PROTECTING PEOPLE AND PLACES FOR 50 YEARS HSE

Skylark, Dense-Gas Dispersion and Research at HSE

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11th NAME User Workshop, Met Office, Exeter, UK 25-26 June 2025

Outline

- Skylark: dispersion of carbon dioxide
- DRIFT model evaluation
- MODISAFE project
- Dispersion of ammonia
  - Jack Rabbit III
  - ARISE
  - SafeAm
- Recent and future activities of the ADMLC

Skylark CO_2 dispersion project: motivation

- Carbon Capture Utilisation and Storage (CCUS) projects in the UK

- Final Investment Decisions reached on
  - HyNet project
    https://hynet.co.uk
  - East Coast Cluster Project
    https://eastcoastcluster.co.uk

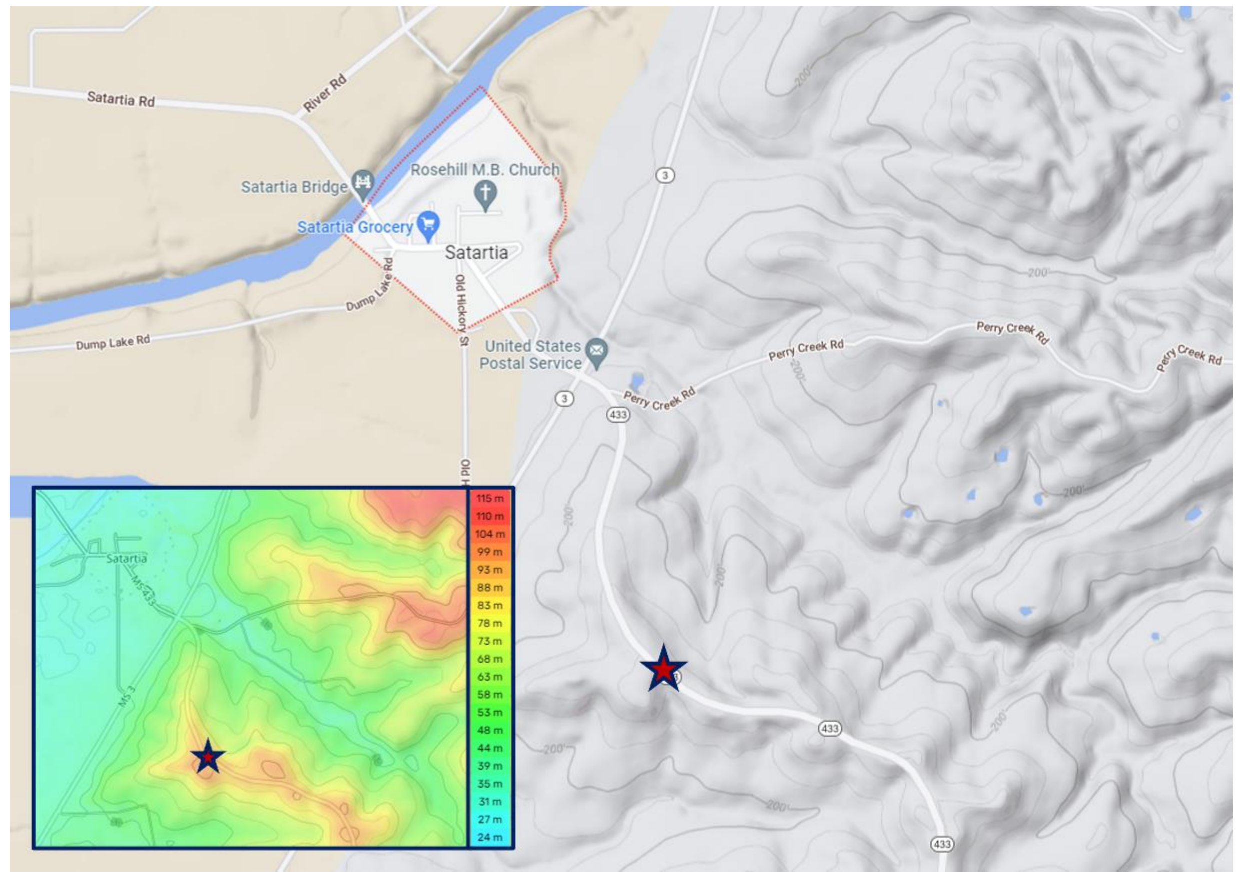
- Government awarded development funding in June 2025 to support
  - Acorn
    https://www.theacornproject.uk
  - Viking CCS project
    https://www.vikingccs.co.uk

Image source: https://www.vikingccs.co.uk/about

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

Skylark CO_2 dispersion project

- Kick-off on 13 May 2025, 3-year duration
    1. CO_2 pipeline craters and source terms – DNV
    2. Wind-tunnel experiments – University of Arkansas
    3. Simple terrain dispersion experiments – DNV
    4. Complex terrain dispersion experiments – DNV
    5. Model validation – HSE
    6. Emergency response – NCEC
    7. Venting – DNV



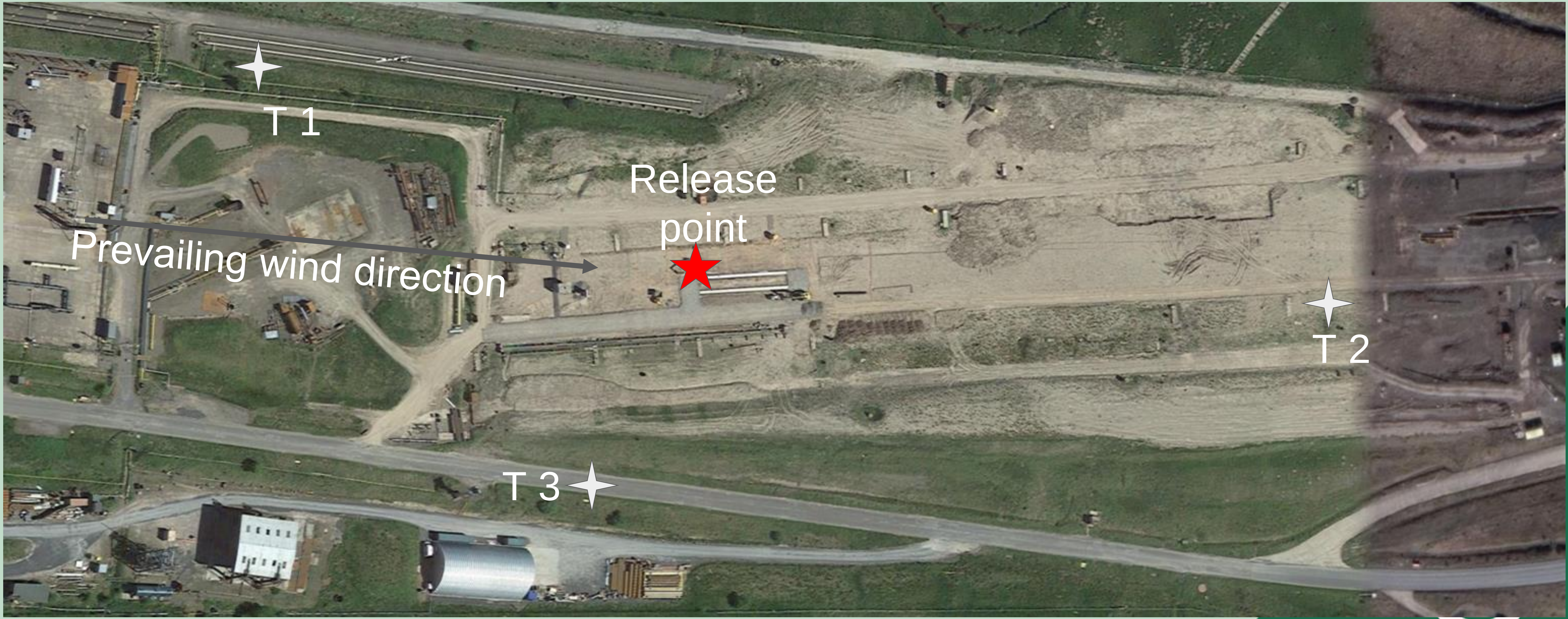



https://www.dnv.com/article/skylark-pioneering-excellence-in-co2-pipeline-safety-250648/

