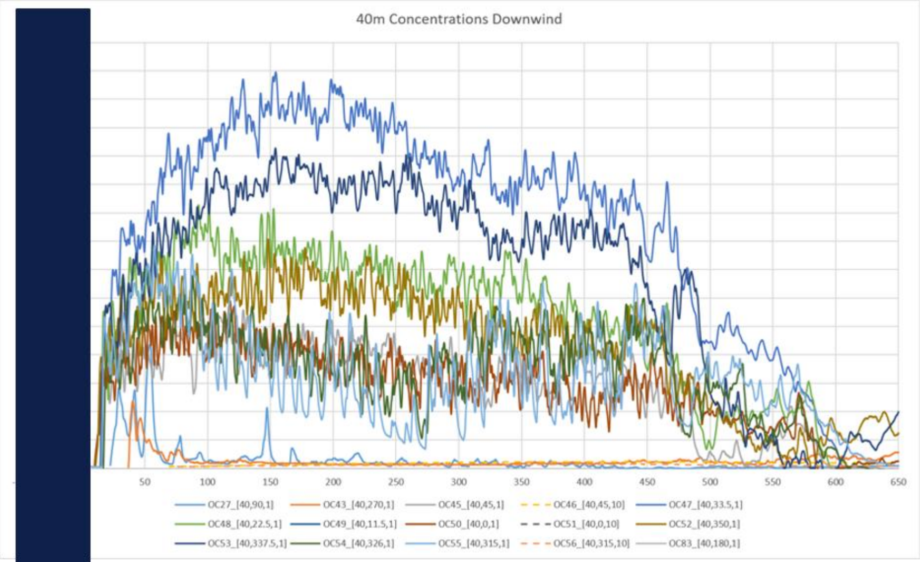
WP1 Test Highlights

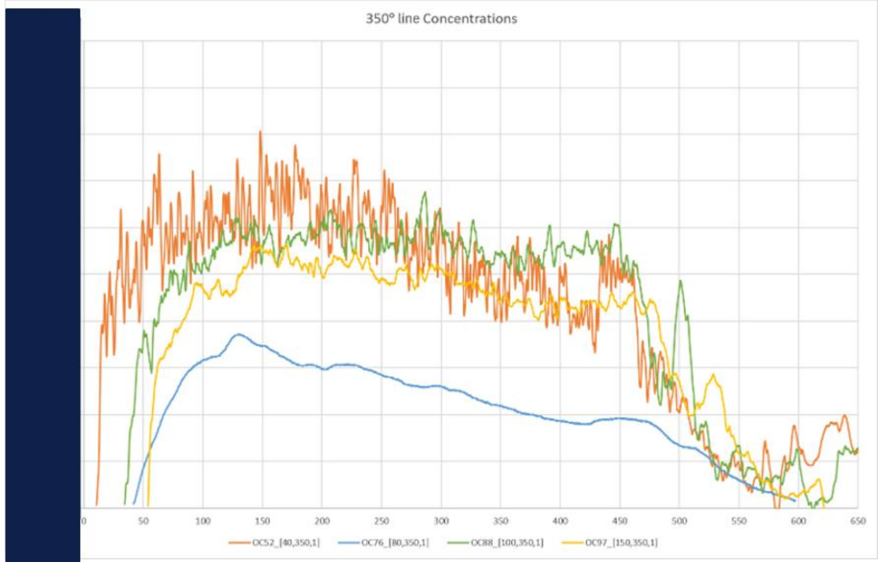
WP1 Test Highlights

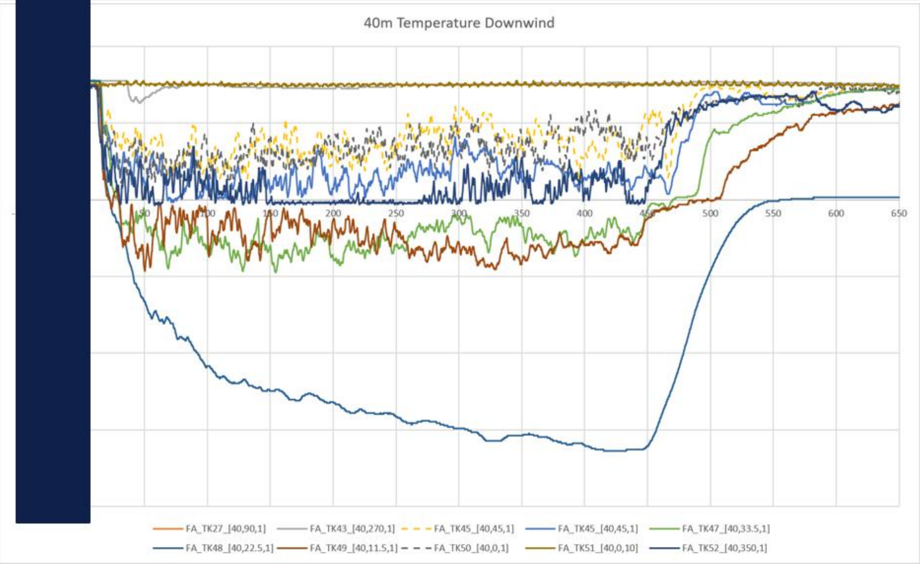


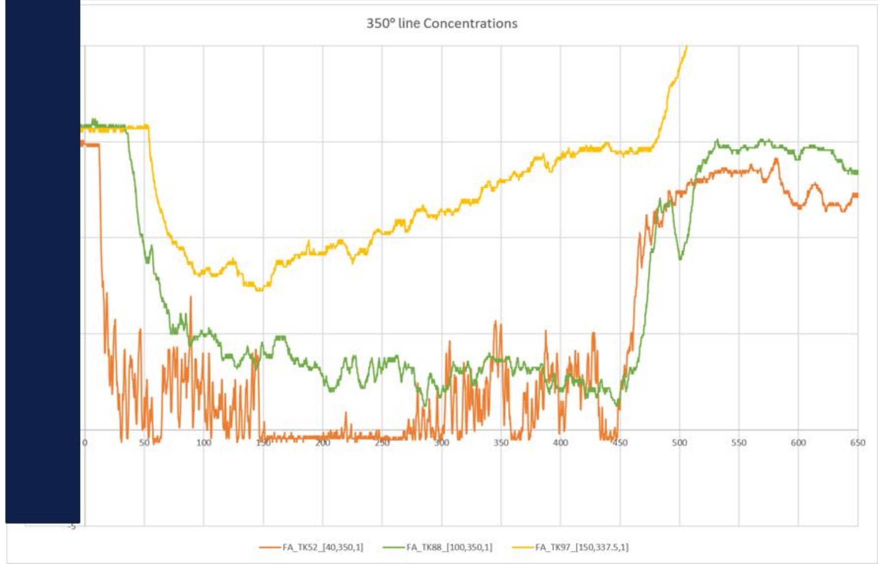


WP1 Sample Dispersion Data



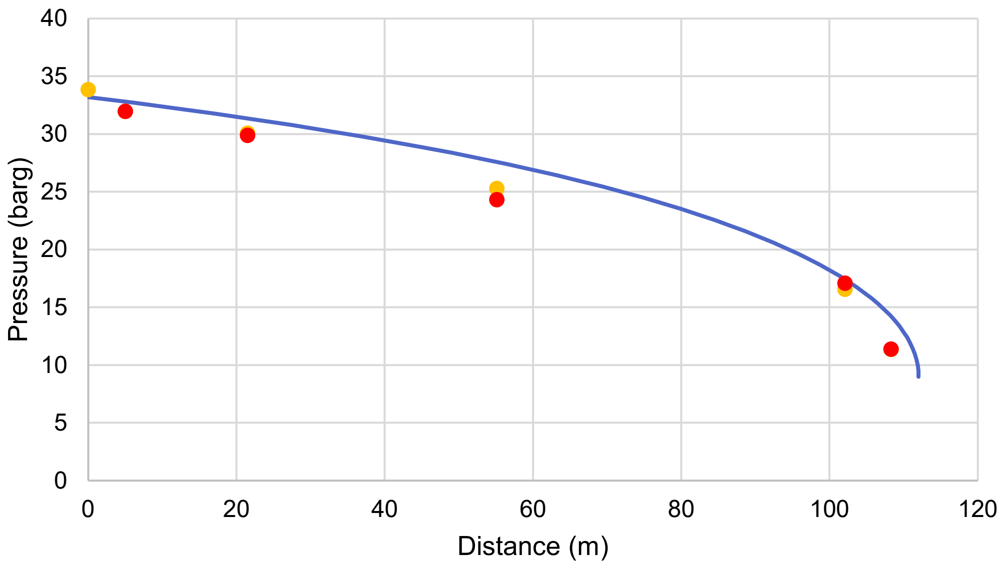






Prediction of Flow from Pressure Gradient

- Compare pressure along 4” pipe predicted by Excel/GasVLe model with measured pressures



- Can be improved with further works on incorporating bends etc. at correct locations
- Useful for verifying outflow supplied to modelling exercise.

WP7: Complex Terrain Experiments

WP4 Programme Update

- 76 experiments scheduled
- 60 jet releases
- 8 punctures
- 12 ‘low momentum’

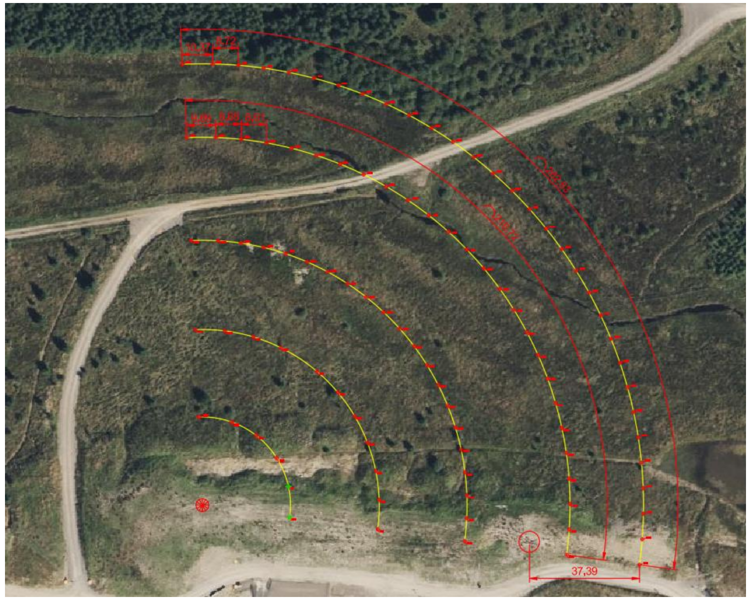
Experiment ID	Completion Date	Type	Location	Orientation / Initial Fluid Condition	Orifice Diameter	Ambient Condition	Comment
4-01		Jet Release	Location A	Horizontal, 150 barg	¼"	Low Wind, co-flowing	Aim for similar conditions
4-02					½"		
4-03					1"		
4-04					¼"	Low Wind, non-co-flowing	Aim for similar conditions
4-05					½"		
4-06					1"		
4-07				Vertical Down, 150 barg	¼"	Low Wind, co-flowing	Aim for similar conditions
4-08					½"		
4-09					1"		
4-10					¼"	Low Wind, non-co-flowing	Aim for similar conditions
