RESEARCH AND GUIDANCE FROM HSE

CO_2 pipeline risk assessment:

Scientific knowledge gaps related to dispersion and terrain effects

Zoe Chaplin, Simon Gant, Mike Wardman, Rory Hetherington

Health and Safety Executive (HSE)

Pipeline Safety Group meeting, 1 December 2022

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

Overview

- Background
- Atmospheric dispersion of CO_2 from pipelines
  - The Satartia incident and terrain effects
- Modelling approaches
- Experiments
- Tentative ideas for next steps

Background

- HSE is the UK Health & Safety regulator for chemicals sites, pipelines, oil and gas and general workplace issues
- HSE has a statutory obligation to provide land-use planning advice around major accident hazard (MAH) pipelines as defined under the UK Pipelines Safety Regulations
- In practice – calculate zones of risk around the pipeline using mathematical models
- MAH pipelines are those carrying "dangerous fluids"
- CO_2 currently not classed as a "dangerous fluid" but this is under review

MISHAP

- MISHAP (Model for the estimation of Individual and Societal risk from HAzards of Pipelines)
- Calculates the land-use planning zones for *flammable* substances
- Needs adapting for CO_2
- Several questions that need answering:
  - Failure rates
  - Release rates for dense-phase CO_2
  - **Influence of terrain on risk and hazard distances**

Satartia CO_2 Pipeline Incident, 2020

- Failure of Denbury Gulf Coast Pipelines 24-inch CO_2 pipeline near Satartia, Mississippi due to landslide
- Dense CO_2 cloud rolled downhill and engulfed Satartia village, a mile away
- Approx. 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

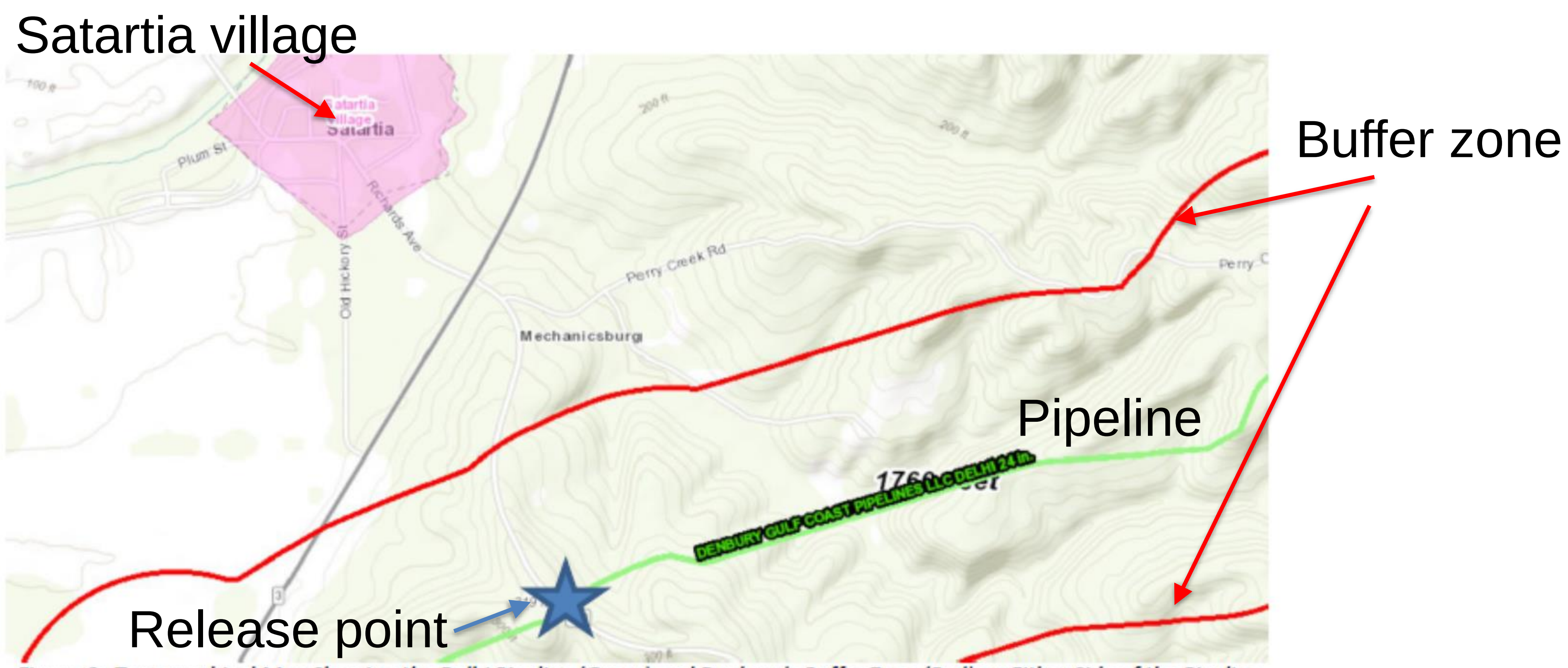
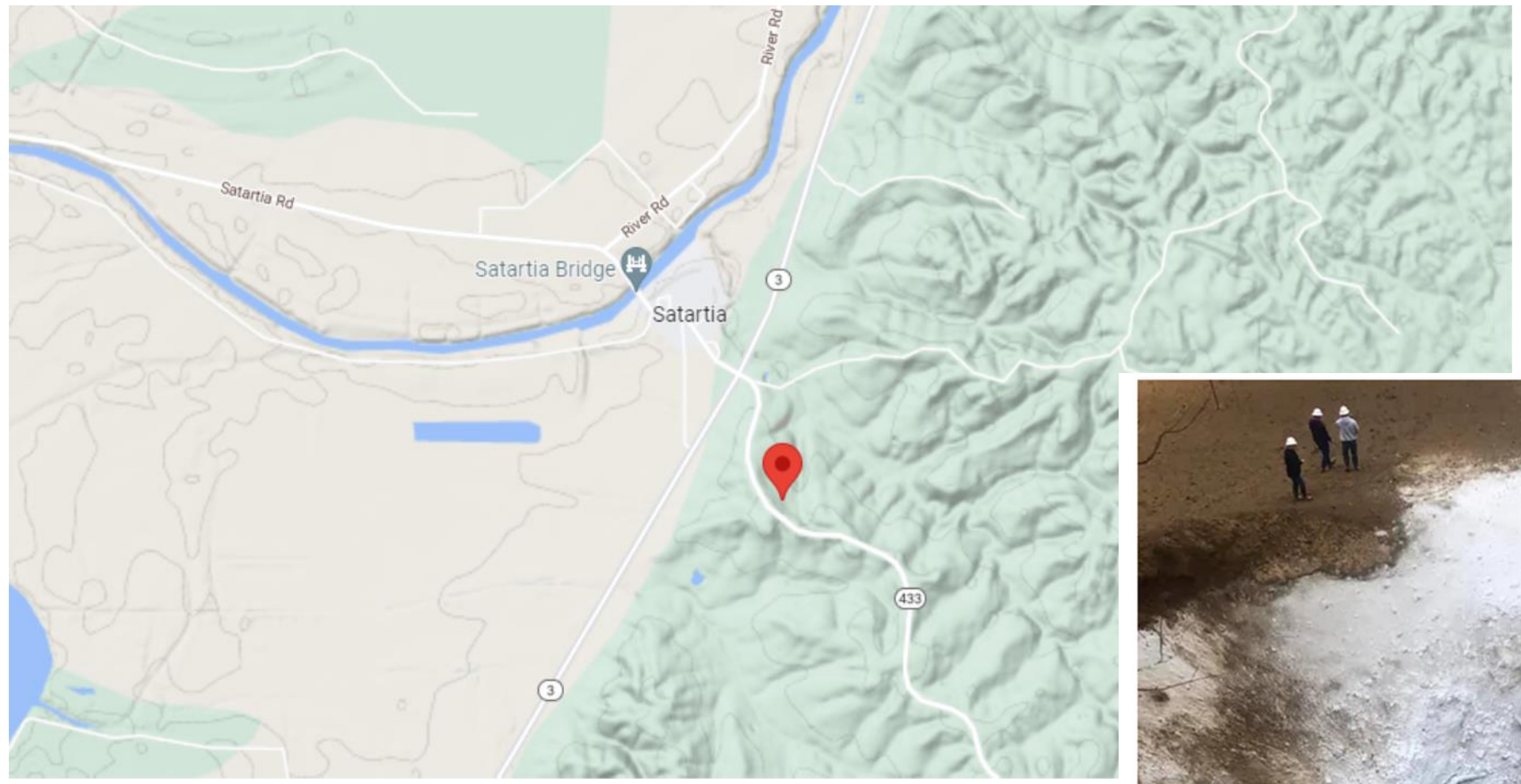


Figure 6: Topographical Map Showing the Delhi Pipeline (Green) and Denbury's Buffer Zone (Red) on Either Side of the Pipeline and the Proximity to Satartia (Blue Star Indicates the Rupture Site)



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: Modelling Approaches

- Possible dispersion modelling approaches available to feed into pipeline risk assessment and account for terrain effects?
  - Integral, Computational Fluid Dynamics (CFD), hybrid CFD and mass-consistent models, smooth particle hydrodynamics, Lattice Boltzmann, shallow-layer, Gaussian puff, emulators and correlations
- However, dispersion models will need to produce results quickly
- Example of modelling requirements:
  - 100 km long pipeline, release locations every 50 m = 2,000 runs
  - 4 release diameters (25 mm, 75 mm, 110 mm, full bore) = 8,000
  - 12 wind directions = 96,000 runs
  - 4 weather classes (F2.4, D2.4, D4.3, D6.7) = 384,000 runs
- Say each simulation requires 1 minute: 384,000 minutes = 267 days run time
- Or maybe a few days, with 100 processors running in parallel?

