PROTECTING PEOPLE AND PLACES

HSE

Skylark CO_2 Dispersion Project

Simon Gant

Fluid Dynamics Team, Health and Safety Executive (HSE) Science and Research Centre, Buxton, UK

Carbon Dioxide (CO_2) Pipelines Working Group

PHMSA Pipeline Safety Research and Development Forum, Arlington, Virginia, USA

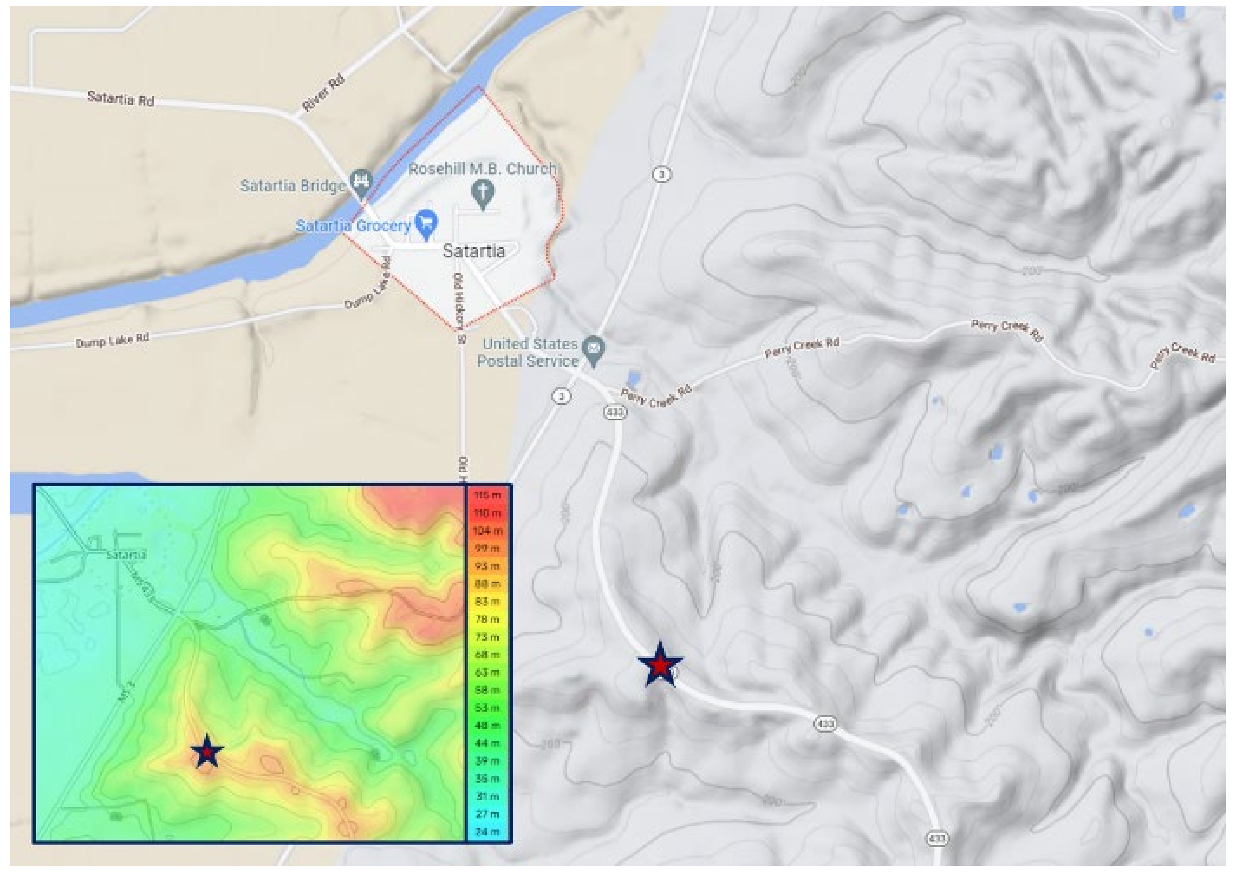
31st October 2023

© Crown Copyright HSE 2023

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)



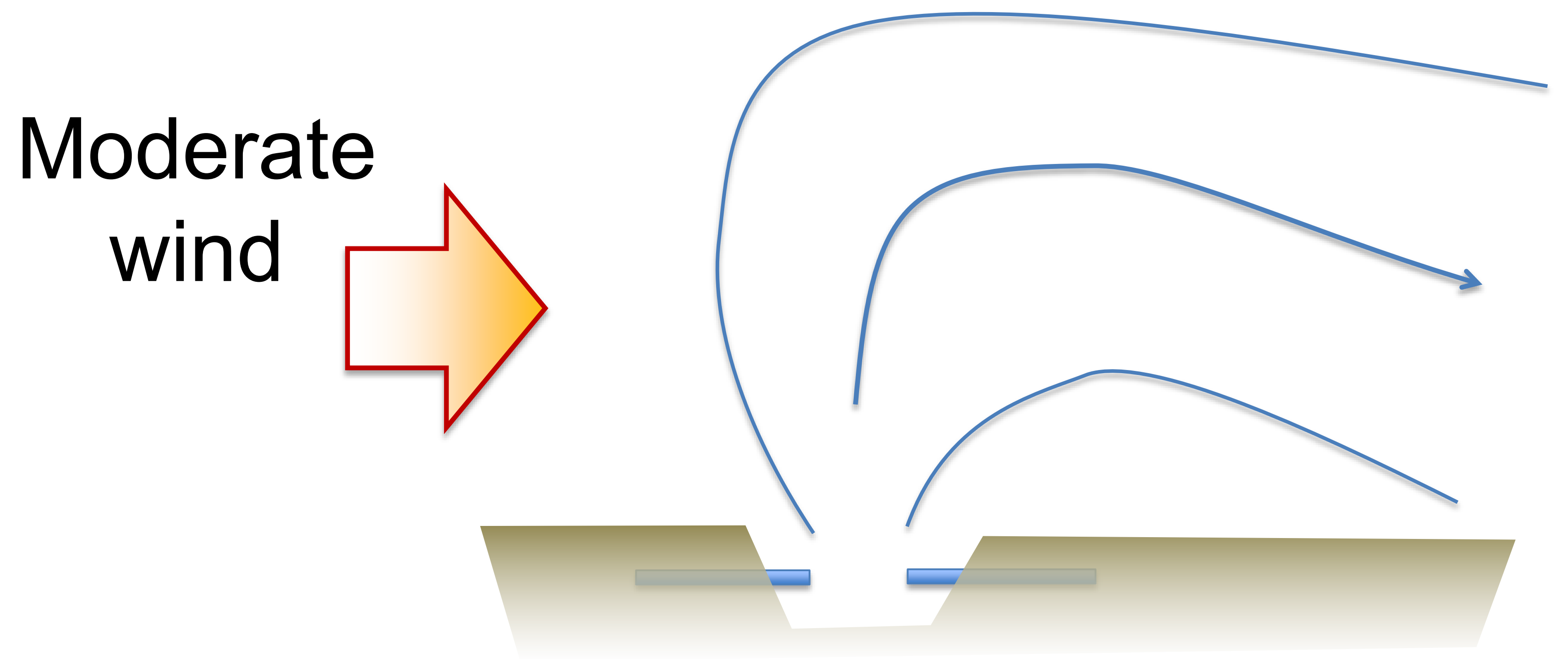
Terrain map taken from Google Maps and contour map taken from topographic-map.com. Approximate location of release marked by a star.

