Carbon dioxide pipeline risk assessment

Plans for a programme of CO_2 dispersion experiments and model development

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Carbon Capture and Storage Association (CCSA), Health and Safety Technical Working Group Meeting, London, UK
31 August 2023

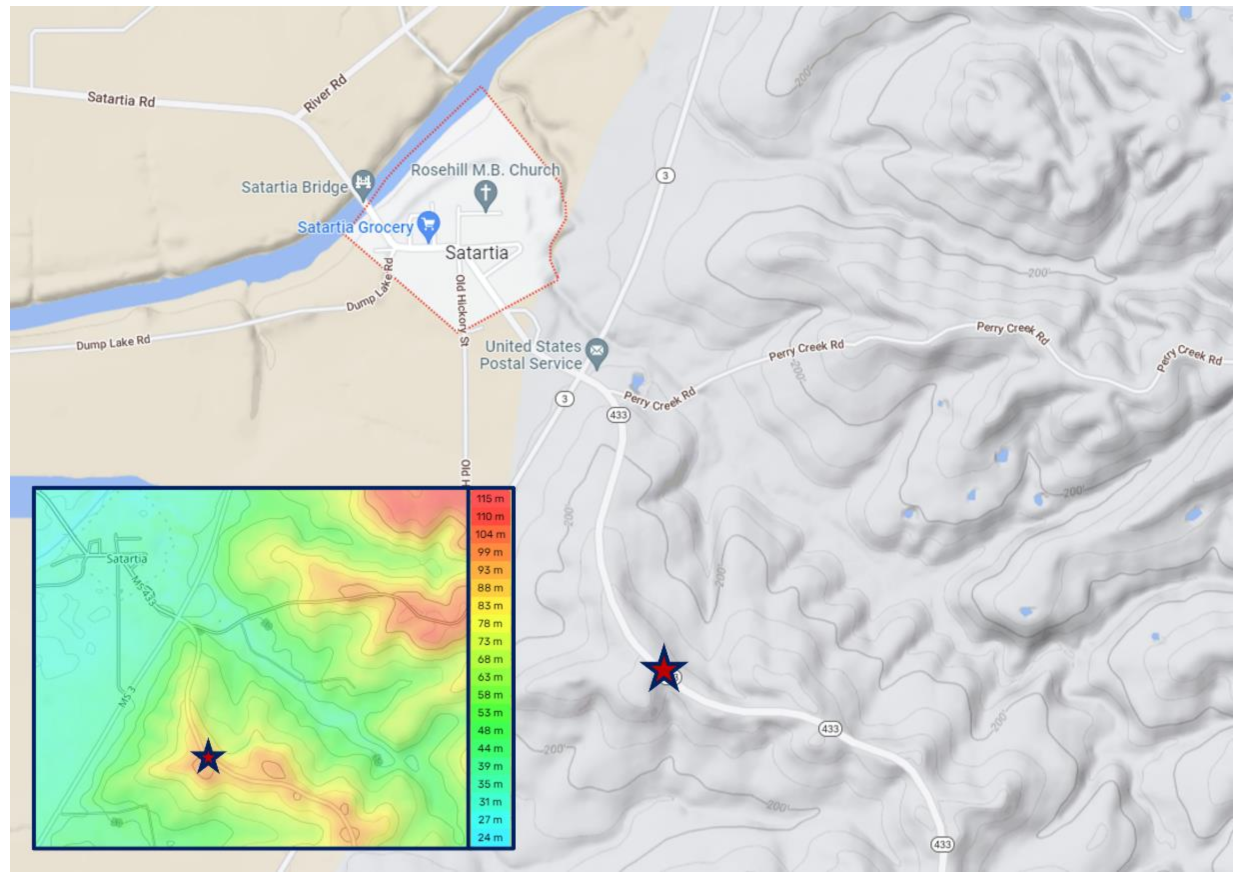
Contents

- Satartia incident
- Previous research
- Recommended practice, guidelines and standards
- Knowledge gaps
- Proposed Joint Industry Project

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

Previous research on CO_2 pipeline safety

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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

Uncertainties:

- Dispersion modelling of (liquid/solid + gas) CO_2 jet releases: how does it behave? Can we predict extent of hazardous zones?
- Implications of severe Joule-Thomson cooling (embrittlement?)
- Solid CO_2 implications for blowdown (blocking valves?)
- Solid CO_2 particles scouring and erosion (jet cleaning and cutting)
- Solid CO_2 deposition as dry-ice bank (prolonged sublimation)
- Running ductile crack propagation along dense-phase CO2 pipelines
- Equation of state for CO_2 + impurities for flow assurance modelling
- Corrosion issues: CO_2 + water = carbonic acid, effects of other impurities

CCS safety research over the period 2007-2017

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

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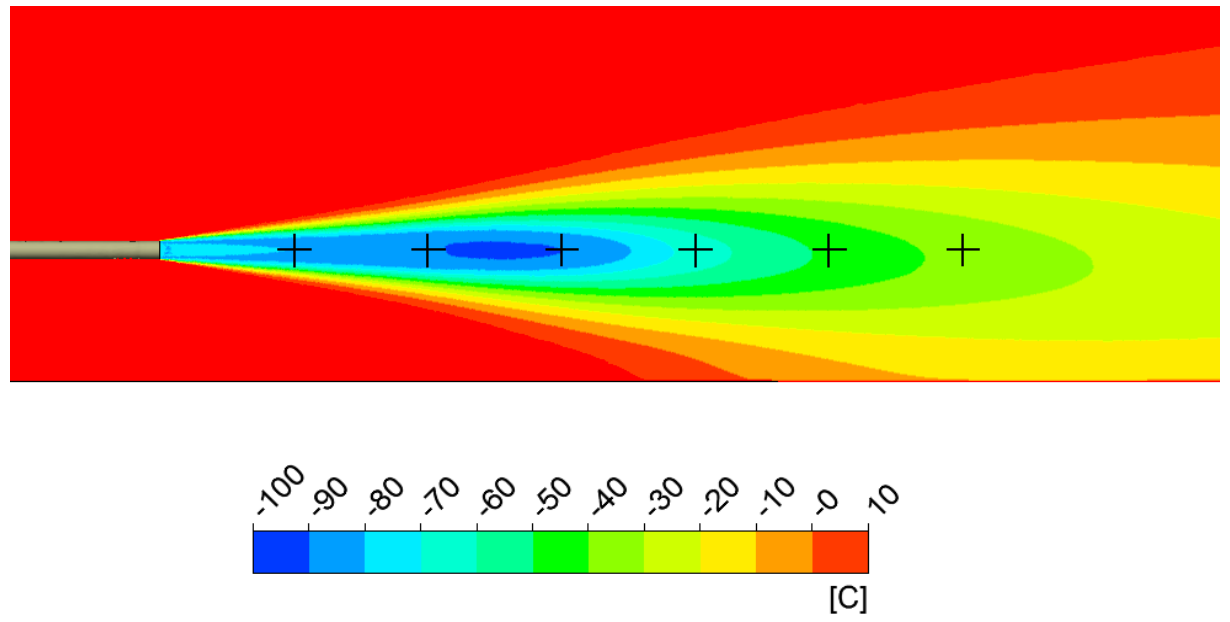

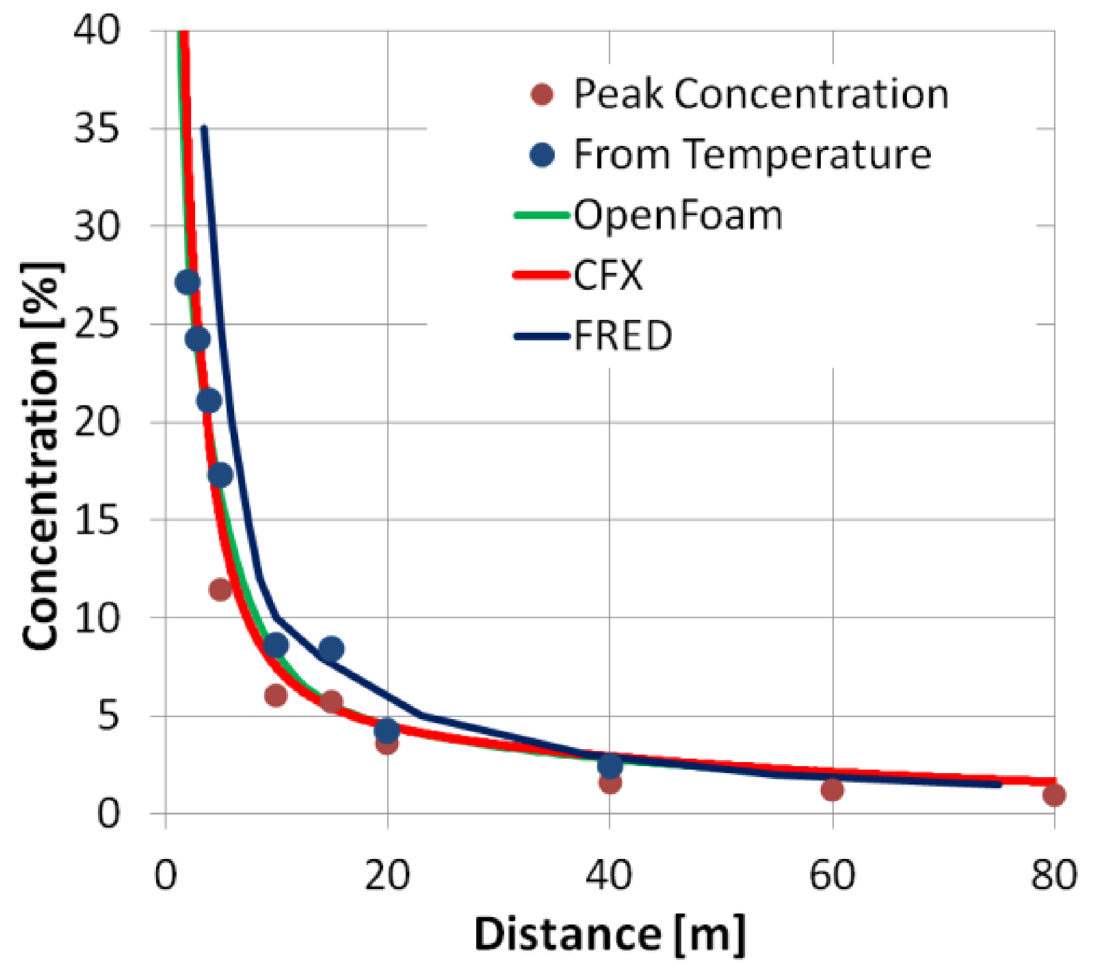

Dixon C.M., Gant S.E., Obiorah C. and Bilio M. "*Validation of dispersion models for high pressure carbon dioxide releases*" IChemE Hazards XXIII Conference, Southport, UK, 12-15 November 2012, https://www.icheme.org/media/9162/paper21-hazards-23.pdf

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

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

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

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DNV GL
Spadeadam Test & Research Centre, UK

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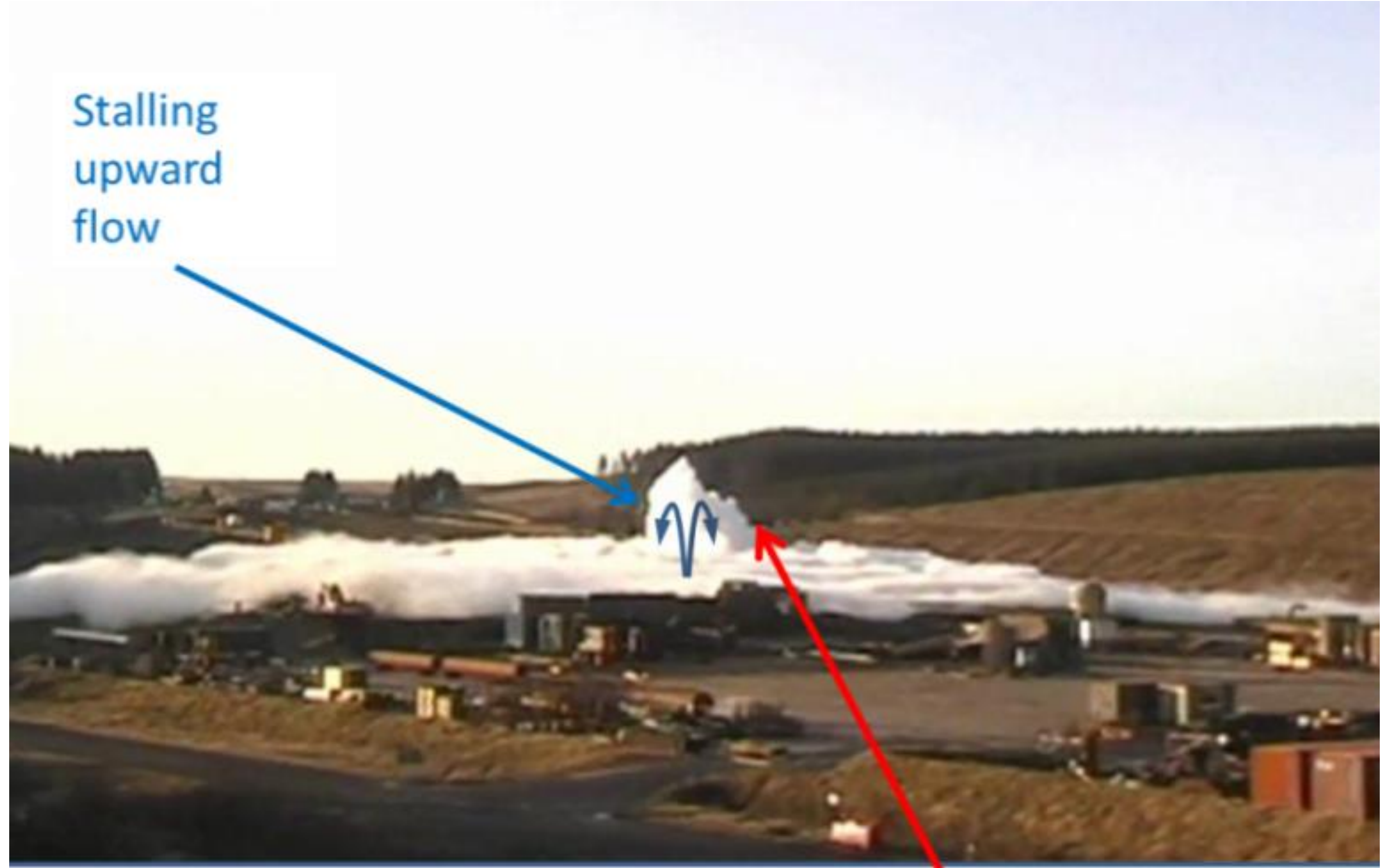
Solihull, UK