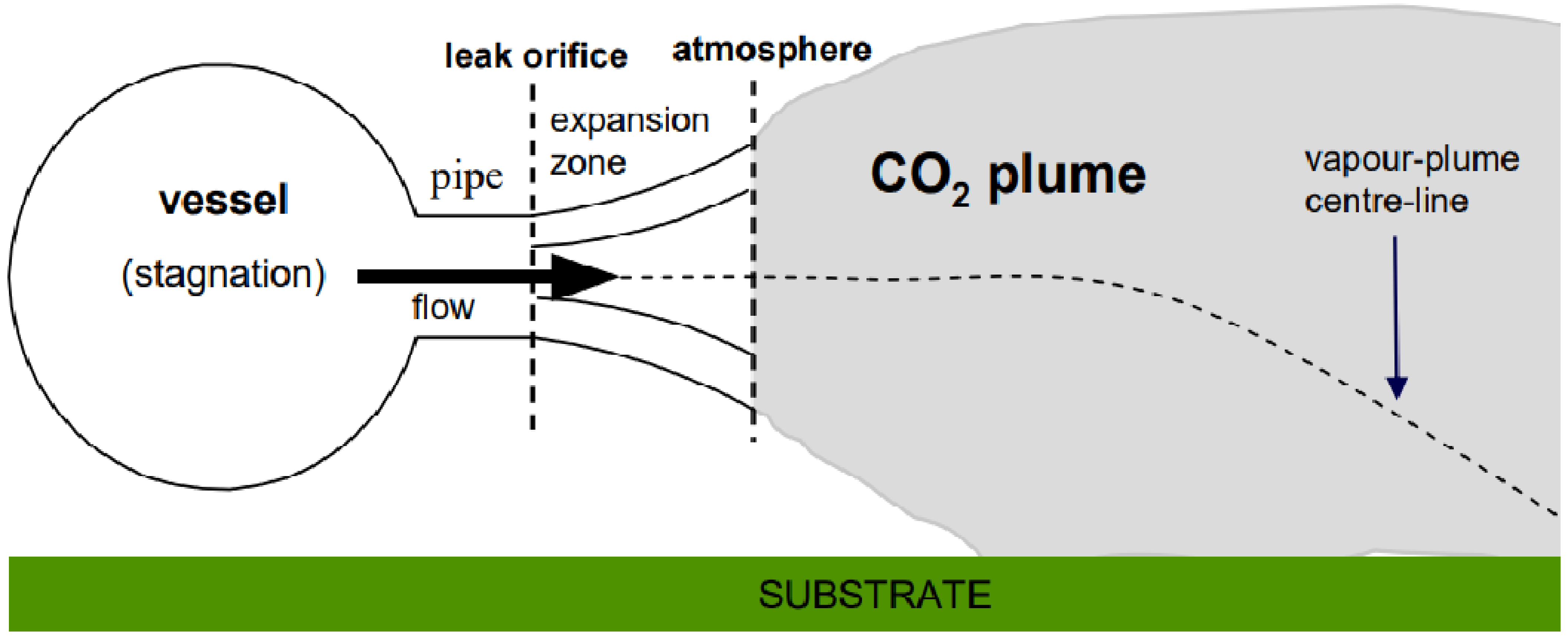
Modelling Approaches: Integral Models

- DNV: PHAST
- ESR: DRIFT
- CERC: GASTAR
- Gexcon: EFFECTS
- Shell: FRED

Flat terrain only

Flat or uniform slope

?



Strengths:
- Complex two-phase flow physics of CO_2 dispersion already coded into integral models and validated
- Quick to compute

Weaknesses:
- Cannot handle complex shaped terrain

Ideas:
- Is it possible to discretize terrain into say 50 m grid cells and use uniform slope within each cell?