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

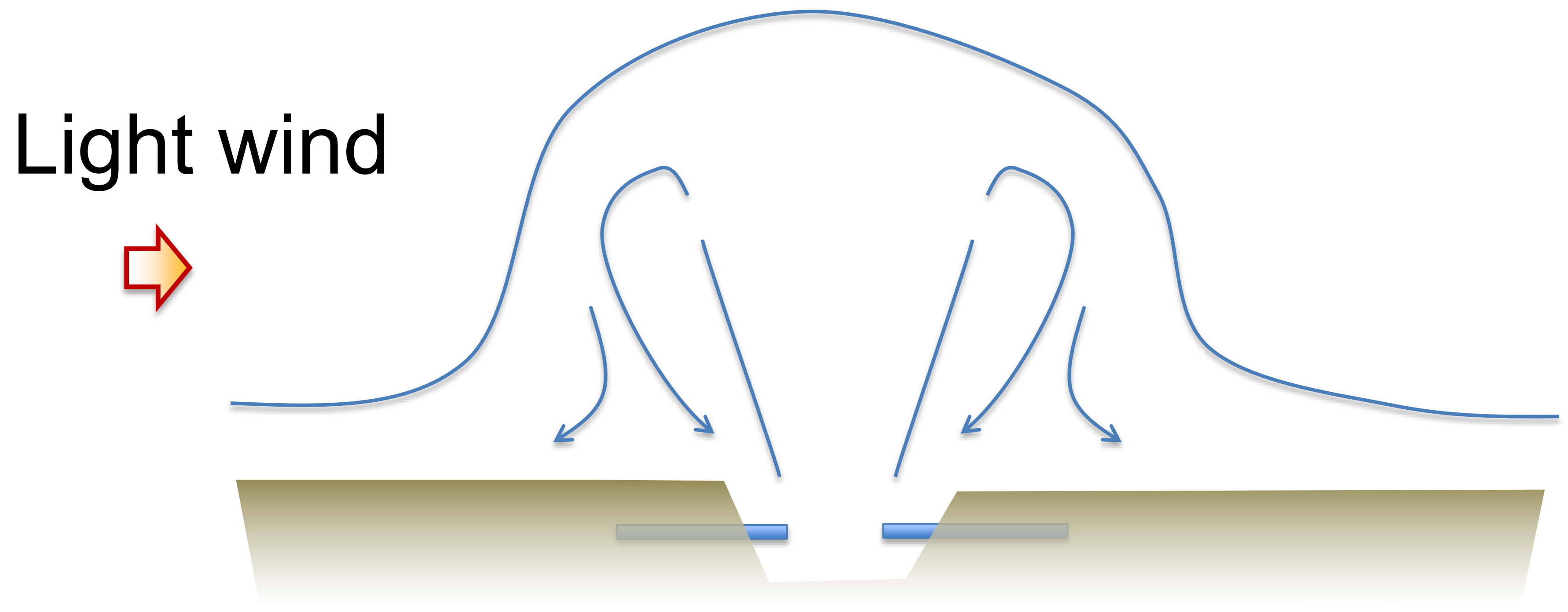
© Crown Copyright HSE 2023

Knowledge Gaps

1. Source characteristics from CO_2 pipeline craters



Bent-over plume, no re-entrainment



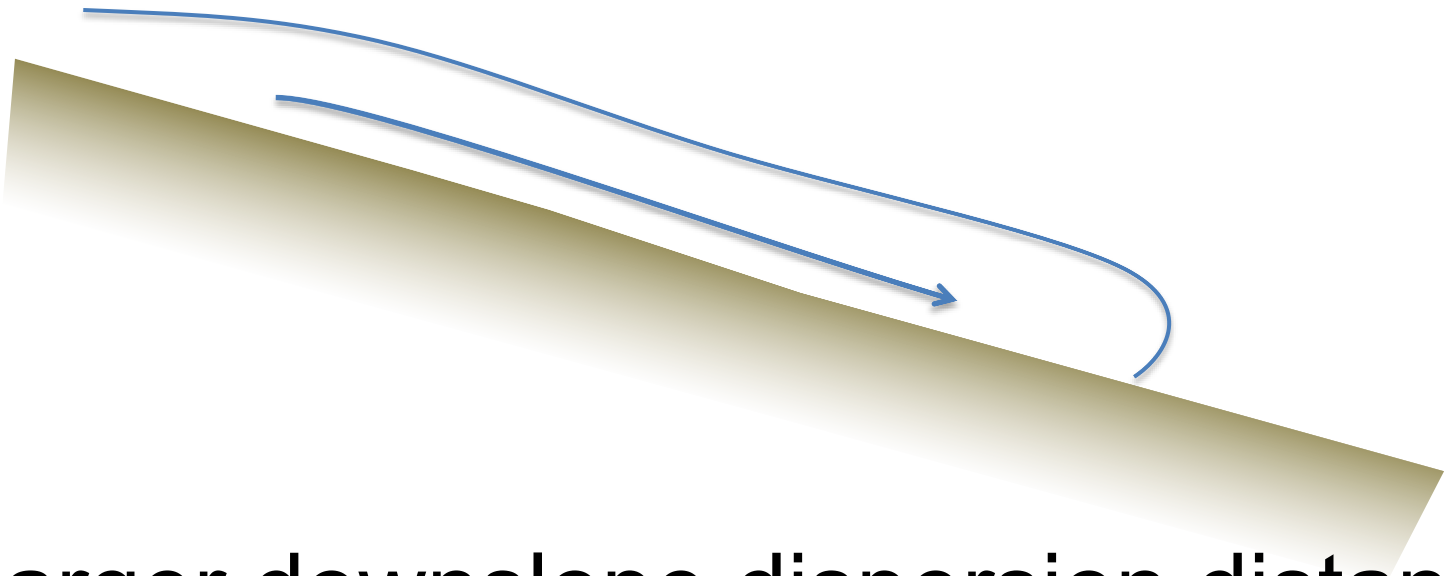
Plume falls onto crater, re-entrainment, blanket

- 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)

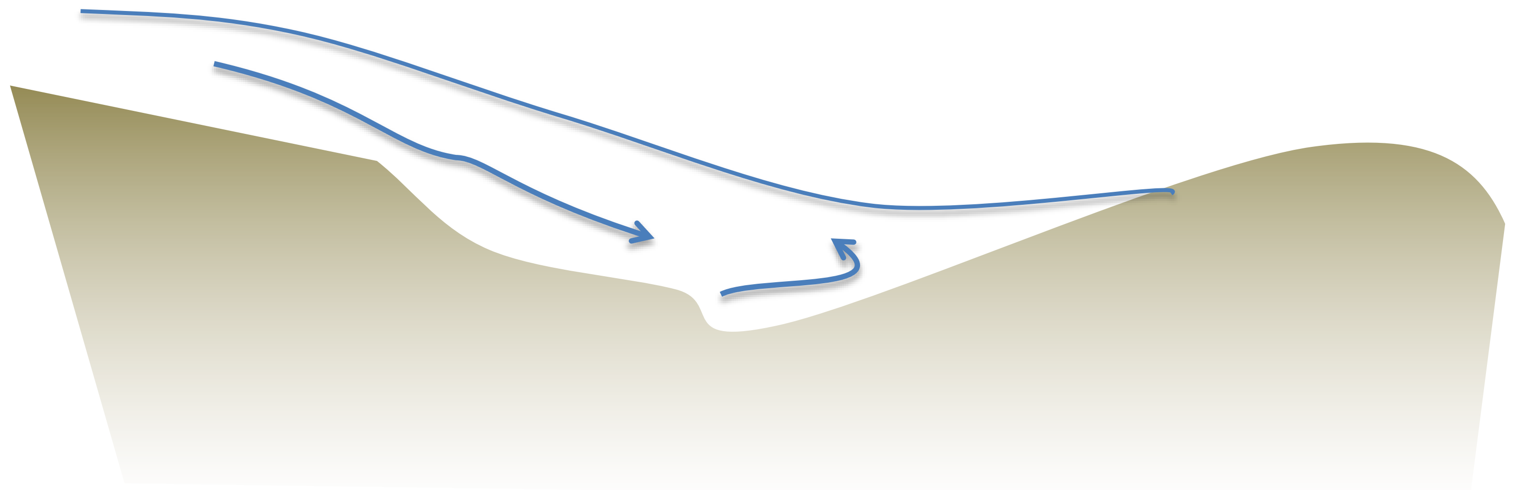
© Crown Copyright HSE 2023

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?