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

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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

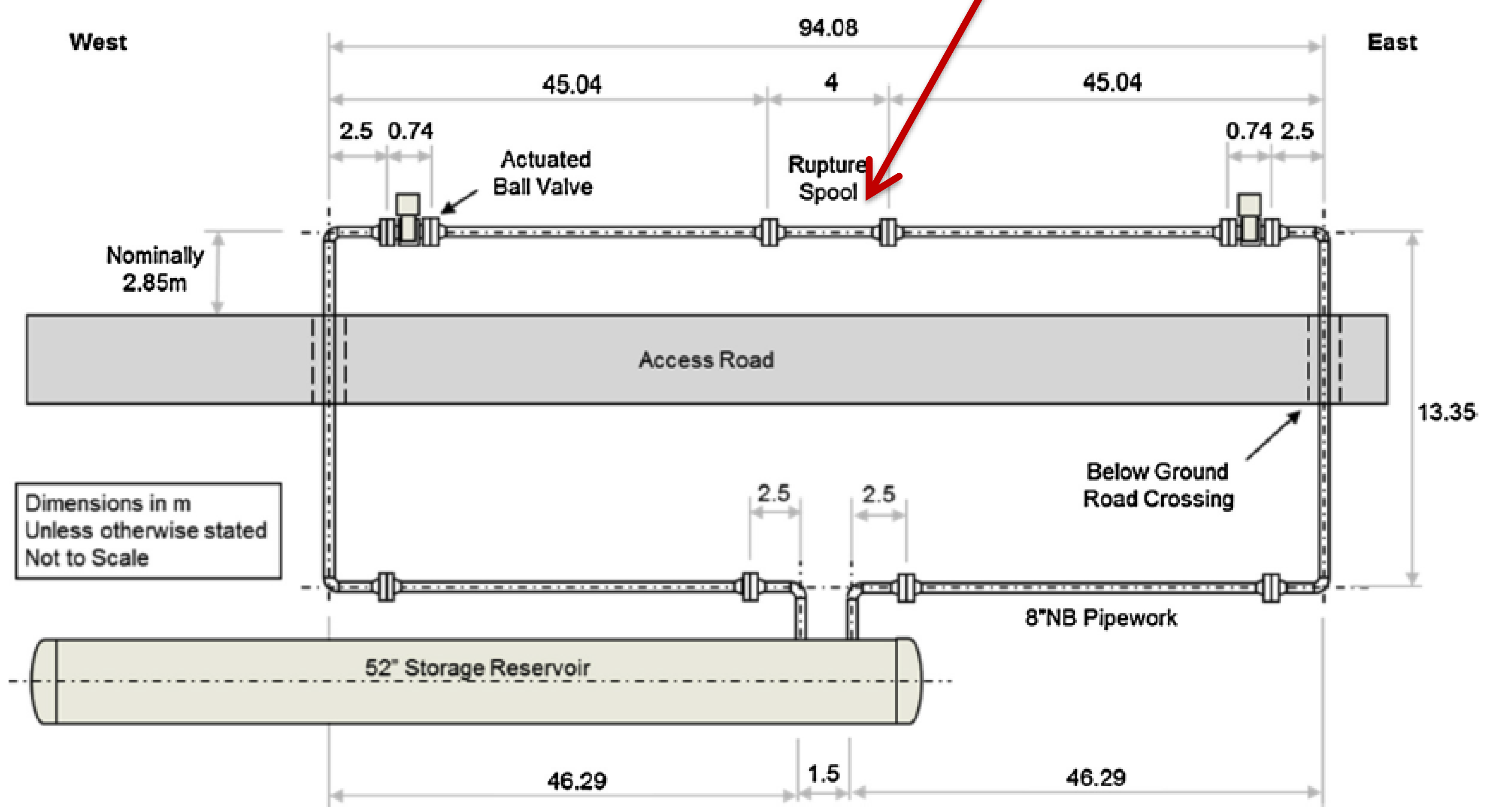


Fig. 1. The pipeline loop (plan view).

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
  - "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)

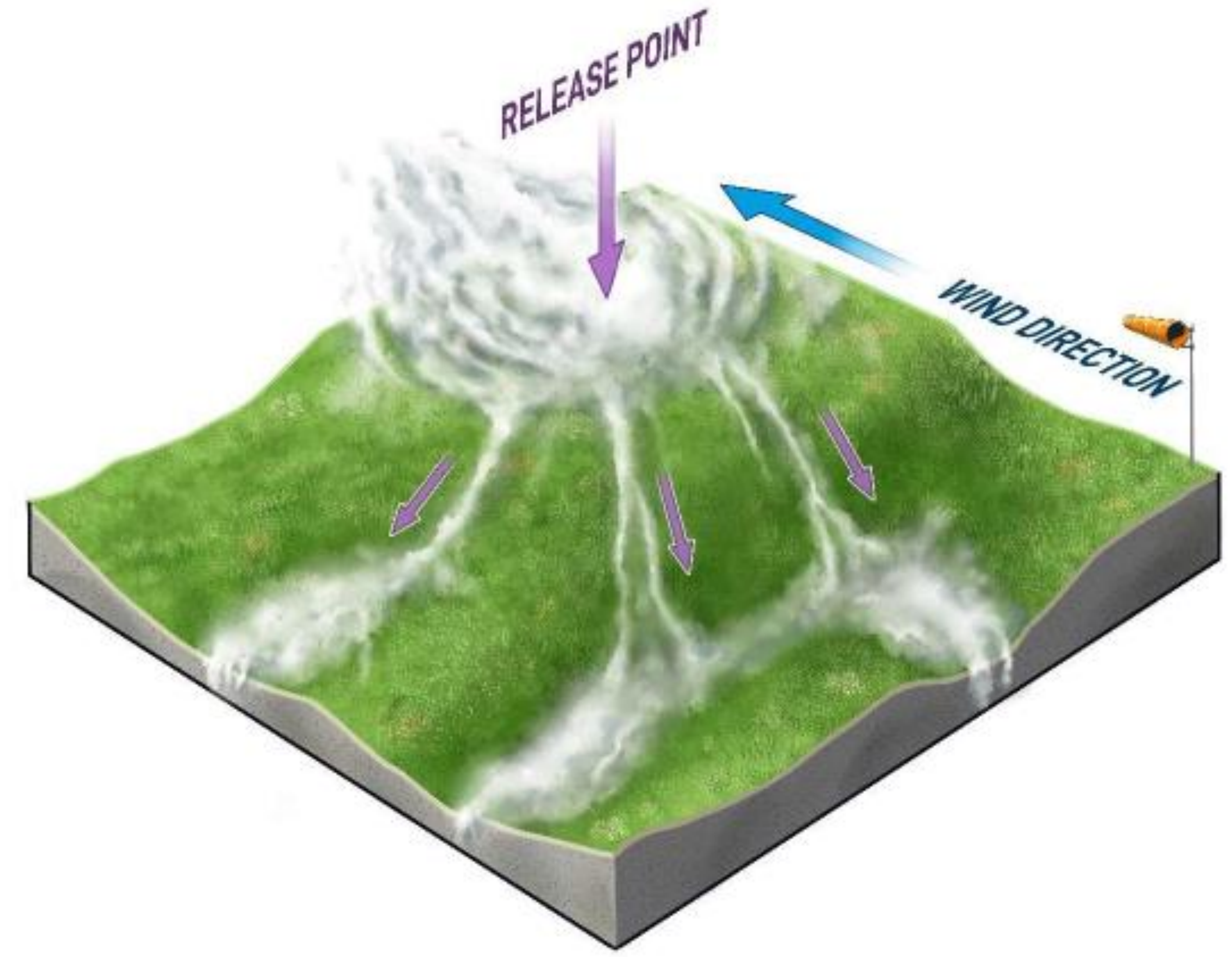
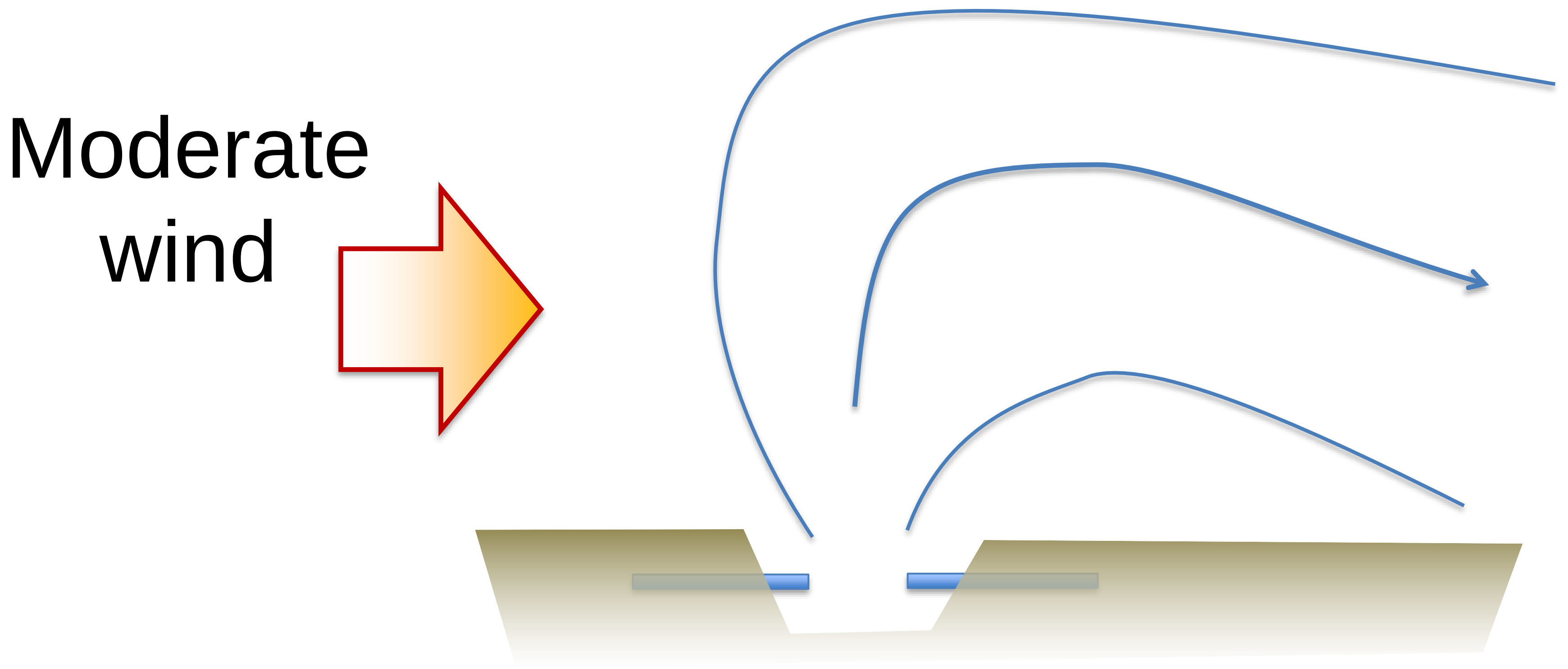