Modelling Approaches: CFD

- DNV KFX
- Gexcon FLACS

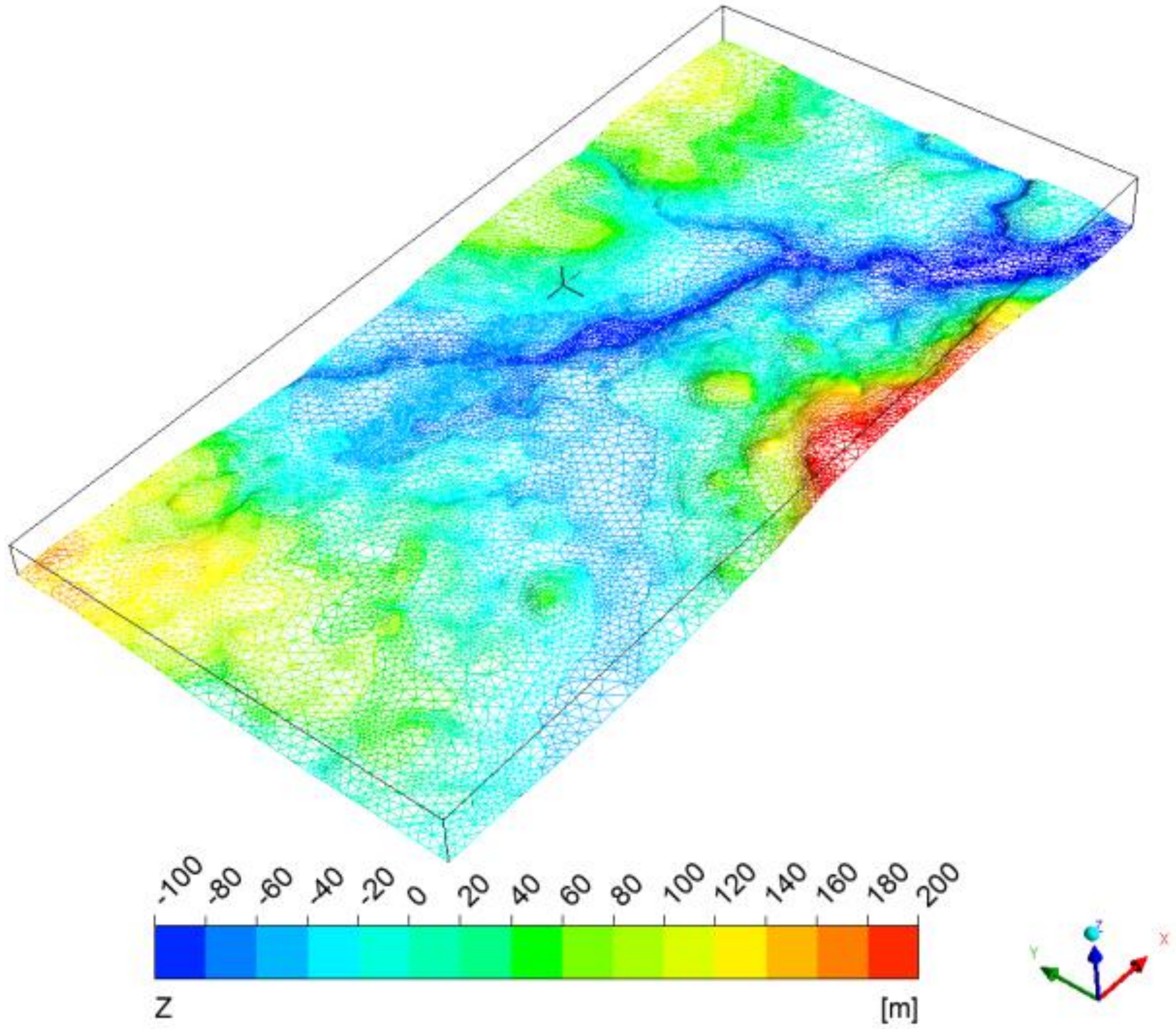
} Cartesian grid, stepped terrain

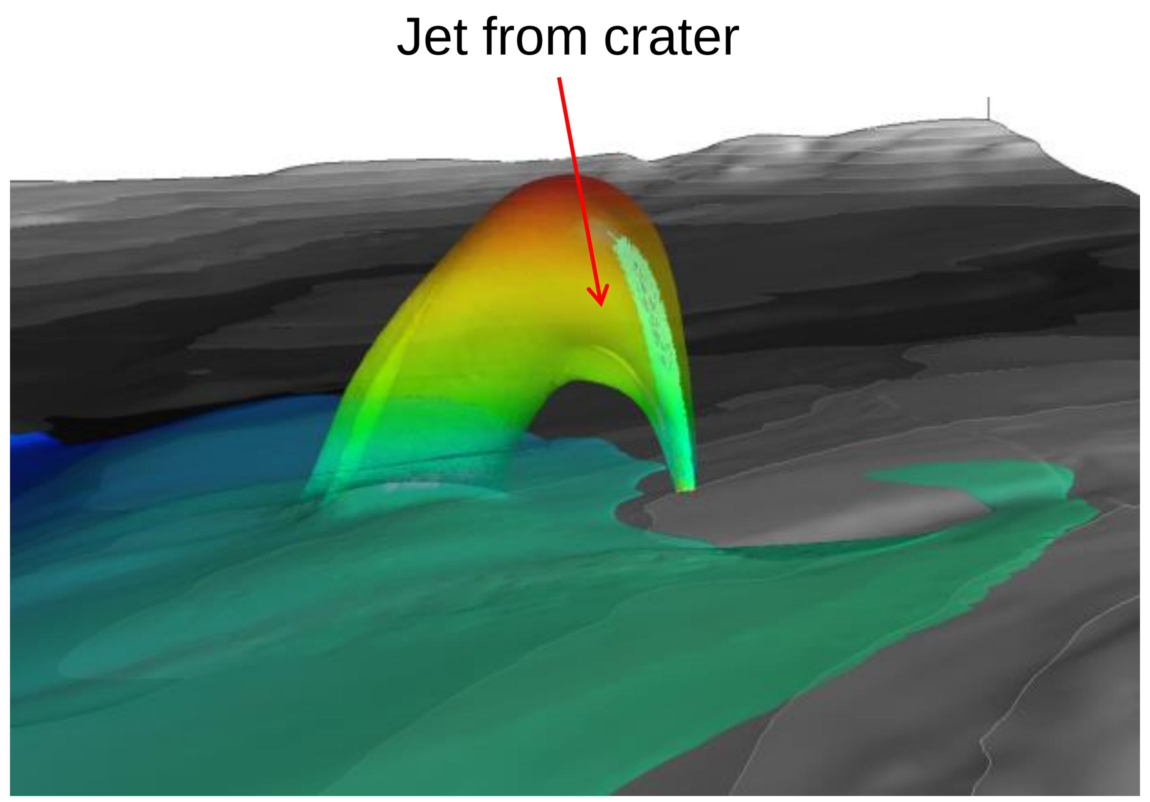
- Ansys Fluent/CFX
- OpenFOAM

} Body-fitted grid, smooth terrain

Strengths:
- Complex two-phase flow physics and terrain could be modelled

Weaknesses:
- Computing time too long for 384,000 simulations
- Need for validation



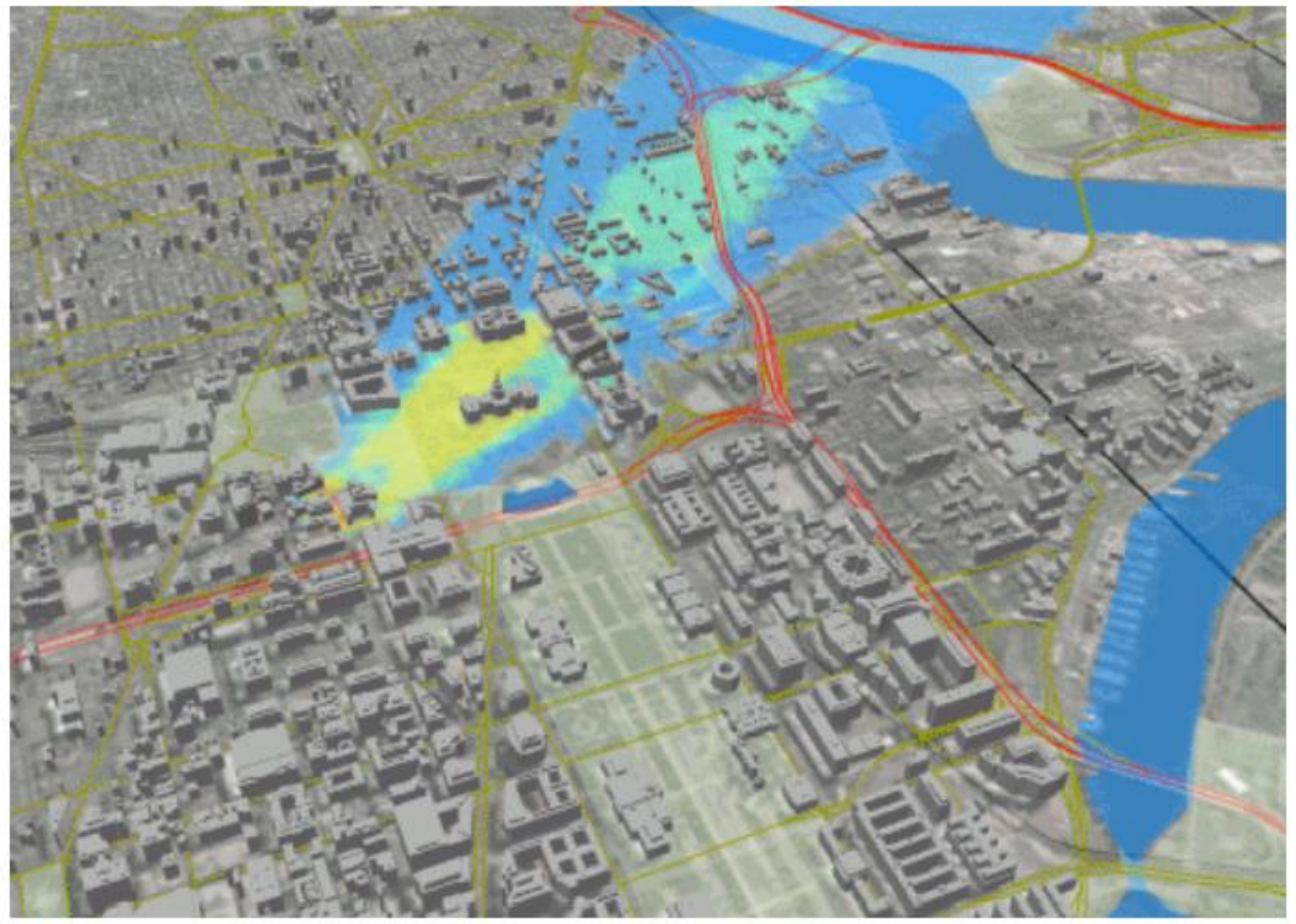


HSE CFD simulations for CO2PipeHaz
http://www.hse.gov.uk/research/rrhtm/rr1121.htm

Modelling Approaches: Hybrid CFD and Mass Consistent

- CHARM
- Los Alamos National Laboratory: QUIC
- Aria Technologies: Parallel Micro Swift Spray (PMSS)
- Rockle models

Faster than full CFD but still too time consuming for hundreds of thousands of simulations?