© Crown Copyright HSE 2023

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/



© Images copyright DHS S&T CSAC and UVU

© Crown Copyright HSE 2023

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 validation – **HSE**
- Work Package 6: Emergency response – **NCEC**
- Work Package 7: Venting – **DNV**

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

© Crown Copyright HSE 2023

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 (some data is not yet publicly available)
- 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: puncture tests, light and moderate wind speeds

© National Grid / DNV

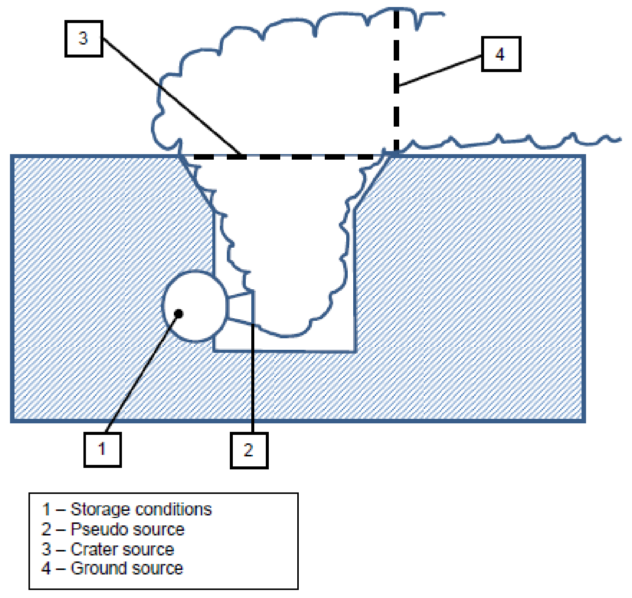


Figure 1 Puncture and crater sources

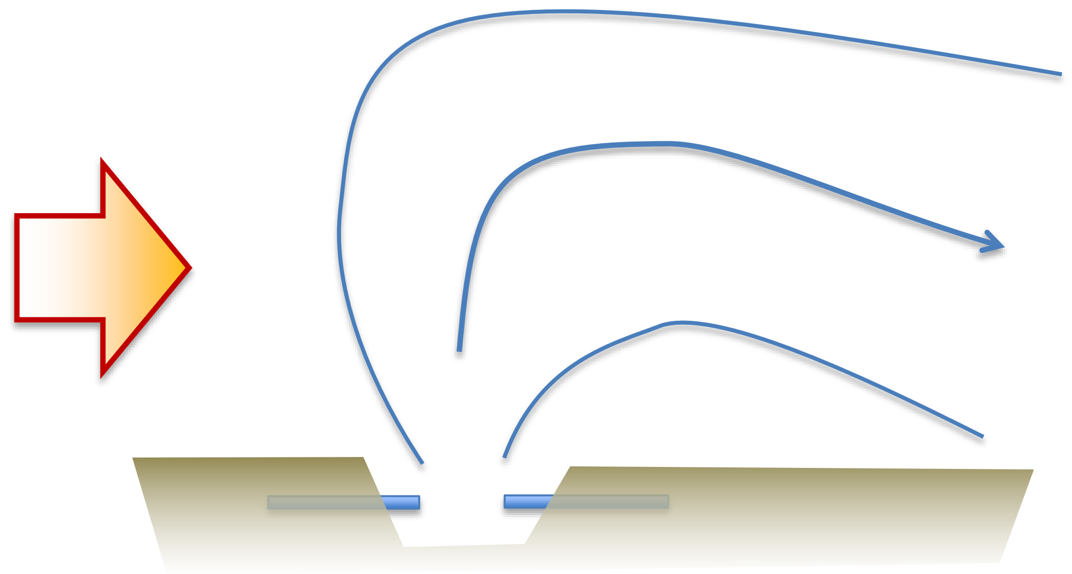
© Crown Copyright HSE 2023

DNV

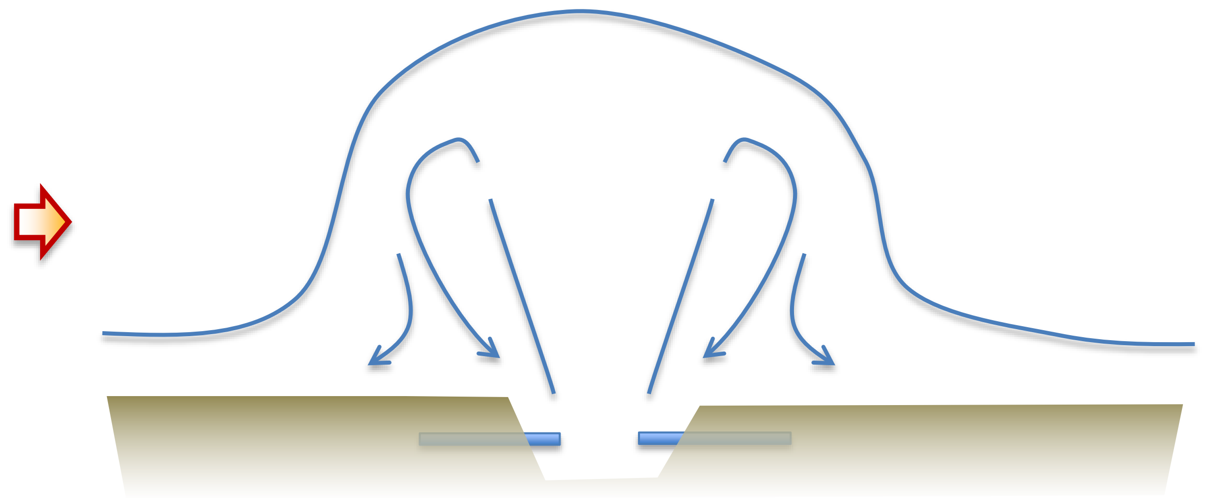
Work Package 2: Wind tunnel studies

- **Aim 1**: to conduct wind-tunnel experiments on crater source behaviour across a wide range of carefully-controlled conditions, with detailed measurements
- Variables: source area, initial jet velocity and density, wind speed
- 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 ?

