RESEARCH AND GUIDANCE FROM HSE

Carbon dioxide pipelines: dispersion modeling challenges and tentative plans for a program of field-scale experiments

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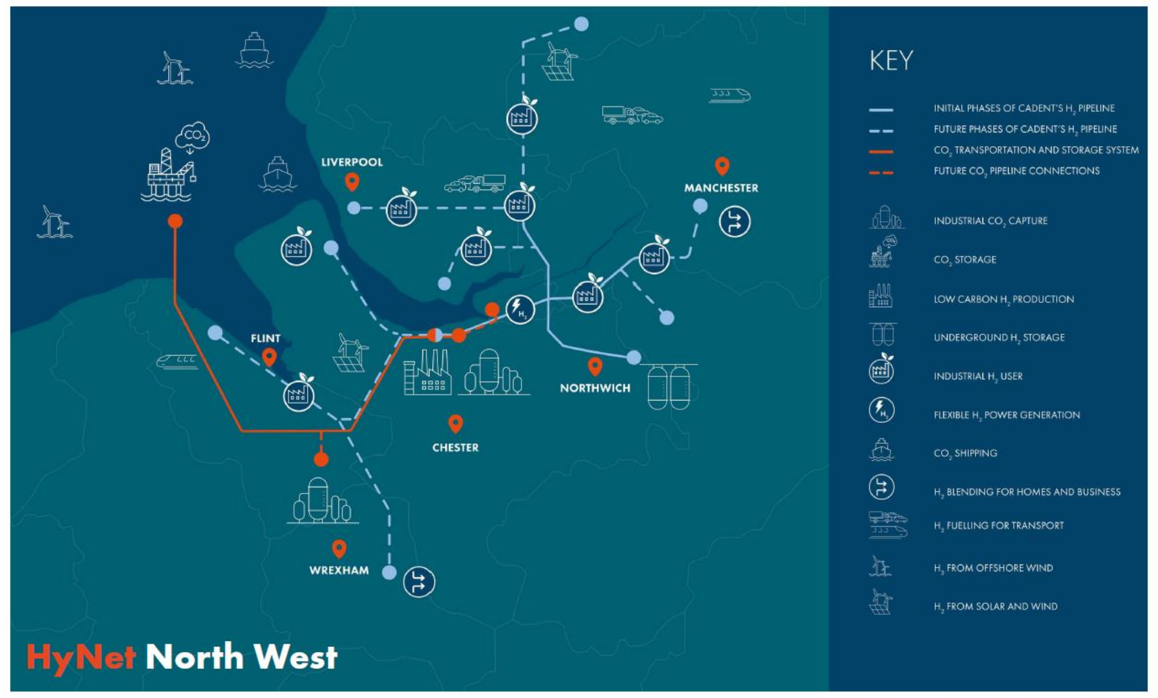
Research - HSE funded to provide evidence which underpins its policy and regulatory activities
Guidance - freely available to help people comply with health and safety law

Contents

Carbon Capture, Utilisation and Storage: Europe

- Net Zero targets are currently driving a rapid growth internationally in Carbon Capture, Utilisation and Storage (CCUS) projects in Europe
- Bulk transport of CO_2 by pipeline and/or ship



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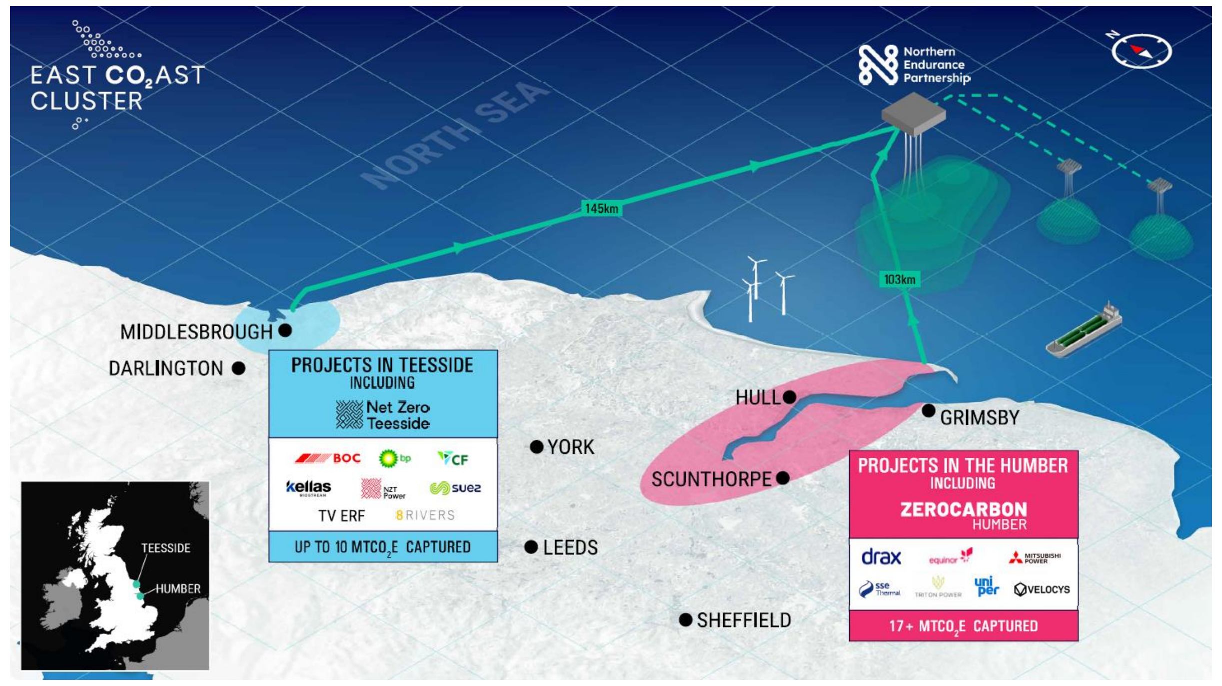
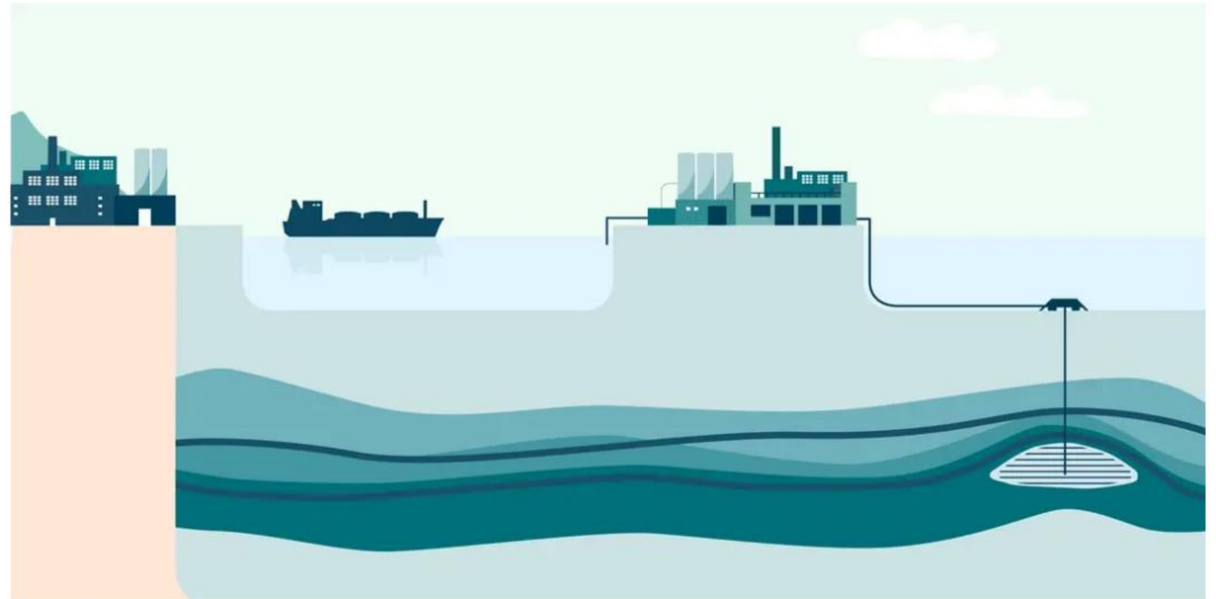