4-11					½"		
4-12					1"		
4-13				TBC – use for repeatability			
4-14				TBC – use for repeatability			
4-15				TBC – use for repeatability			
4-16				TBC – use for repeatability			
4-17				TBC – use for repeatability			
4-18				TBC – use for repeatability			
4-19				TBC – use for repeatability			
4-20				TBC – use for repeatability			
4-61		Puncture	Location ABC	Upwards, 150 barg	1"	Low wind	All experiments buried and orientation achieved by rotating puncture spool
4-62				Horizontal, 150 barg	1"	Low wind	
4-63				Vertical Down, 150 barg	1"	Low wind	
4-64				Upwards, 150 barg	2"	Low wind	
4-65				Horizontal, 150 barg	2"	Low wind	
4-66				Vertical Down, 150 barg	2"	Low wind	
4-67				Vertical Down, ~40barg	1"	Low wind	Gas phase
4-68				Vertical Down, ~40barg	2"	Low wind	Gas phase
4-69		Low Momentum	Location A	Low Momentum, 150 barg	Size 1	Low Wind, co-flowing	Aim for similar conditions
4-70					Size 2		
4-71					Size 1	Low Wind, non-co-flowing	Aim for similar conditions
4-72					Size 2		
4-73					TBC	TBC	TBC
4-74			Location B (different to 4-69)	Low Momentum, 150 barg	Size 1	Low Wind, co-flowing	Aim for similar conditions
4-75					Size 2		
4-76					Size 1	Low Wind, non-co-flowing	Aim for similar conditions
4-75					Size 2		
4-76					TBC	TBC	TBC