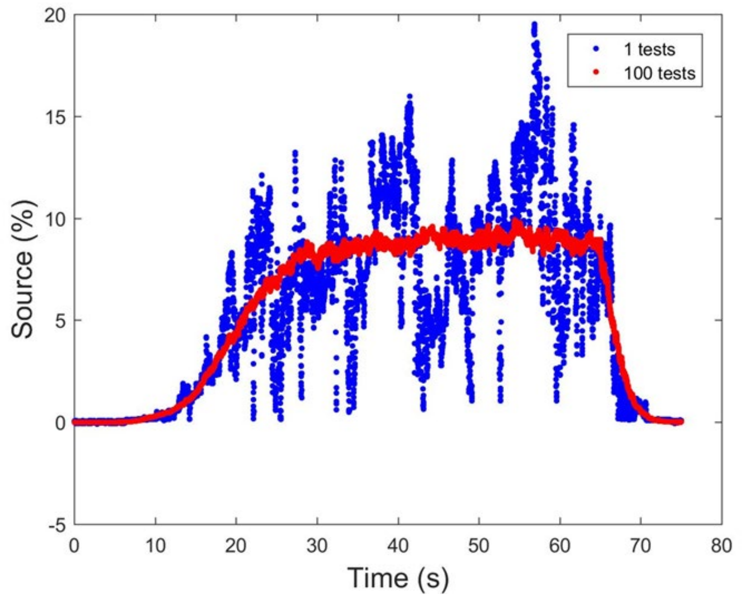


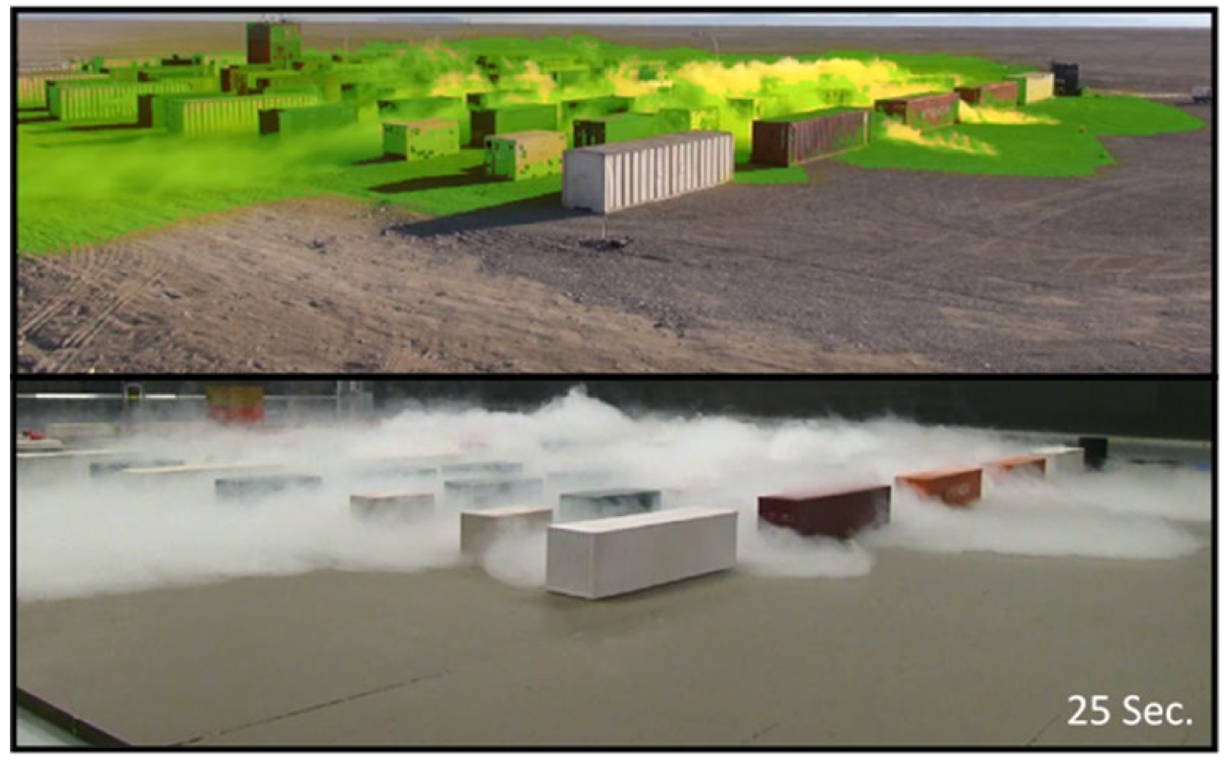
- **Aim 2**: to conduct wind-tunnel experiments on dense-gas dispersion in sloping terrain, comparing flat terrain to cases with uniform slopes in different directions with range of wind speeds
- **Aim 3**: to conduct wind-tunnel experiments to support complex terrain field trials