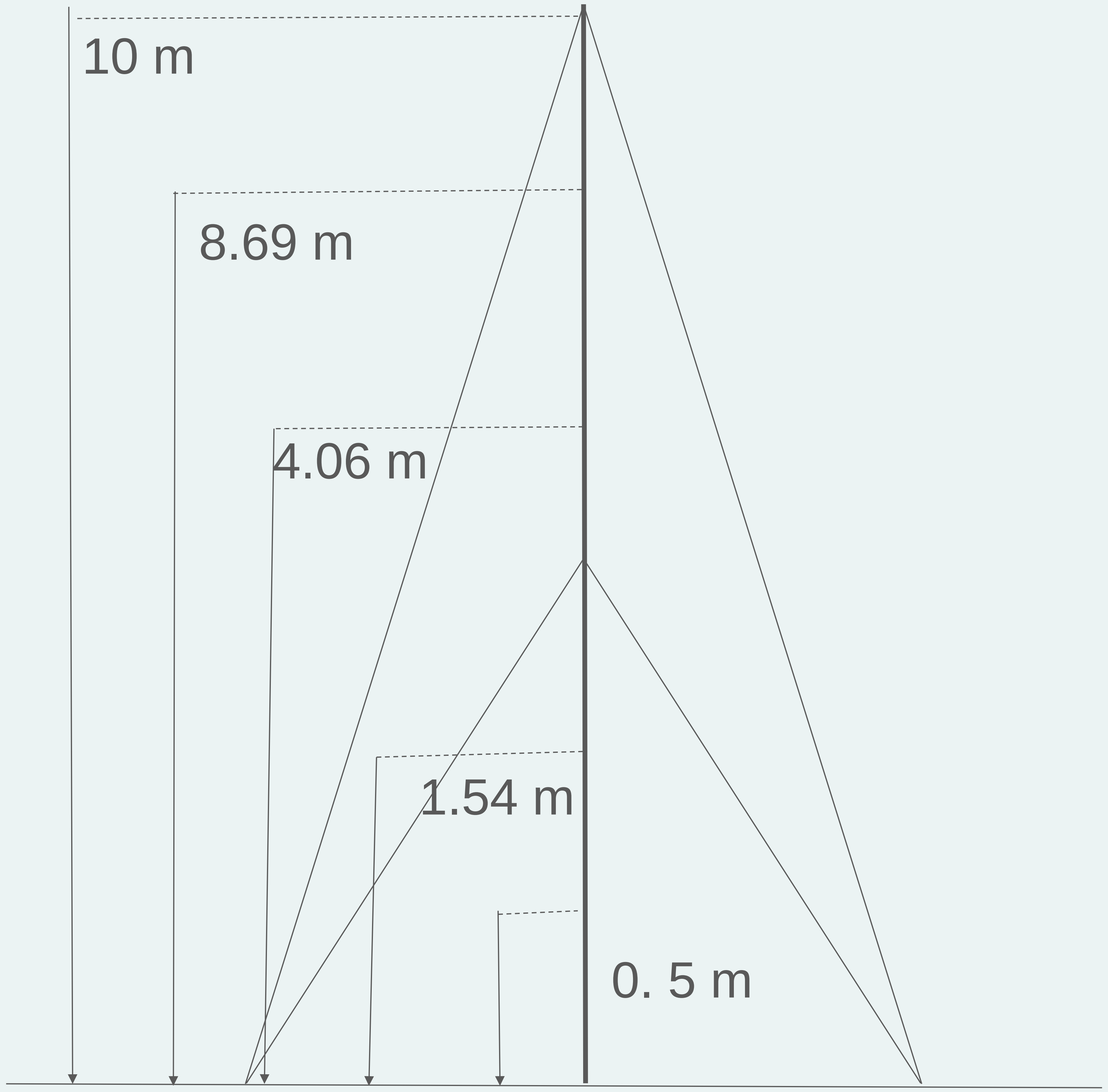
Source of images: Allason D., Armstrong K., Barnett J., Cleaver P. and Halford A. “Behaviour of releases of carbon dioxide from pipelines and vents”, Paper IPC2014-33384, Proc. 10th International Pipeline Conference IPC2014, Calgary, Alberta, 29 September – 3 October 2014, © Copyright National Grid / DNV / ASME