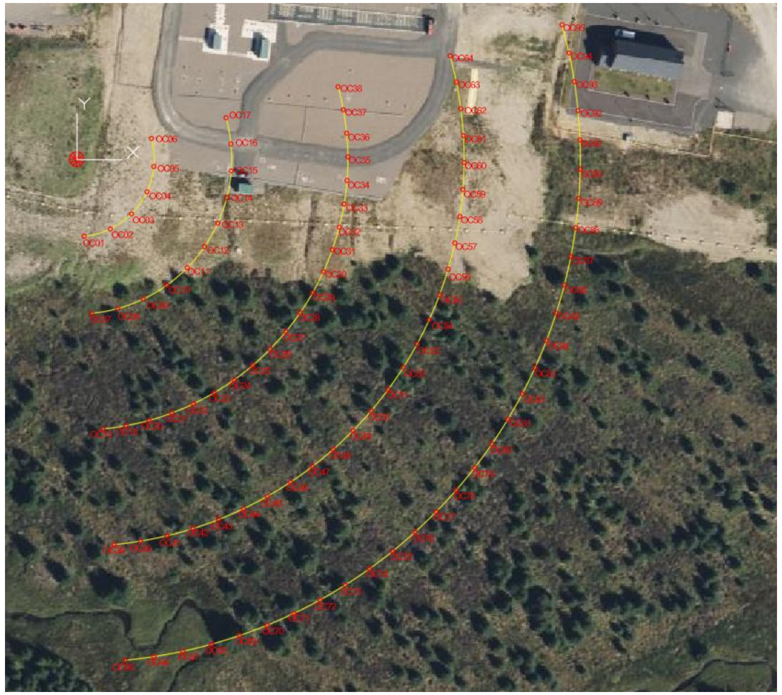
WP4 Build Update

- Vessel build complete
- Vessels at location 1 (releasing North + East)
- Release pipework build in progress
- Test procedure in progress

WP4 Build Update – Field Array

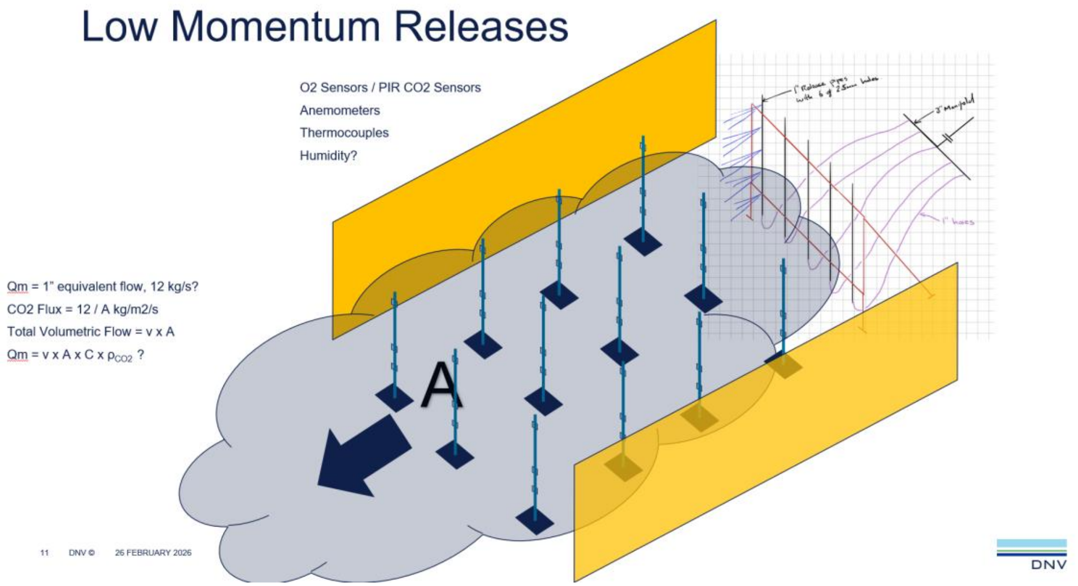
- Field Array setup for 2 release locations
- 95 sensors in the field array + 5 additions sensors for measurement at height
- Oxygen cells and thermocouples 0.3m above ground level
- 20 additional sonic anemometers in the array