© Crown Copyright HSE 2023

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





UNIVERSITY OF ARKANSAS
COLLEGE OF ENGINEERING

© Crown Copyright HSE 2023

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

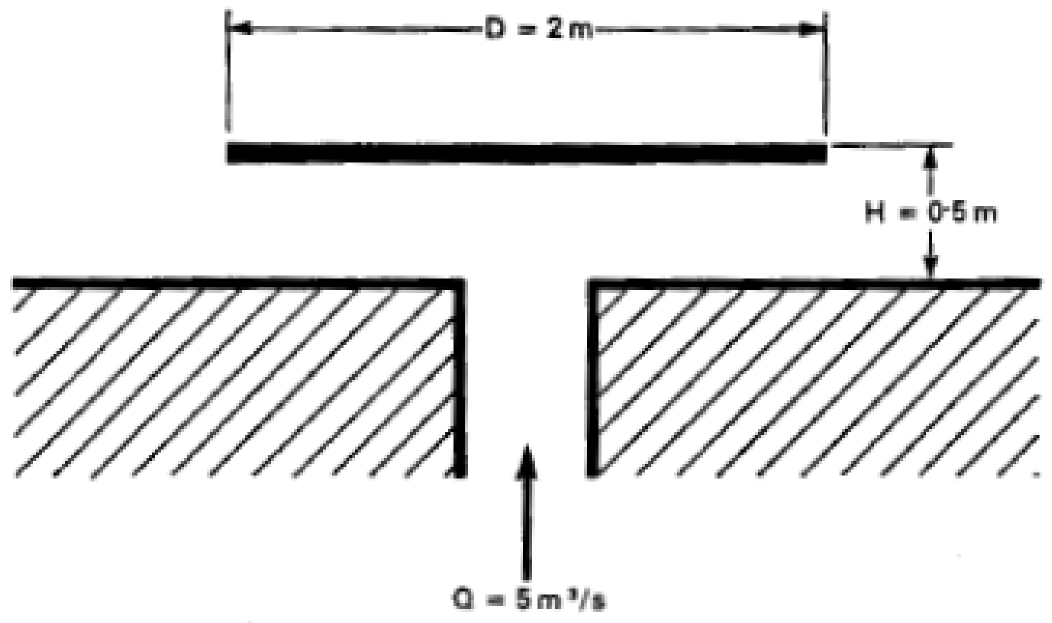


Fig.22.4 Geometry of ground-level source for continuous release experiments

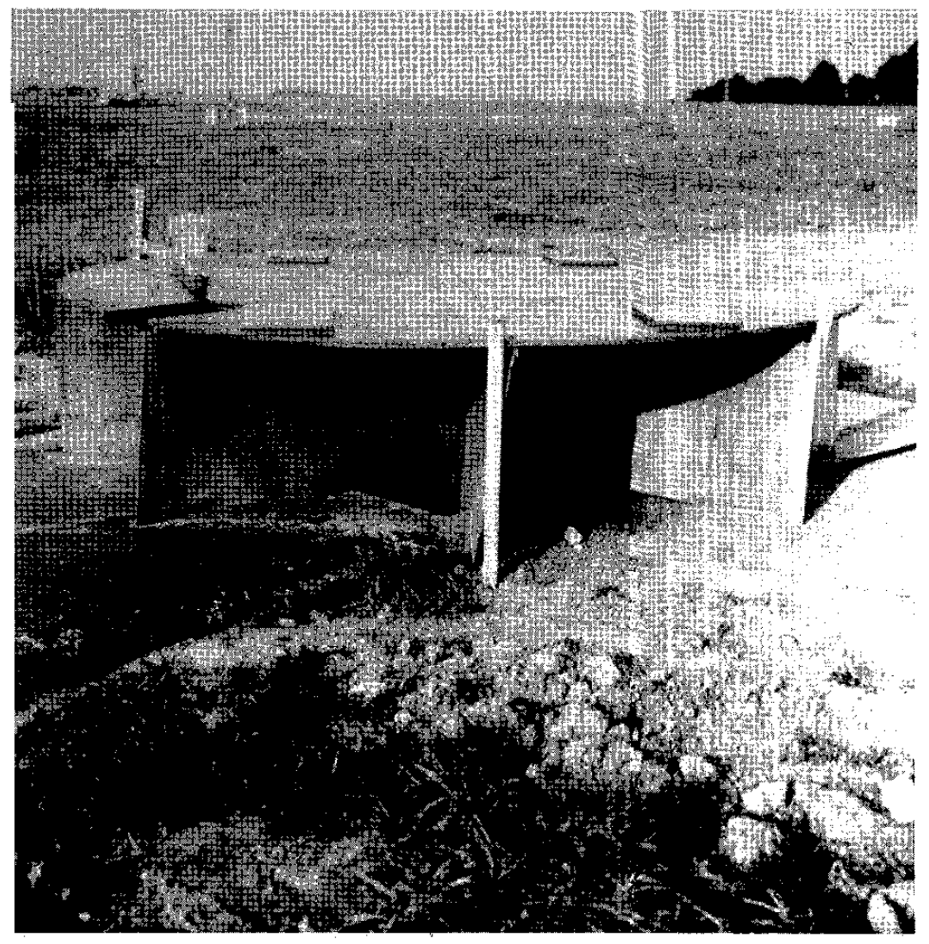
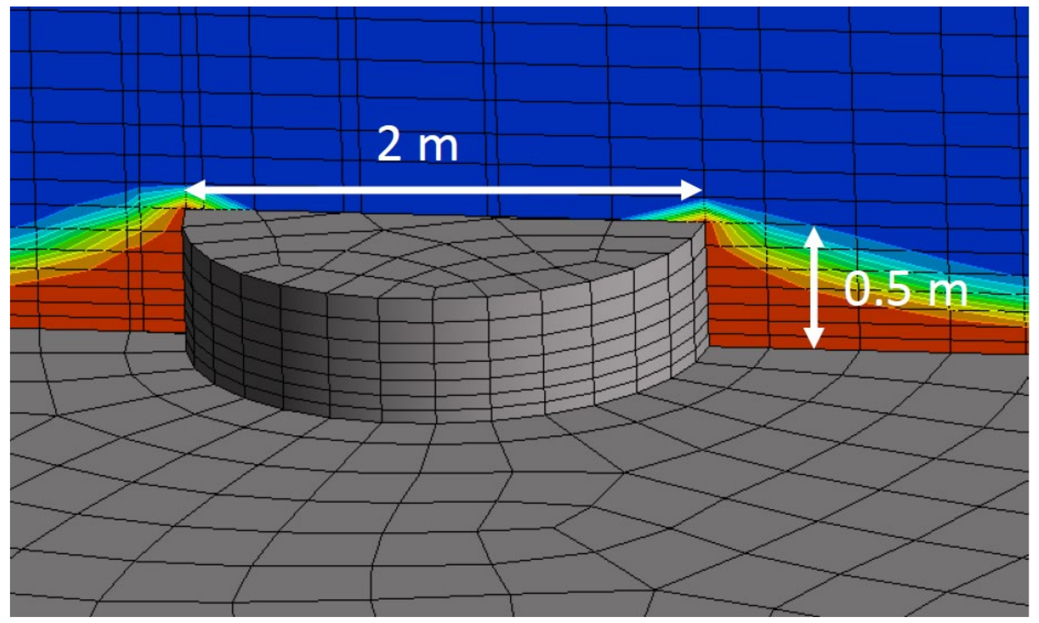
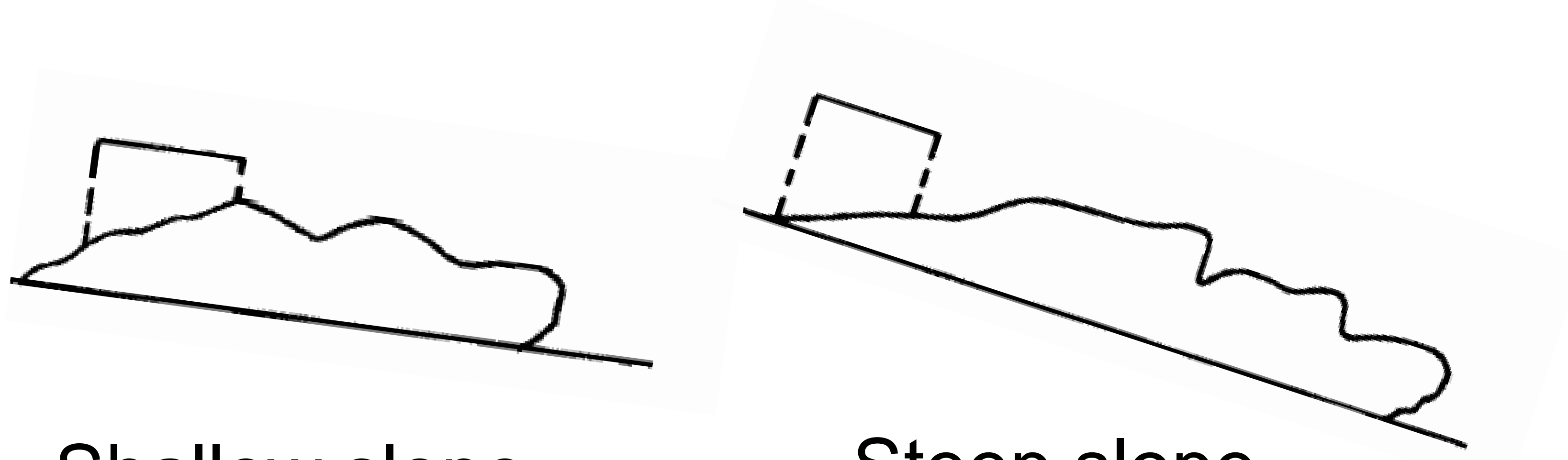


Fig. 22.2 Outlet from the gas supply duct at the release point



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?

© Crown Copyright HSE 2023

Work Package 4: Complex Terrain Dispersion Exps

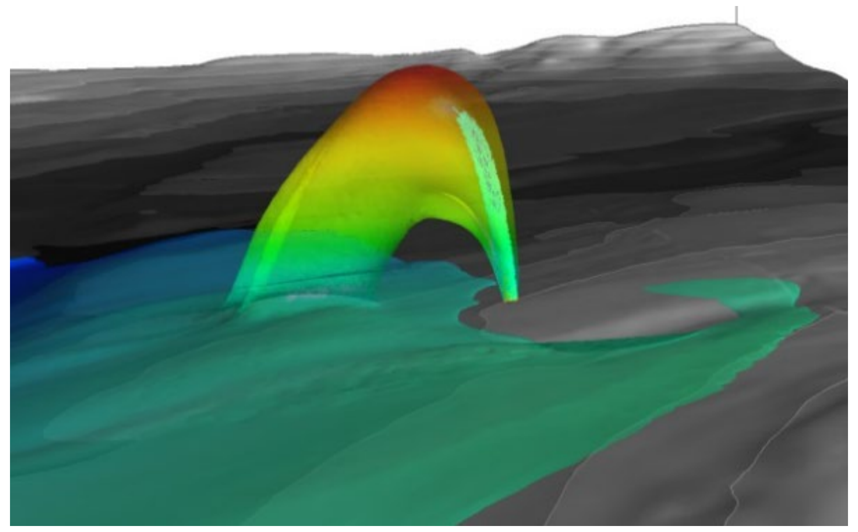
- **Aim**: to conduct series of CO_2 release experiments with complex terrain including valleys, hills, obstacles, changing roughness, buildings etc.
- DNV Spadeadam ideally suited to these tests, with multiple possible release locations and large exclusion distances
- Proposed to use mobile rig with 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)?