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

Example Deployment Scenario

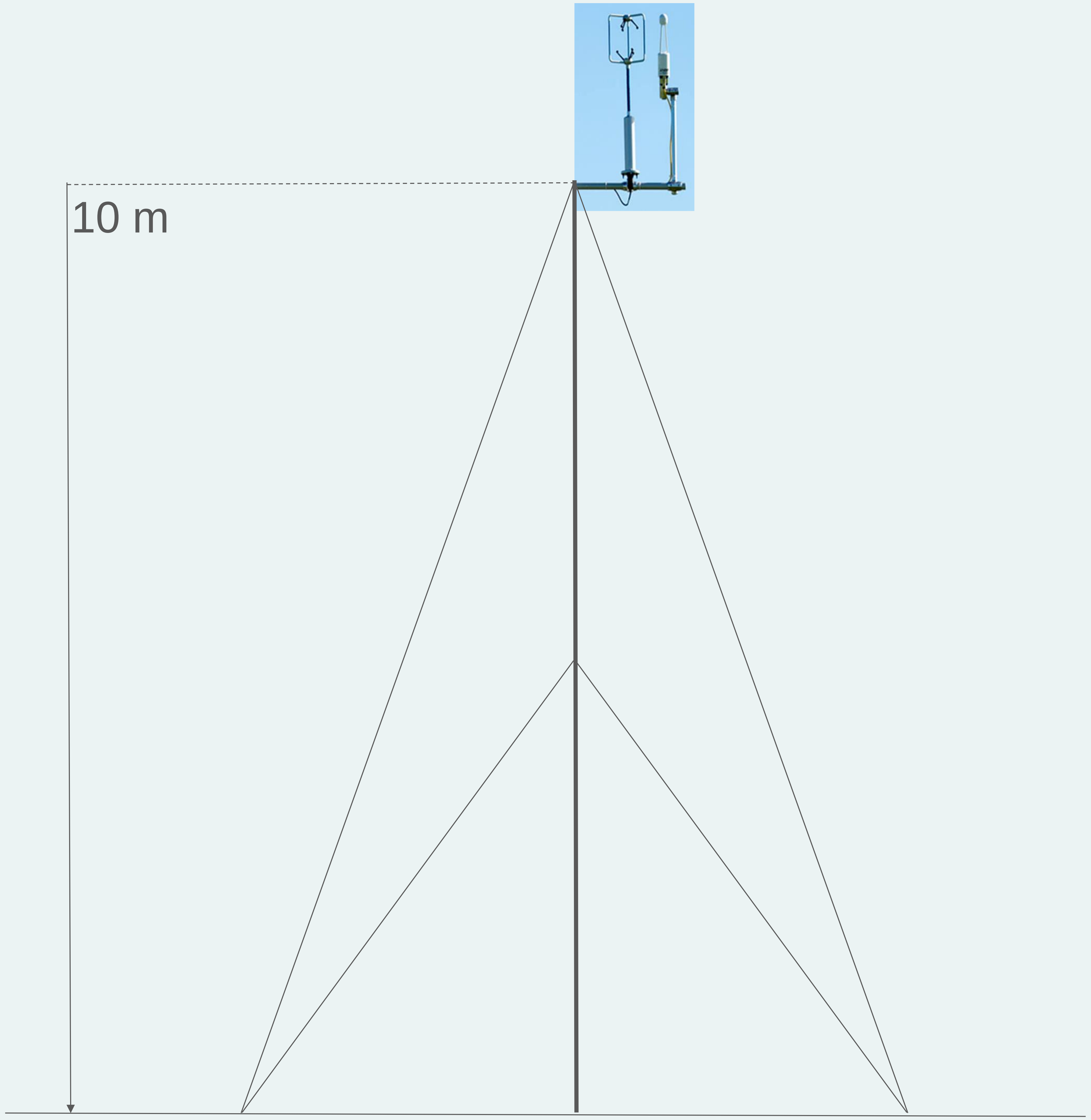


Surface site - Mean Meteorology Profiles



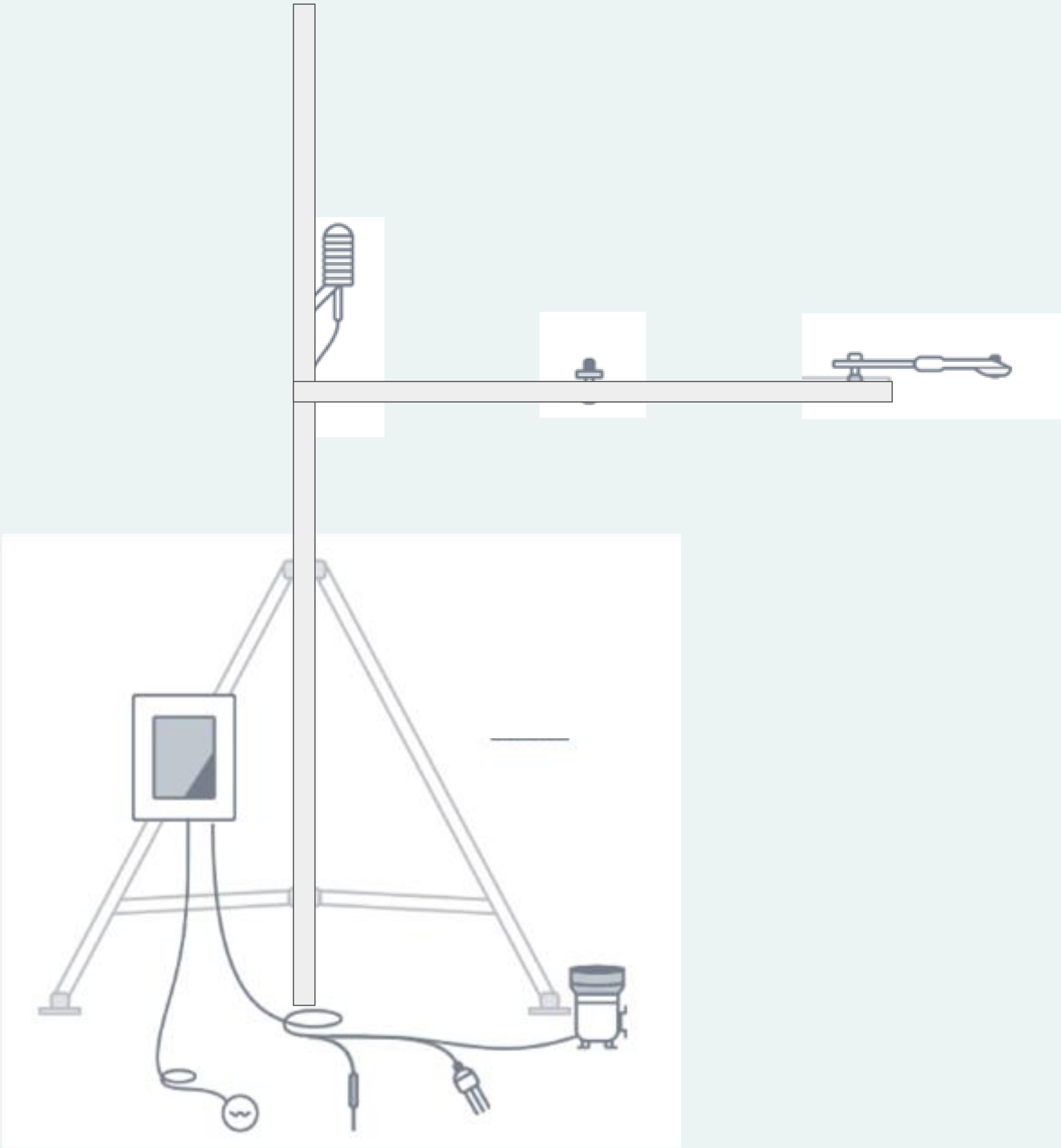
- 10 m lattice mast
- 5 measurement levels
- Measured parameter at each level:
  - Pressure
  - Air Temperature
  - Relative Humidity
  - Wind Speed
  - Wind Direction
- Measurement frequency: 1 Hz
- Integration period: 1 minute

Surface site - Flux Estimates (Eddy Covariance)



- 10 m lattice mast
- 3D sonic & Li Cor CO_2 & H_2O analyser @ 10m
- Measured parameters:
  - Wind Components
  - Air Temperature
  - Pressure
  - CO_2 & H_2O concentration
  - Sonic temperature
- Measurement frequency: 40 Hz
- Integration period: 30 minute

Surface site - Energy Balance



- 2 m lattice mast
- Measured parameters:
  - Soil Heat Flux
  - Soil Temperature
  - Soil Moisture
  - Pressure
  - Air Temperature
  - Relative Humidity
  - 4 component net radiation
  - Precipitation
  - Photosynthetically Active Radiation
- Measurement frequency: 1 Hz
- Integration period: 1 minute

University of Leeds

Proposed PhD project

Accelerated Fluid Dynamics of CO2 dense gas dispersion in complex terrain

Academic lead: Dr Amirul Khan, School of Civil Engineering, a.khan@leeds.ac.uk
Industrial lead: Dr Simon Gant, Health and Safety Executive (HSE), simon.gant@hse.gov.uk
Co-supervisor(s):
Dr Andrew Ross, School of Earth and Environment, A.N.Ross@leeds.ac.uk, Dr Rory Hetherington, Health and Safety Executive (HSE), rory.hetherington@hse.gov.uk (External)
Project themes:
Clean Energy, Computational & Analytical Tools, Data-driven methods, Multiphysics & Complex Fluids

Carbon Capture and Storage (CCS) is recognised as a crucial element in reaching the target of Net Zero. To support this, an infrastructure of pipelines are required to transport liquid CO2. However, safe operation of pipelines relies on accurately predicting the consequences of a leak or rupture (e.g. 2020 Satartia pipeline release in Mississippi). Key factors in modelling pipeline releases, especially when a risk assessment is undertaken along the full length, include (i) the computational cost of a model and (ii) its capacity to account for complex terrain.