WP4 Low Momentum tests

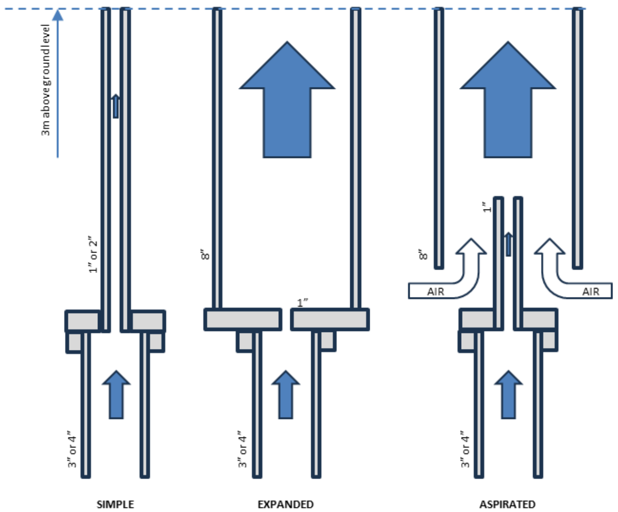
- ISO container for reduction of momentum
- Characterisation of flow through container
- Accounting for solid formation
- Repeatability?



WP7: Venting Programme

Experiment ID	Completion Date	Orientation / Initial Fluid Condition	Orifice Diameter	Comment
7-01		1” Vent, upwards, 150 barg, dense phase	Low Wind (2-3m/s)	WP1
7-02			Higher Wind (5-7+ m/s)	
7-03		1” Vent, upwards, 40 barg, gaseous	Low Wind (2-3m/s)	WP1
7-04			Higher Wind (5-7+ m/s)	
7-05		2” Vent, upwards, 150 barg, dense phase	Low Wind (2-3m/s)	WP1
7-06			Higher Wind (5-7+ m/s)	
7-07		2” Vent, upwards, 40 barg, gaseous	Low Wind (2-3m/s)	WP1
7-08			Higher Wind (5-7+ m/s)	
7-09		1" < 8" Expanded Vent, 150 barg, dense phase	Low Wind (2-3m/s)	WP1
7-10			Higher Wind (5-7+ m/s)	
7-11		1” < 8" Aspirated Vent, upwards, 150 barg, dense phase	Low Wind (2-3m/s)	WP1
7-12			Higher Wind (5-7+ m/s)	

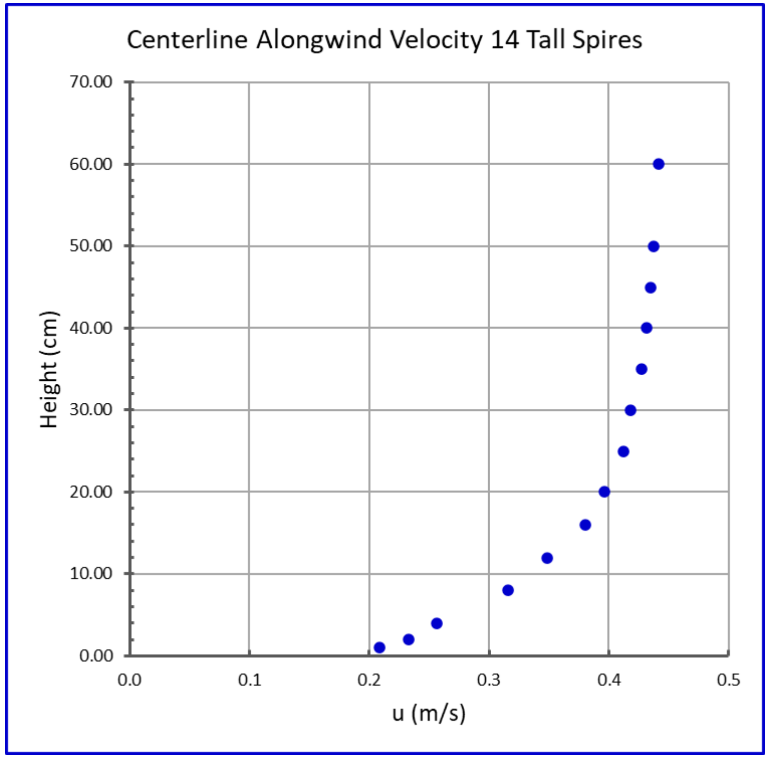
CO2PIPETRANS (DNV)