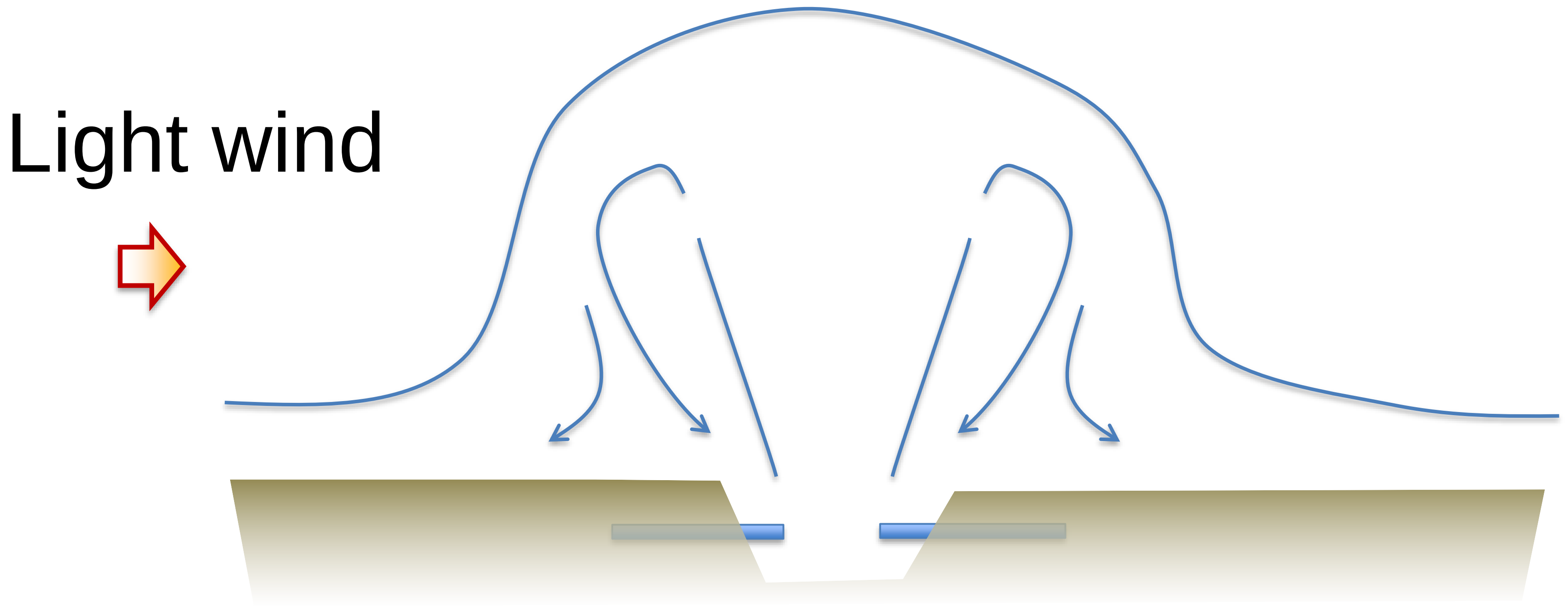
Figure 6—Transport and Dispersion of Released Carbon Dioxide with Topographical Features

Knowledge Gaps

1. Source characteristics from CO_2 pipeline craters



Bent-over plume, no re-entrainment

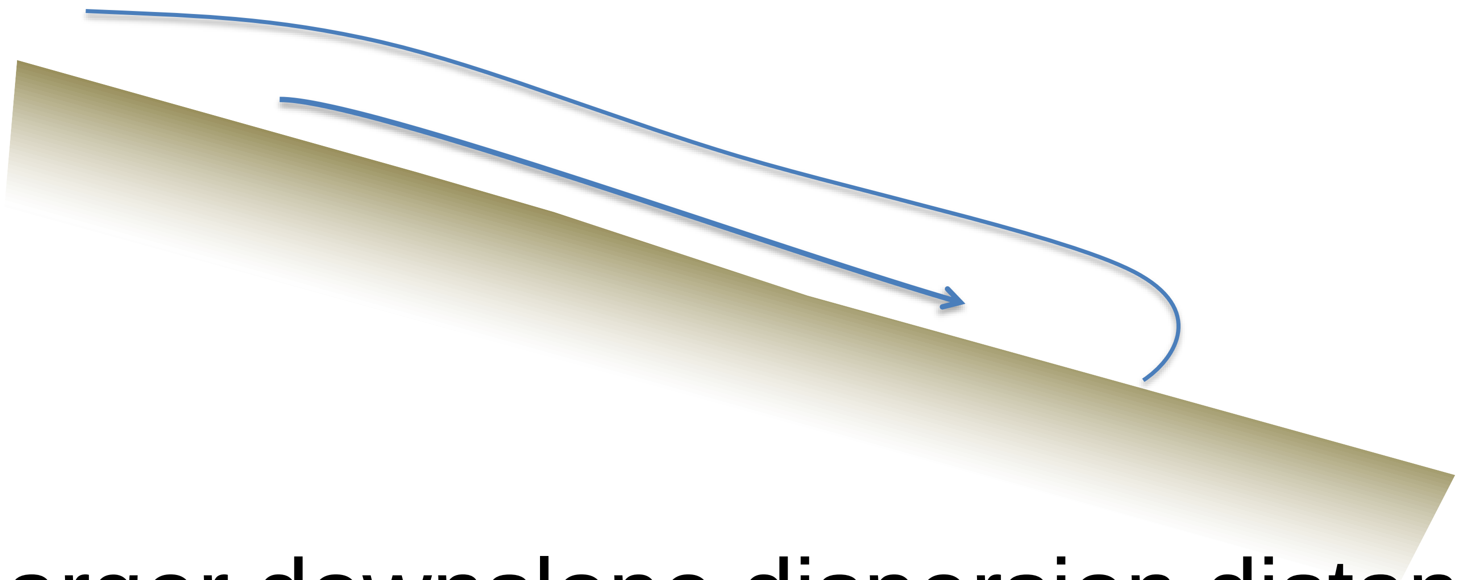


Plume falls onto crater, re-entrainment, blanket

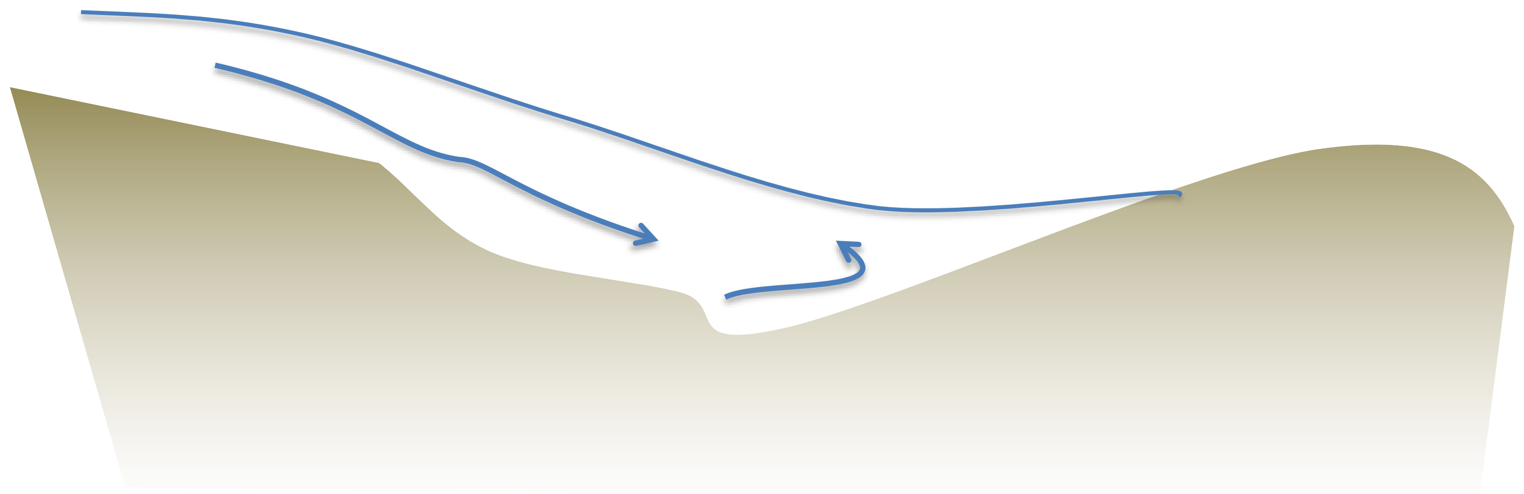
- Questions:
  - Which set of conditions give rise to these two different sources (wind speed, release size etc.)?
  - What are the characteristics of the dispersion source term (composition, flow rate, temperature etc.)?
  - Experimental data is limited to just two COSHER tests (COOLTRANS data is currently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

Knowledge Gaps

2. Terrain effects on dense clouds



Larger downslope dispersion distances?

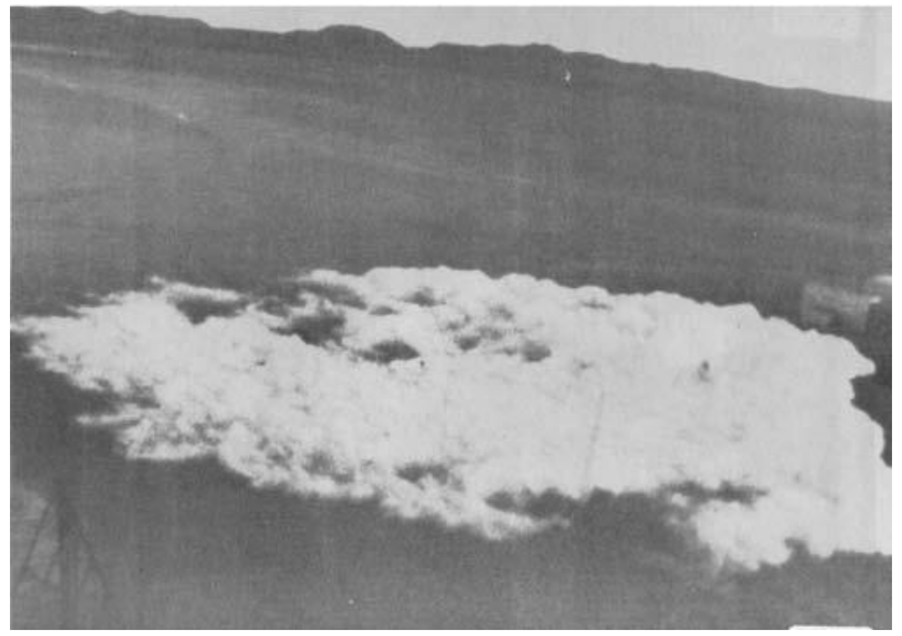


Channelling effects in complex terrain, vapour hold-up in valleys

- 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

- Field-scale experimental data to validate dense-gas dispersion models in complex or sloping terrain is very limited
  - Dispersion datasets were reviewed by Batt (2021) http://www.admlc.com/publications
    - Burro 8 trial: LNG spill on water https://doi.org/10.1016/0304-3894(82)80034-4
    - COOLTRANS CO_2 trials at DNV Spadeadam https://doi.org/10.1115/IPC2014-33384
    - Jack Rabbit I chlorine and ammonia trials https://www.uvu.edu/es/jack-rabbit/
    - Picknett (1981) refrigerant trials at Porton Down https://doi.org/10.1016/0004-6981(81)90181-5
  - All of the above trials have limitations
- Cannot be confident in model predictions without reliable validation data



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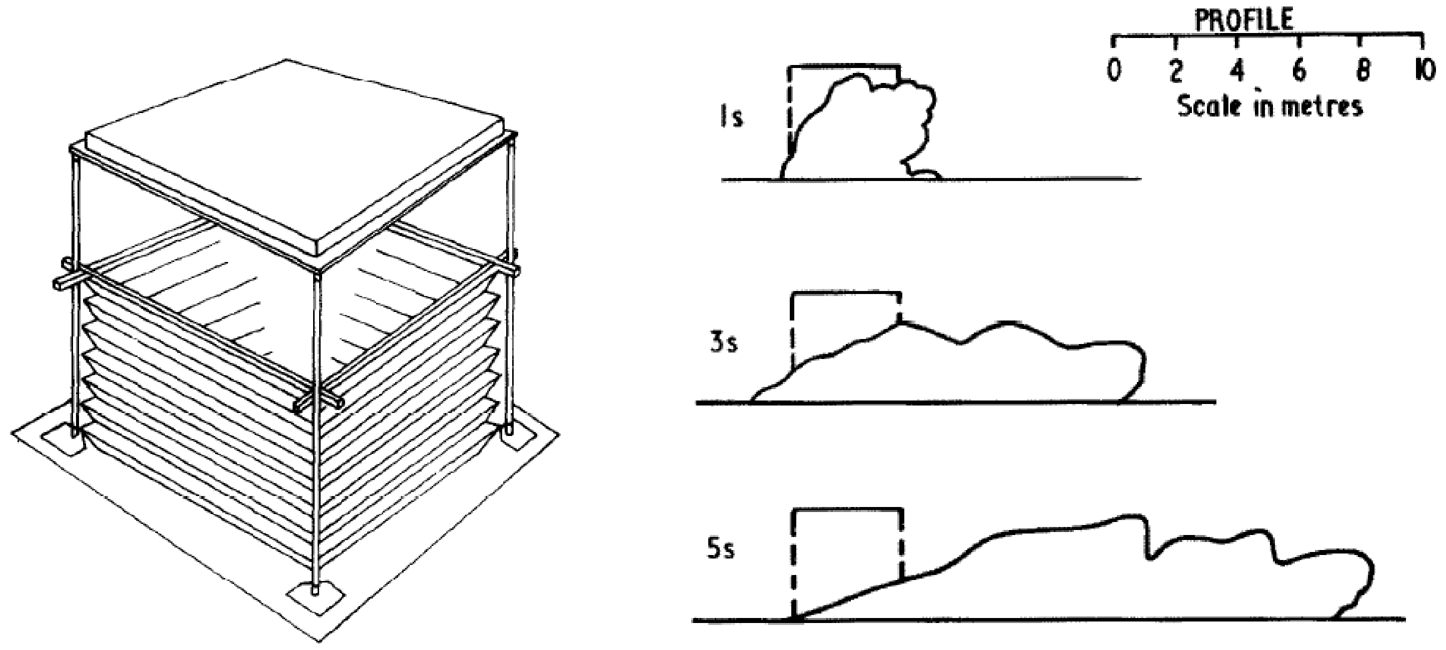

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Knowledge Gaps

- Example of risk assessment modelling requirements:
  - 100 km long pipeline, model release location every 50 m = 2,000 simulations
  - 4 hole diameters (25 mm, 75 mm, 110 mm, full bore) = 8,000 simulations
  - 12 wind directions = 96,000 simulations
  - 4 weather classes (F2.4, D2.4, D4.3, D6.7) = 384,000 simulations
  - If each dispersion simulation takes 1 hour of computer run-time:

    380,000 hours = 384,000 / (24 × 365) = 44 years of computer run-time
- Current complex terrain models use Computational Fluid Dynamics (CFD)
- Other possible faster modelling approaches could be developed and tested:
  - Integral, Gaussian puff, shallow-layer, hybrid CFD/mass-consistent models, Lattice Boltzmann, emulators, correlations, machine learning
- PHMSA is currently funding development of machine learning model (based on CFD) at Texas A&M for application to CO_2 pipeline risk assessment
  - Led by Dr. Sam (Qingsheng) Wang https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=987
- Also: IChemE Hazards conference 7 Nov 2023 “Development of a Practical Methodology for Assessing the Major Accident Risks Associated with Carbon Dioxide Pipelines in Areas of Topography” Robert Melville, Alison Thackery and Ian Lines, Kent PLC, UK

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/

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Plans for Joint Industry Project

- 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 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 in both light and moderate wind speeds

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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

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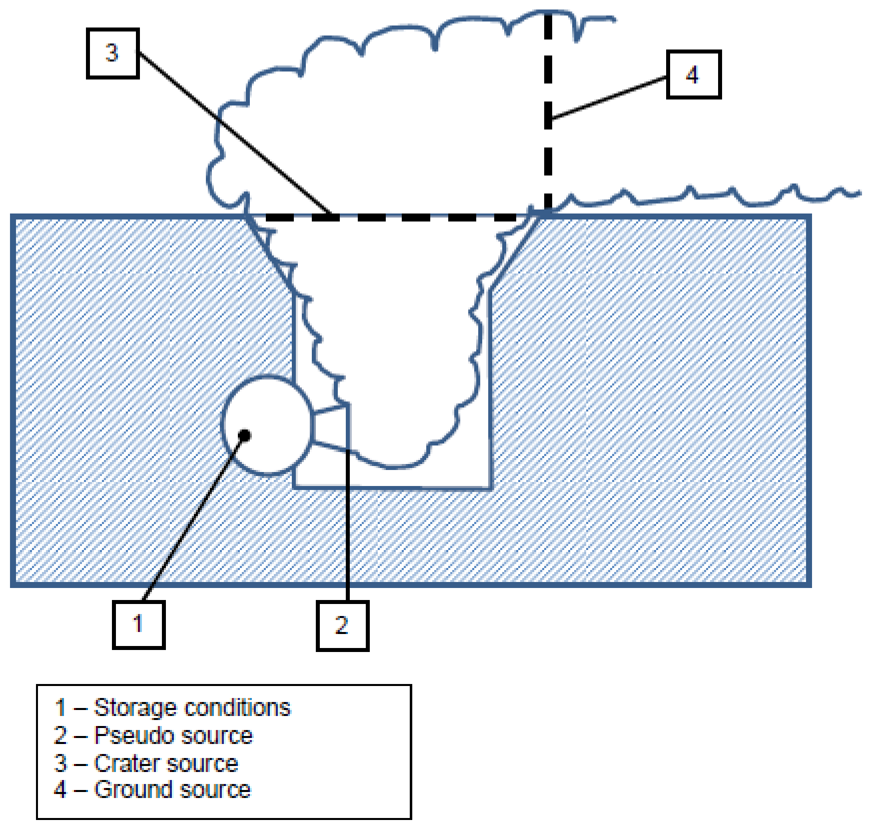


Figure 1 Puncture and crater sources

DNV

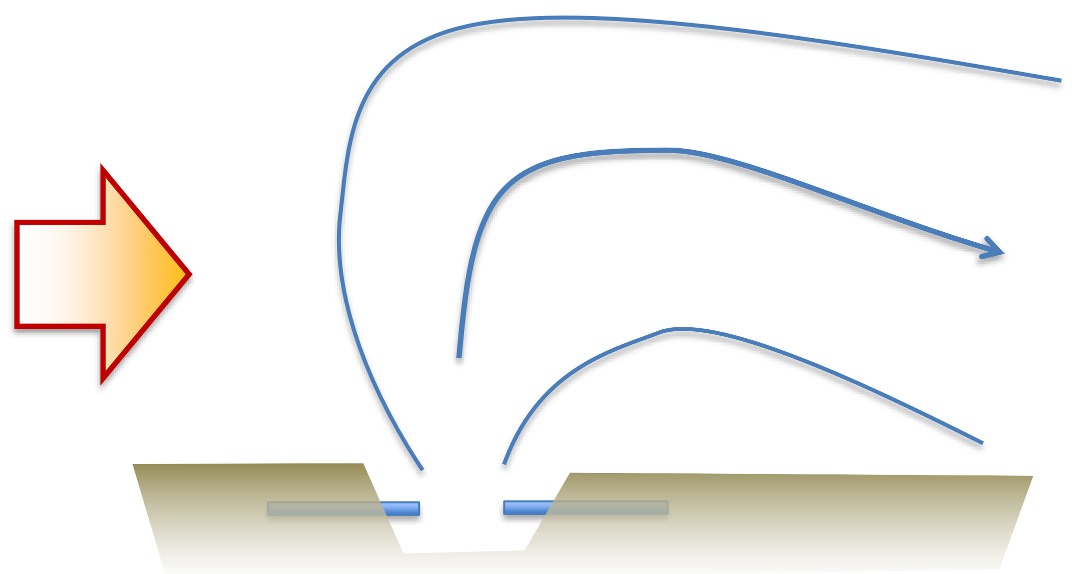
Work Package 1: CO_2 pipeline craters and source terms

- 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

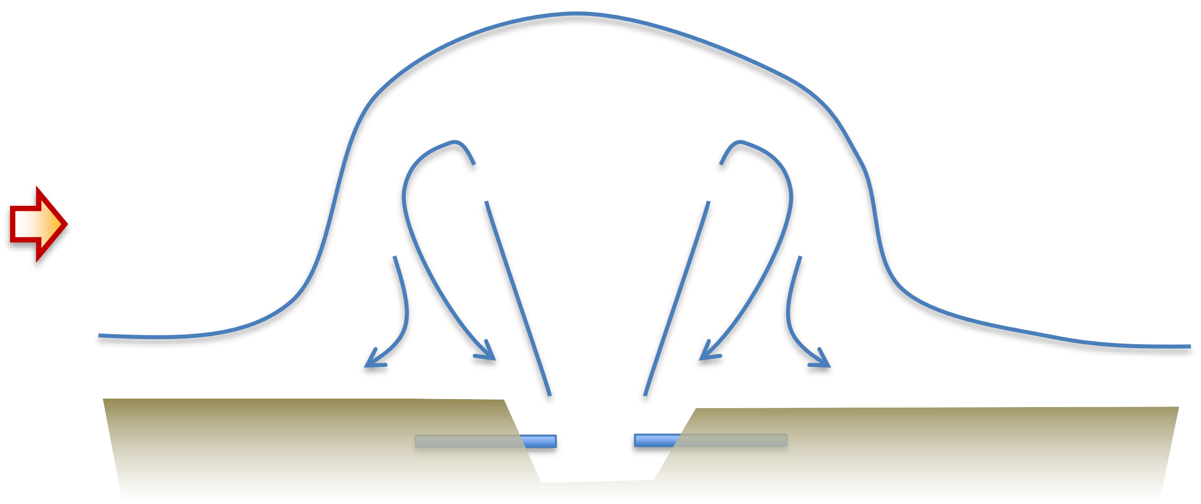
Work Package 2: Wind tunnel studies

- **Aim**: 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:

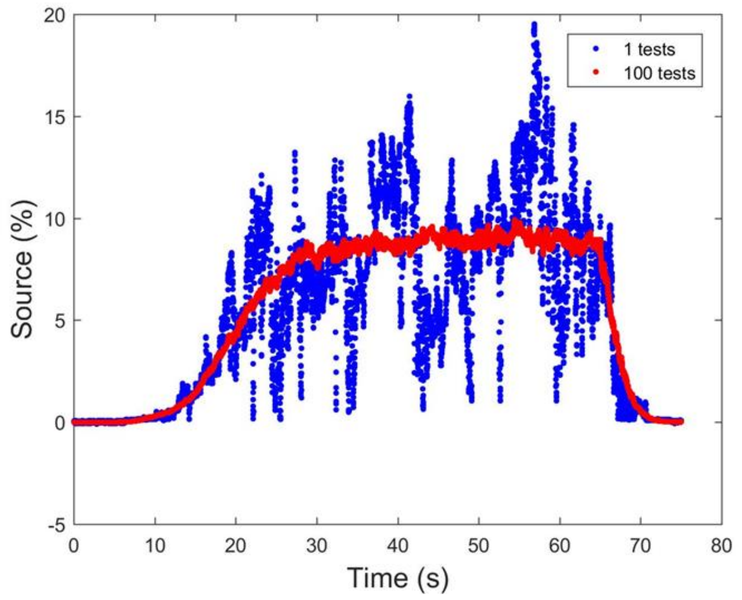


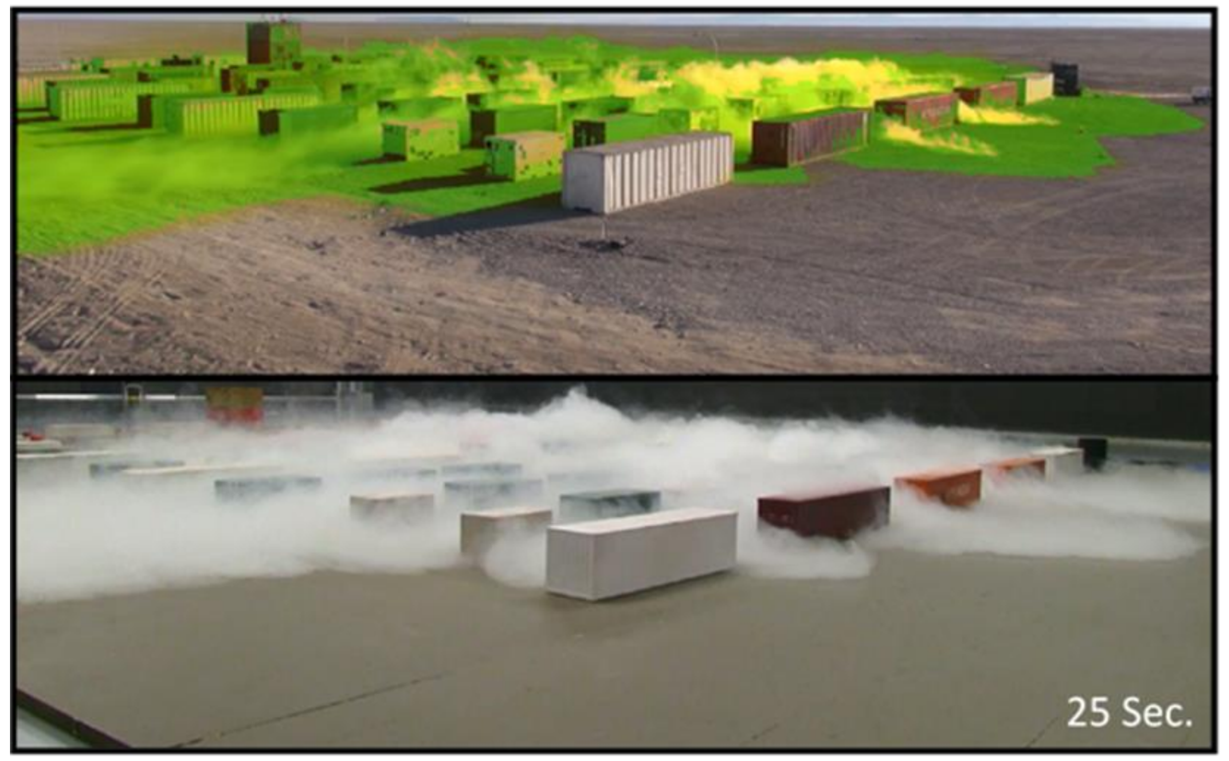
Or ?