https://www.lanl.gov/projects/quic/

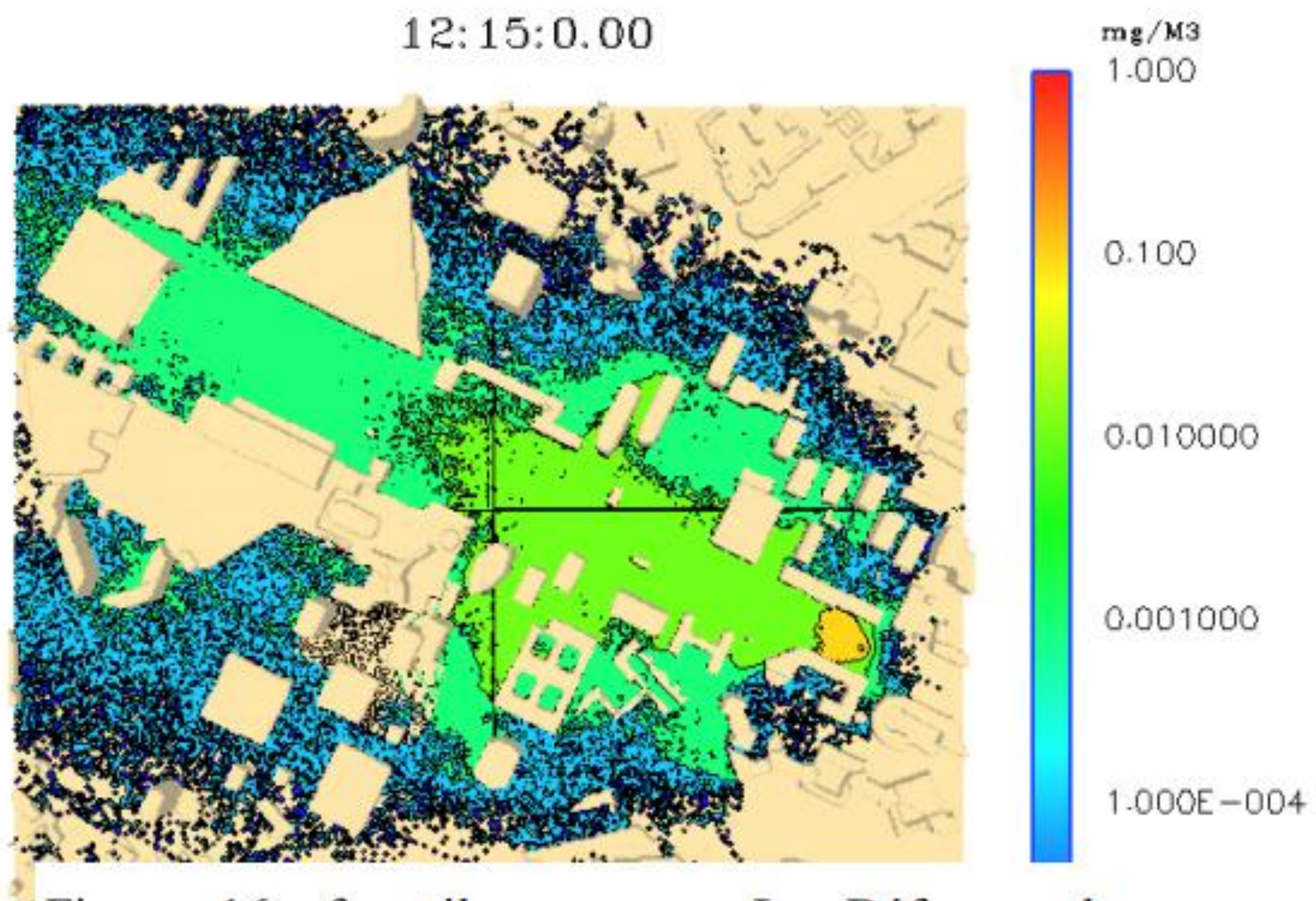
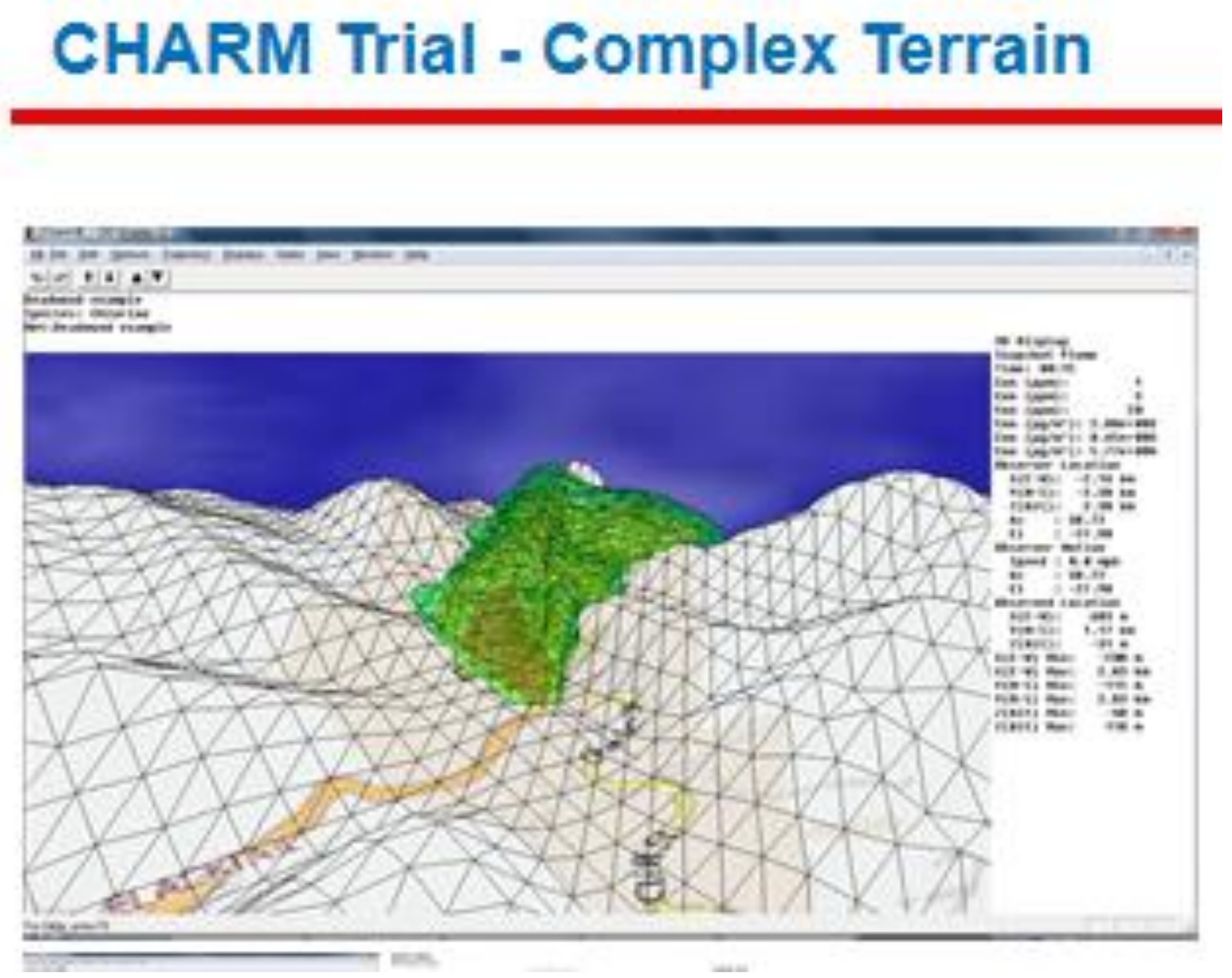