https://eastcoastcluster.co.uk/

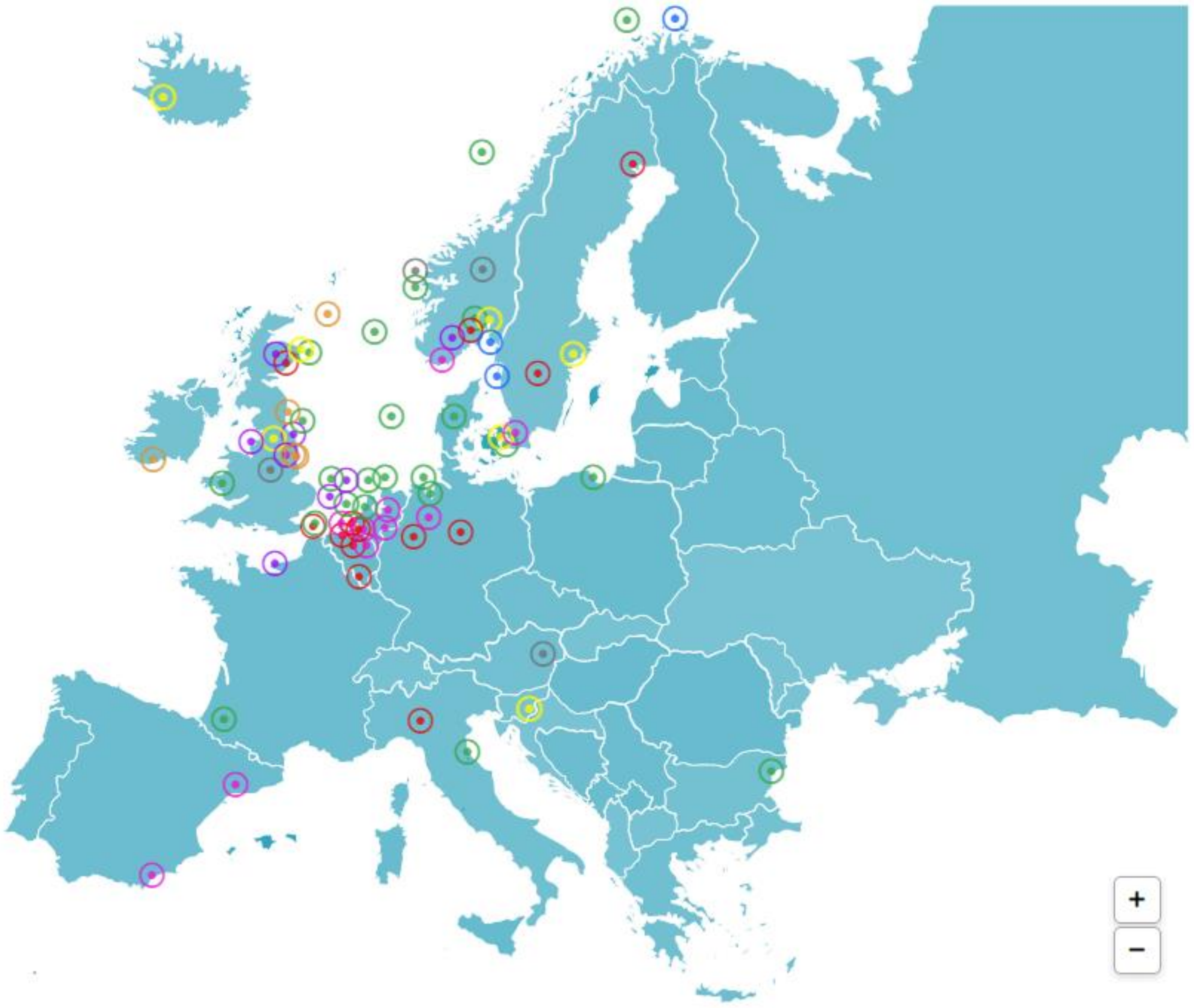
https://www.porthosco2.nl



https://norlights.com

Carbon Capture, Utilisation and Storage : Europe

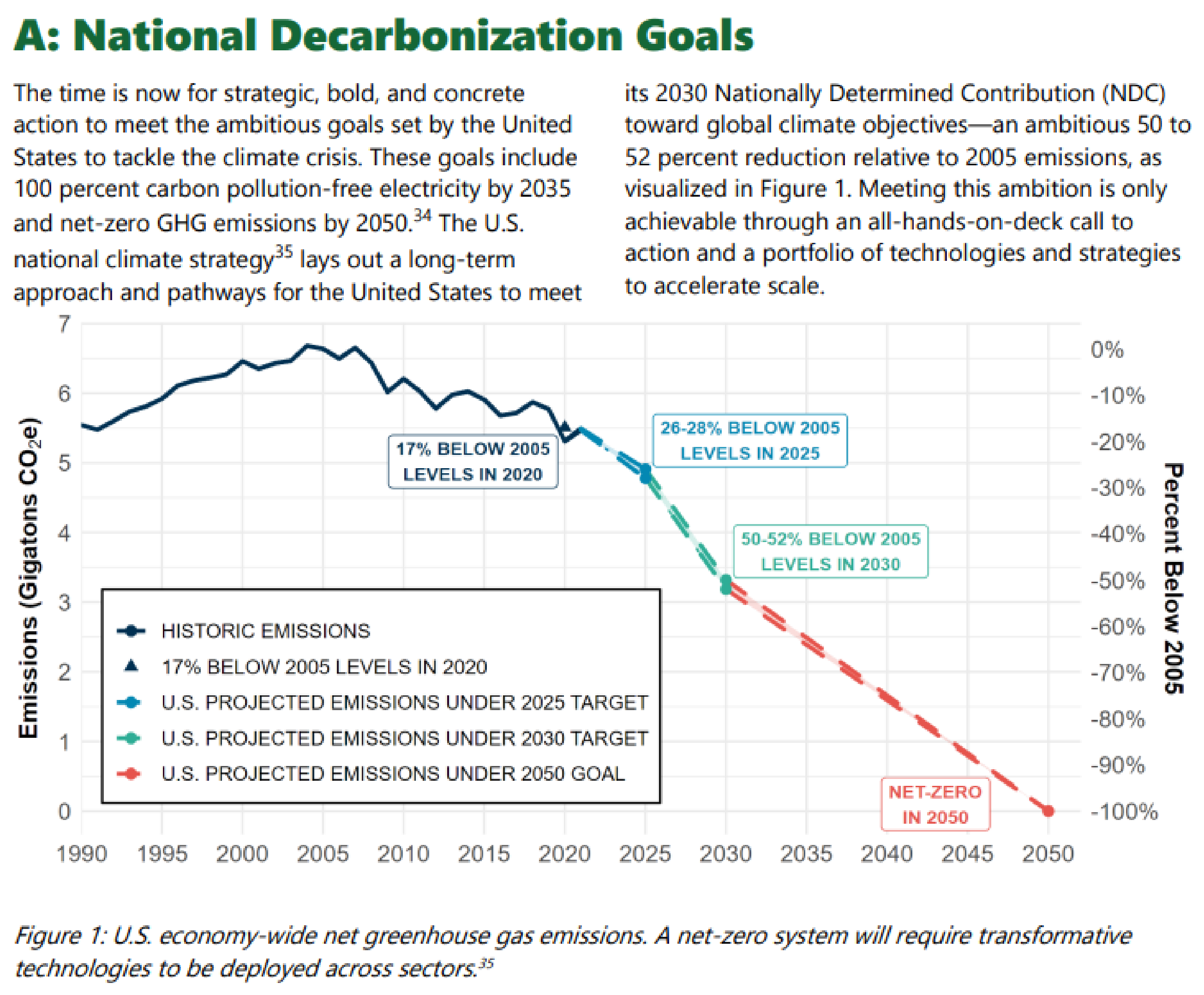
- Market-ready CCUS projects on track to become operational before 2030, provided that supportive policy and financial frameworks are in place https://zeroemissionsplatform.eu/



- Full-chain CCS – 4 (Orange)
- CO_2 transport and storage – 19 (Green)
- CCS in industry – 12 (Red)
- CCS in energy production – 7 (Yellow)
- Low-carbon hydrogen production – 8 (Purple)
- Carbon Capture and Utilisation – 9 (Pink)
- Test centre – 4 (Grey)
- Limited information available (3) (Blue)

Carbon Capture, Utilisation and Storage : USA

- Inflation Reduction Act (2022) increased 45Q tax credit to \$85/tonne of CO_2 permanently stored and \$60/tonne of CO_2 used for enhanced oil recovery
- US National Clean Hydrogen Strategy and Roadmap, released June 5, 2023, https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf



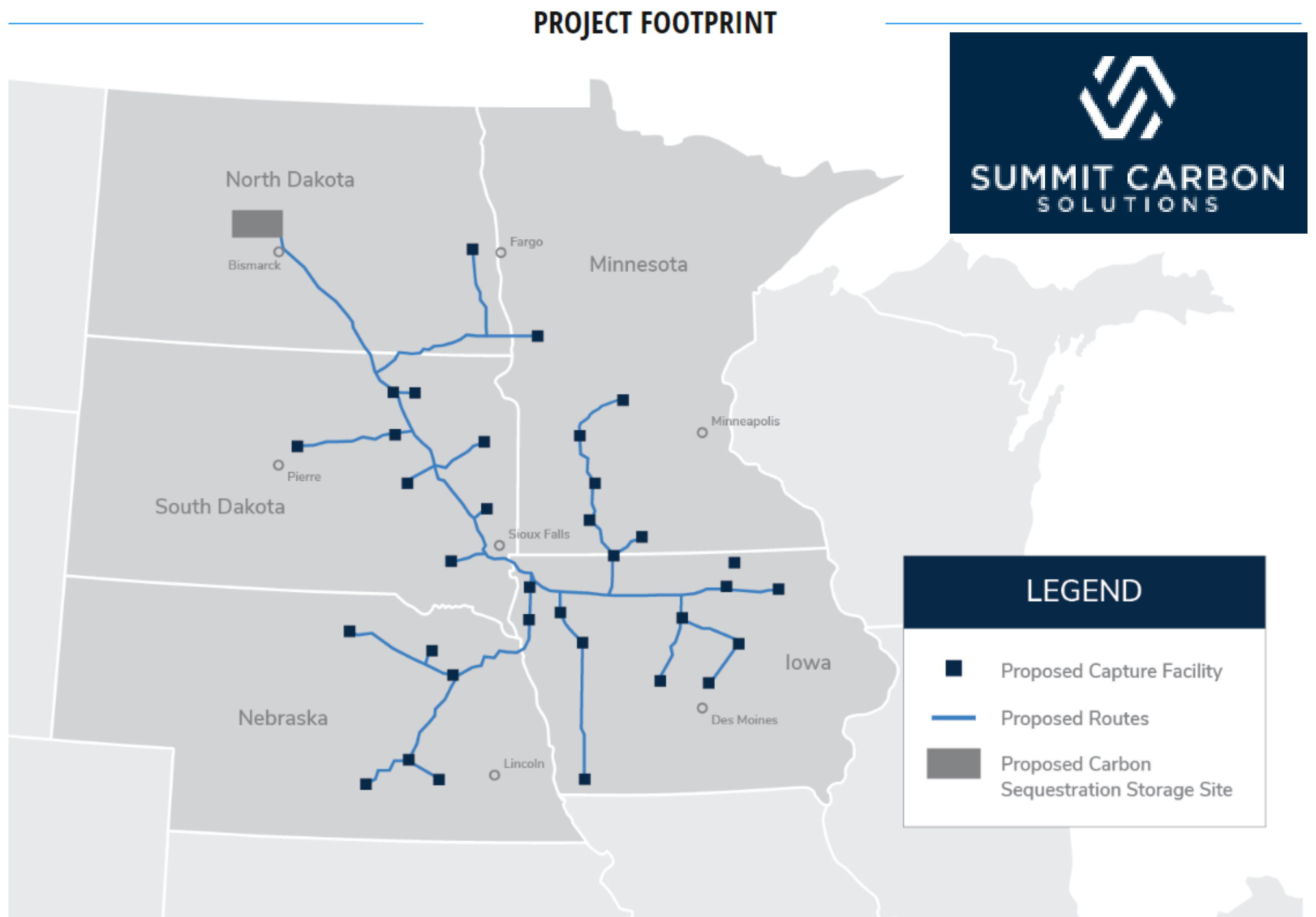
A: National Decarbonization Goals

The time is now for strategic, bold, and concrete action to meet the ambitious goals set by the United States to tackle the climate crisis. These goals include 100 percent carbon pollution-free electricity by 2035 and net-zero GHG emissions by 2050.[34] The U.S. national climate strategy[35] lays out a long-term approach and pathways for the United States to meet its 2030 Nationally Determined Contribution (NDC) toward global climate objectives—an ambitious 50 to 52 percent reduction relative to 2005 emissions, as visualized in Figure 1. Meeting this ambition is only achievable through an all-hands-on-deck call to action and a portfolio of technologies and strategies to accelerate scale.