Work Package 2: Wind tunnel studies

- 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

Work Package 2: Wind tunnel studies

- Outcomes:
  - Comprehensive dataset of vertical dense-gas releases from craters
  - Criteria that define the set of conditions when CO_2 jet
    - 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

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

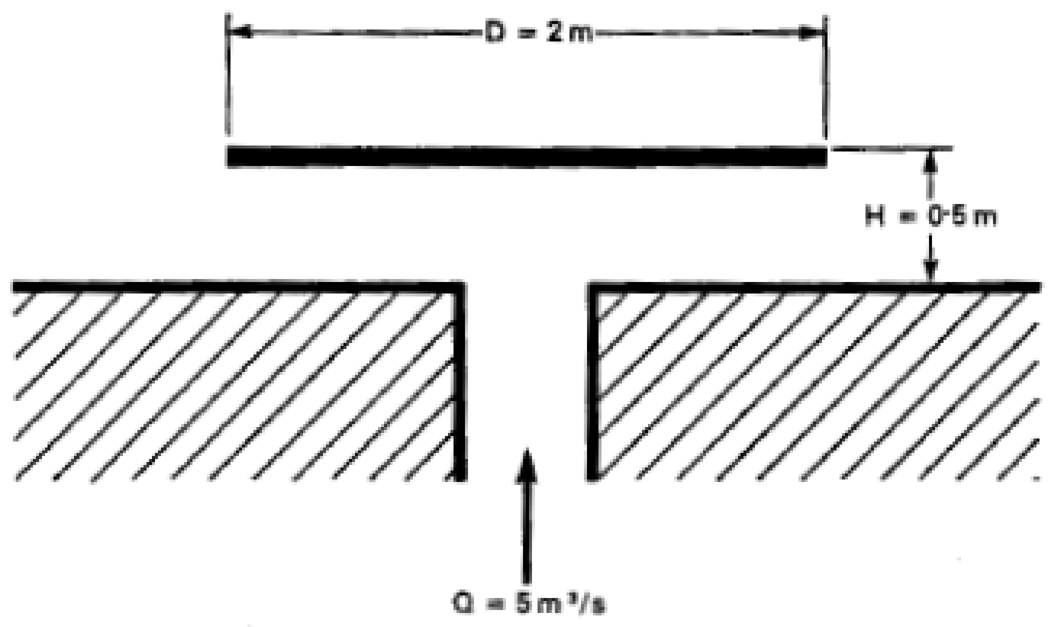


Fig.22.4 Geometry of ground-level source for continuous release experiments

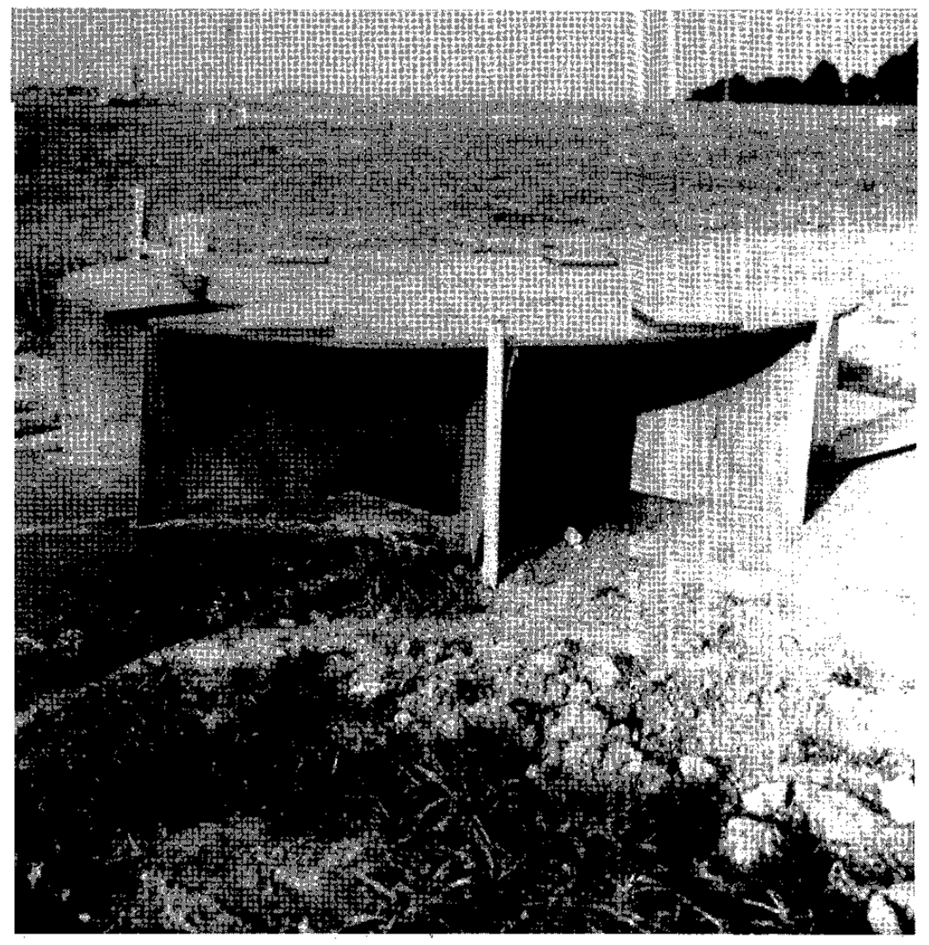
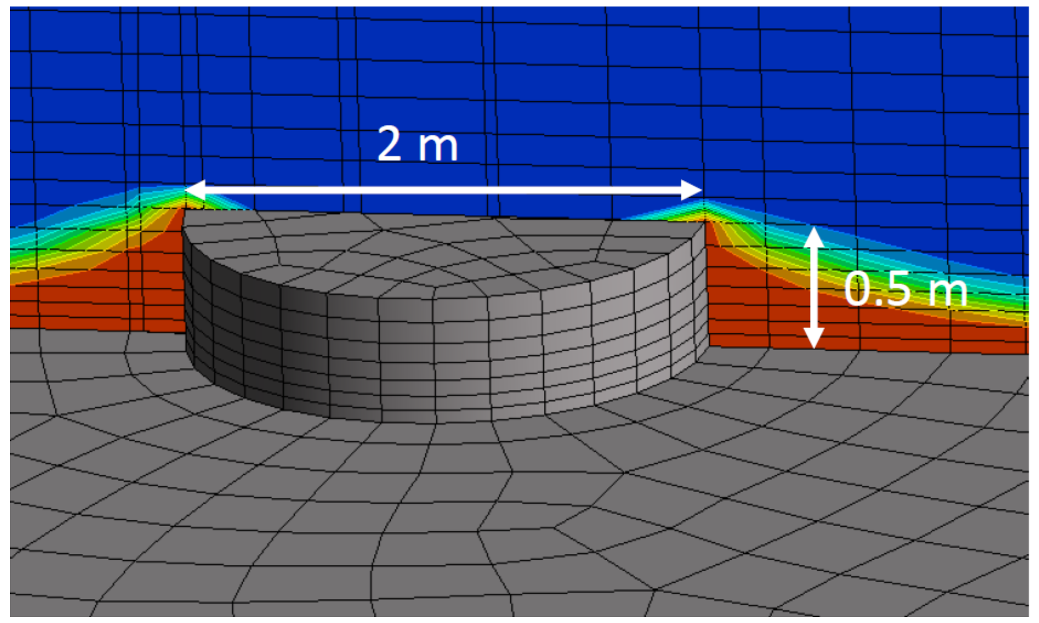
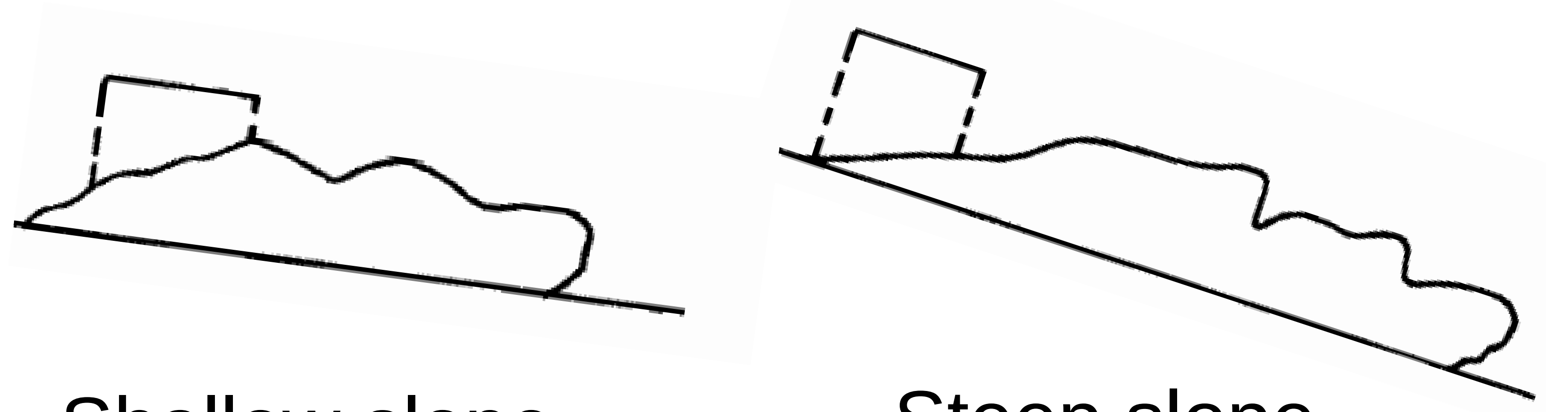


Fig. 22.2 Outlet from the gas supply duct at the release point



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



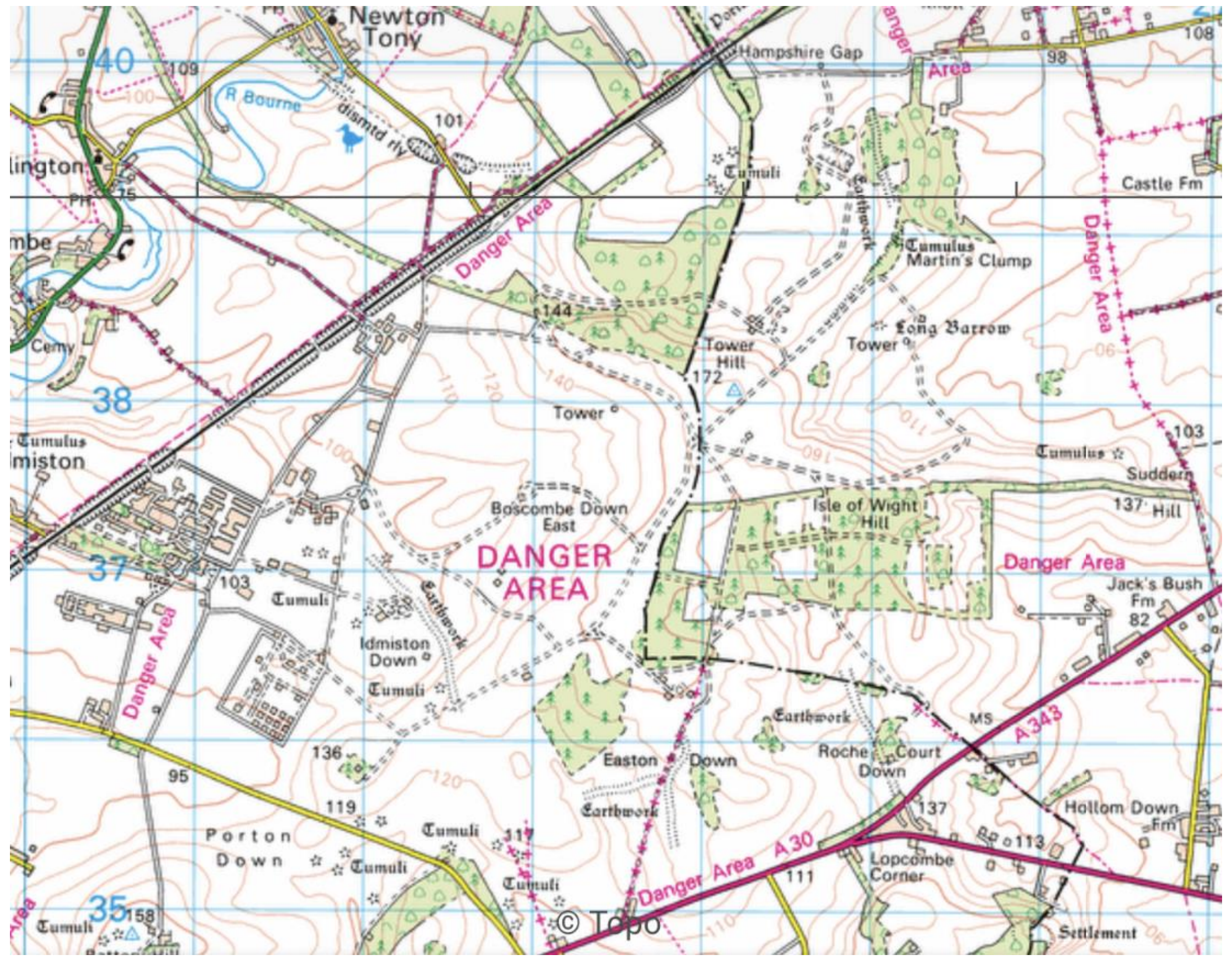
Shallow slope Steep slope

How does dispersion behaviour compare to flat terrain?

dstl The Science Inside

Work Package 3: Simple sloping terrain dispersion exps

- Grassland slopes at Porton Down ideally suited to simple terrain tests
- Two chalk-downland bowls: one shallow, one steeper
- Site previously used for HSE trials on instantaneous releases (Picknett, 1981)
- Complementary expertise: dispersion trials officers and modelling team at DSTL, who use the HPAC model (SCIPUFF Gaussian puff model)
  - Provides rapid-response Reachback service for UK defence and security related incidents
- Support from Met Office for meteorological data



Met Office

[dstl] The Science Inside

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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