Figure 16: four-tile case on La Défense, the financial district west of Paris

https://www.harmo.org/Conferences/Proceedings/_Kos/publishedSections/H14-176.pdf



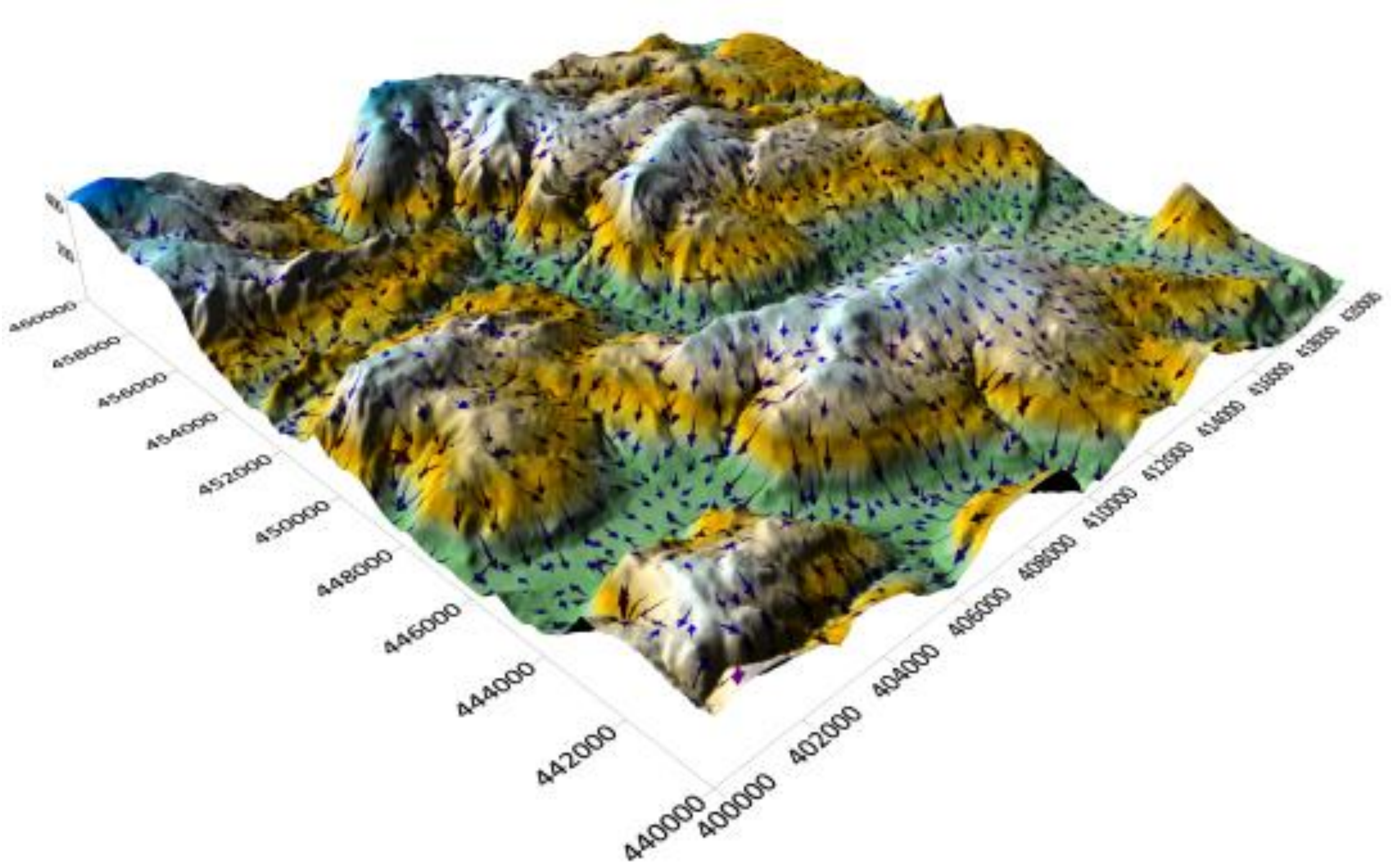
https://www.charmmodel.com/

Other Possible Modelling Approaches

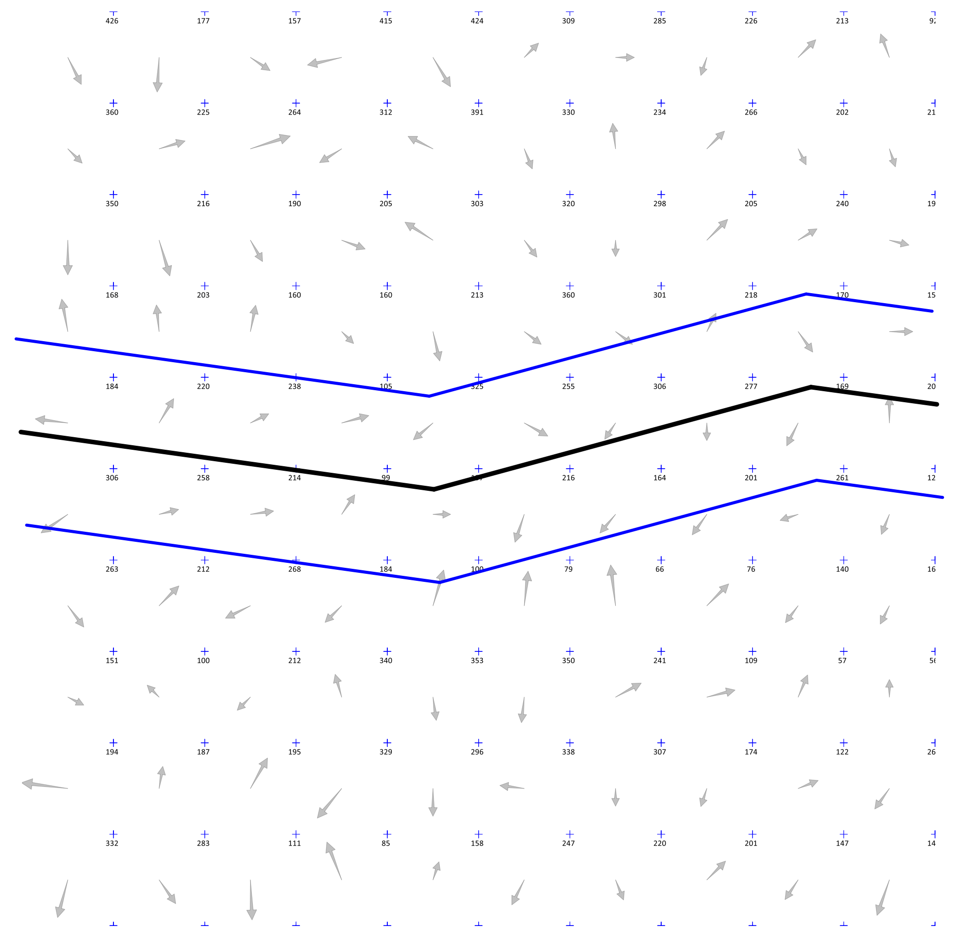
- **Smooth particle hydrodynamics**: a type of grid-free CFD model used for free surface flows, e.g., dam failures, and also computer graphics. Can it be used for dense gases and run quickly?
- **Lattice Boltzmann:** A fast CFD method. Is it fast enough for 384,000 runs?
- **Shallow-layer**: Depth-averaged CFD (2D faster than 3D). Can numerical issues with the TWODEE model be resolved? Promising recent work by CEA/CNRS in France
- **Gaussian puff**: Similar to Lagrangian model with convected Gaussian puffs, e.g., the SCIPUFF model used operationally by US/UK defence agencies. Fast runs times but can it handle all the physics of dense gas dispersion in complex terrain?
- **Emulators**: Sophisticated parameterised curve-fit to results from a more complex model, e.g., a fit to CFD results. Very quick to run. Is it possible to parameterise complex terrain? Could terrain be discretized on a grid to reduce the number of degrees of freedom, e.g., fitted to average slope within each grid cell?
- **Correlations**: Simple rules to lengthen cloud down slopes and shorten clouds upslope

Modelling Approach: Correlation Example

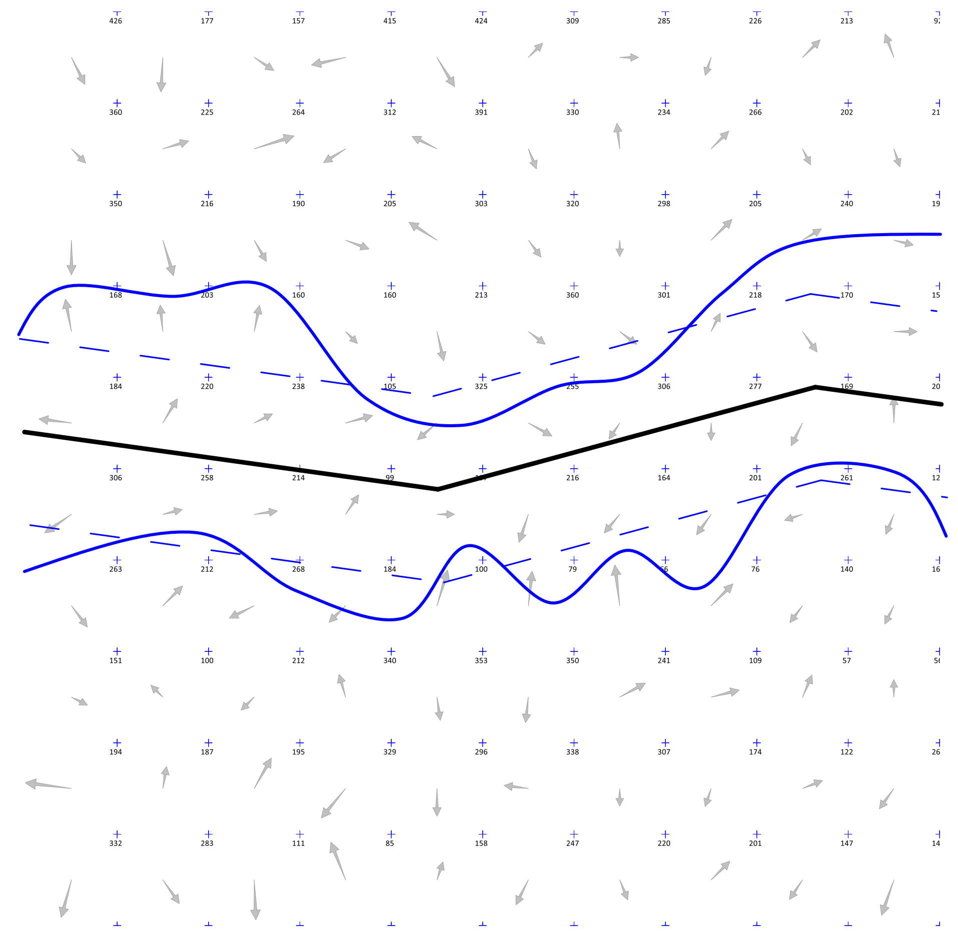
- Vector arrows indicate magnitude and direction of slope
- Zones initially generated around pipeline using an integral model, e.g., PHAST
- Zones then displaced, as a function of the slope angle



Gridded terrain data converted to slope vectors



Pipeline route and zones overlaid on slope vectors

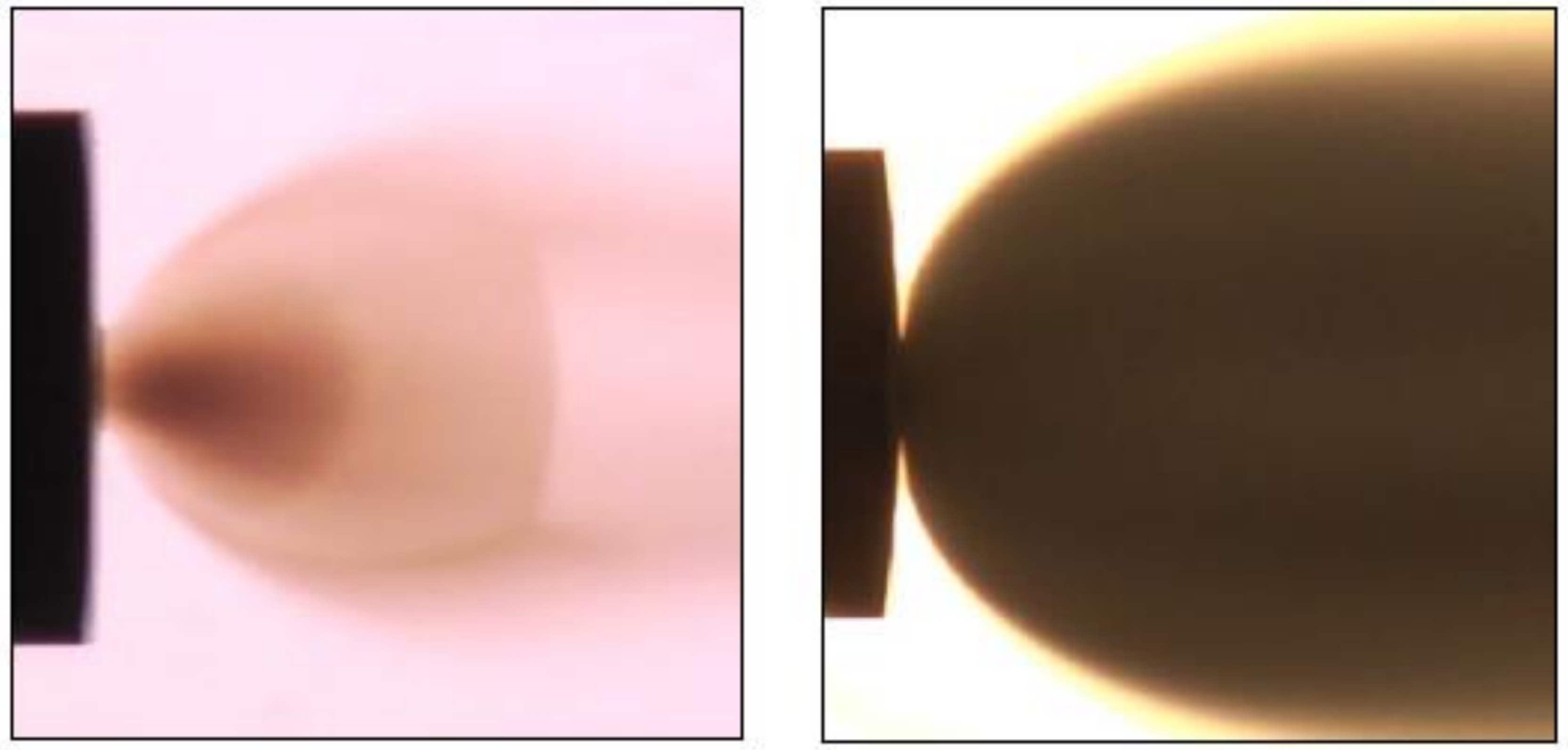


Pipeline zones displaced according to slope vectors

- Need to validate this approach using experimental data…

Experiments

- CO_2 release experiments
  - CO2PIPETRANS[1]
  - COSHER[2]
  - CO2PipeHaz[3]
  - MATTRAN[4]
  - CATO2[5]