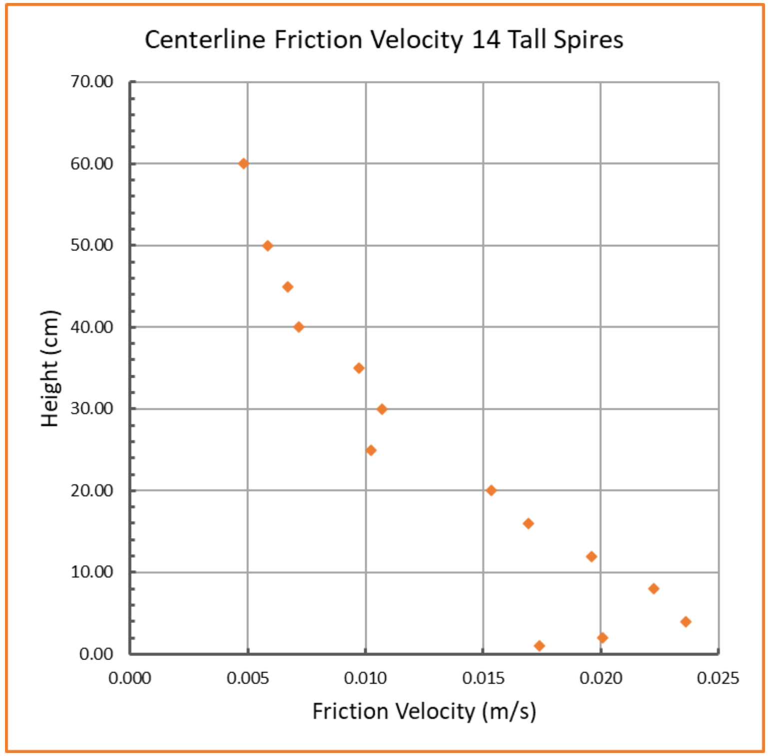


WP2: Wind Tunnel Experiments

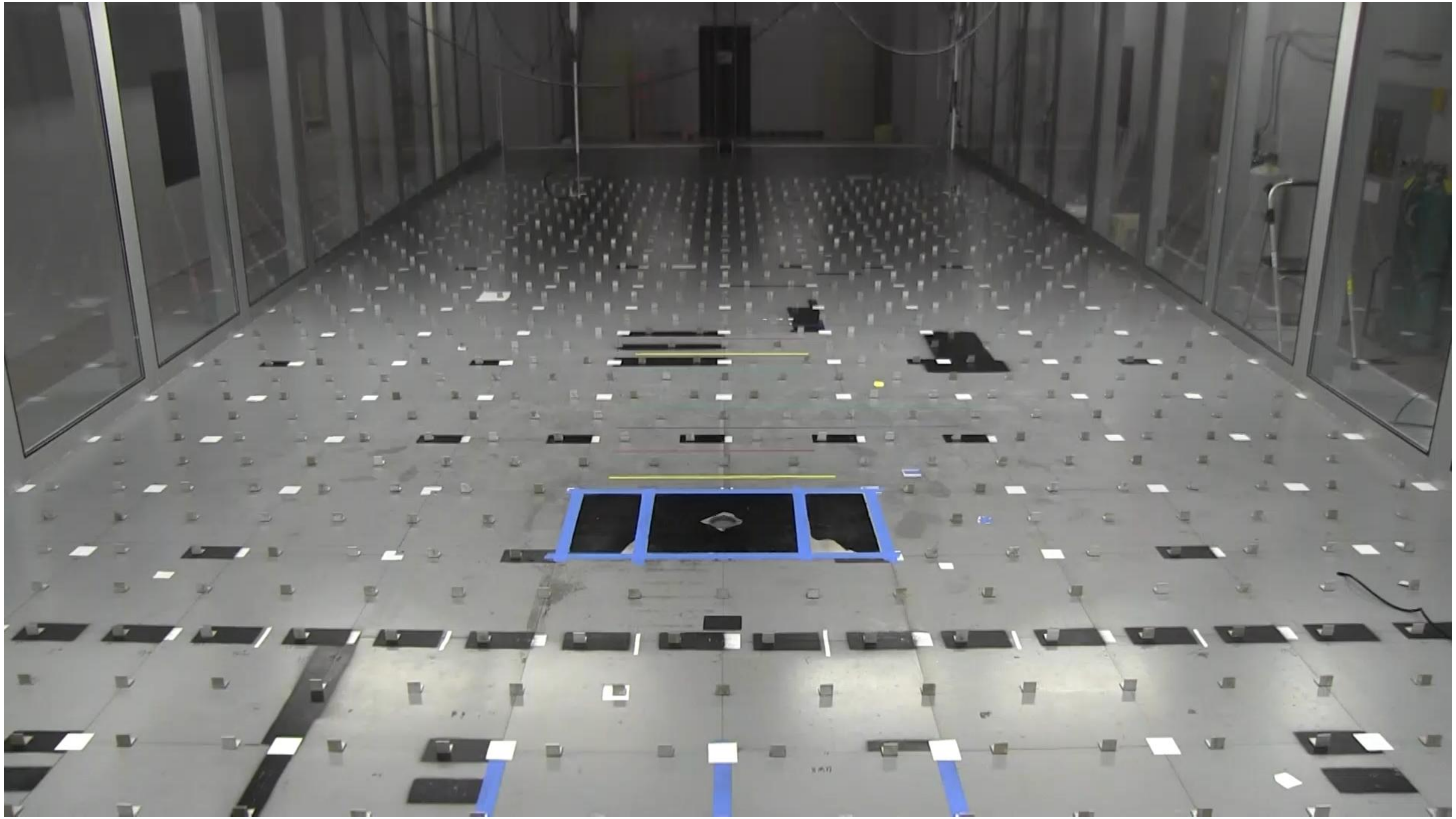
Low Speed Wind Profile

- Target: 2 m/s at 2 m elevation field scale (50:1 length scale; 7.1:1 velocity scale)
- Measured Profile at field scale: 1.81 m/s at 2 m (0.26 m/s at 4 cm)