© Crown Copyright HSE 2023


~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
DNV
Google Earth

Work Package 5: Model validation

- **Aim**: to test and validate dispersion models that can be used for CO_2 pipeline risk assessment and emergency planning/response
- Many international modelling teams and software developers are keen to test and validate their models against this data (DNV, Gexcon, Kent, CERC, Met Office etc.)
- Opportunity to involve research groups who are developing rapid dispersion models (e.g., Texas A&M, Leeds University) to inform future commercial software development
- Aim to have an open and collaborative approach, like in Jack Rabbit projects
- Welcome input from government labs, industry, academia and consultants
- 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



© Crown Copyright HSE 2023

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)


Examples of emergency responders' involvement in the Jack Rabbit II project https://www.uvu.edu/es/jack-rabbit/
© Images copyright DHS S&T CSAC and UVU

NCEC RICARDO

© Crown Copyright HSE 2023

Work Package 7: Venting

- **Aim**: to assess if CO_2 vents 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
- Planned to test:
  - Two vent diameters (up to 2” NB diameter pipes)
  - Dense, supercritical and gaseous CO_2
  - Repeated tests on three days (low, moderate and high winds)
- Measure outflow rate, vent conditions (pressure / temperature), CO_2 concentrations near ground level, plume temperature, videos (normal, thermal and high-speed)
- Conducted alongside other work packages whilst rigs are available
- Is interest in testing certain valve designs, following reports of some blowdown valves blocking in the open position due to solid CO_2?

© National Grid / DNV

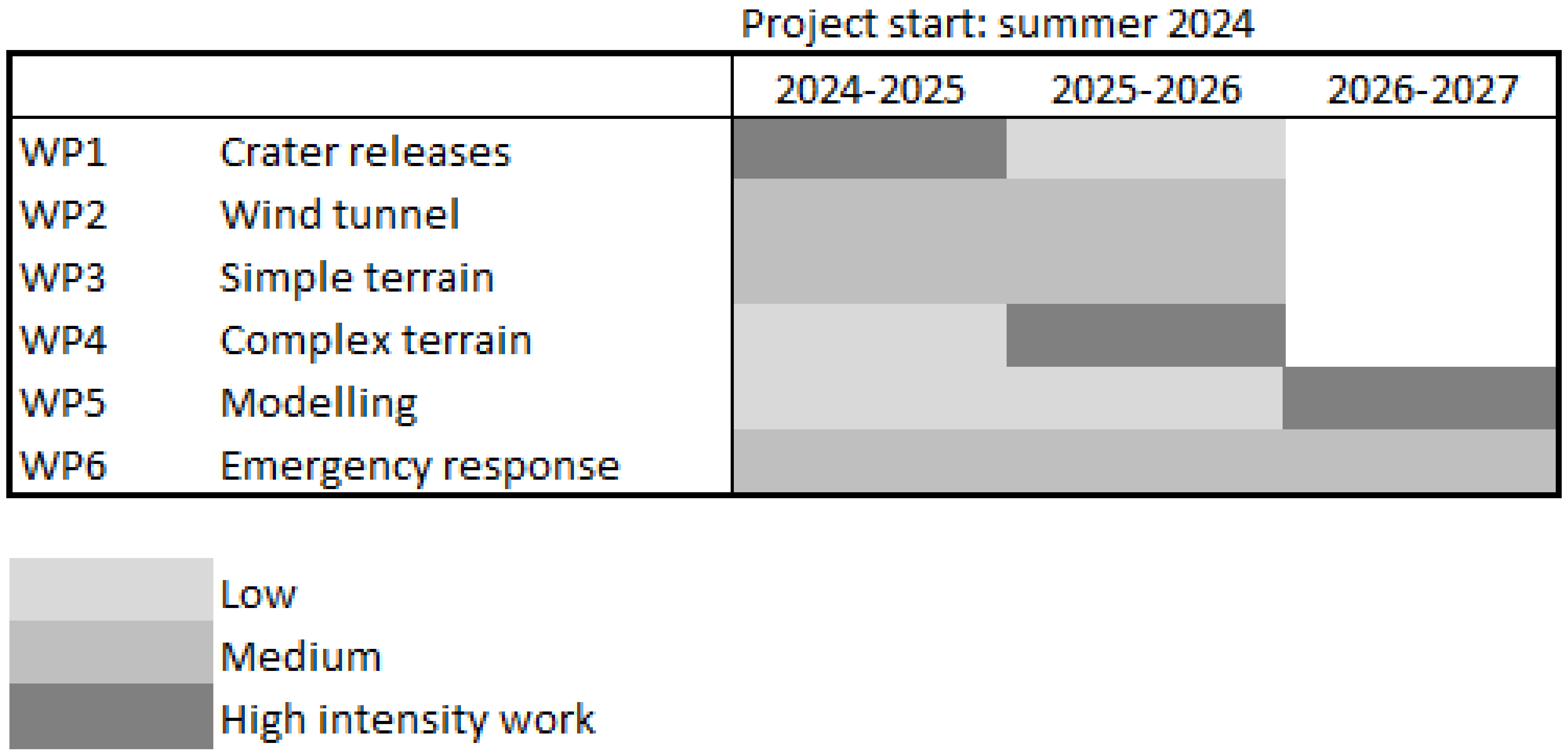
© Crown Copyright HSE 2023

Work Package 0: Project Management

- Project delivery team
  - DNV (experiments): Dan Allason, Rob Crewe, Keith Armstrong
  - DNV (modelling): Ann Halford, Karen Warhurst, Mike Harper, Jan Stene and Gabriele Ferrara
  - HSE: Simon Gant, Zoe Chaplin and Rory Hetherington
  - University of Arkansas: Tom Spicer
  - NCEC: Ed Sullivan
  - Met Office: Matt Hort and Frances Beckett
  - External advisers: Steven Hanna (USA), Joe Chang (Rand Corporation), Gemma Tickle (UK)
- 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

© Crown Copyright HSE 2023

Timeline (approximate)



© Crown Copyright HSE 2023

Costs

- Summary of costs (approx. estimate, non-binding)
  - DNV
  - HSE
  - University of Arkansas
  - NCEC
  - Met Office
  - External advisors

Total cost, approximately £10m ($12m)

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 ($6m)
- Ideal ten sponsors: £0.5m ($0.6m) per sponsor, spread over 3 years
- Potential consortium sponsors and US Government: discussions welcomed

© Crown Copyright HSE 2023

Concluding Remarks

- Current plans have been developed following discussions at two main meetings
  - Carbon Capture and Storage Association (CCSA) on 31 August
  - Skylark Project meeting at Spadeadam and online on 6 October
- Keen to have wider engagement with CCS industry to shape proposals
  - Are there other work packages that we should consider?
  - Are there particular scenarios or tests that we should include?
  - Would it be possible to involve US/Canadian emergency responders?
  - Are there modelling teams who would like to participate?
- Following feedback and discussions
  - Aim to develop more detailed scope and costing
  - Some iteration may be needed on scope/costing, depending on funding available
- Feedback welcome

https://forms.office.com/e/DyLkS24C5z

© Crown Copyright HSE 2023

Thank you

- Contact: simon.gant@hse.gov.uk, daniel.allason@dnv.com
- The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy

© Crown Copyright HSE 2023

Extra material

© Crown Copyright HSE 2023

Why the name Skylark?