- Dense gas dispersion experiments with terrain
  - Next slides…

1. https://www.dnv.com/news/large-scale-experimental-data-released-to-enhance-co2-pipeline-design-safety-26241
2. https://doi.org/10.1016/j.ijggc.2015.04.001
3. http://dx.doi.org/10.1016/j.egypro.2014.11.274
4. https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/G061955/1
5. https://www.co2-cato.org/publications/library1/co2-pipeline-transport-experimental-investigations

Dense Gas Dispersion in Complex Terrain: Experiments

- Literature review by Batt (2021) https://admlc.com/publications/

Trial Name	Substance	Flammable	Toxic	Field	Wind tunnel	Instantaneous	Unobstructed	Obstructions	Topography
BA Hamburg	SF6				•	•	•	•	•
Burro	LNG	•		•			•		•
China Lake	Argon, Freon-12				•		•		•
COOLTRANS	CO2		•	•			•	•	•
EMU-ENFLO	Krypton				•			•	•
Guldemond	Argon				•		•	•	•
Jack Rabbit I	Chlorine, ammonia	•	•	•			•		•
McBride	Propane				•	•		•	•
MODITIC	CO2				•			•	•
Muller	SF6				•		•		•
Porton Down	Freon-12			•		•	•		•

- Only four field-scale dense-gas dispersion trials with topography

Experimental Data: Burro 8

- LNG spills of between 24 m^3 and 39 m^3 onto water
- Eight tests at the Naval Weapons Centre (NWC), China Lake, California
- Downwind of the release basin, the terrain sloped upwards at about 7 degrees for 80 m before levelling out to about 1 degree
- In one test, Burro 8, wind speed was very low and dispersion behaviour was influenced by the terrain
- Issue: uncertainties with source of LNG vapour from the boiling pool

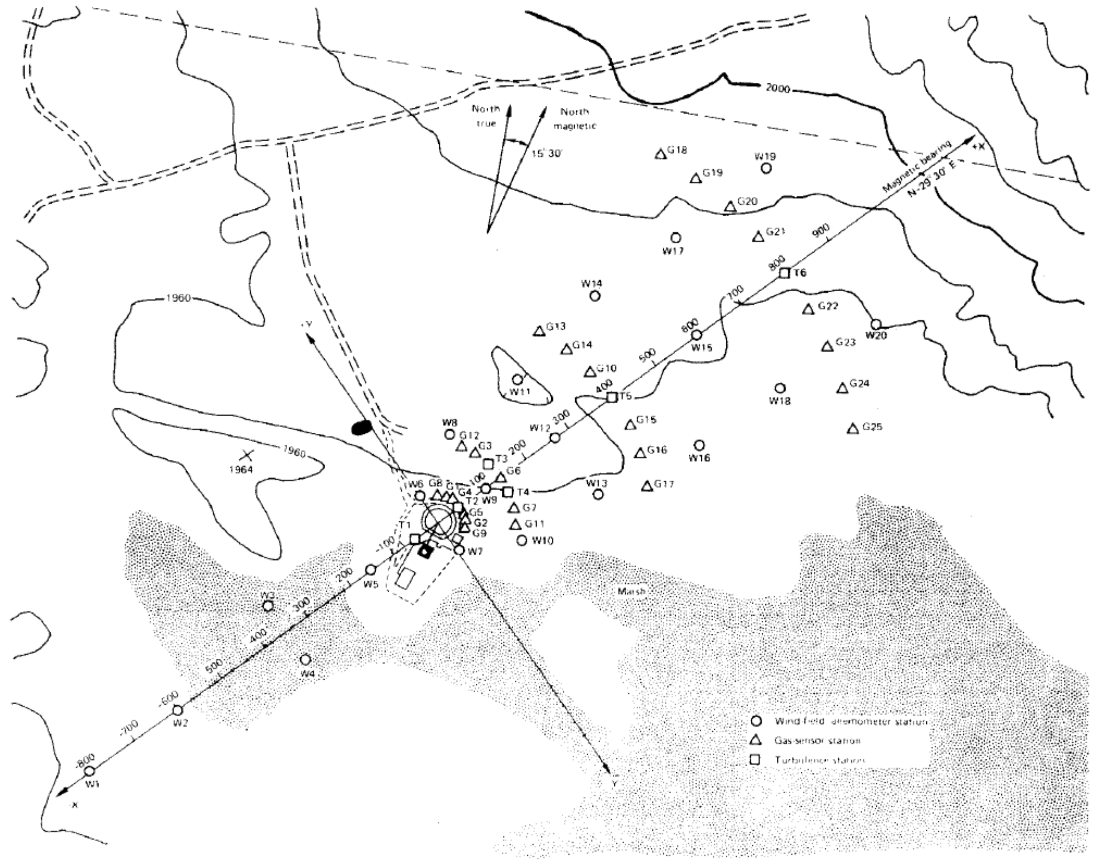
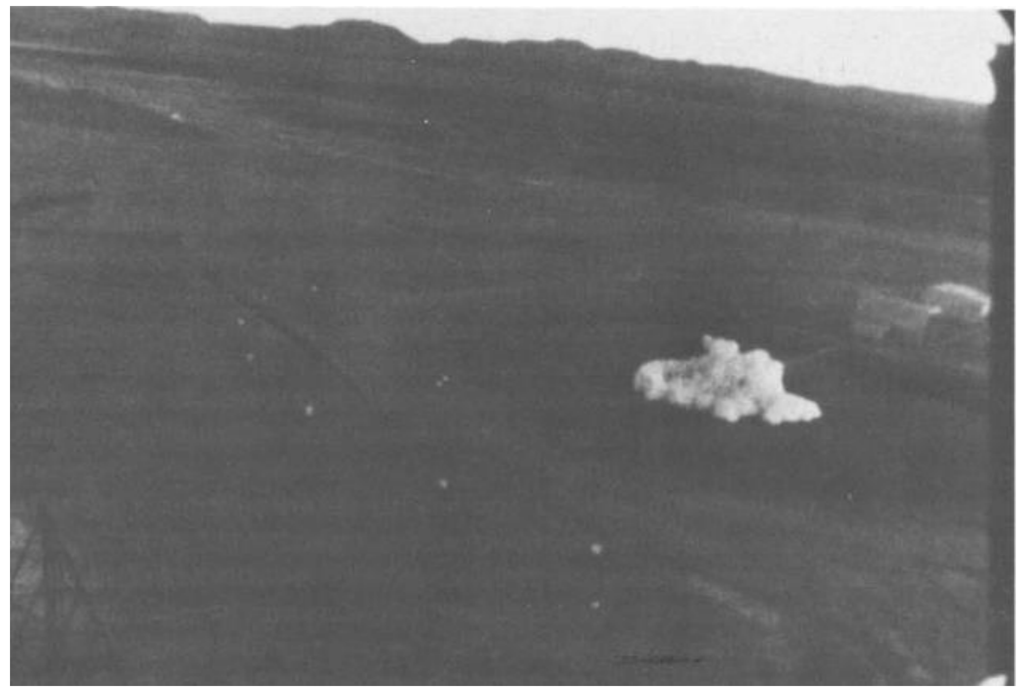
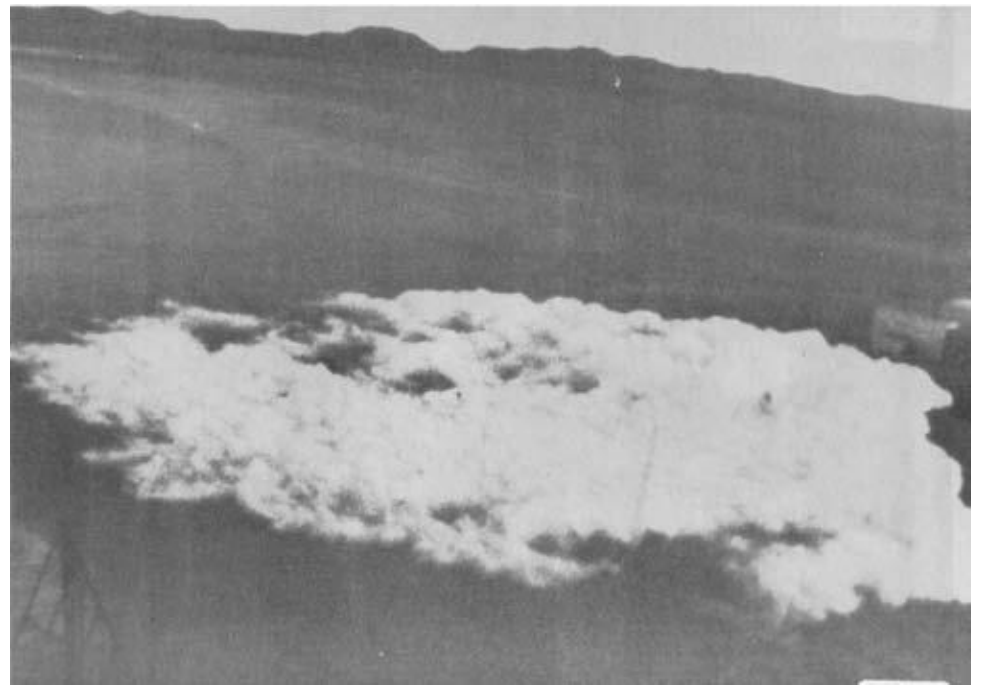


Fig. 2. Instrumentation array for 1980 LNG dispersion tests at the NWC, China Lake.