https://fluid-dynamics.leeds.ac.uk/projects/accelerated-fluid-dynamics-of-co2-dense-gas-dispersion-in-complex-terrain/

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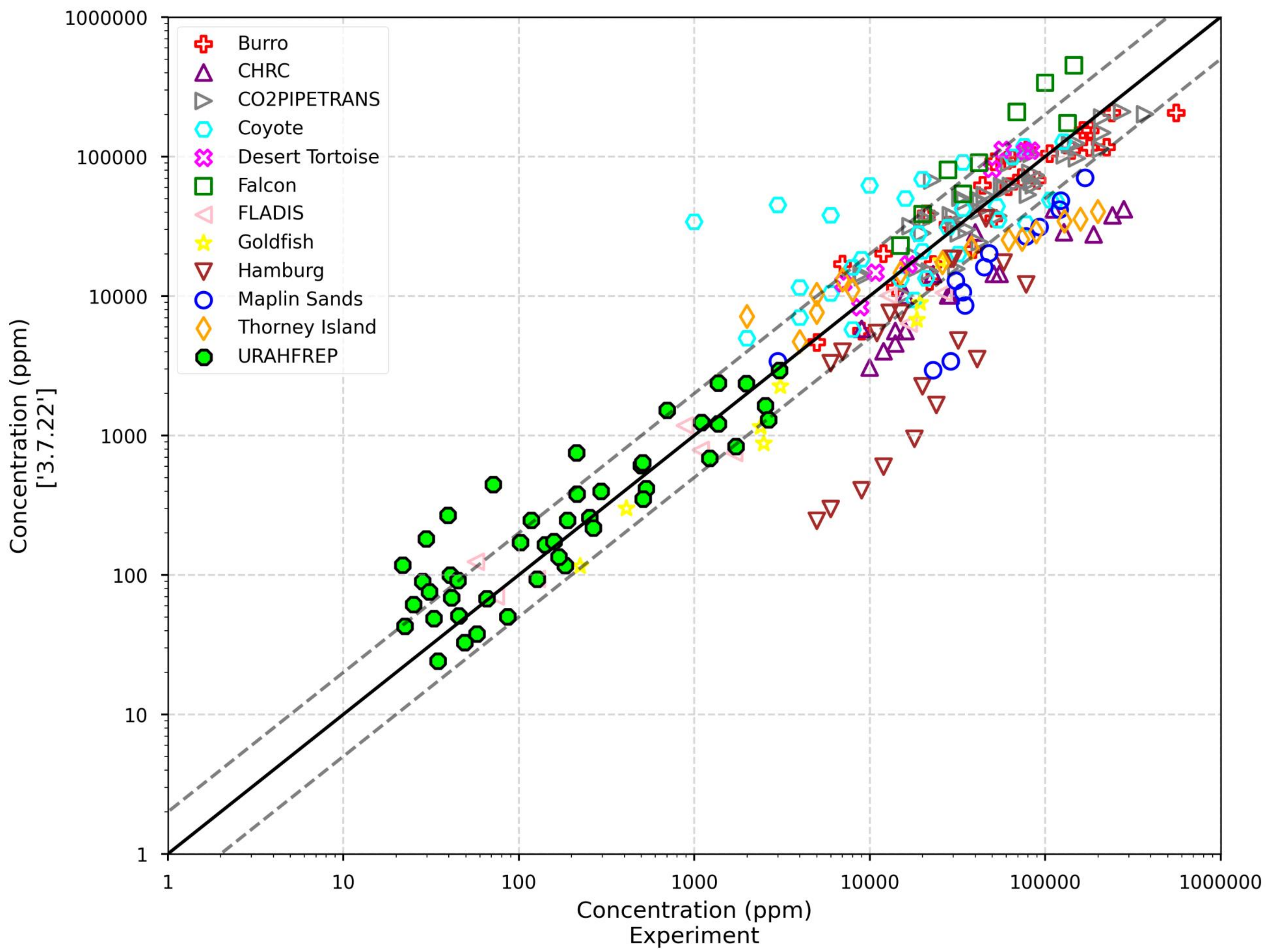
DRIFT Model Evaluation

- DRIFT is the integral dispersion model developed by ESR Technology for HSE
- Used for both regulatory and research purposes: toxic and/or flammable substances
- Developments in DRIFT 3: pool re-evaporation, changes to the grounded jet model, transition from jet to wind-blown spreading, ammonia-water interactions, dry deposition
- Scientific assessment extended to cover:
  - Buoyant lift-off and buoyant rise
  - Dry deposition
  - Re-evaporation
  - Chemical reactions with moist air
- Peak and time-averaged data for the field-scale trials within model evaluation acceptance criteria:

  0.67 < MG < 1.5 ; VG < 3.3 ; FAC2 > 50%



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- CBRN modelling of sources and agent fate
- Follow-on from previous MODITIC project (modelling the dispersion of toxic industrial chemicals in urban environments)
- International collaboration between Swedish, Norwegian and French defence agencies (FFI, FOI, DGA), HSE, INERIS and Surrey University:
  - Evaporation from porous and non-porous substrates
  - Deposition and resuspension
  - Buoyant dispersion in urban areas
- In each research area, new experimental data have been produced, which will be made publicly available (uploaded to the ADMLC website)
- Data used for model development, model intercomparison and validation exercises
- There will be a special session on the MODISAFE project at the HARMO conference in Hamburg, Germany on 15-19 September 2025 www.harmo.org

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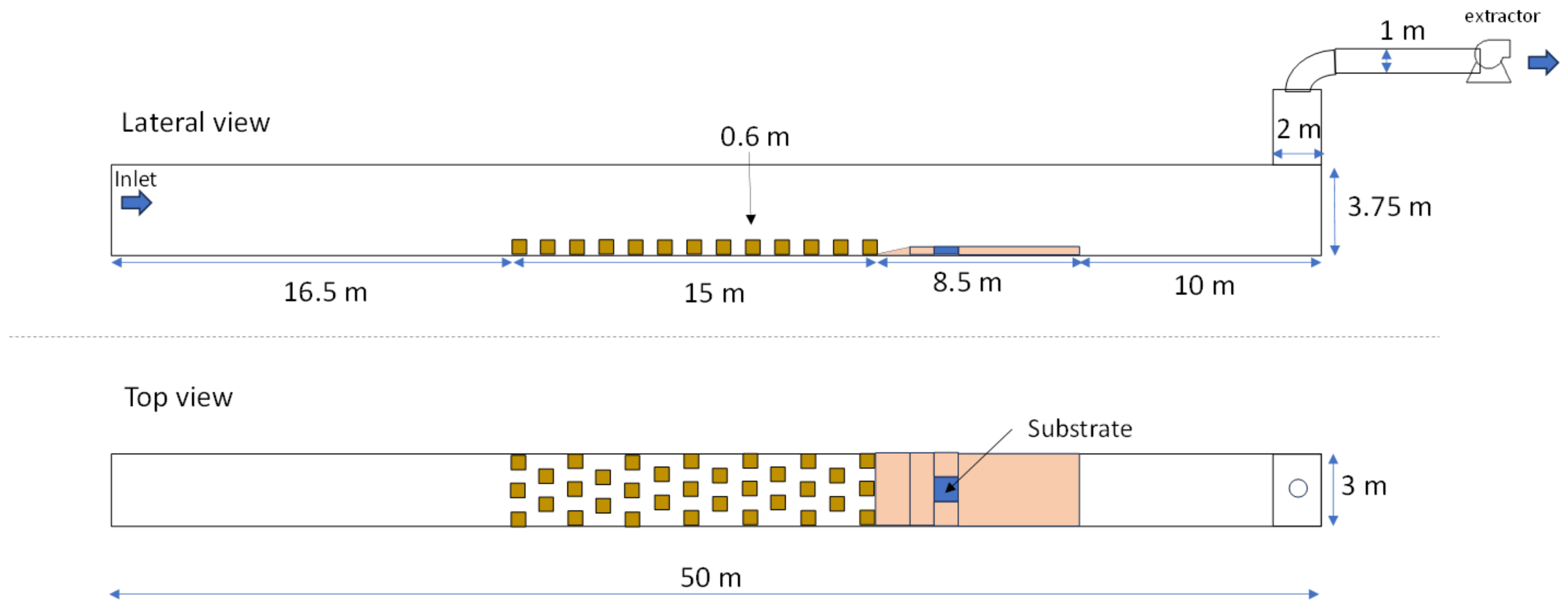
MODISAFE: Pool evaporation