Figure 1: U.S. economy-wide net greenhouse gas emissions. A net-zero system will require transformative technologies to be deployed across sectors.[35]

Expected to start operating in 2026

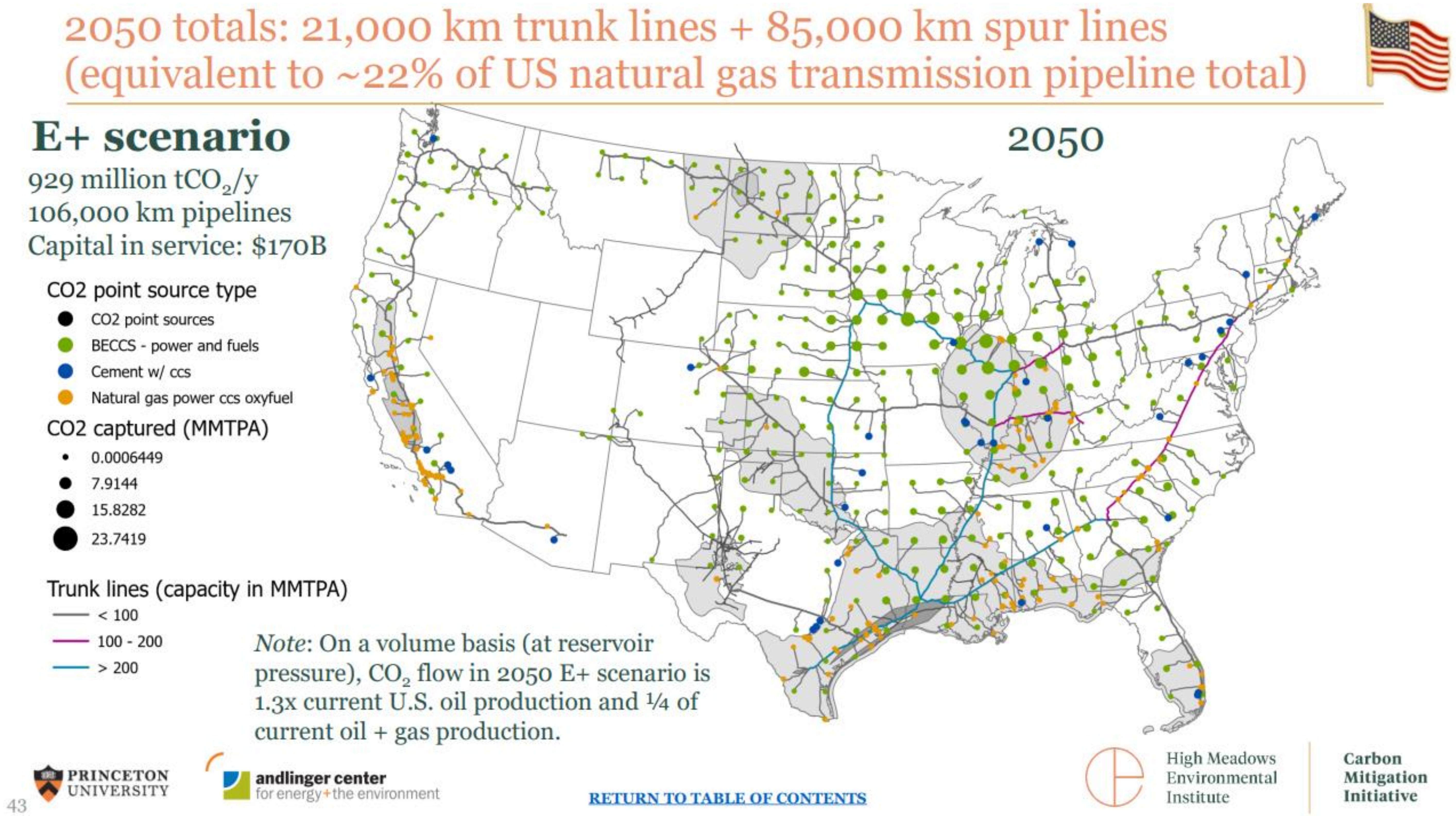
https://www.airproducts.com/campaigns/la-blue-hydrogen-project



CO_2 pipelines from Green Plains biorefineries expected to start operating in late 2024
https://summitcarbonsolutions.com/

Carbon Capture, Utilisation and Storage : USA

- Princeton Net Zero report (2021) https://netzeroamerica.princeton.edu

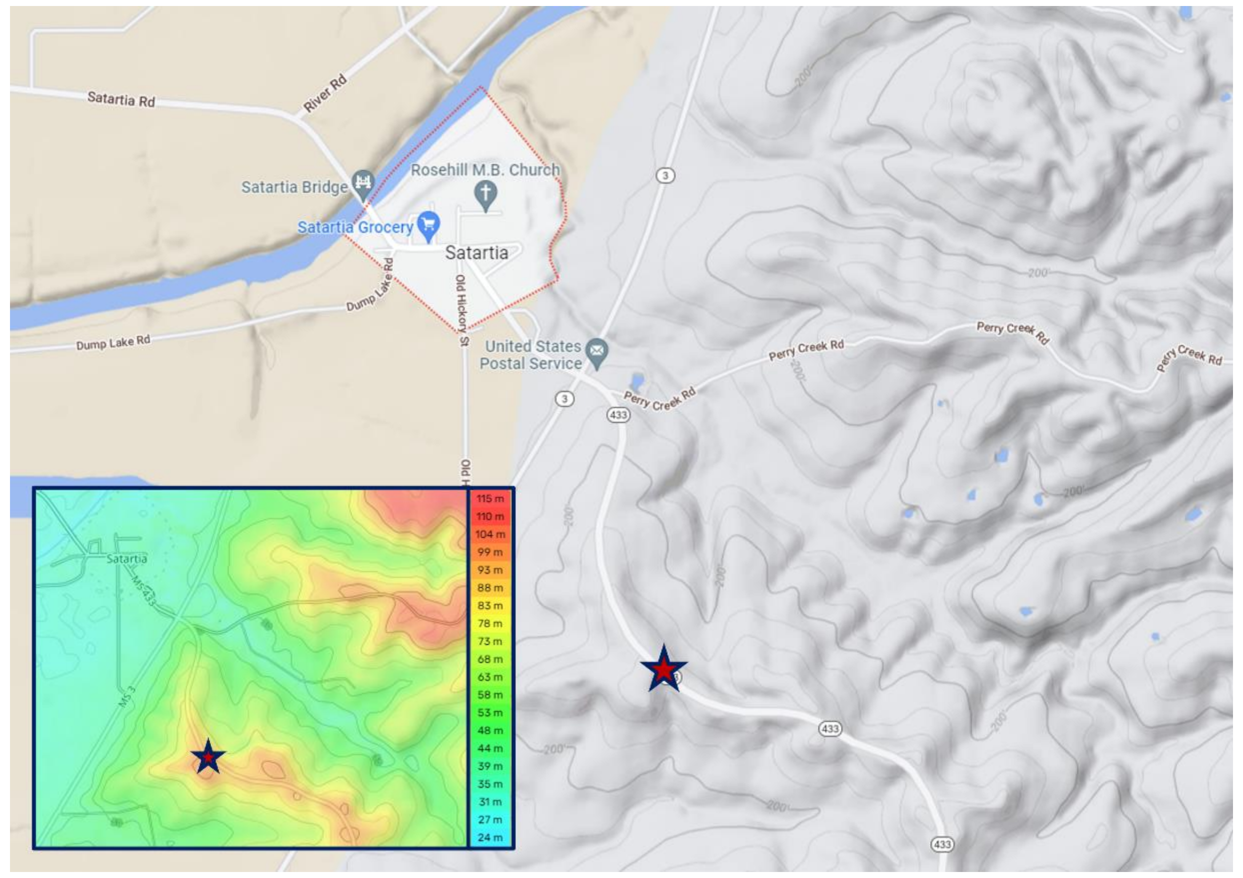


- Current situation: 5,000 miles of CO_2 pipelines
- Princeton projection: growth to 66,000 miles of CO_2 pipelines by 2050
- In comparison, the current total length of US interstate highways is 47,000 miles

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)