Burro 8 trial after 2 s



Burro 8 trial after 30 s

Koopman *et al*. (1982) https://doi.org/10.1016/0304-3894(82)80034-4

Experimental Data: COOLTRANS

- Project led by National Grid in 2011-2014
- Dense-phase CO_2 releases at DNV Spadeadam test site, UK
- Above-ground vertically-upwards and horizontal releases, below-ground releases from pipelines into craters
- Pipeline rupture tests: 230 m long, 6-inch pipe at initial pressure 150 barg
- Site mainly flat and open but some obstructions and slopes in largest tests
- Concentration measurements using 63 sensors upwind/downwind from -150 m to 500 m
- Data not yet fully released to the public

Figure 3: Appearance of the dispersing cloud from a puncture in a case in which the plume returns to ground downstream of the crater compared with a case in which a 'blanket' is formed

Photos © National Grid / DNV

Allason *et al.* (2014) https://doi.org/10.1115/IPC2014-33384

Experimental Data: Jack Rabbit I

- Project led by US Departments of Homeland Security and Defense at US Army Dugway Proving Ground, Utah – a flat, dry lake bed
- Eight 1 and 2 ton releases of pressure-liquefied chlorine and ammonia
- Vertically downwards releases into a shallow 2 m deep, 50 m wide depression that was excavated into the desert playa
- Sensors located in concentric rings at radii of 50 m, 100 m, 150 m, 200 m, 250 m, 500 m, 1250 m, and 2500 m
- Data not yet examined fully in dispersion model validation exercises

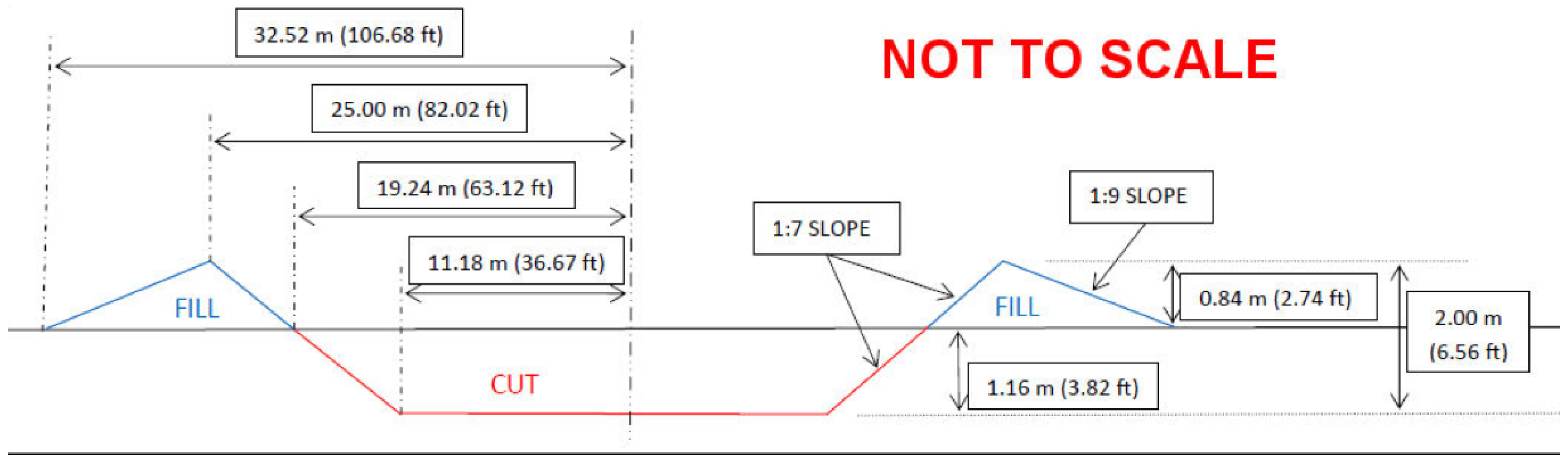
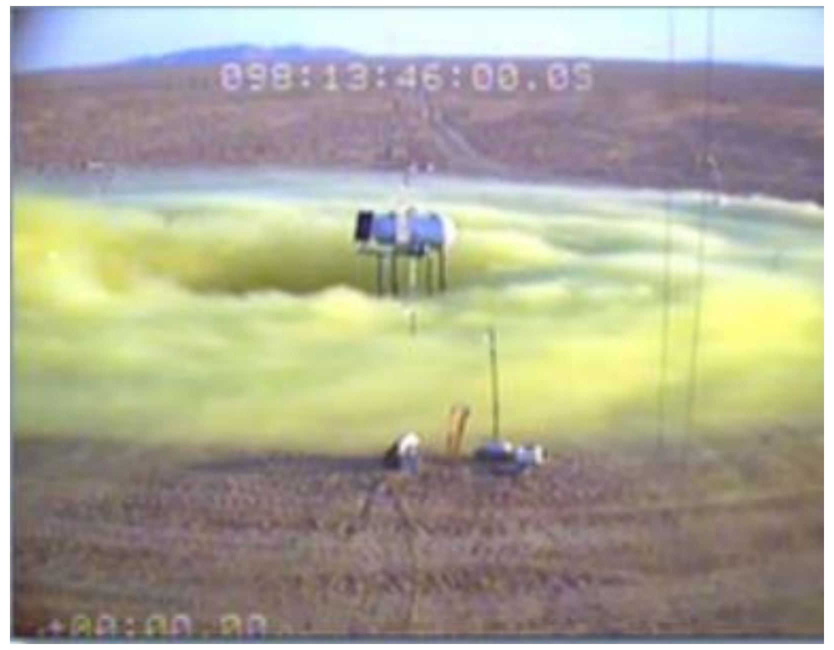


Figure 1. Graphic Depiction of Jack Rabbit Depression; Jack Rabbit Test Program.



Photos © DHS S&T, CSAC

Experimental Data: Porton Down

- 42 tests funded by HSE at the UK Chemical Defence Establishment in 1970's
- Instantaneous 40 m^3 releases of refrigerant gas from tent with collapsible walls
- Refrigerant gas mixtures: initial density ratios of 1.03 and 4.2 (relative to air).
- Five different grassland test sites, of which two involved sloping ground
- Majority of the measurements consist of time-integrated concentrations (doses) on four arcs located at distances of 25, 50, 100 and 150 m
- Dataset not much used for model validation, because measurements consist of doses and not concentration