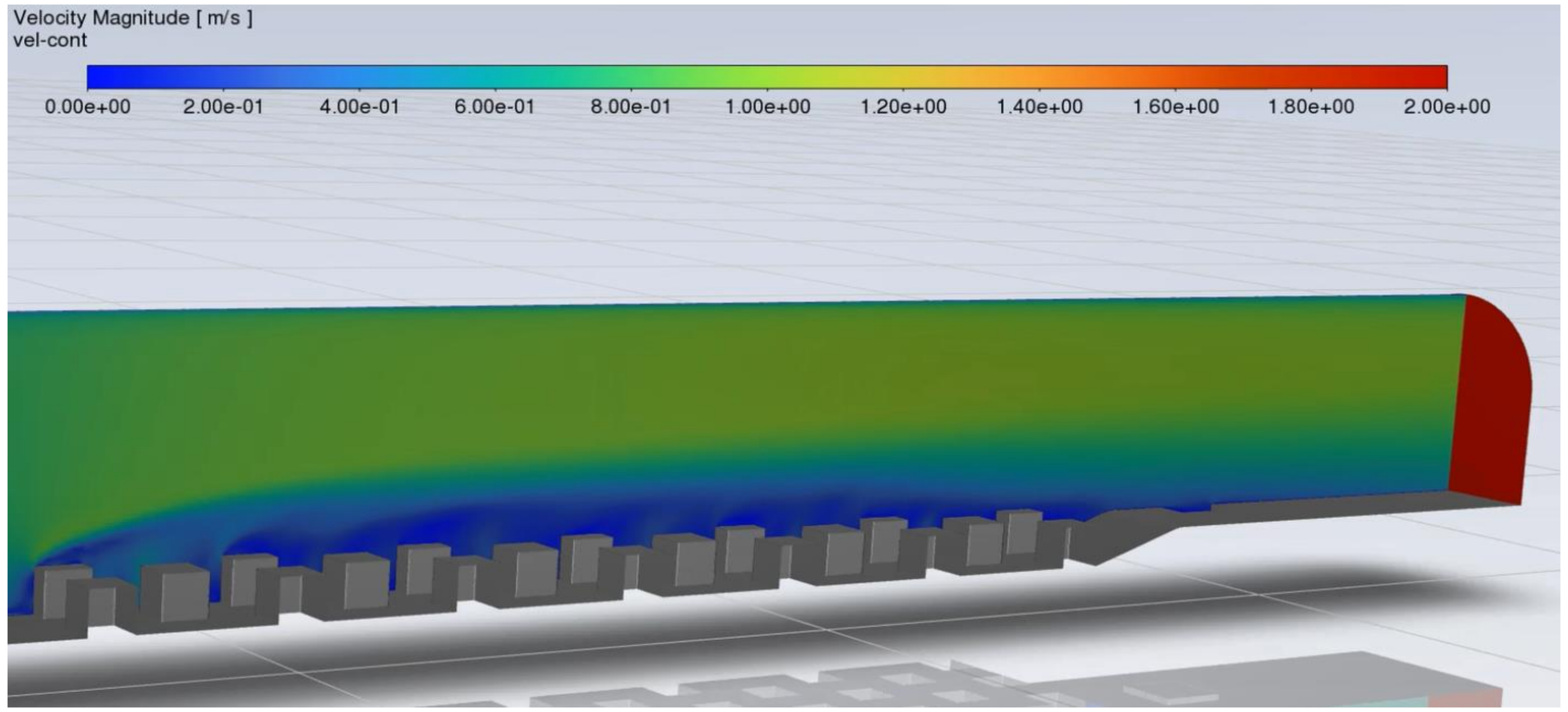
Experiments

- 30 tests investigating pool evaporation and droplet evaporation on impermeable and permeable substrates in the INERIS fire tunnel
- Varying the substance, substrate, wind speed, pool depth

Modelling

- Integral modelling of pool evaporation using GASP and SLOPS
- CFD modelling to understand fire tunnel flow field
- Inter-model comparison exercise with MODISAFE partners' own codes





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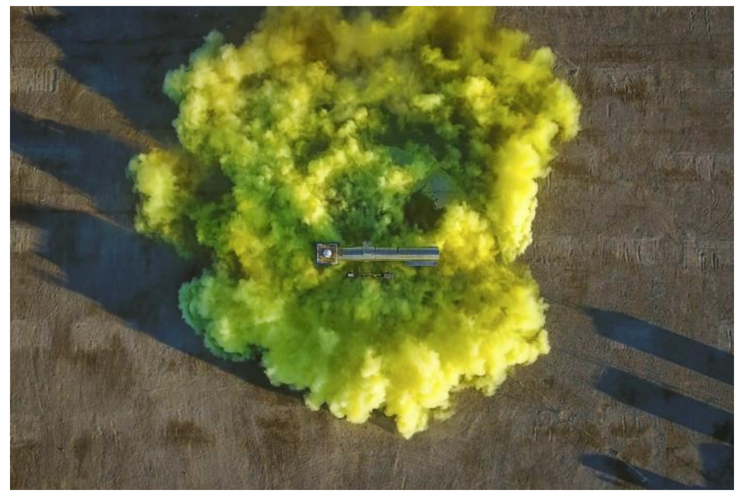
Jack Rabbit III project

- Jack Rabbit III ammonia release experiments (2021-ongoing)
  - Led by US Departments of Homeland Security and Defense
  - Aims:
    - Conduct large-scale releases of ammonia, similar to Jack Rabbit II chlorine trials
    - Validate dispersion models
    - Improve preparedness of emergency responders
  - HSE co-chairs the Jack Rabbit III Modelling Working Group and has coordinated international dispersion model inter-comparison exercises
  - Recent indoor ammonia release experiments at Battelle Memorial Institute, Columbus, Ohio
  - Updates to be shared at GMU conference, 24-25 June 2025 http://camp.cos.gmu.edu/announcement.html