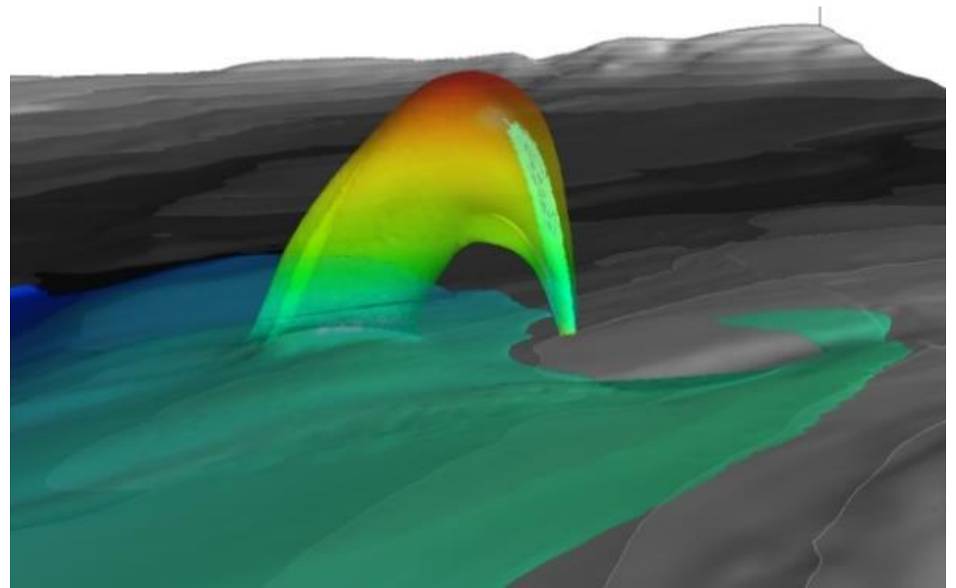


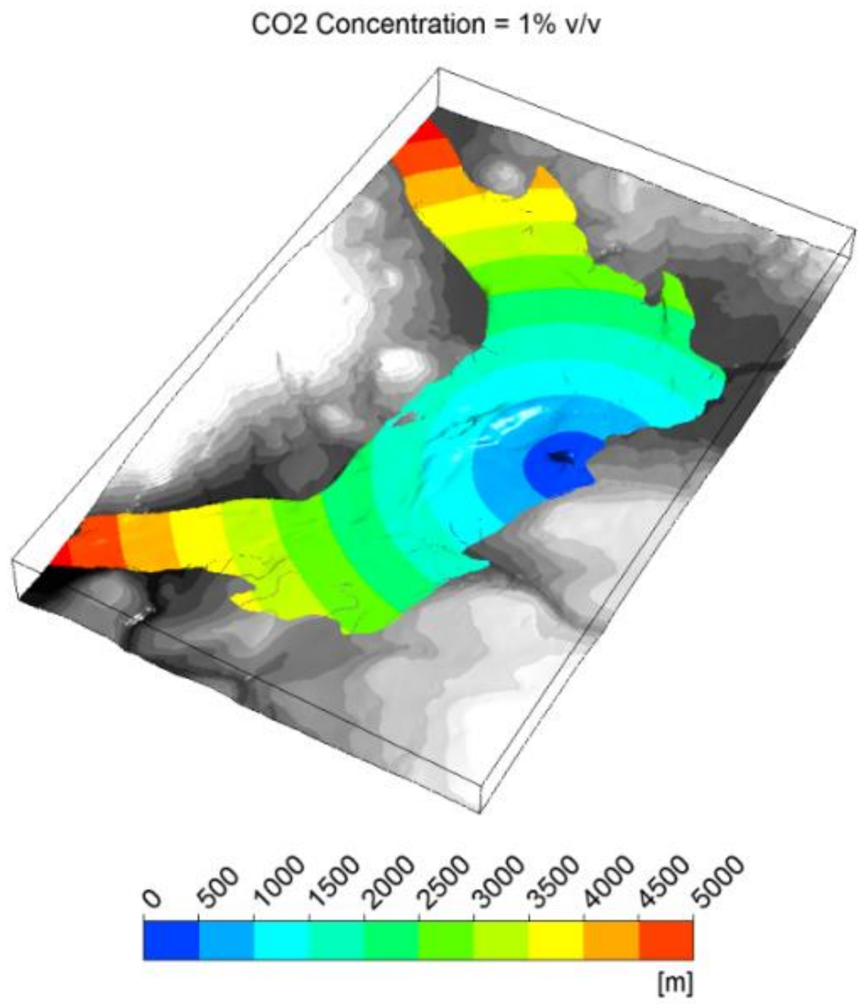
Terrain map taken from Google Maps and contour map taken from topographic-map.com. Approximate location of release marked by a star.

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

Atmospheric dispersion of CO_2 from pipelines

- Significant research into CO_2 pipeline safety in period 2005-2015
  - e.g. COOLTRANS, CO2PipeTrans, COSHER, MATTRAN projects
- CO_2 is either a vapour or solid at atmospheric pressure
- Sublimation temperature -78°C at atmospheric pressure
  - CO_2 vapour density at -78°C is 2.3 times greater than air density
- Cold CO_2 gas from pipeline release would tend to flow along the ground, collecting in low-lying areas
- Toxicity https://doi.org/10.1186%2Fs12245-017-0142-y
  - Concentration > 5% v/v: hyper-ventilating, confusion, lethargy
  - Concentrations > 10% v/v: convulsions, coma, death



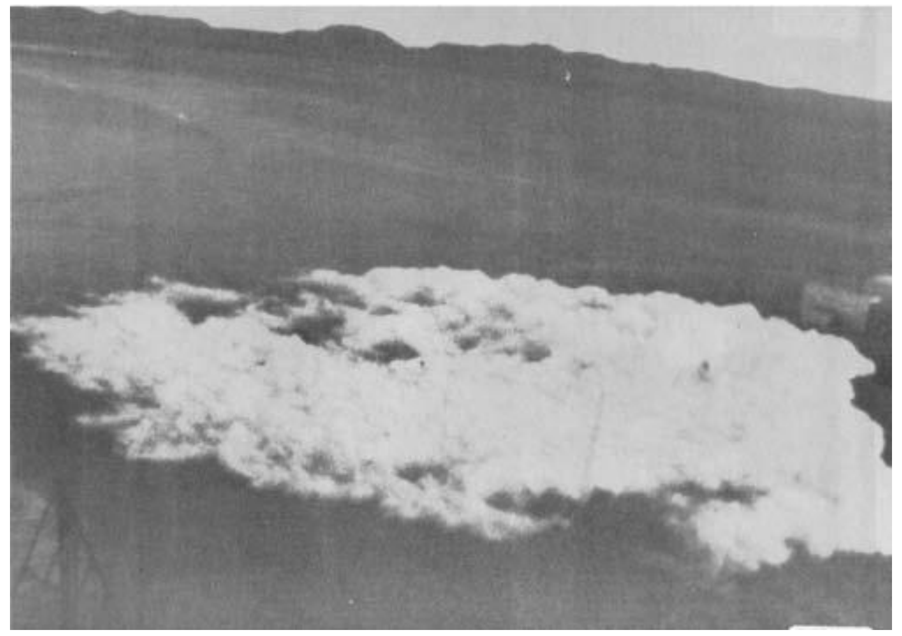


Knowledge gaps in pipeline risk assessment, emergency planning and response

- Satartia CO_2 pipeline incident demonstrated that terrain can influence dispersion of dense CO_2 clouds
- Can dispersion models take into account terrain effects for pipeline risk assessment and emergency planning and response?
- Different modelling approaches:
  - Integral, Gaussian puff, shallow-layer, Computational Fluid Dynamics (CFD), hybrid CFD/mass-consistent models, Lattice Boltzmann, emulators, correlations
- Example of modelling requirements:
  - 100 km long pipeline, model release location every 50 m = 2,000 runs
  - 4 release diameters (25 mm, 75 mm, 110 mm, full bore) = 8,000 runs
  - 12 wind directions = 96,000 runs
  - 4 weather classes (F2.4, D2.4, D4.3, D6.7) = 384,000 runs
  - If each dispersion simulation takes 1 minute computer run-time:
  - 384,000 minutes = 267 days run time
  - If each simulation took 1 hour, then it would require 44 years run-time

Knowledge gaps: experimental data

- Do we have sufficient field-scale experimental data to validate dense-gas dispersion models with terrain?
  - Review of dense gas dispersion 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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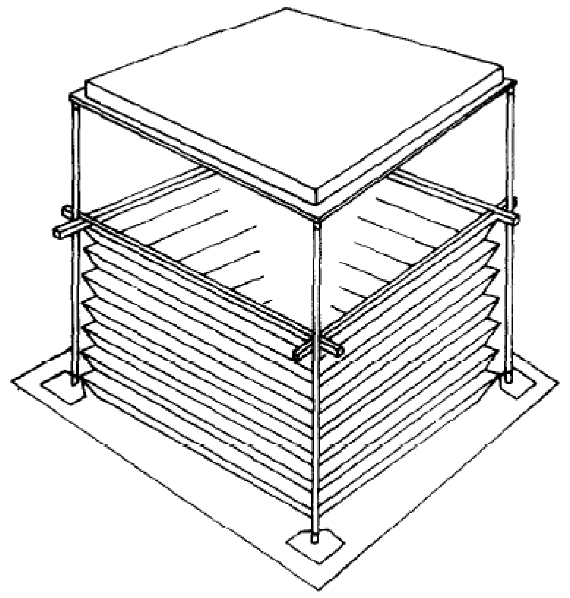

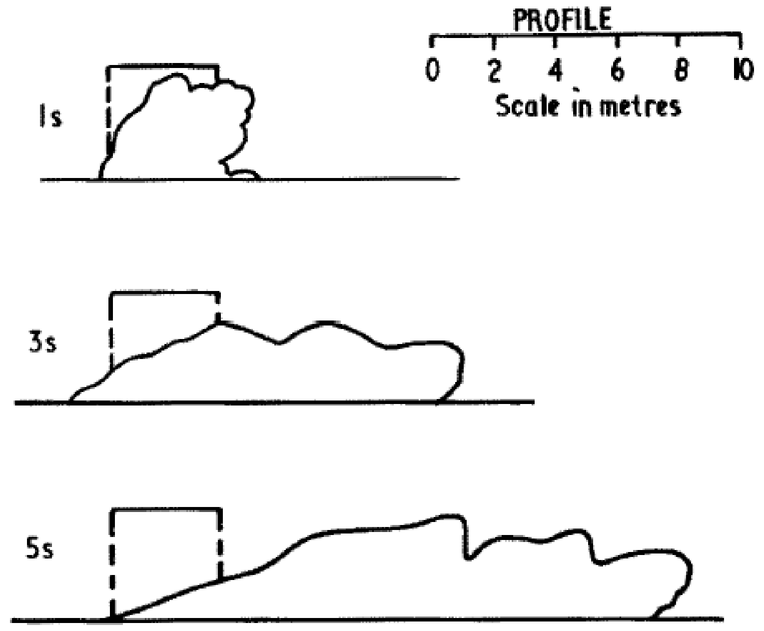

Tentative Proposal for Joint Industry Project

- Work Package 1: CO_2 pipeline craters and source terms
- Work Package 2: Simple terrain dispersion experiments
- Work Package 3: Complex terrain dispersion experiments
- Work Package 4: Model development and validation

Tentative Proposal for Joint Industry Project

- Work Package 1: CO_2 pipeline craters and source terms
  - Review existing data for CO_2 pipeline craters, both punctures and ruptures (some data is not yet publicly available)
  - If necessary, conduct further puncture/rupture experiments to define shape/size of crater and measure source concentrations and flow rates
  - Assess/develop source models for crater releases
  - Construct physical crater to be used for dispersion experiments