Met Office

[dstl] The Science Inside

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
1186 m
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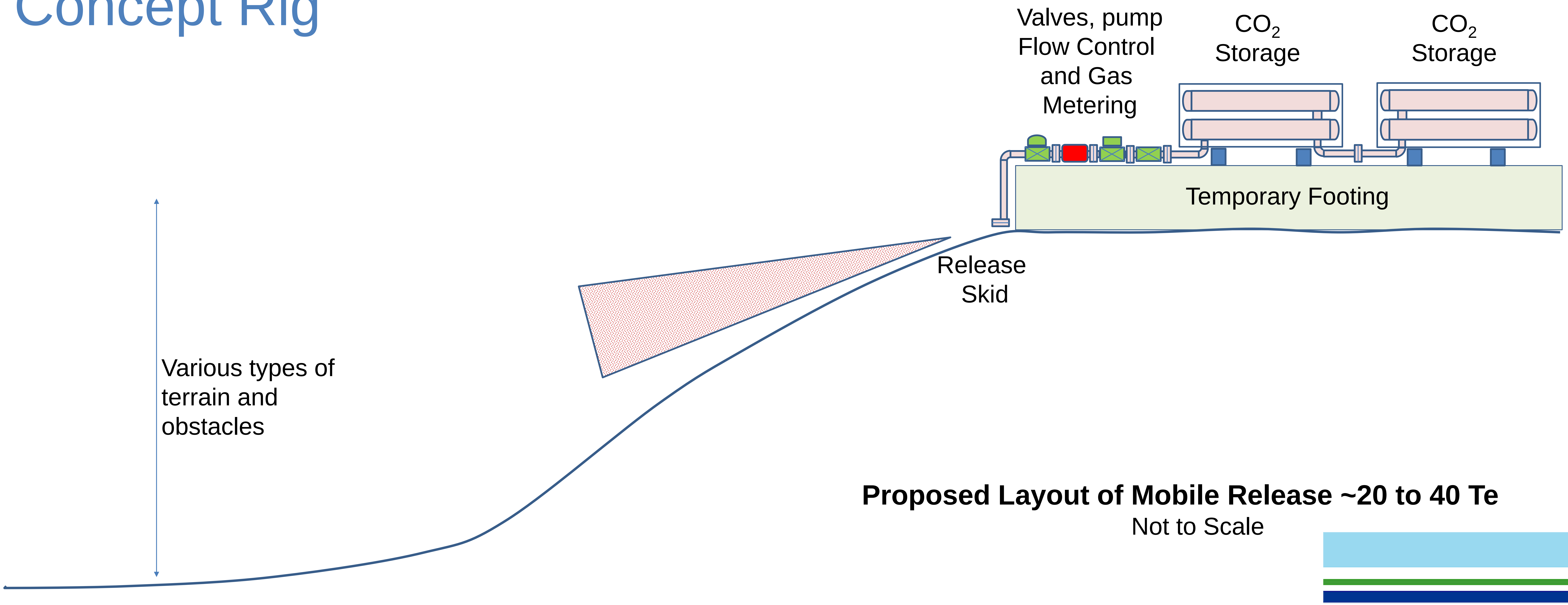
Google Earth

Work Package 4: Complex Terrain Dispersion Exps

Concept Rig



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

DNV

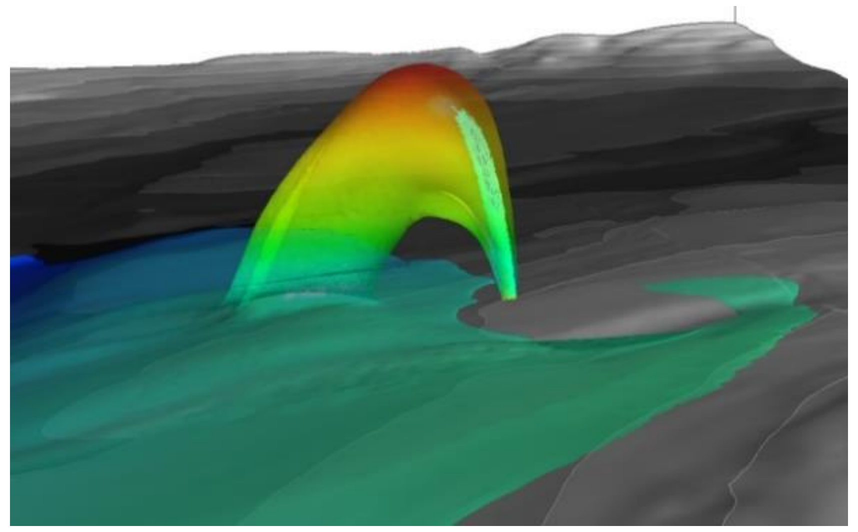
Work Package 4: Complex terrain dispersion exps

- 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

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 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



Work Package 5: Model development and validation

- Outcomes:
  - Understanding of strengths and weaknesses of different modelling approaches
  - Model input to help define the scope and parameters of the experimental programme
  - Detailed scrutiny of measurement data from the experimental work packages
  - Potential to see development of new rapid dispersion modelling approaches
  - Useful information for behaviour of other dense gases, e.g., chlorine, ammonia

- Potential challenge:
  - NDA: agreement not to disclose measurement data for defined period?

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/
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NCEC RICARDO

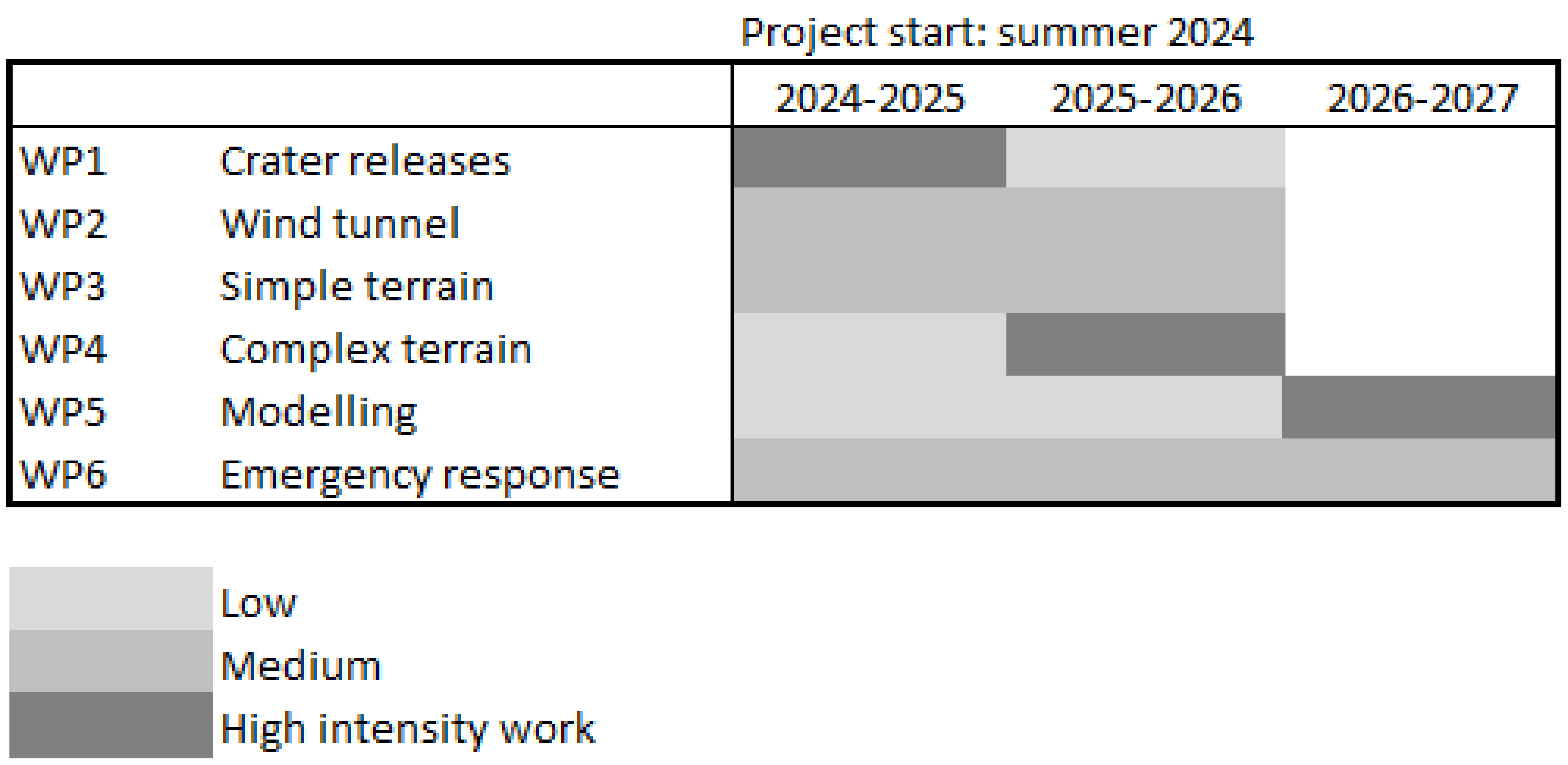
Work Package 6: Emergency response

- National Chemical Emergency Centre (NCEC)
  - Established in 1973 by the UK Government to provide emergency response support to incidents involving hazardous chemicals
  - 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 >2,000 calls per year
  - Strong links with UK Hazmat 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

- Outcomes:
  - Improved knowledge and awareness of emergency response to CO_2 incidents
  - Possible training of 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

Timeline (approximate)



Concluding Remarks

- Current plans have been developed following discussions with DNV, DSTL, Met Office, Arkansas University and NCEC
- 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?
  - For example, operational tests on valves, exposure of structural elements to cold CO_2 jets (embrittlement?), accumulation of dry ice in enclosures, venting
  - Is the approach involving multiple modelling teams with an NDA acceptable?
- Following feedback and discussions
  - Aim to develop more detailed scope and rough costing
  - Some iteration may be needed on scope/costing, depending on funding available
- Feedback welcome

NCEC RICARDO

Thank you

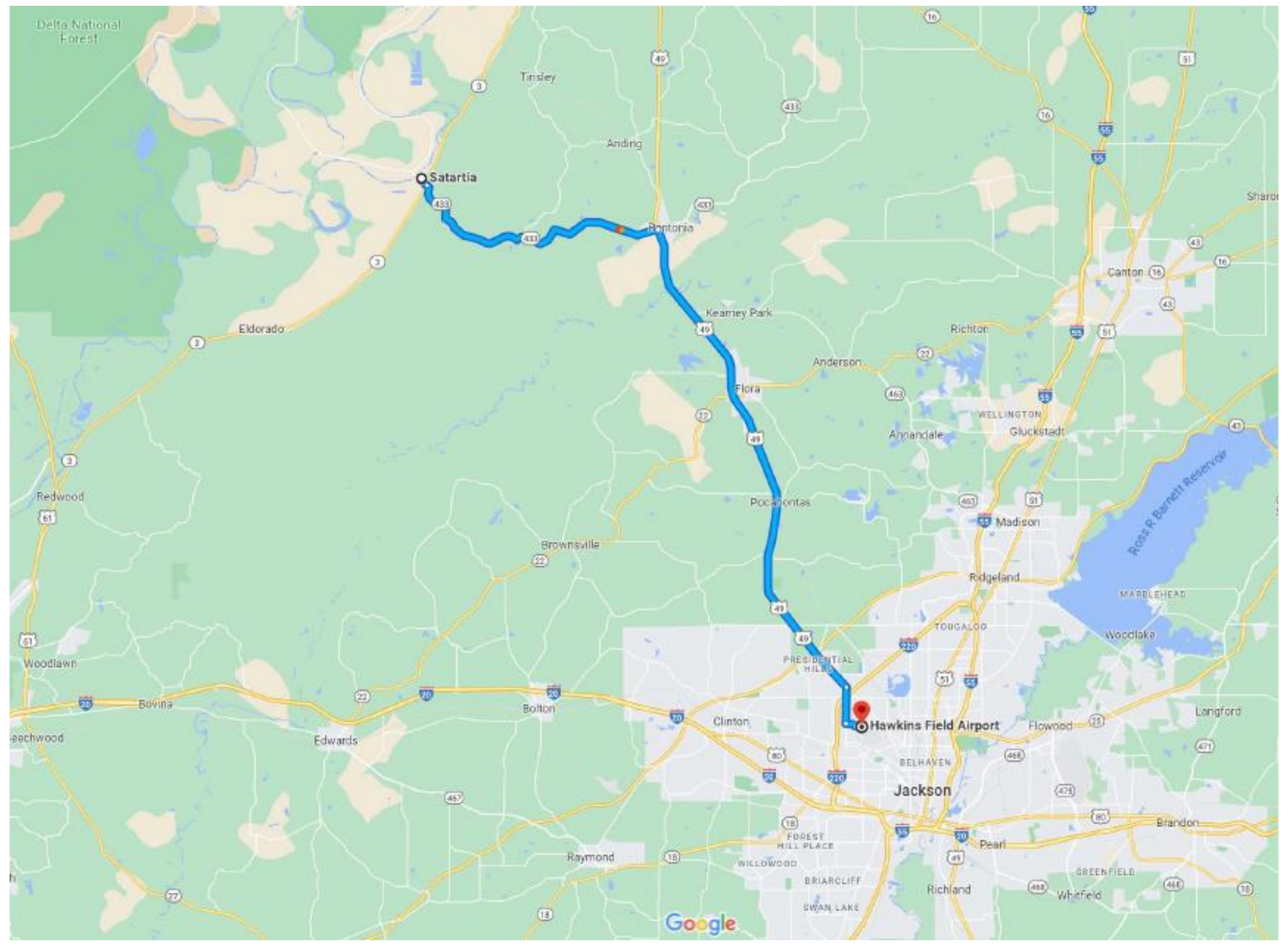
Any questions?

- Contact: simon.gant@hse.gov.uk
- 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

Additional slides

Satartia Incident Weather Conditions

Nearest weather station at Hawkins Field Airport, Jackson, MS (37 miles by road)



PWS WEATHER BY AERISWEATHER

KHKS ACTIVE

Jackson Hawkins, MS, US

https://www.pwsweather.com/station/khks?timespan=day&date=2020-02-22

Time of incident, 7:06 pm CST February 22, 2020 (PHMSA Incident Report)

Failure Investigation Report – Denbury Gulf Coast Pipelines LLC
Pipeline Rupture/Natural Force Damage
February 22, 2020

Executive Summary

On February 22, 2020, at 7:06 p.m. Central Standard Time (CST[1]), Denbury's 24-inch Delhi (Delhi) Pipeline ruptured, releasing liquid CO_2 that immediately began to vaporize at atmospheric conditions. The site of the rupture was on the northeast side of Highway 433 (HWY 433), approximately one mile southeast of Satartia, Mississippi. Denbury subsequently reported the rupture released an estimated total of 31,405[2] barrels of CO_2. Following the accident, investigators from the Pipeline and Hazardous Material Safety Administration's (PHMSA's) Accident Investigation Division (AID) and Southwest Regional Office, conducted an investigation, including an onsite investigation.