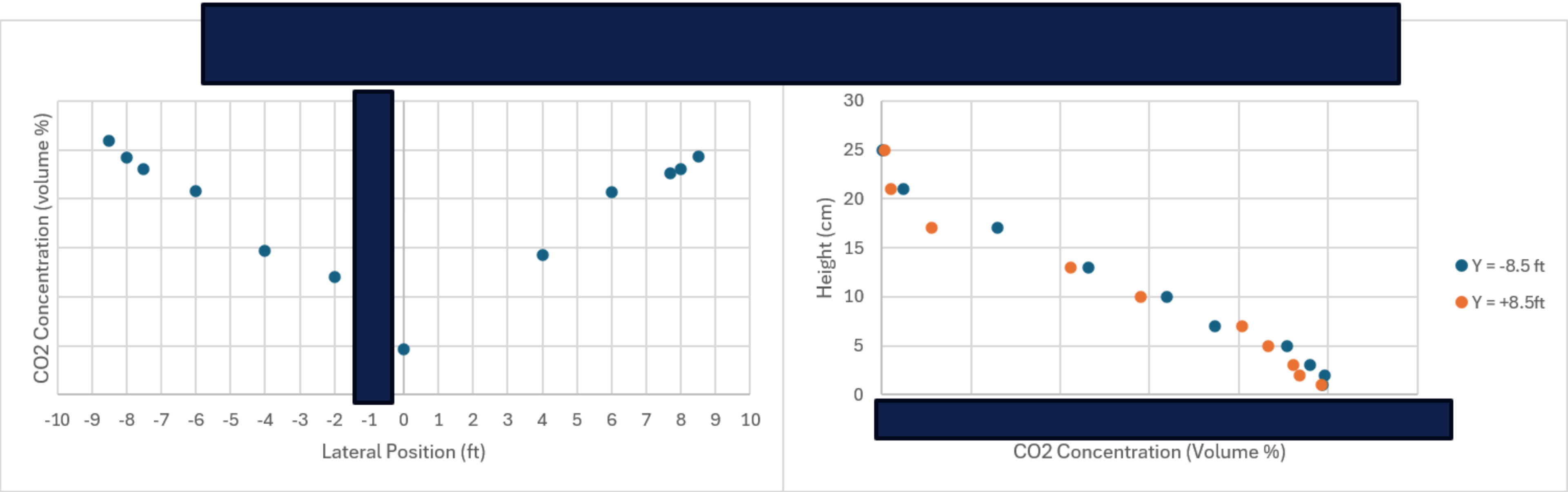


UNIVERSITY OF ARKANSAS
COLLEGE OF ENGINEERING



UNIVERSITY OF ARKANSAS
COLLEGE OF ENGINEERING

[redacted]



Make concentration measurements for lateral profiles at 2 cm height based on visualization experiments:

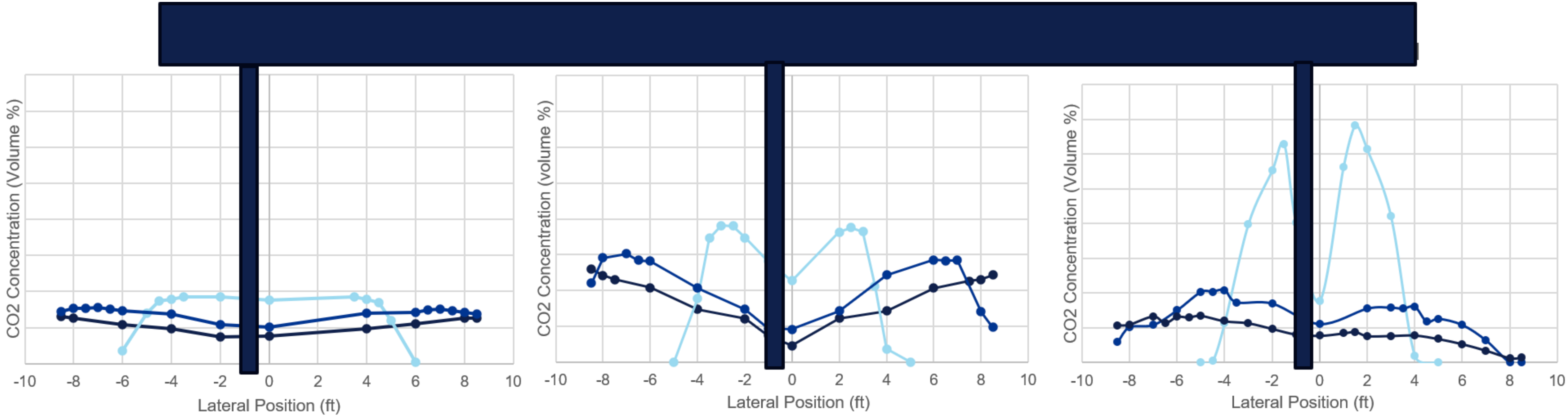
- Middle of initial touchdown
- Just upwind of the location where the cloud has spread to the tunnel walls
- At least one intermediate distance

Make concentration measurements for a vertical profile at the lateral distance with the largest measured concentration at 2 cm

DNV

UNIVERSITY OF ARKANSAS
COLLEGE OF ENGINEERING

Lateral Concentration Profiles



10 ft downwind from source
14 ft downwind from source
18 ft downwind from source

5 ft downwind from source
9 ft downwind from source
12 ft downwind from source

2 ft downwind from source
10 ft downwind from source
16 ft downwind from source

WP5: Model Evaluation Exercise

Ongoing Skylark WP5 tasks at HSE

- **To support WP1 tests**
  - Discuss with NCAS and DNV the weather data needed for future WP1 model evaluation activities
  - Prepare document on processing of weather data for MWG
  - Prepare initial specification document for modellers, describing model inputs requested outputs
  - Communicate developments with Modellers’ Working Group and ask for feedback on initial specification document
  - Develop method for processing test data for MWG
- **To support WP4 tests**
  - Evaluate empirical formulae for CO_2 detrainment from valley, to assess when terrain is significant
  - Examine terrain data for WP4 tests and put into format for modellers
- **Other**
  - Administration of NDA forms for MWG