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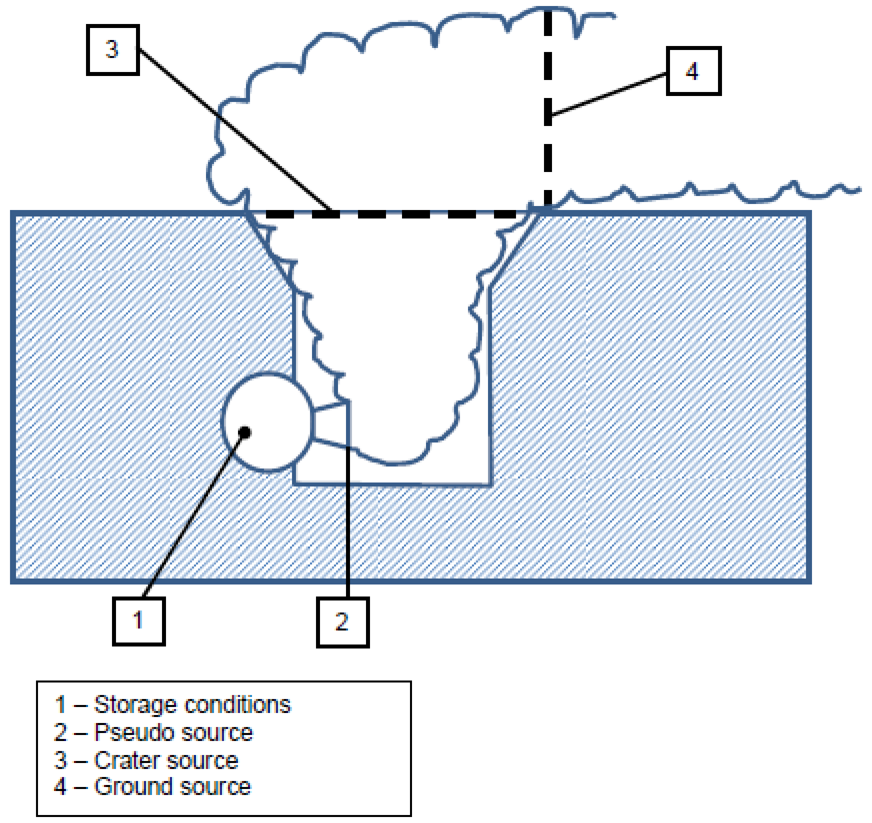
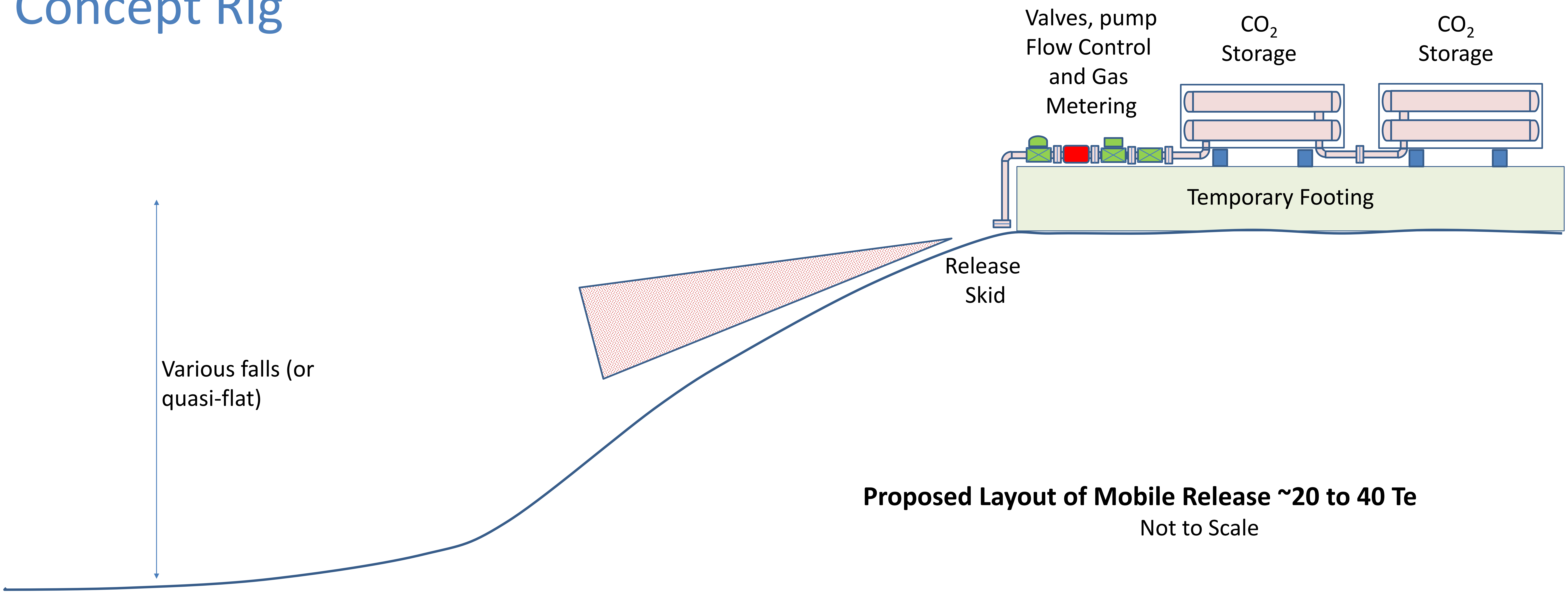


Figure 1 Puncture and crater sources

Concept Rig

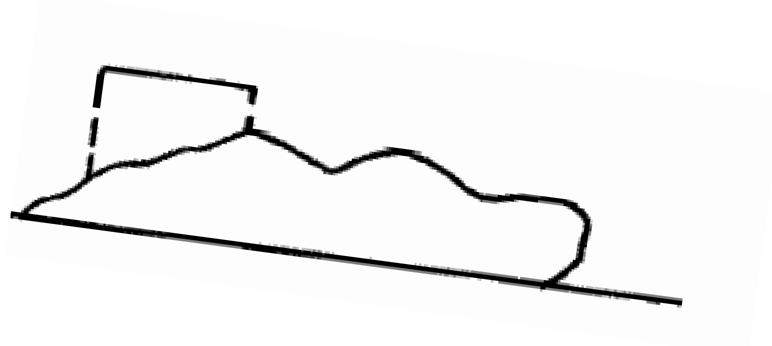


Proposed Layout of Mobile Release ~20 to 40 Te

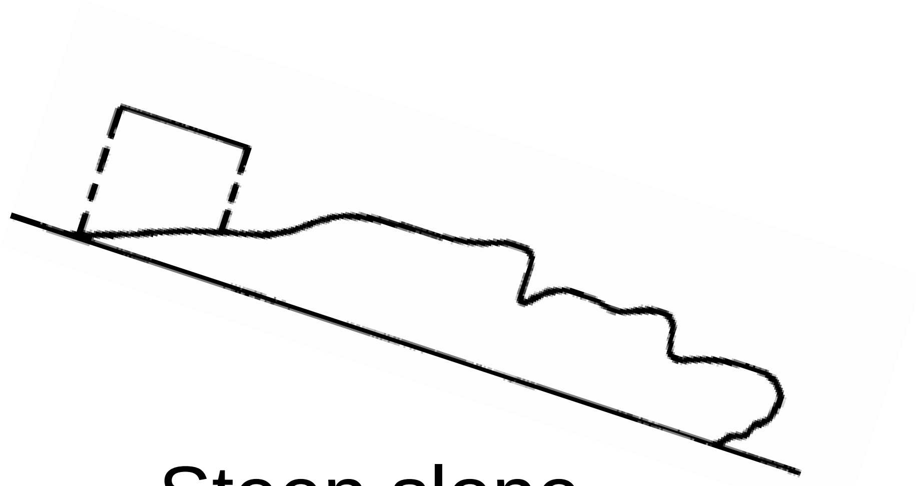
Not to Scale

Tentative Proposal for Joint Industry Project

- Work Package 2: Simple sloping terrain dispersion experiments
  – Uniform slope, consistent surface roughness
  – Variables: flat/shallow/steep slopes, wind direction, wind speed, release rate
  – Conduct sufficient number of tests to sample combinations of conditions (e.g., 20-30 tests to enable correlations to be developed)



Shallow slope



Steep slope

How does dispersion behaviour compare to flat terrain?

Different behaviour in windy and still conditions with jet re-entrainment and source blanket in light winds

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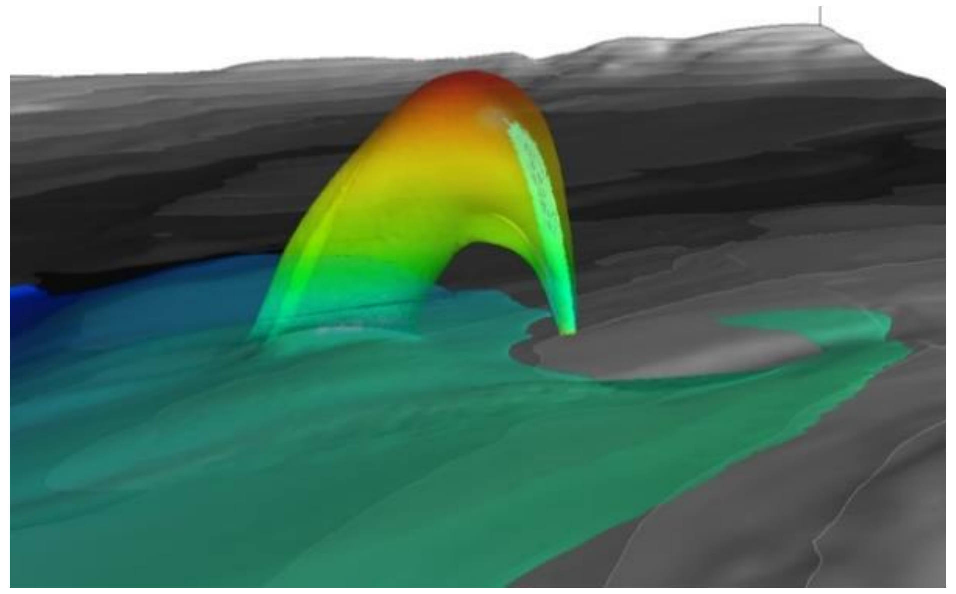
Tentative Proposal for Joint Industry Project