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf

Observation History

GRAPHS | TABULAR

TIME	TEMP	DEW PT	HUMIDITY	WIND			PRESSURE	SOLAR RAD	UV	PRECIPITATION	
				SPEED	DIRECTION	GUSTS	ALTIMETER			TOTAL	ACCUM
9:53 pm	7.2°C	1.7°C	68%	Calm	N	--	1026.4mb	0 W/m²	--	0.0 mm	0.0 mm
8:53 pm	7.2°C	1.1°C	66%	Calm	N	--	1026.7mb	0 W/m²	--	0.0 mm	0.0 mm
7:53 pm	7.8°C	1.1°C	63%	Calm	N	--	1026.7mb	0 W/m²	--	0.0 mm	0.0 mm
6:53 pm	8.9°C	0.6°C	56%	Calm	N	--	1026.7mb	0 W/m²	--	0.0 mm	0.0 mm
5:53 pm	12.2°C	-2.2°C	37%	Calm	N						
4:53 pm	13.9°C	-2.8°C	32%	Calm	N	--					
3:53 pm	13.9°C	-3.9°C	29%	Calm	N	--	1027.4mb	354 W/m²	--	0.0 mm	0.0 mm

Wind speed "calm"
(less than 5.6 km/h or 1.5 m/s)

Recent review of CO_2 pipeline incidents in the USA

Journal of Loss Prevention in the Process Industries 77 (2022) 104799

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

ELSEVIER

Statistical analysis of incidents on onshore CO_2 pipelines based on PHMSA database

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https://doi.org/10.1016/j.jlp.2022.104799

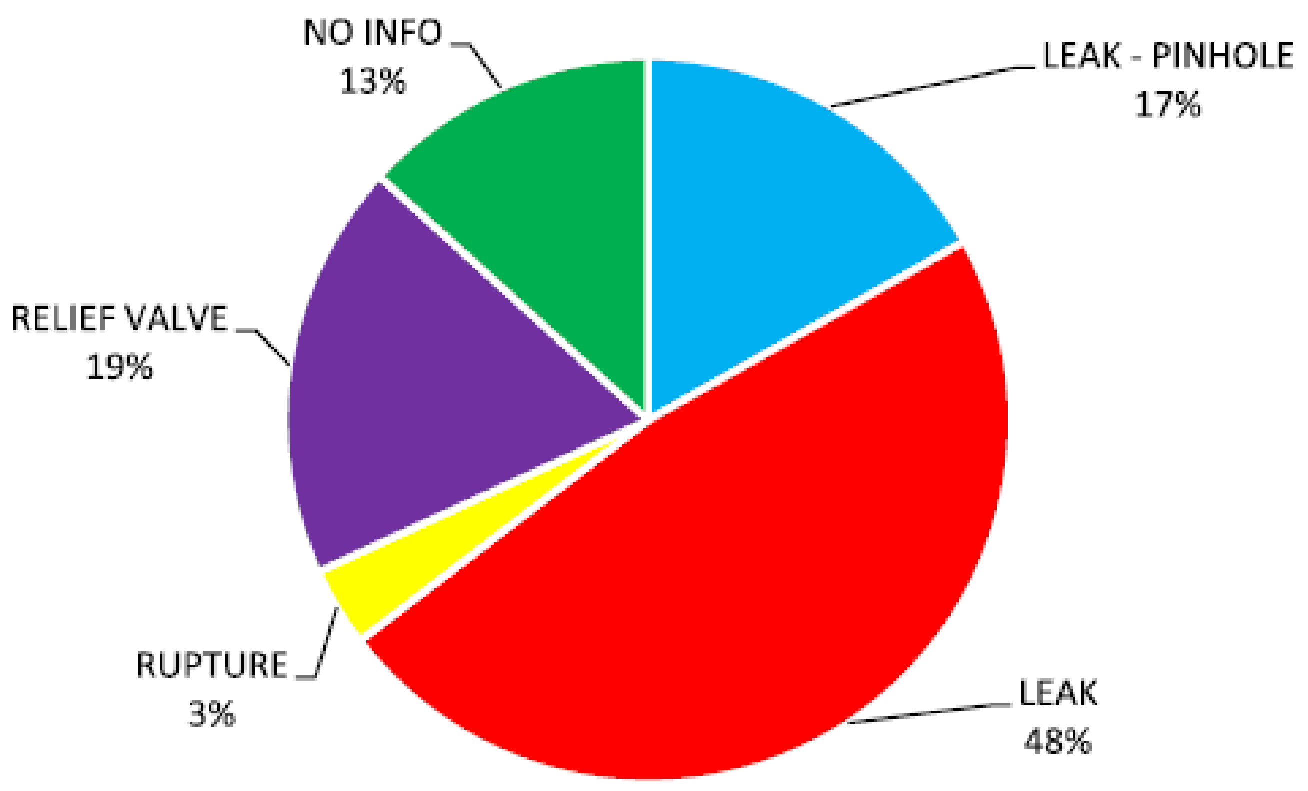


Fig. 6. Release type distribution for CO_2 pipeline incidents (1994–2021).

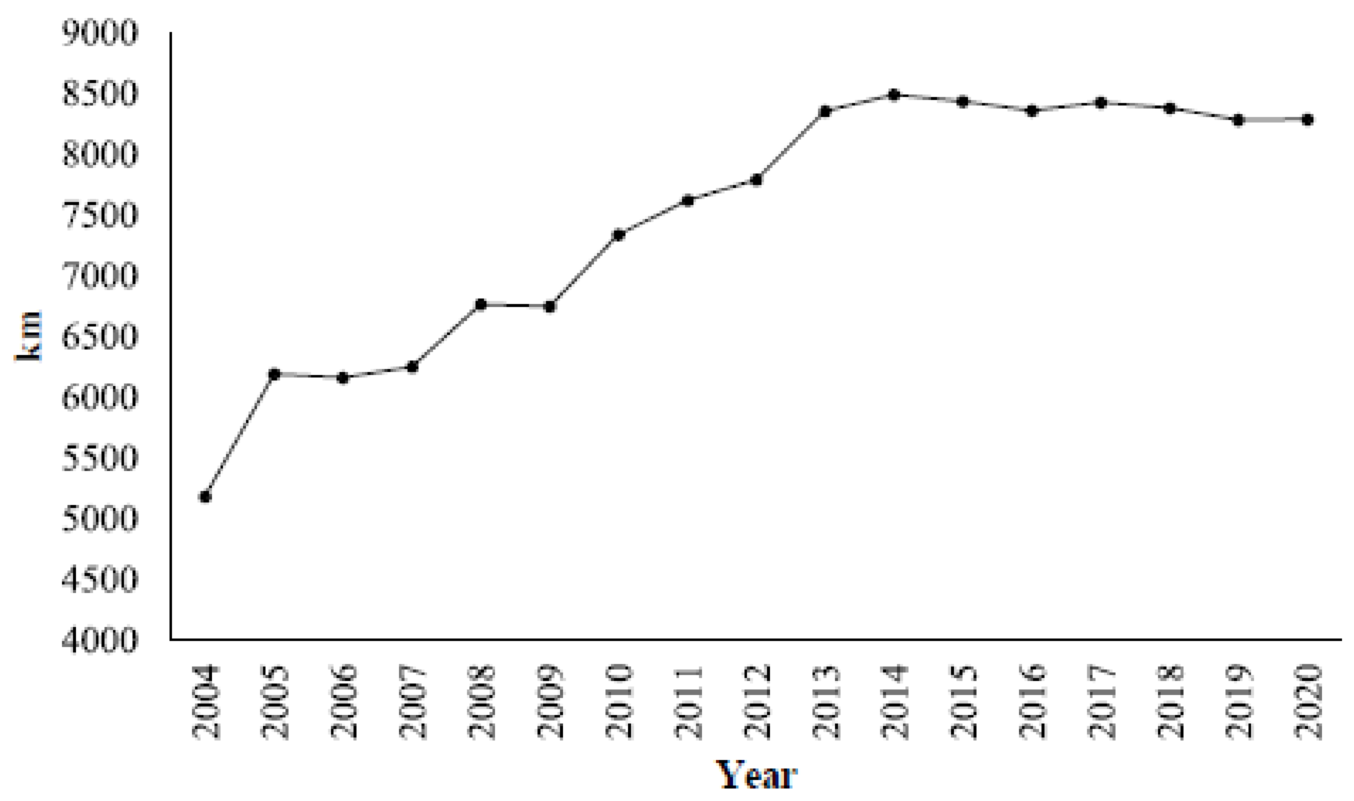


Fig. 1. Evolution of total kilometers of CO_2 pipeline in the USA from 2004 to 2020.

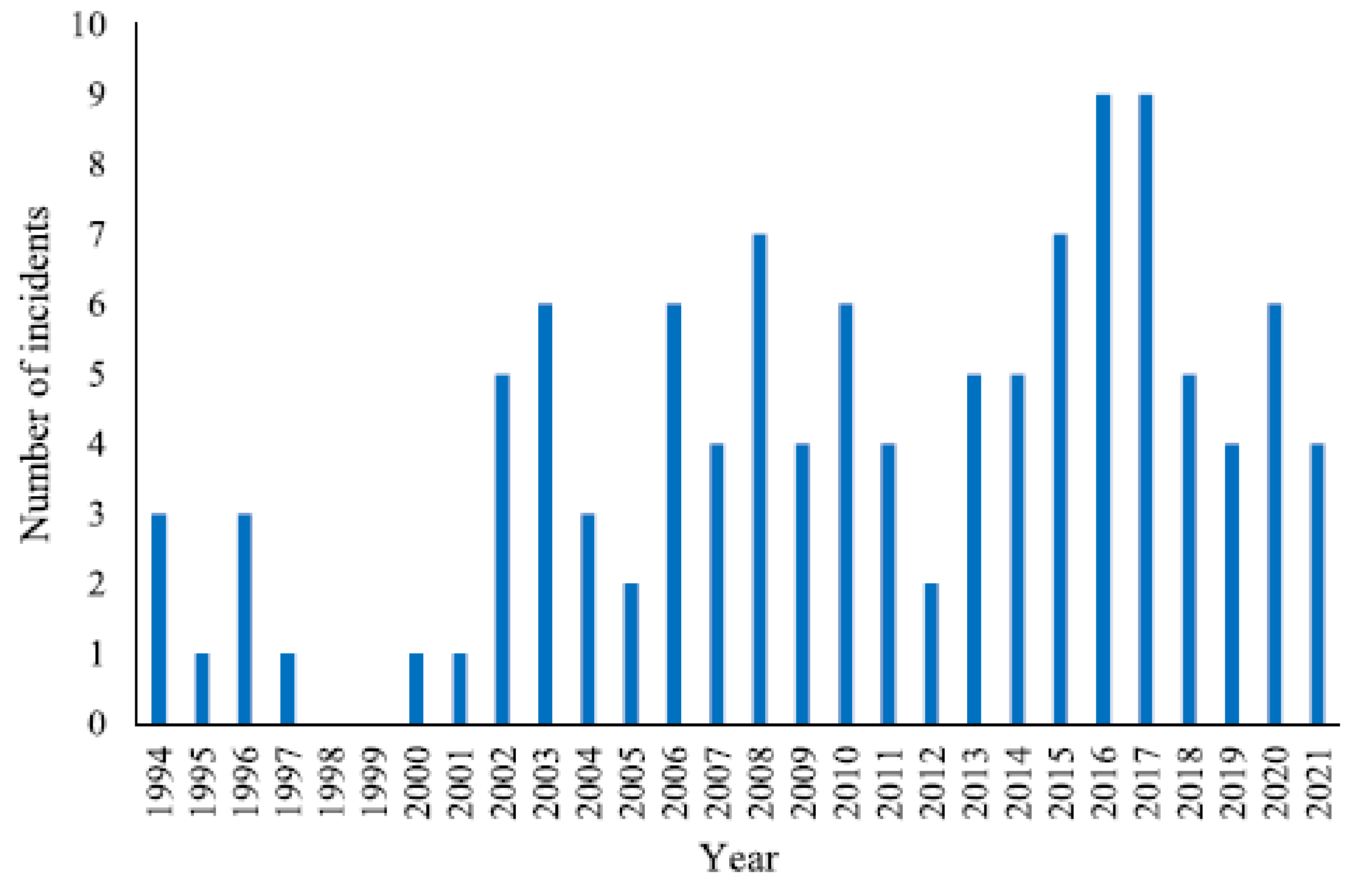
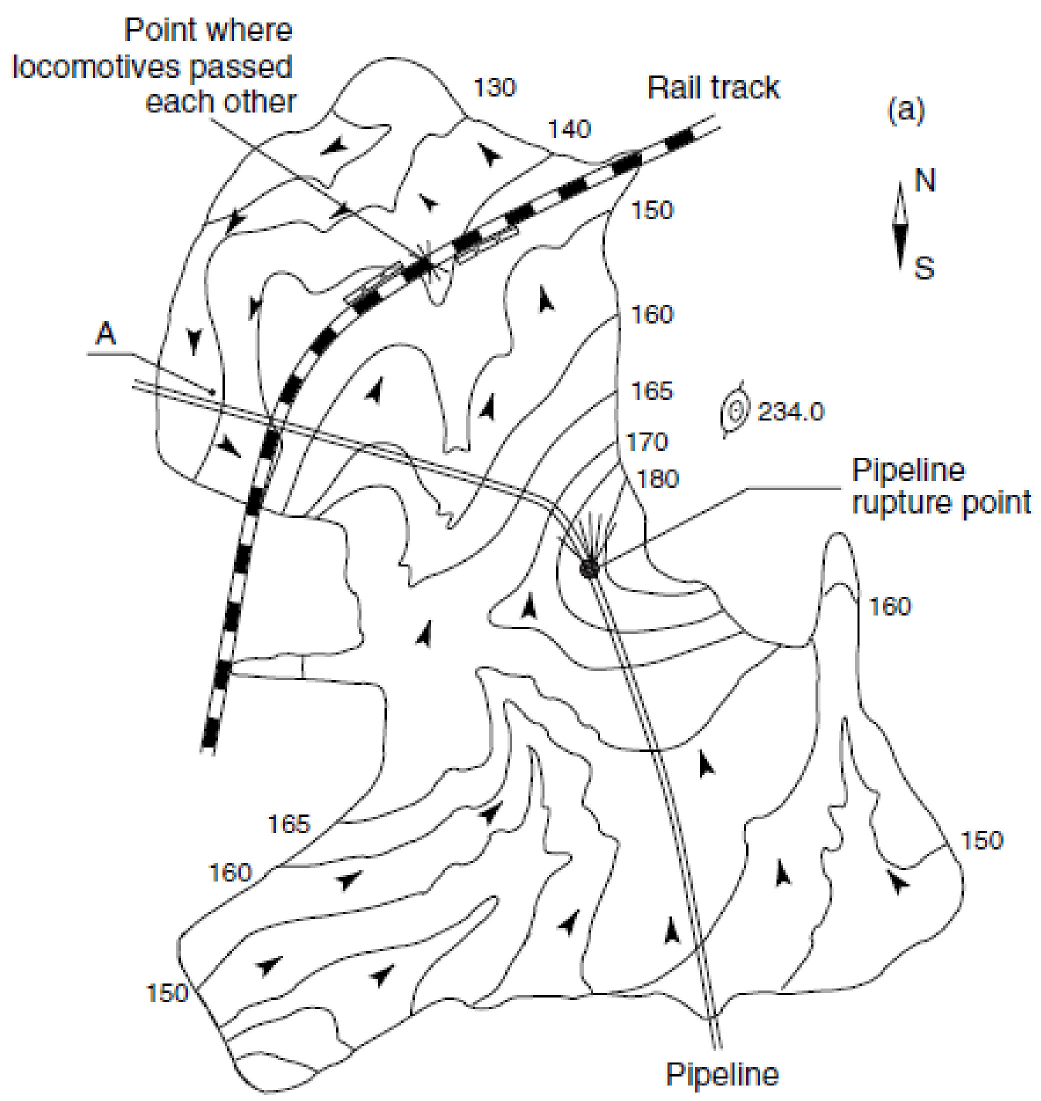