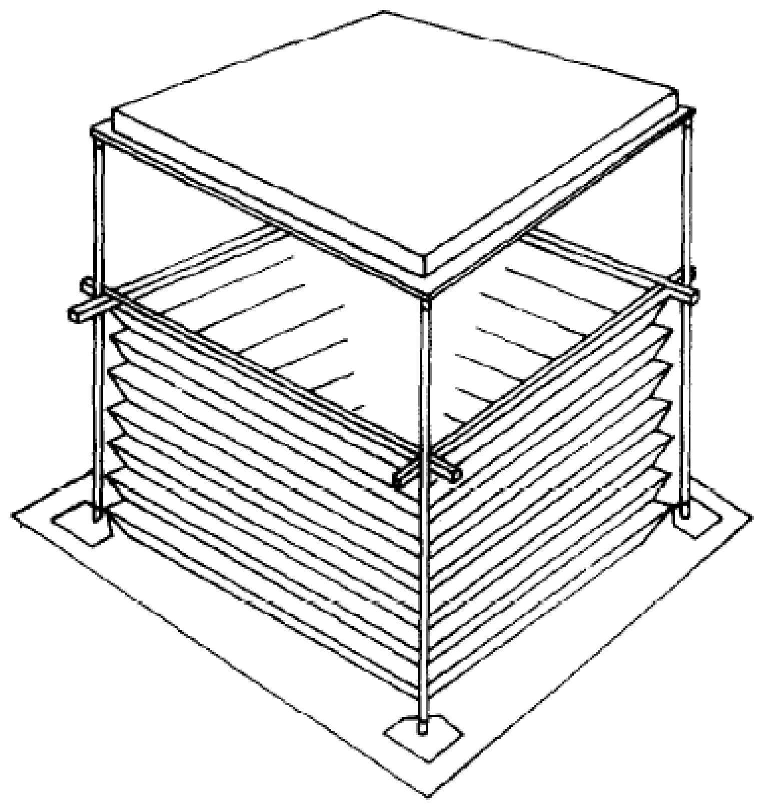
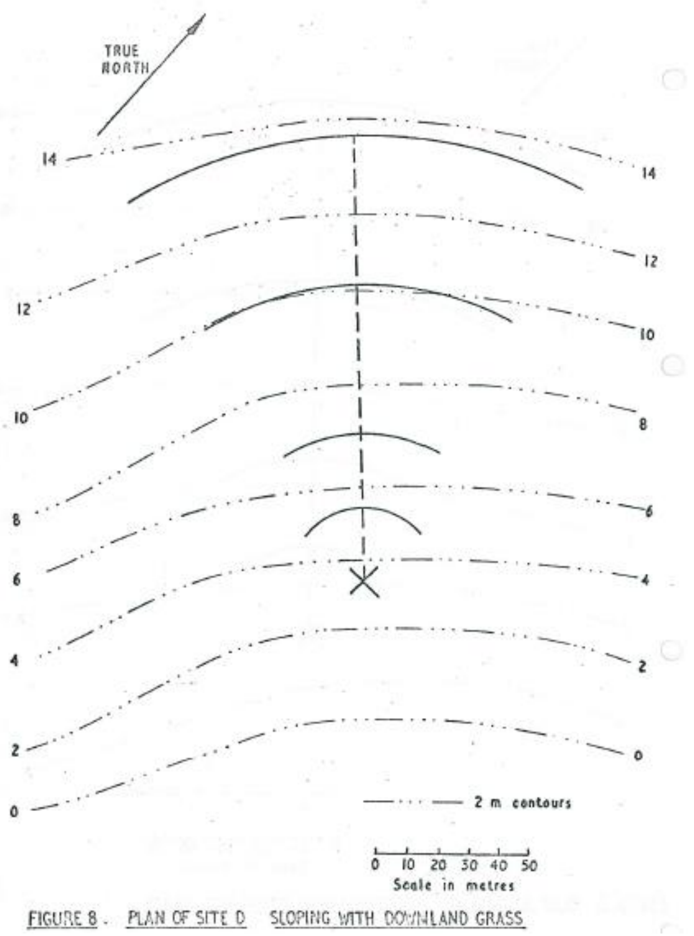
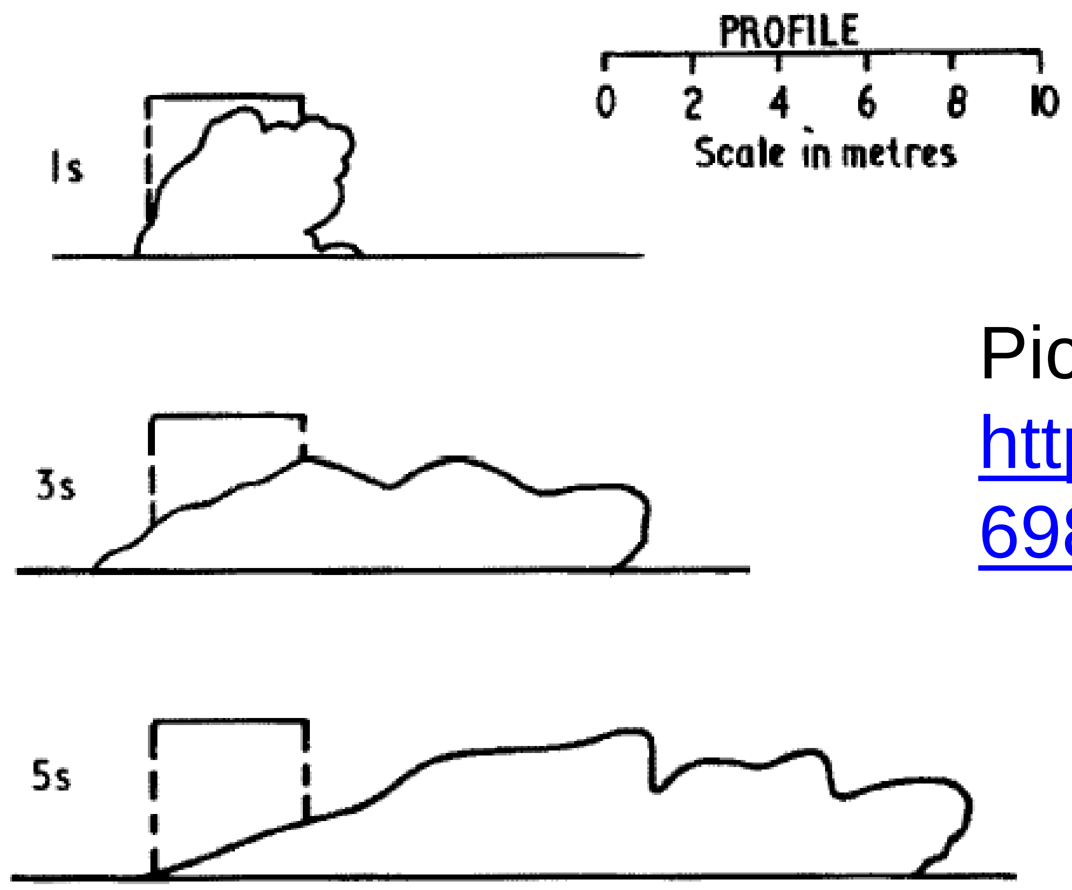


Fig. 1. Sketch of the 40 m^3 collapsible tent used as the cloud source.





Picknett (1981)
https://doi.org/10.1016/0004-6981(81)90181-5

Experimental Data: Issues

- Burro
  - Only one trial exhibited terrain effects, uncertain source conditions
- COOLTRANS
  - Data not publicly available, not previously used for model validation (?)
- Jack Rabbit I
  - Shallow circular depression on otherwise flat terrain
- Porton Down trials
  - Only doses not concentrations

- Need for dense-gas dispersion experiments with complex terrain raised as significant knowledge gap by Hanna *et al*. (2021) https://doi.org/10.1002/prs.12289
- Without experimental validation, how can we trust model predictions?

Tentative Ideas for Future Activities?

- HSE would like to work with other partners to address the issues raised here
- Informal discussions with risk consultants (DNV, CERC, Gexcon etc.) at recent conferences indicated there is significant interest in this topic
- Proposing to hold a webinar in 2023, organised by the UK Atmospheric Dispersion Modelling Liaison Committee (www.admlc.com), to bring together international dispersion modelling experts and discuss possible solutions
- Regarding need for field-scale experiments:
  - Jack Rabbit III project led by US Departments of Homeland Security and Defense are planning future large-scale trials in next few years: topography is an option. HSE can make introductions to JRIII project leaders if organisations are interested in joining JRIII
  - INERIS have conducted CO_2 dispersion experiments at French army test site in an urban environment. Some tests completed in 2022, further tests planned in 2023. Contact: Olivier.Gentilhomme@ineris.fr or Jean-Marc.Lacome@ineris.fr

Acknowledgements

- Contact email: zoe.chaplin@hse.gov.uk, simon.gant@hse.gov.uk

Thank you

- 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

CO_2 phase diagram

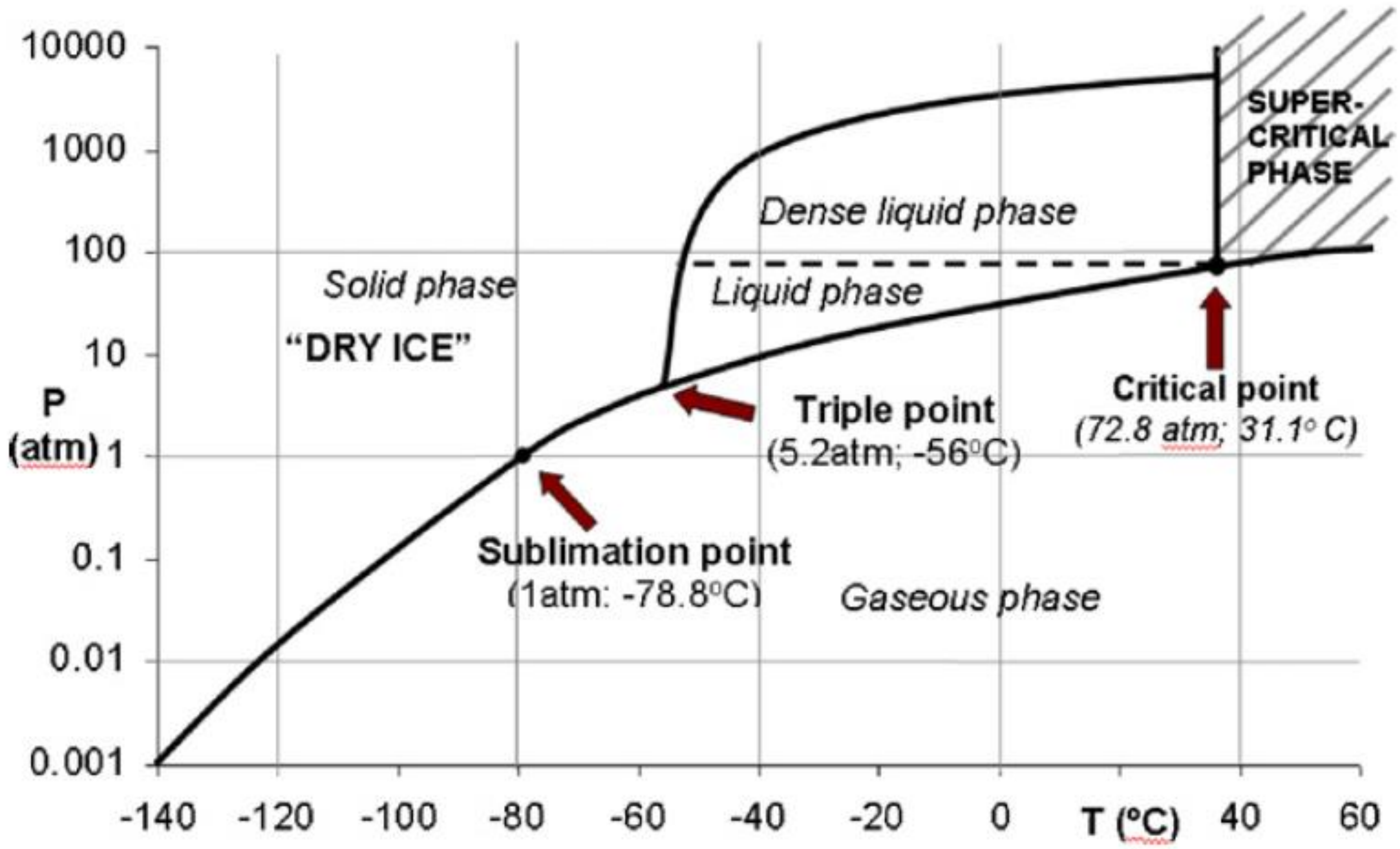


Fig. 1. CO_2 phase diagram (Pasquetto and Patrone, 1994).