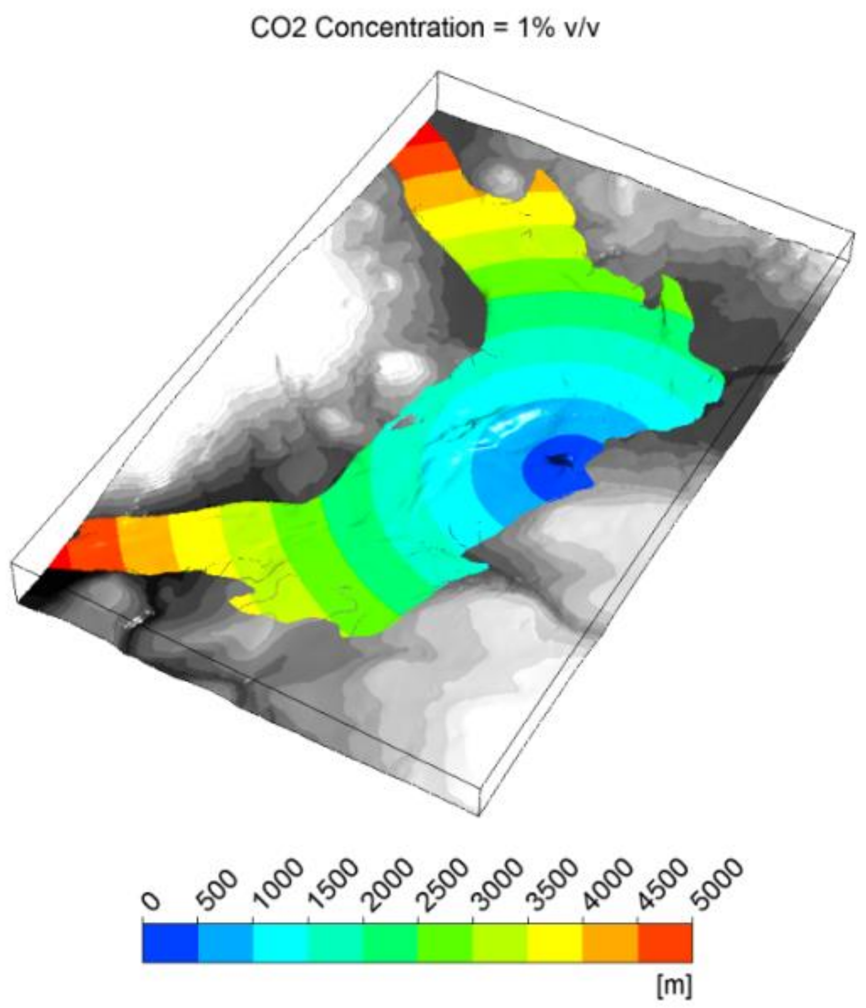
- Work Package 3: Complex terrain dispersion experiments
  - Tests on valleys, hills, obstacles, changing roughness, buildings
  - More challenging configuration for modelling
  - Answer practical questions:
    - How long does CO_2 persist in depressions?
    - What shelter-in-place guidance should be given?
  - Perhaps also inform emergency response, e.g., test fire department equipment, vehicles?

© Utah Valley University https://www.uvu.edu/es/jack-rabbit/

Tentative Proposal for Joint Industry Project

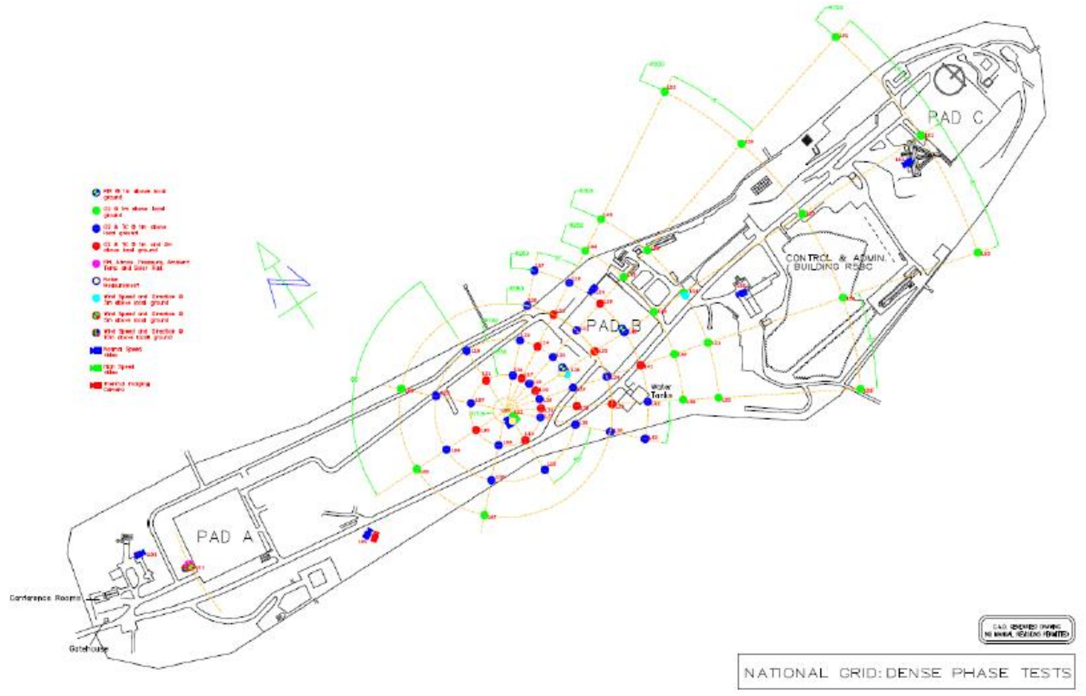
- Work Package 4: Model development and validation
  - Aim to have an open and collaborative approach, like in Jack Rabbit projects
  - Input welcome from government labs, industry and consultants
  - Modellers given access to data in return for sharing results and collaborating
  - Aim to test spectrum of models, e.g., correlations, Gaussian puff, shallow layer, machine learning tuned to CFD





Possible test sites: DNV Spadeadam

- Pros
  - Site previously used for large number of CO_2 experiments, including pipeline punctures and ruptures, crater measurements
  - Very large, remote area: possibility to run tests in evenings with wide exclusion zones
  - Complex terrain with valleys, hills, obstacles and changing roughness (trees and rough ground)
  - Infrastructure in place and experience in handling CO_2
  - Experience in working closely with pipeline industry
- Cons
  - Possible scheduling issues: site is very busy with many other experiments
  - Terrain is all complex: lack of large areas with simple uniform slopes and consistent roughness



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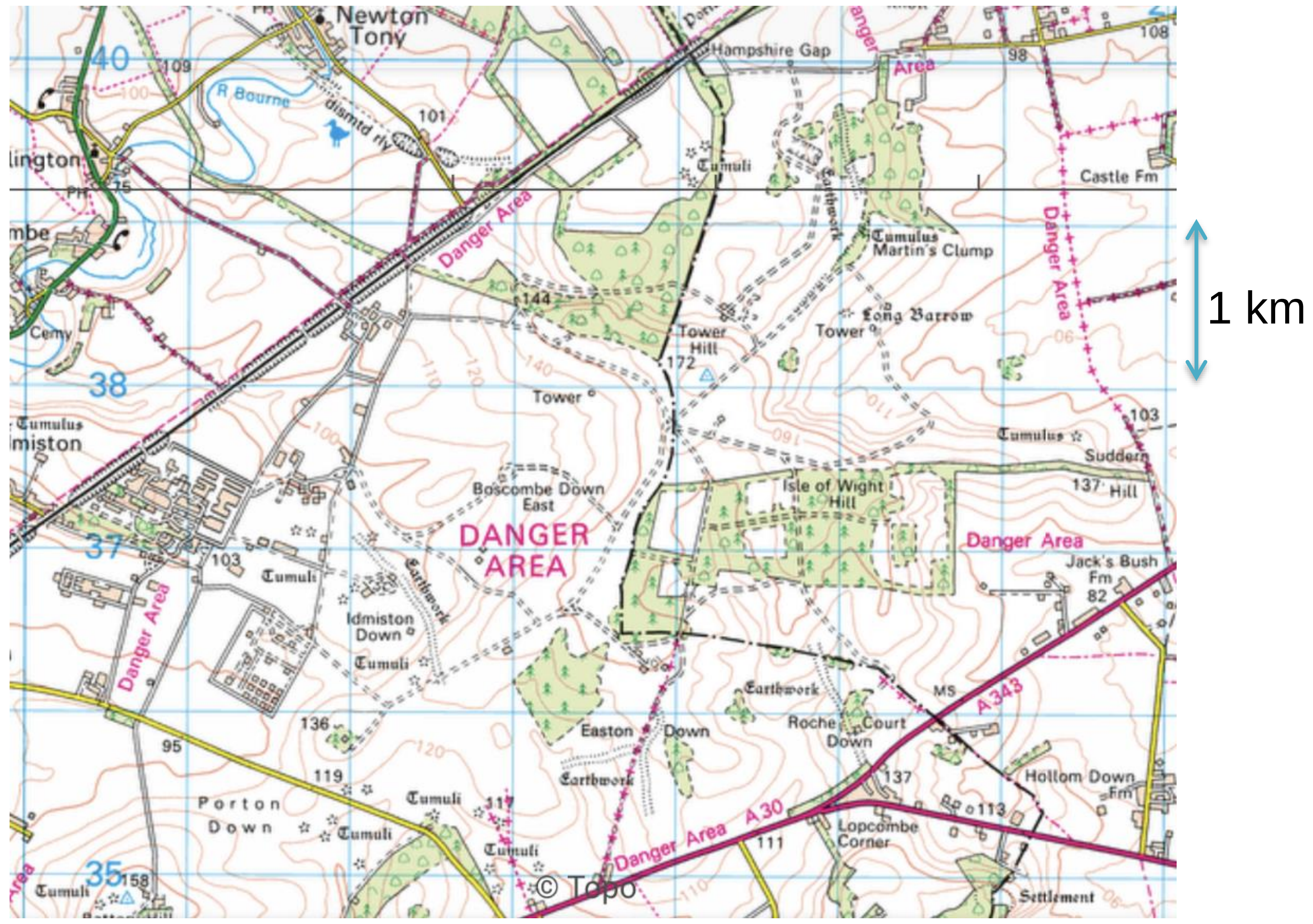
Possible test sites: DSTL Porton Down

- Pros
  - Experience with running atmospheric dispersion experiments (e.g., Picknett trials)
  - Two large open grassland bowls several hundred metres across (steep and shallow uniform slopes)
  - DSTL dispersion modelling expertise
  - Collaboration with Met Office: meteorological instrumentation
- Cons
  - Lack of experience in running CO_2 release experiments from pipelines
  - Terrain is less complex than Spadeadam



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Summary and Possible Future Directions

- Aim to develop proposal for joint-industry project using complementary features and expertise of two UK test sites
  - DNV Spadeadam: WP1 and WP3 on craters and complex terrain
  - DSTL Porton Down: WP2 on simple uniform slopes

- Questions
  - Is there a test area for flat terrain comparisons?
  - Are other (international) test sites suitable?
  - What funding and data-sharing agreement should be used?
    - Make data publicly available after delay period of 1 – 2 years?
  - Could wind tunnel tests be conducted alongside field tests?
  - Details of scaling of field-scale or wind-tunnel to full-scale tests to be determined