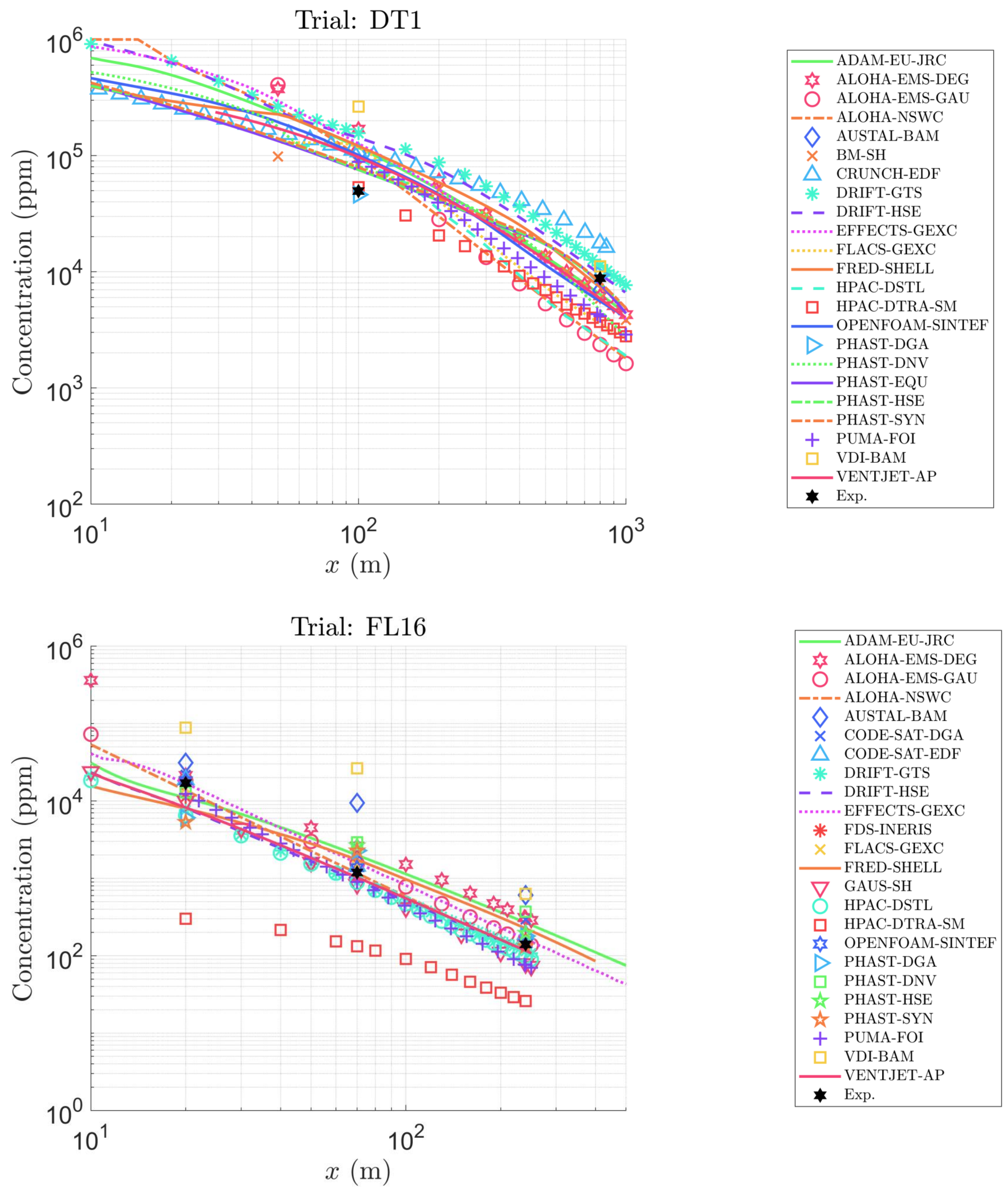
Images of previous series of Jack Rabbit II chlorine trials conducted in 2015-2016

Images © DHS S&T CSAC and Utah Valley University https://www.uvu.edu/es/jack-rabbit/

Jack Rabbit III model inter-comparison exercise

- Aims: to assess the performance of atmospheric dispersion models for simulating releases of pressure-liquefied ammonia using existing data from Desert Tortoise and FLADIS trials
- 21 independent modelling teams participated in the exercise
- Models tested: (A) empirically-based nomograms and Gaussian; (B) integral; (C) Gaussian-puff and Lagrangian particle; (D) CFD
- Draft journal paper due to be submitted to Atmospheric Environment X imminently

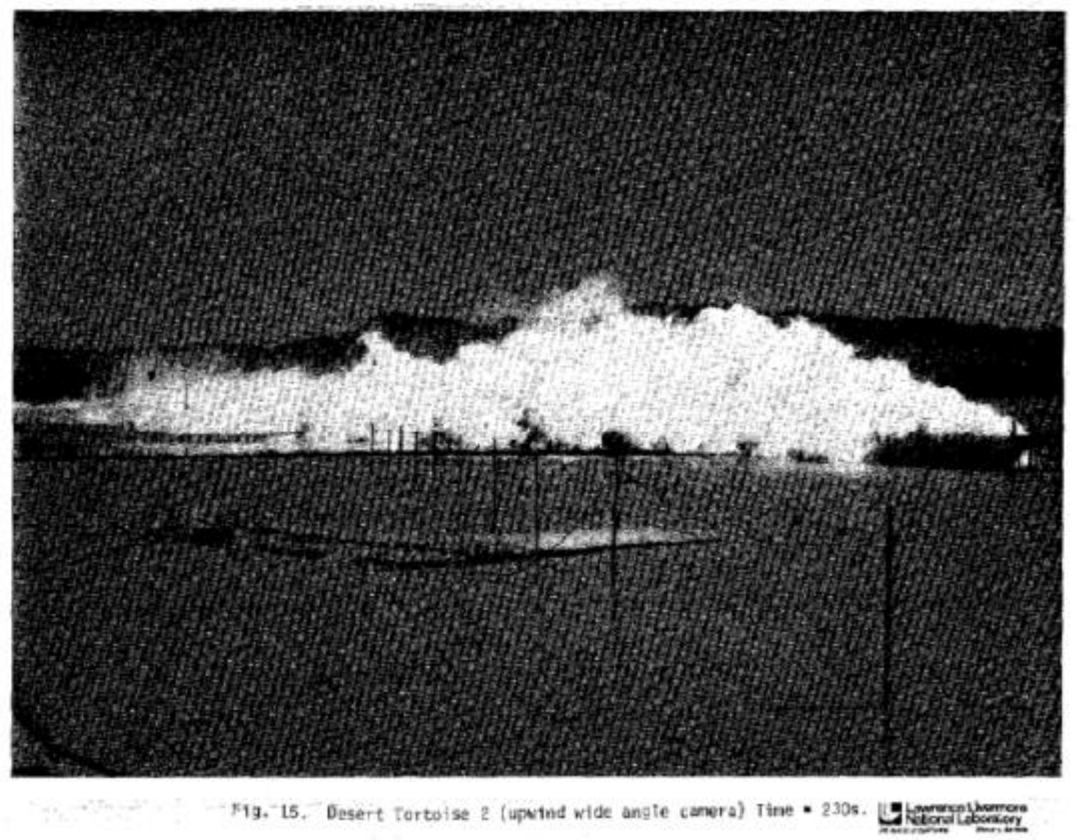


Arc-max concentration predictions for the Desert Tortoise DT1 trial (top), and FLADIS 16 trial (bottom)