PROTECTING PEOPLE AND PLACES HSE

MWG update

- Skylark modellers' working group meeting on 01 July 2026
  - To provide a progress update on Skylark
    - To discuss the first Skylark model evaluation exercise
    - Simulating the DNV Work Package 1 experiments on pipeline craters and source terms
    - Explain what model inputs will be provided (in general terms)
    - Present what outputs will be requested
    - Discuss proposed timeline
- NDA forms largely complete

PROTECTING PEOPLE AND PLACES HSE

Processing concentration data for the MWG

- What do modellers need from the trials?
  - Peak and average concentrations at each sensor
  - Transient data- arrival and exit times
- Can we develop an algorithm which extracts this data?
- Some work was undertaken in by HSE in 2014 to develop a method[1], using experimental data:
  - Dense-phase CO2 releases from buried pipelines (**COOLTRANS**)
  - Horizontal, above-ground releases of dense-phase CO2 over unobstructed terrain- Shell tests, for which data has been released as part of the **CO2PipeTrans** project
  - Obstructed CO2 vapour releases in the **CHRC** wind tunnel
- This method has been used in the analysis which follows…

[1]internal report

DNV

Processing concentration data for the MWG

Consider some typical concentration time-series

- Sharp rise at arrival
- Plateau of sustained concentration
- Decay once the cloud passes
- Fluctuations

Steps in the original algorithm:

- Pre-compute a 3s moving average of the signal
- Find a dose window from $C(t)$
- Find an averaging window from $C(t)$

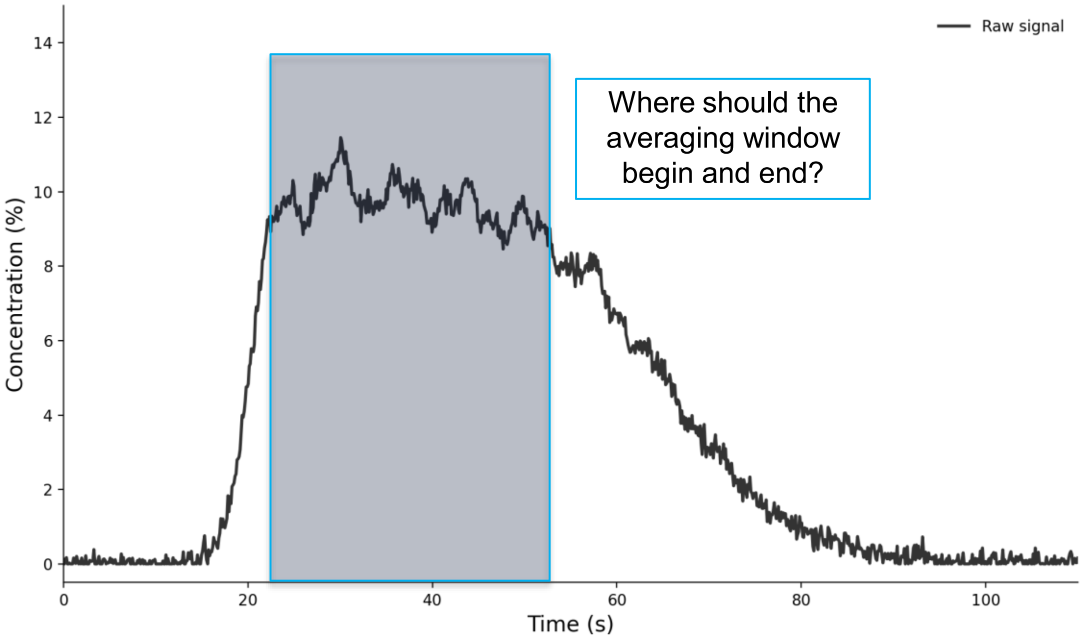


Figure: Time-series of concentration (synthetic data)

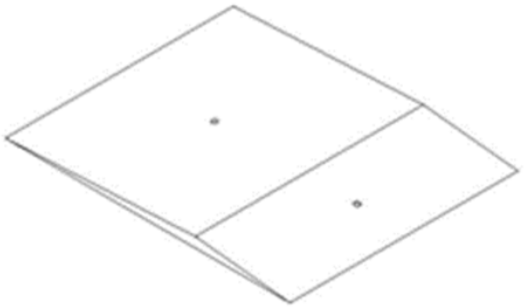
Processing wind field data

- Wind field data has been collected during the WP1 rupture tests from NCAS Mast A, and a DNV mast near the source (see figure below)
- Both NCAS Mast A and the DNV masts are upwind from the WP1 release location
- NCAS and HSE are reviewing the data to extract input parameters for the MWG (i.e. calculation of z_0)
- HSE wrote a report on the data processing method which has since been reviewed
- A meeting is scheduled with NCAS and other meteorological experts for 12 August to review the methods used

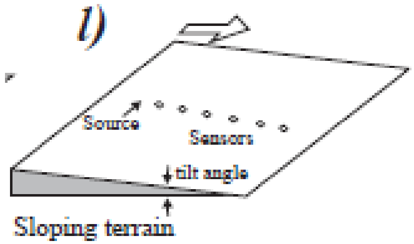
Figure: approx. locations of the NCAS Mast A and DNV mast used for WP1 tests

Complex terrain in the wind tunnel

- Discussions ongoing with UoA and the technical group with regards to the design of the terrain wind tunnel experiments
- HSE have reached out to several modellers to gauge interest in modelling dense gas dispersion on slopes
- Wind tunnel experiments will provide an opportunity for model development with quality validation data



WP2 Wind tunnel tests- slope terrain



Case l, from Nielsen and Ott (1996)