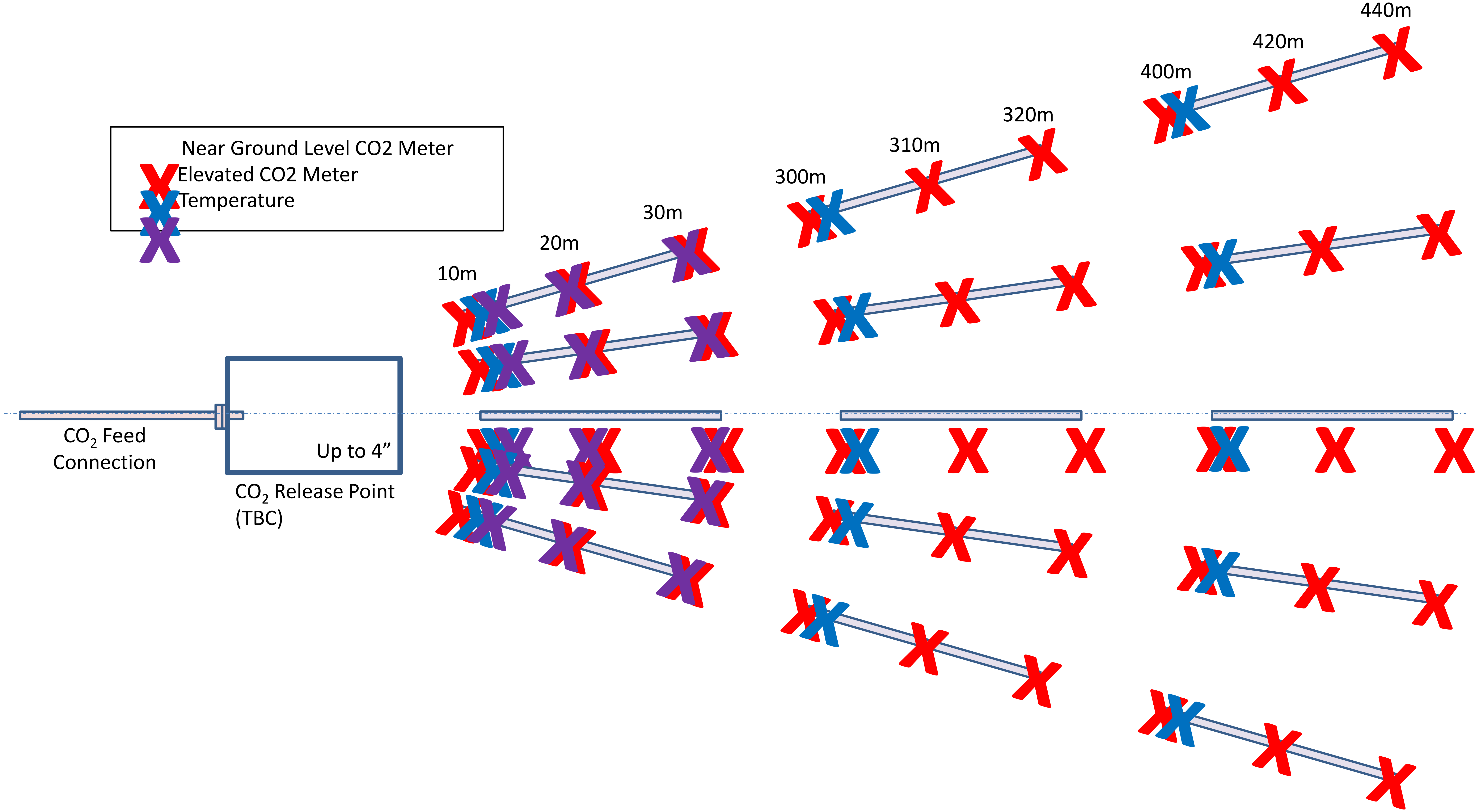
Thank you

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 from DNV



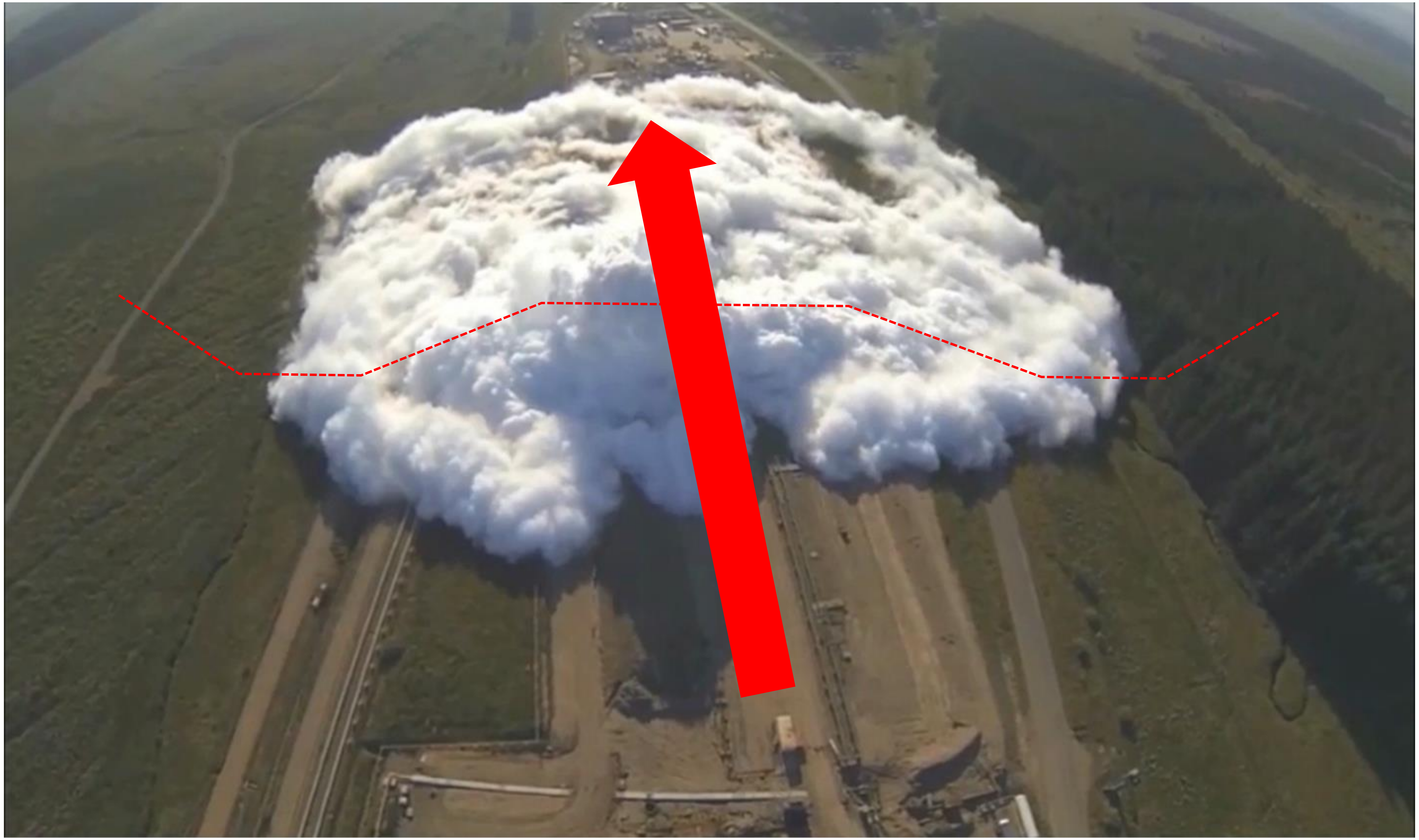
Proposed (example) Down-wind, Down-Slope Wireless Instrumentation Array for CO_2 Releases


DNV Spadeadam
DNV Spadeadam
Image © 2023 Getmapping plc
Image © 2023 Maxar Technologies
1186 m
Google Earth