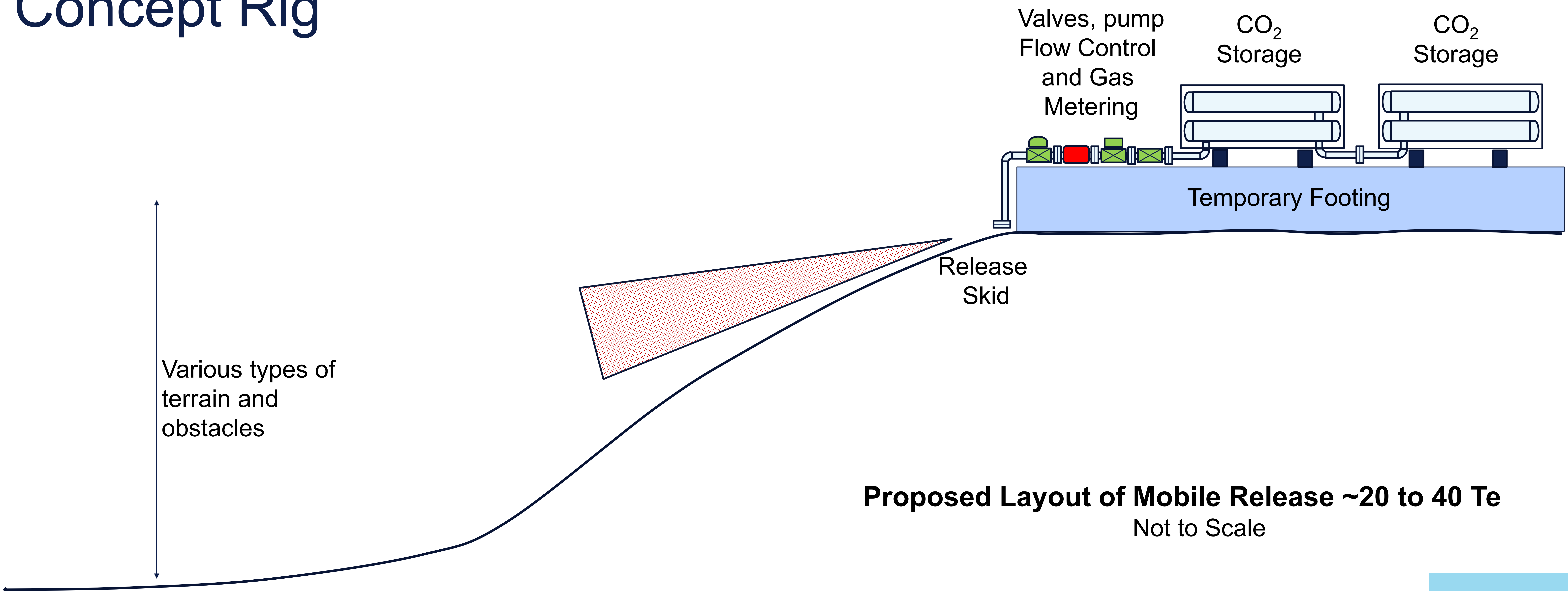
- Historical dispersion trials
  - Avocet: LNG
  - Burro: LNG
  - Coyote: LNG
  - Desert Tortoise: ammonia
  - Eagle: nitrogen tetroxide
  - Falcon: LNG
  - Goldfish: hydrogen fluoride
  - Kit fox: carbon dioxide
  - Jack Rabbit: chlorine and ammonia
  - Red Squirrel: ammonia
  - **Skylark: carbon dioxide**

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

© Crown Copyright HSE 2023

Work Package 4: Complex Terrain Dispersion Exps

Concept Rig



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

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

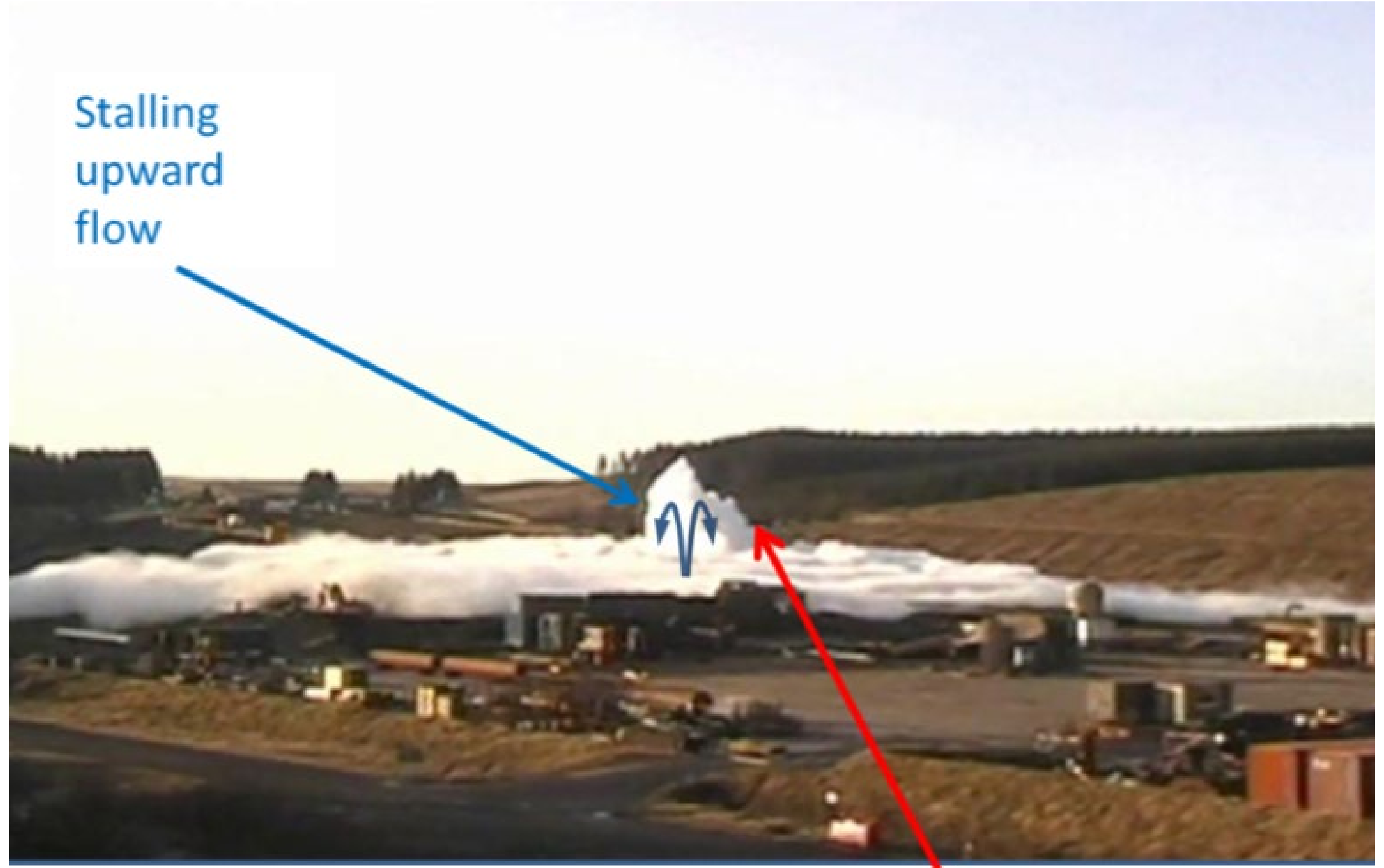
Julian Barnett
National Grid
Solihull, UK