Jack Rabbit III model inter-comparison exercise

#	Organisation	Model	Model Type				Desert Tortoise			FLADIS		
			A	B	C	D	1	2	4	9	16	24
1	Air Products, USA	Ventjet		■			■	■	■	■	■	■
2	BAM, Germany	AUSTAL			■		■	■	■	■	■	■
3		VDI	■				■	■	■	■	■	■
4	CEREA (EDF/Ecole des Ponts), France	Code-Saturne v7.0				■					■	
5		Crunch v3.1		■			■	■	■			
6	DGA, France	PHAST v8.6		■			■	■	■	■	■	■
7		Code-Saturne v6.0				■				■	■	■
8	DNV, UK	PHAST v8.61		■			■	■	■	■	■	■
9	DSTL, UK	HPAC v6.5			■		■	■	■	■	■	■
10	DTRA, ABQ, USA	HPAC v6.7			■		■	■	■	■	■	■
11	EM Solutions, Inc., USA	ALOHA v5.4.7 Gaussian	■				■	■	■	■	■	■
12		ALOHA v5.4.7 Integral		■			■	■	■	■	■	■
13	Equinor, Norway	PHAST v8.6		■			■	■	■			
14	FOI, Sweden	PUMA			■		■	■	■	■	■	■
15	Gexcon, Netherlands	EFFECTS v11.4		■			■	■	■	■	■	■
16	Gexcon, Norway	FLACS				■	■	■	■	■	■	■
17	GT Science & Software	DRIFT v3.7.19		■			■	■	■	■	■	■
18	Hanna Consultants, USA	Britter & McQuaid WB	■				■	■	■			
19		Gaussian plume model	■							■	■	■
20	HSE, UK	DRIFT v3.7.19		■			■	■	■	■	■	■
21		PHAST v8.4		■			■	■	■	■	■	■
22	INERIS, France	FDS v6.7				■				■	■	■
23	JRC, Italy	ADAM v3.0		■			■	■	■	■	■	■
24	NSWC, USA	RAILCAR-ALOHA	■				■	■	■	■	■	■
25	Shell, UK	FRED 2022		■			■	■	■	■	■	■
26	SINTEF, Norway	OpenFOAM v2206				■	■	■	■	■	■	■
27	Syngenta, UK	PHAST v8.61		■			■	■	■	■	■	■

Note: Model Type: A = Empirically-based nomograms/Gaussian plume model; B = Integral model; C = Gaussian puff/Lagrangian model; D = CFD. Shading in the right six columns indicates model was run for that trial. See Glossary for the full names of the organisations and models.

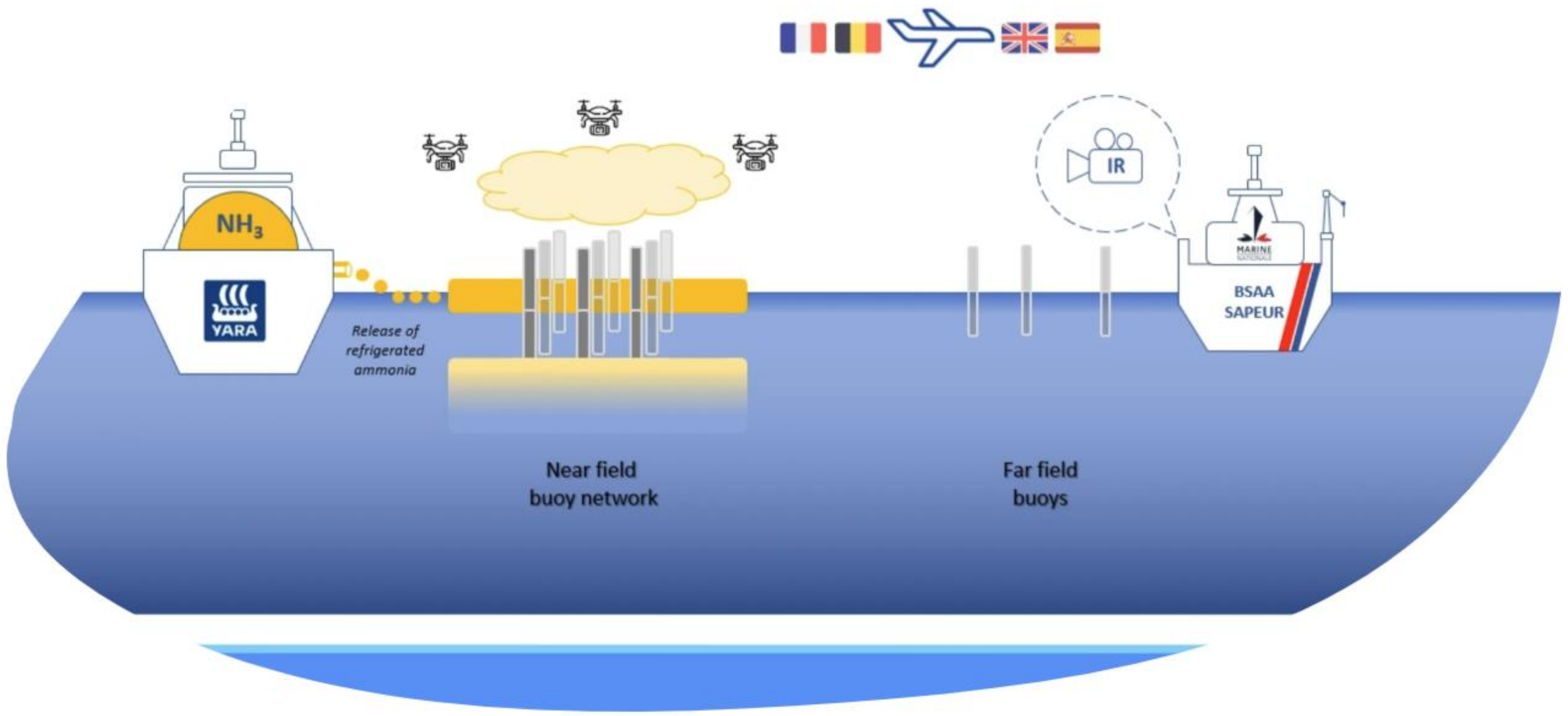


Desert Tortoise ammonia release, Nevada, USA, 1983

FLADIS ammonia release, Sweden, 1993-1994

Ammonia spills onto water: ARISE

- HSE is partner in the ARISE Joint Industry Project led by INERIS, CEDRE and Yara Clean Ammonia
- Aims:
  - Conduct multi-tonne spills of ammonia at sea
  - Improve understanding of dispersion in water and air
  - Provide dataset for validation of models
  - Develop methodology for risk assessment for marine applications
- Experiments planned for Sept 2025
- Contacts: Laurent.Ruhlmann@yara.com
  Olivier.Salvi@ineris-developpement.com



ARISE
Ammonia Response In Sea Emergencies

www.arise-partnership.org

INERIS · Cedre · Yara Clean Ammonia · ONERA · museum · HSE · INERIS Développement · IMT Mines Alès · SINTEF

Ammonia spills on water: SafeAm

https://www.sintef.no/en/projects/2023/safeam__increased_safety_of_ammonia_handling_for_maritime_operations

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Recent and future activities of the ADMLC

- Atmospheric Dispersion Modelling Liaison Committee www.admlc.com
- One-day conferences:
  - Investigating the impact of applying different grid resolutions of NWP data in atmospheric dispersion modelling, UKHSA, Harwell, UK, 18 Oct 2024
  - Atmospheric dispersion modelling of wildfire smoke, Met Office, Exeter, UK, 13 Feb 2025
  - Future event planned: machine learning applications in dispersion modelling
- ADMLC funded research projects:
  - Review of model evaluation procedures (CERC and Hanna Consultants)
  - Benchmarking nitrogen deposition models (CERC participation in RIVM-led study)
  - Future project planned: impact of climate change on dispersion model predictions used for regulatory impact assessments

Thank you

Any questions?