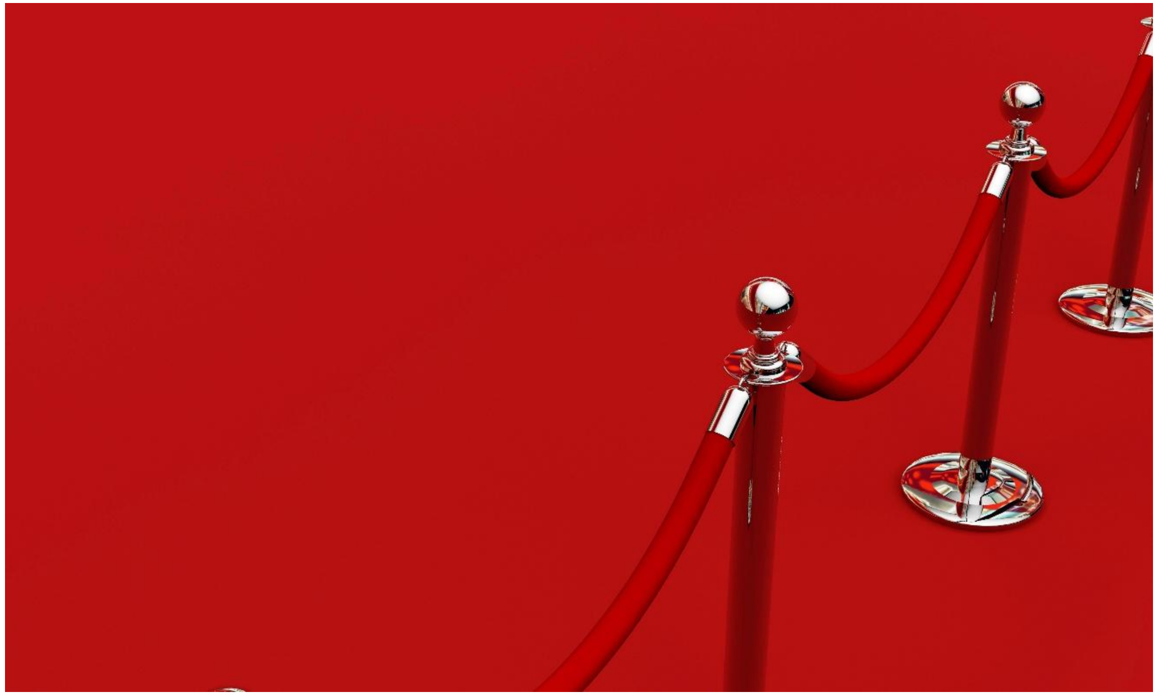
WP6: Emergency Response (WSP)

Emergency response Proposed test areas have been approved and developing the programme

- 1 - We want to establish how much of a safe haven a car provides.
- 2 - We want to establish how the gas permeates a house and how long it takes to clear.
- 3 – Most effective way to ventilate an enclosed space
- 4 – Measure the persistence of carbon dioxide in a low-lying areas.
- 5 – Effectiveness of natural barriers such as tree lines
- 6 – Effectiveness of a fire service water curtain

Building credible data for informing operational procedures

- In the meantime we continue to collect data with repeat data for 100, 200 and 300m
- Data are building our confidence in the guidance for standard cordons
- Initial testing with the thermal camera has shown no difference from visible plume
- We will carry out further tests at a closer distance to confirm results
- Dedicated tests will inform the operational guidance further



We continue to engage with industry partners to embed best practice in the emergency response ops

- Operational teams from Netherlands, Norway, Denmark and US have been consulted
- Working with industry partners to develop additional empirical data to compliment their operational gaps
- Has led to some good discussions on how best to design the dedicated releases and provide robust evacuation and shelter guidance
- We will continue to engage ahead of the remaining tests alongside input from the RWG

WP6: Emergency Response (WSP)

Transportation of carbon dioxide forms an important element of any accelerated decarbonisation initiative. Repurposed and new-build capture, transportation and storage infrastructure will be required and **must** be delivered safely.

Identify the Challenges

Challenge 1: Source characteristics from CO_2 pipeline craters

Challenge 2: Terrain effects on dense clouds

Challenge 3: Emergency Response

Challenge 4: Operational Issues (venting)

Address the Challenges

Project Skylark

WP0 - Project Management

Coordination of the JIP throughout its ~3 year duration.

WP1 - CO_2 Pipeline Craters and Source Terms

Large scale experiments involving gaseous and dense-phase buried pipeline ruptures to assess crater formation and generation of different source terms.

WP2 - Wind Tunnel Experiments

Reduced-scale experiments at University of Arkansas to investigate crater sources and complex terrain effects for a wide range of precisely controlled atmospheric conditions.

WP3 - Simple Terrain Dispersion Experiments

Well-defined large-scale releases of CO_2 onto simple slopes of varying inclination in one plane with dispersion measurements.

WP4 - Complex Terrain Dispersion Experiments

Large, dense phase releases of CO_2 onto complex terrain including multi-planar slopes (valleys, hills, obstacles) with dispersion measurements.

WP5 - Model Evaluation

HSE SD will coordinate a series of model validation exercises using the experimental data generated in this project. The aim is to encourage the development of a variety of tools of differing complexity to enable robust pipeline risk assessment, permitting studies and emergency planning and response.

WP6 - Emergency Response

Led by Ricardo's NCEC, this work package will engage with emergency responders to make best use of the CO_2 dispersion trials. Development of training materials and best-practices for emergency response will be developed with the learning from the experiments and critical pieces of equipment will be tested for their operability in emergency scenarios.

WP7 - Venting

Near full-scale venting experiments will be conducted alongside other work packages to assess the dispersion behaviour and measure temperatures.

DNV