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

© Images copyright National Grid / DNV

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

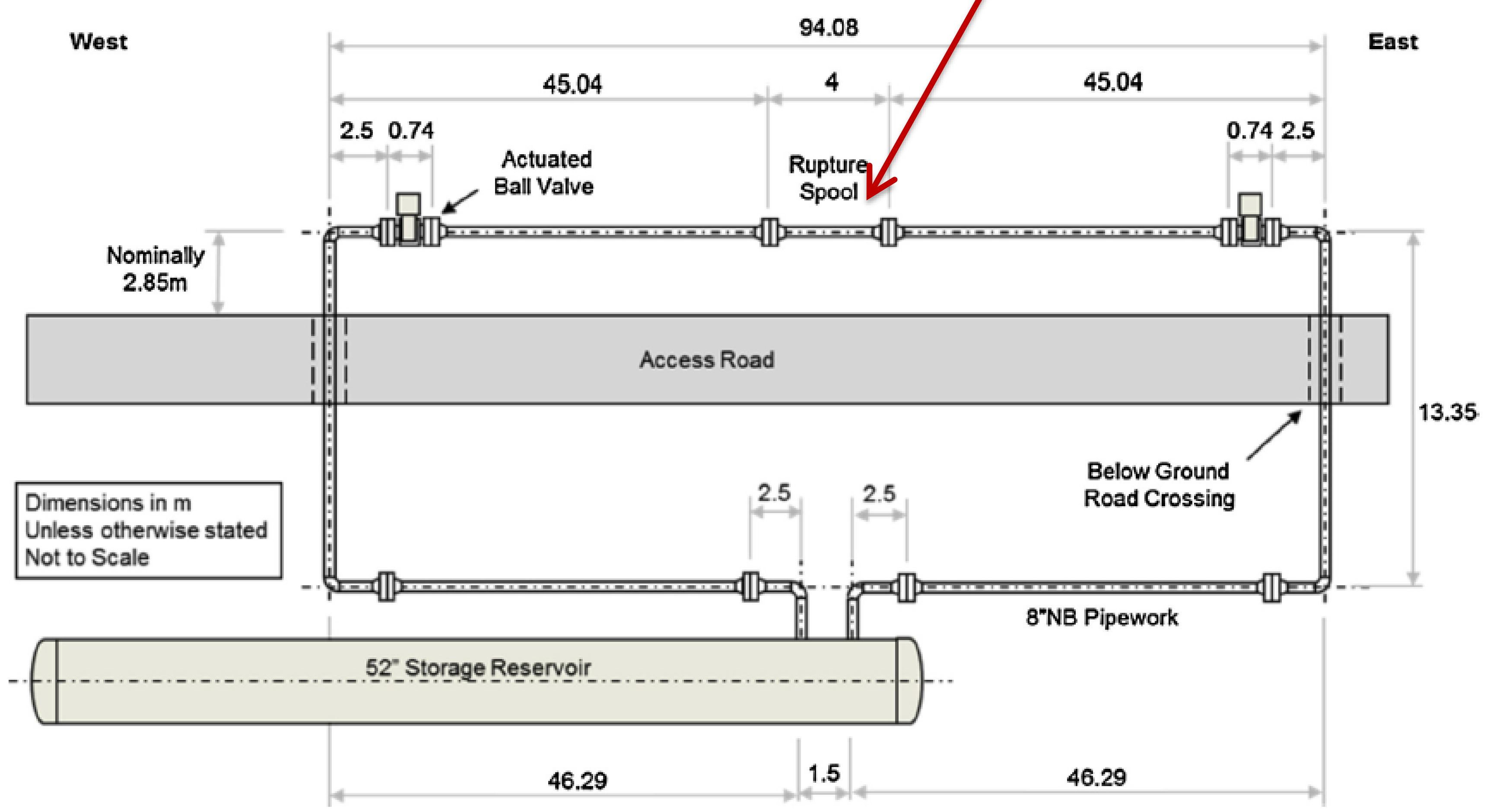


Fig. 1. The pipeline loop (plan view).

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

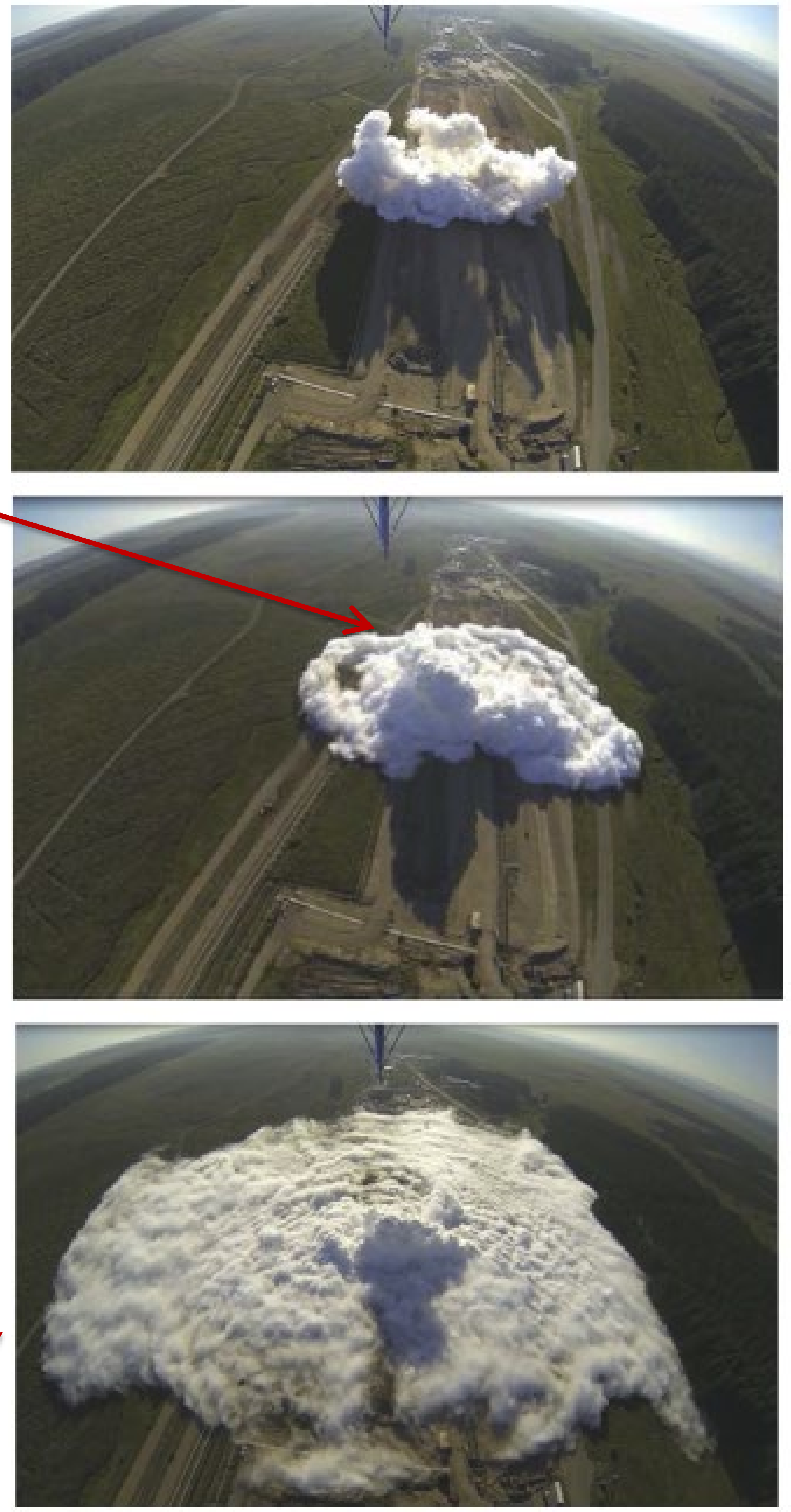


Fig. 4. The visible cloud at 10 s (top), 30 s and 120 s (bottom) after the rupture.

© Crown Copyright HSE 2023