Fig. 3. Number of incidents recorded for CO2 pipelines in the U.S.A. (1994–2021) from PHMSA.

Examples of other incidents where dense-gas dispersion was affected by terrain

Ufa, Russia, 1989

- Rupture of 700 mm diameter LPG pipeline operating at 38 bar
- Large vapor cloud accumulated, detected by villages up to 7 km away before explosion
- Ignition occurred as two trains passed each other within the cloud
- 1224 people on the trains were killed or severely injured
- Pipeline fractured at head of valley with steep slopes, vapour cloud formed in valleys



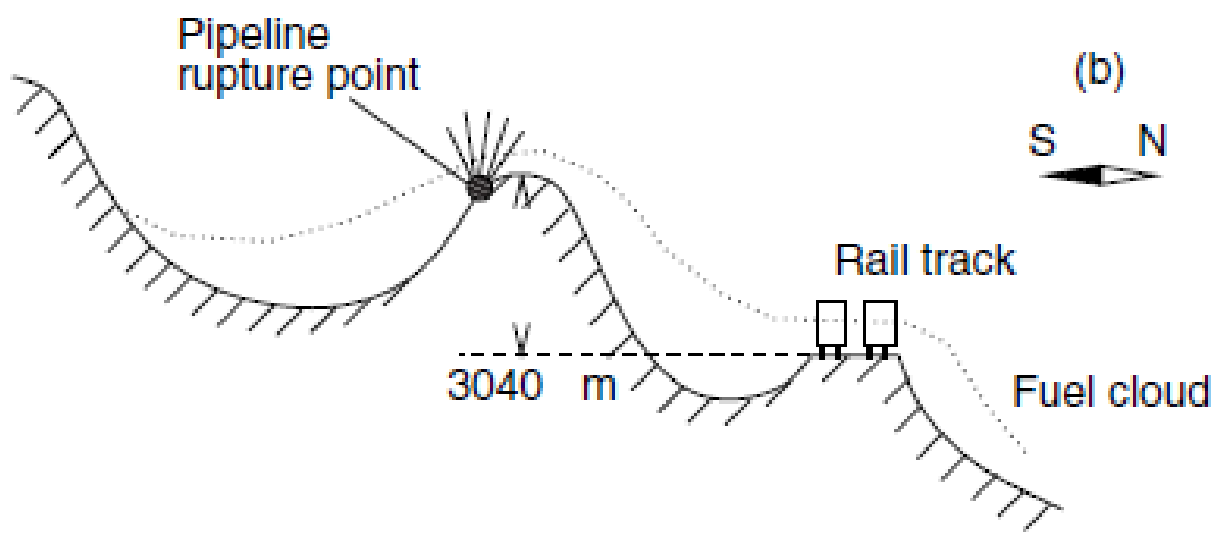
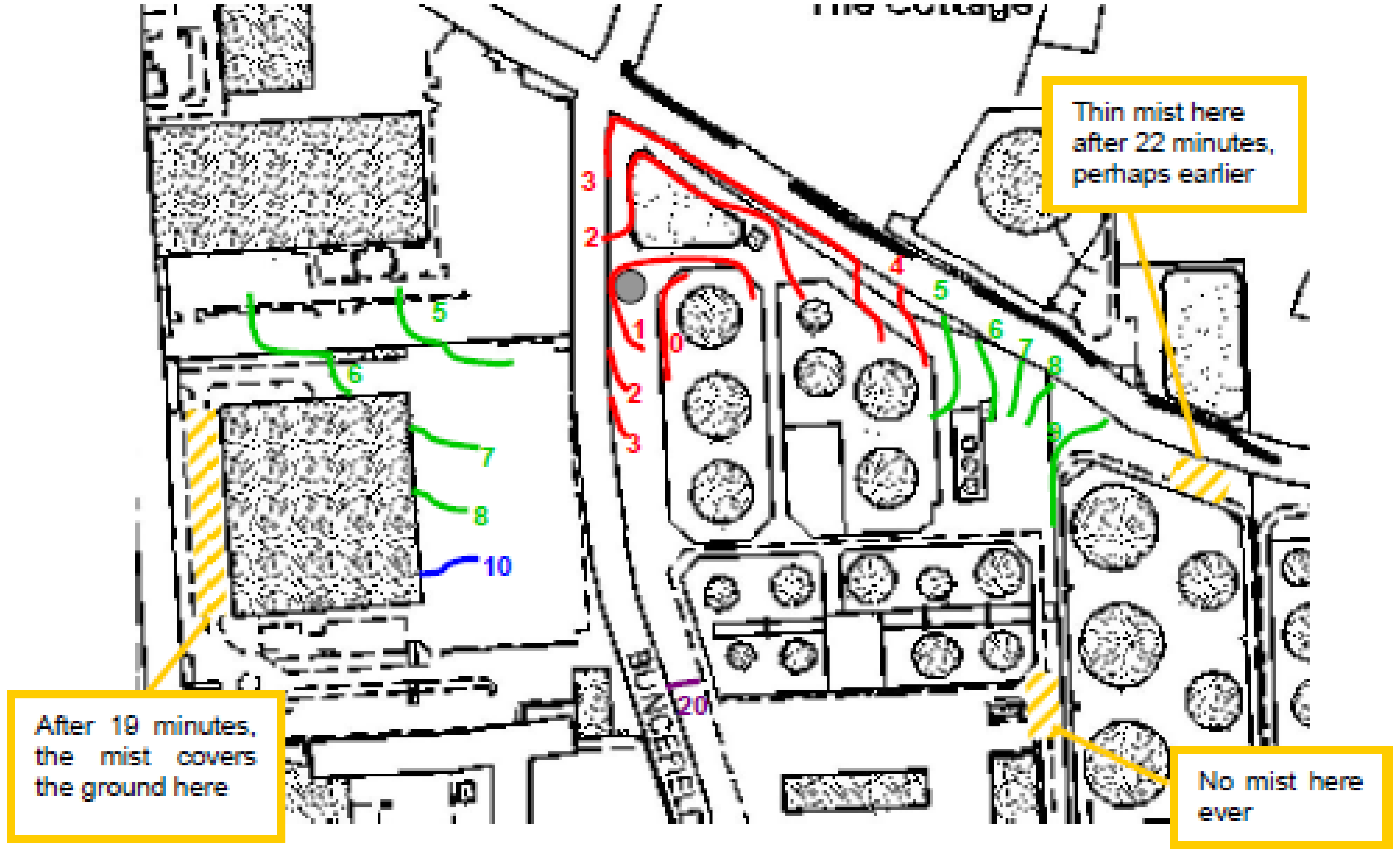


FIG. 9. Ufa accident: (a) sketch of demolished area (direction of tree fell is shown by arrows); (b) terrain profile (not to scale). View of accident site from region of point A is given in Fig. 10.

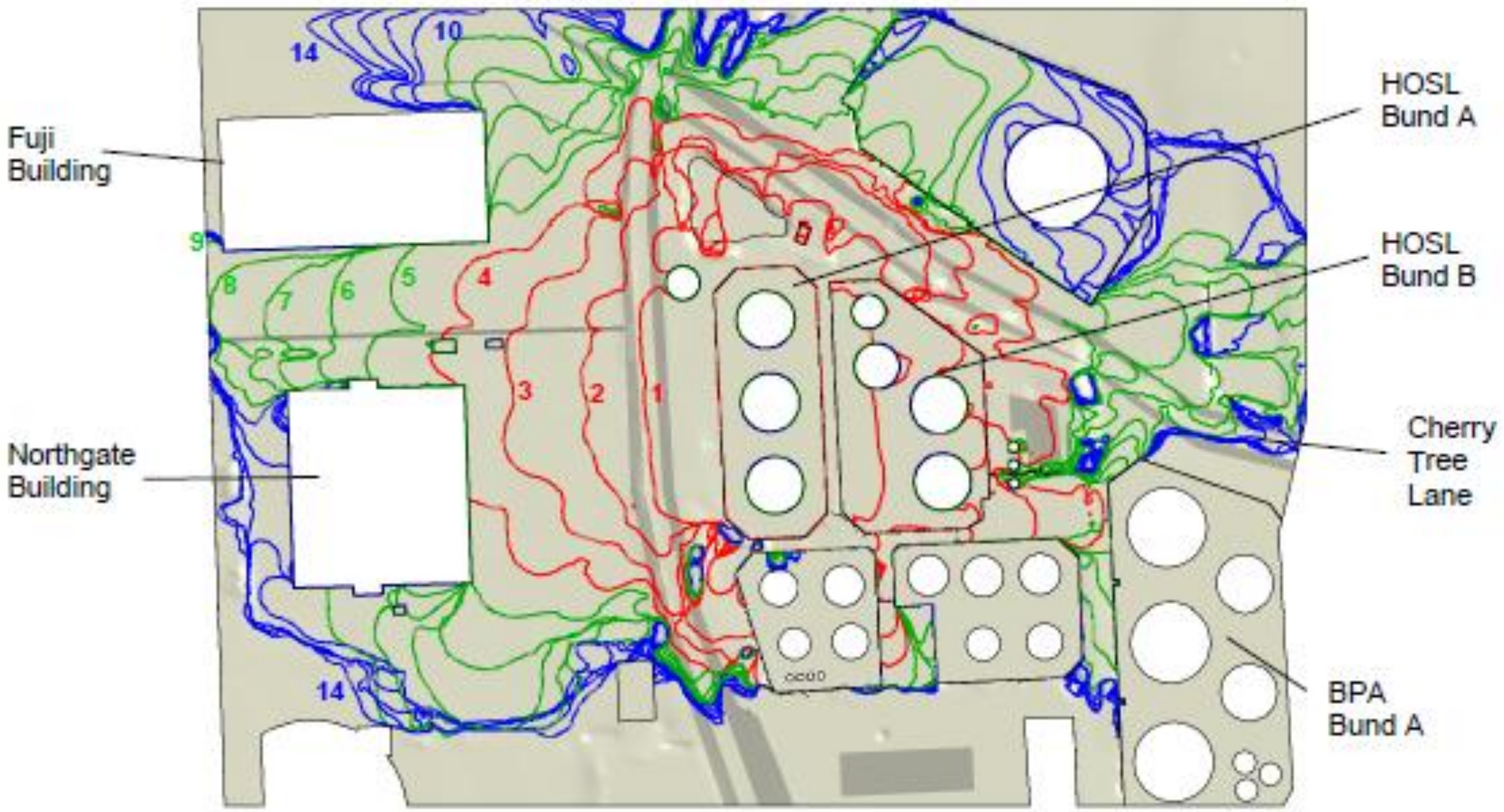
FIG. 10. Accident site viewed from region of point A in Fig. 9. On the right of the railway is the remainder of one of the trains.

Makhviladze & Yakush (2005) https://doi.org/10.1016/S1540-7489(02)80028-1

Buncefield, UK, 2005



CCTV Observations



CFD Modelling

Comparison of CFD predictions and CCTV observations for the progress of the dense gasoline vapour cloud or mist across the Buncefield site. Times shown are in minutes from the moment the mist appeared over the wall of Bund A

Gant & Atkinson (2018) https://www.hse.gov.uk/research/rrpdf/rr1129.pdf