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

Surface is 2-dimensional…

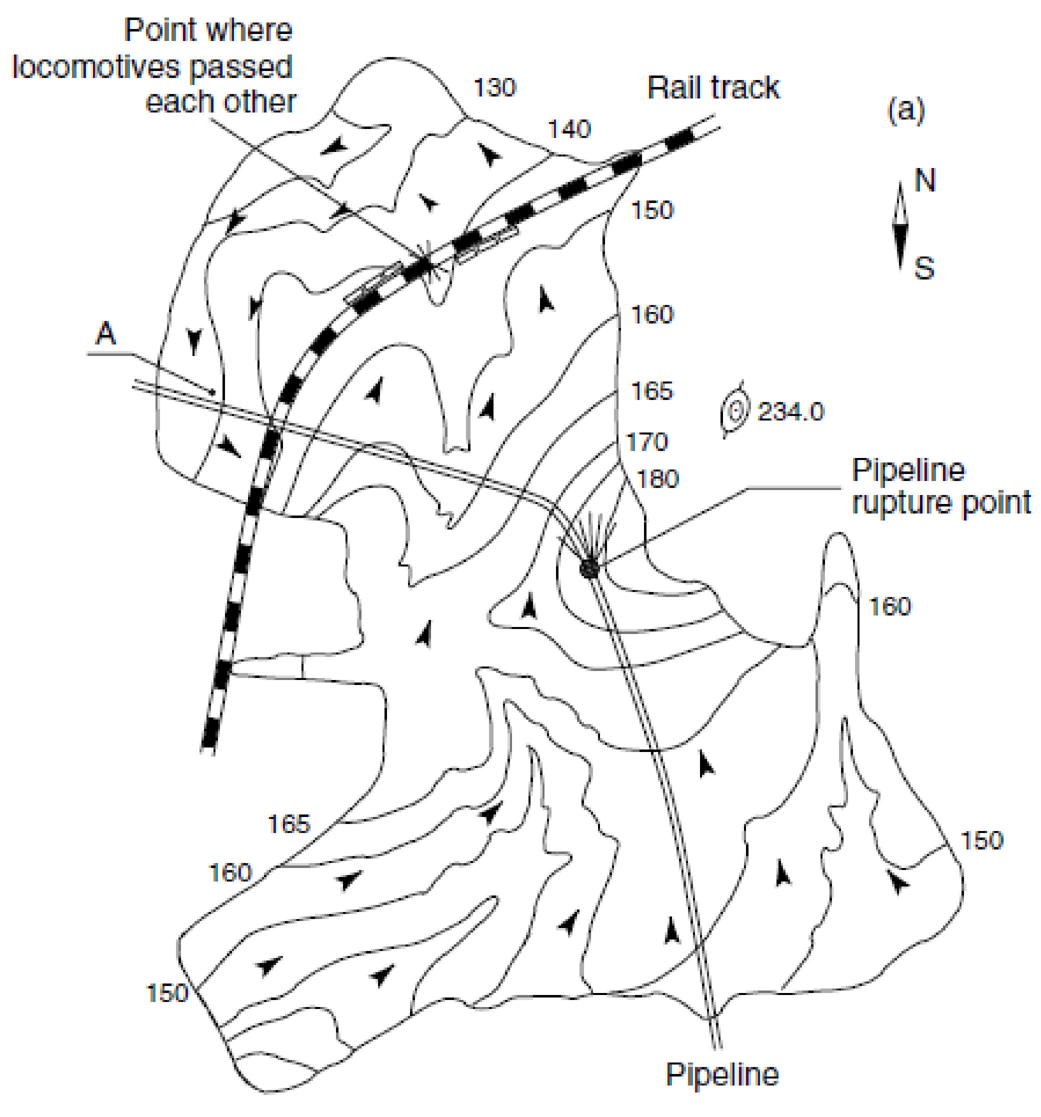
Surface is 2-dimensional…



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



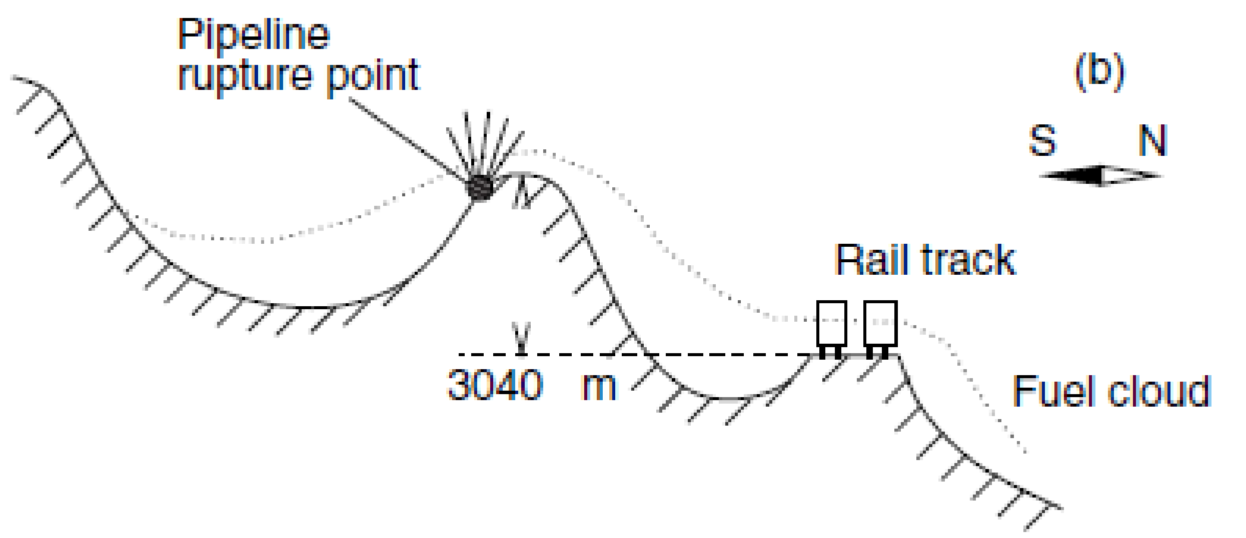
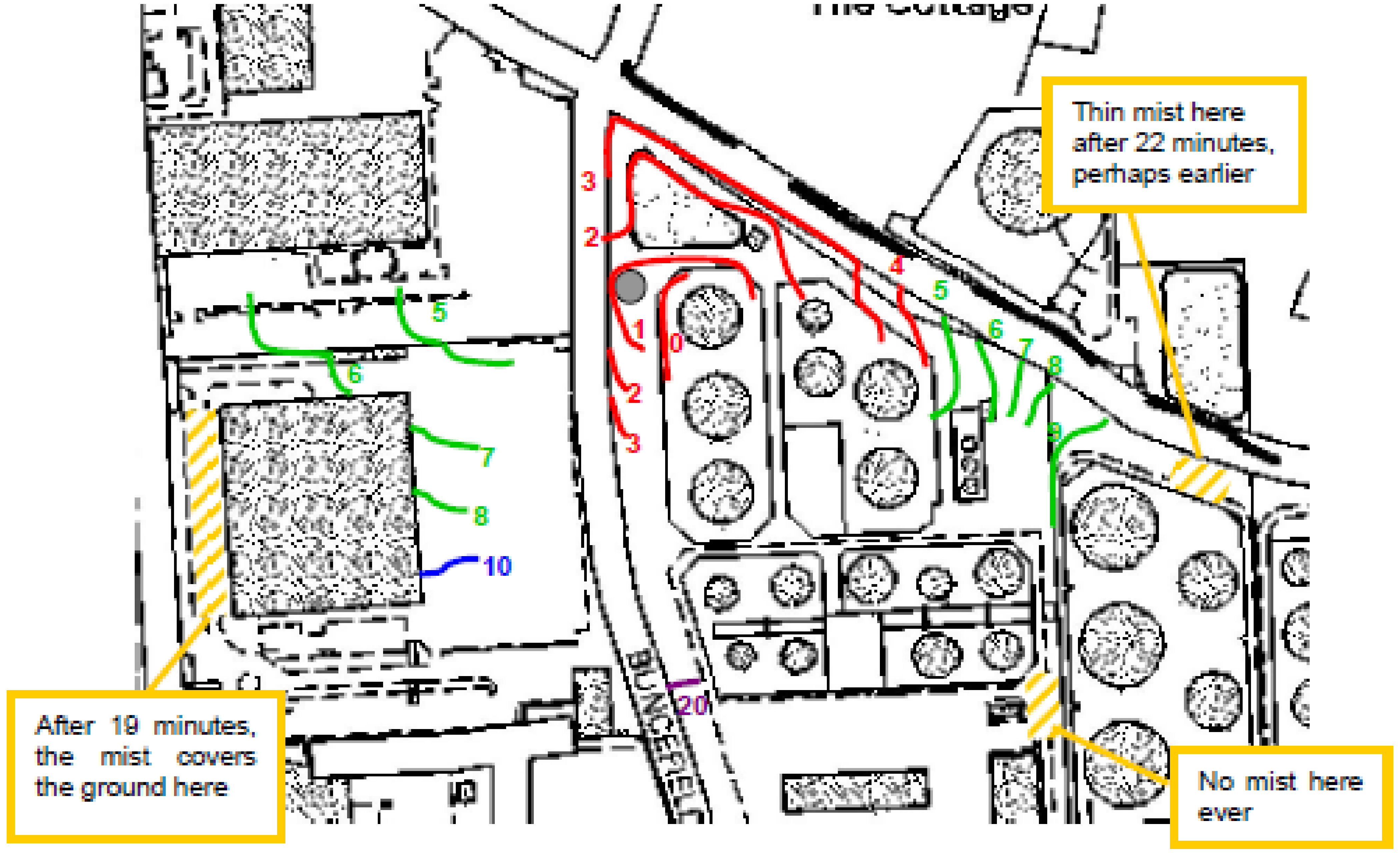


FIG. 9. Ufa accident: (a) sketch of demolished area (direction of tree fell is shown by arrows); (b) terrain profile (not to scale). View of accident site from region of point A is given in Fig. 10.

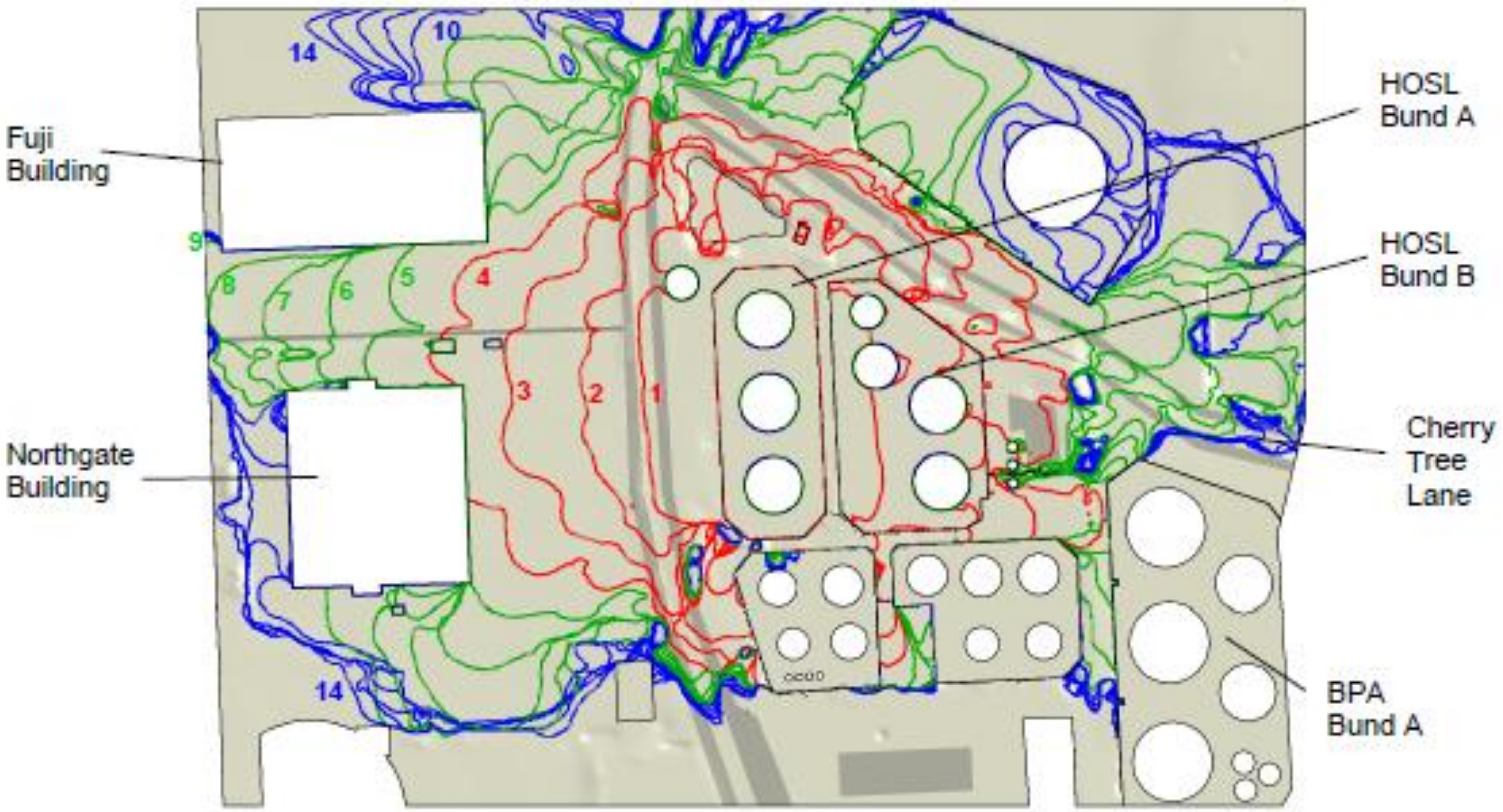
FIG. 10. Accident site viewed from region of point A in Fig. 9. On the right of the railway is the remainder of one of the trains.

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