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- Disclaimer: 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
- To review HSE areas of research interest, search here: https://ari.org.uk/ or https://int.octopus.ac/

Additional material

Potential future HSE dispersion-related research topics

- Understanding hydrogen flammability ranges: ignition and flame propagation
- Buoyancy-induced ventilation in enclosures produced by a hydrogen cloud
- Develop and validate source models for bulk catastrophic storage tank failure of:
  - Liquid hydrogen (recent Air Products experiments at Baker Risk)
  - Refrigerated liquid CO_2 (experiments needed?)
- Dispersion of CO_2 from vents in capture plants, pipelines and offshore installations
  - Vent CO_2 from the underside of offshore platforms rather than from the flare stack?
  - Potential impact of CO_2 on floating support vessels and lifeboats?
- Subsea CO_2 releases
  - Develop and validate models for dispersing waterborne plume of CO_2, absorption into seawater and characteristics of the airborne source of CO_2
  - Large-scale subsea CO_2 release experiments planned in connection with Northern Lights dewatering campaign in 2025 (SINTEF DACOLSS-CO2-NL project)
  - Possible DNV SubCO2 Phase 3 project: subsea CO_2 release experiments in Scotland

MODISAFE: Deposition

- Deposition boundary condition developed in Fluent CFD
- Deposition is handled by experimentally-derived parameters k_s (which controls the flux), and M_{max} (which determines saturation)
- See the Spicer *et al*. (2021) paper for details of the experiments

Sample	k_s (m/s)	M_{max} (kg/m^2)
Clover	0.0001	0.0002
Rye Grass	0.00008	0.00008
Soil (4% moisture)	0.006	0.003
Soil (12% moisture)	0.004	0.004
Soil (20% moisture)	0.003	0.0015

Initialise

Step 0a: Identify cells neighbouring boundary patch

Step 0b: Set $a_s = 1$ (saturation parameter)

Loop Step 1

Step 1: Calculate flux into ground

$$f_s = C\ k_s\ a_s$$

Step 2: Accumulate mass (and store)

$$M_s \to M_s + f_s\ \delta t$$

Step 3: Contaminant sink calculation

Spicer T.O., Fox S.B., Hicks B.B. (2021) "Preliminary assessment of chlorine reactivity with environmental materials accounting for boundary layer and maximum deposition effects". *Atmospheric Environment* 256, 118274. https://doi.org/10.1016/j.atmosenv.2021.118274.

Data Products: Eddy Covariance (Variables #1)

Corrected fluxes

Net vertical turbulent fluxes of **momentum**, **sensible heat**, **latent heat, H_2O** and **CO_2** calculated from uncorrected fluxes, by correcting for spectral attenuations, air density fluctuations and instrument-specific effects. Quality flags and random uncertainty estimates are provided for all fluxes.

Storage fluxes

Storage fluxes of **sensible** and **latent heat, H_2O** and **CO_2** estimated from concentrations and based on a 1-point profile.

Vertical advection fluxes

Vertical advection **H_2O** and **CO_2** fluxes obtained by multiplication of the mean vertical wind speed and mean gas concentration. These are zero if the mean vertical velocity is forced to zero, as is the case with the double rotations schemes for tilt correction.

Data Products: Eddy Covariance (Variables #2)

Gas densities, concentrations, and time lags

Average molar density, mole fraction (moles of gas per mole of wet air) and mixing ratio (moles of gas per mole of dry air) for $\mathbf{H_2O}$ and $\mathbf{CO_2}$. Quantities are either calculated or estimated from raw data, depending on the available measurements.

Time lags used for flux calculation and a flag indicating whether the time lag used was calculated with the covariance maximization procedure (value "F") or was the nominal one ("T").

Air properties

- Evapotranspiration flux, expressed as millimetres of water per hour
- Mean ambient pressure and temperature, either calculated or estimated, depending on the content of raw files
- Mean ambient air density and molar volume and heat capacity, calculated
- Mean ambient water vapour density, partial pressure, partial pressure at saturation
- Mean ambient specific and relative humidity, water vapour pressure deficit and
- dew point temperature

Data Products: Eddy Covariance (Variables #3)

Un-rotated and rotated wind

- Mean wind components in the anemometer coordinate framework
- Wind components after rotations for tilt correction
- Mean wind speed, instantaneous maximum wind speed and mean wind direction

Rotation angles

- Yaw, pitch, and roll angles used to correct anemometer tilting, according to the selected method.

Turbulence

Turbulence parameters: **friction velocity**, **Monin-Obukhov length**, **stability parameter**, **turbulent kinetic energy**, **Bowen ratio**, and **scaling temperature**.

Footprint

Estimation of crosswind integrated footprints: model used, along wind distances providing peak, 10%, 30%, 50%, 70%, and 90% contributions to total fluxes. Footprint offset is the distance from the tower providing less than 1% contribution to total fluxes.

Data Products: Eddy Covariance (Variables #4)

Uncorrected fluxes

- Net vertical turbulent fluxes of **momentum**, **sensible heat**, **latent heat** for **H_2O** and **CO_2**, calculated from corresponding covariances by conversion of physical units, prior to application of corrections.
- Spectral correction factors calculated according to the selected method.

Statistical flags

Results of selected statistical tests, applied to all time series.

Diagnostics

- Number of spikes detected for each sensitive variable used for flux computation.
- Detailed summary of diagnostics for LI-7500A/RS gas monitor. T
- Average AGC and Signal Strength

Data Products: Eddy Covariance (Variables #5)

Variances

Variances of all sensitive variables, calculated at the end of the whole raw data processing, including despiking, corrections, rotations and detrending.

Covariances

Covariances between w (vertical wind component) and all non-anemometric sensitive variables calculated at the end of the whole raw data processing, including despiking, corrections, rotations, detrending, and time lag compensation.

Data Products: Mean Meteorology Profiles

- Mean & STD:
  - Wind Speed
  - Wind Direction
  - Pressure
  - Air Temperature
  - Relative Humidity
  - Horizontal wind components
- Max Gust Speed
- Max Gust Direction

Data Products: Flux profile method

- A widely used, method to make use of mean wind, temperature, and humidity measurements (made with robust instruments) and convert these mean values to surface fluxes by way of Monin–Obukhov (M-O) similarity theory.
- The profile method's accuracy is heavily dependent on the atmospheric stability.
- Under stable conditions (e.g., during nighttime), turbulence is reduced, and the flux becomes more difficult to measure accurately using the profile method. The heat flux and Reynolds stress approach zero at the same rate, and the Monin-Obukhov length approaches zero, potentially leading to large errors.
- Conversely, in unstable conditions, the method may perform better, but uncertainties can still arise due to the complexity of turbulent flow.
- If requested by science stakeholders, the profile method will be employed.

Data Products: Energy Balance

- Soil Water Content
- Soil Temperature
- Photosynthetic Photon Flux Density
- Global Radiation
- Air Temperature
- Relative Humidity
- Precipitation (rain)
- Net Radiation
- Shortwave Incoming Radiation
- Shortwave Outgoing Radiation
- Longwave Incoming Radiation
- Longwave Outgoing Radiation
- Net Radiometer Temperature
- Net Radiometer Temperature
- Albedo
- Soil Heat Flux
- Soil Heat Flux Sensitivity
- Soil Heat Flux Plate Heater