RESEARCH AND GUIDANCE FROM HSE

Dense gas dispersion

An introduction from the perspective of HSE Science Division

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Presentation to Atmospheric Dispersion and Air Quality (ADAQ) group, Met Office, UK

18 April 2024

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

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- Introduction to HSE
- Dense gas dispersion physics
- Examples
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  - Naturally-occurring gravity currents
- Modelling approaches
- Experiments
- Knowledge gaps
- Ongoing HSE research activities

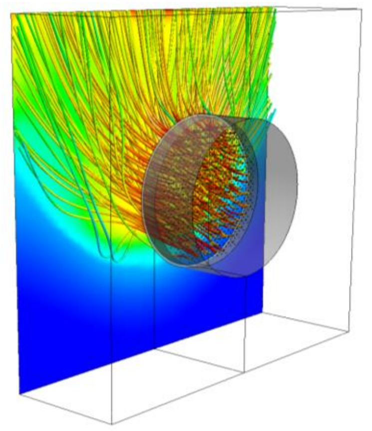
Acknowledgment: this work draws heavily on the review by Rachel Batt (2021) for the Atmospheric Dispersion Modelling Liaison Committee www.admlc.com/publications

Introduction to HSE

- HSE is the UK regulator for workplace health and safety
  - Includes onshore/offshore pipelines, chemical/oil/gas infrastructure, offshore platforms etc.
  - Activities: evidence gathering, policy development, consultation, regulation, incident investigation, enforcement
  - HSE acts as an enabling regulator, supporting the introduction of new technologies
  - 2,400 total staff
  - £230M ($280M) budget: 60% from the Government, 40% from external income



- HSE Science and Research Centre, Buxton, UK
  - 400 staff, 550-acre test site
  - Scientific support to HSE and other Government departments
  - “Shared research” or joint-industry projects co-funded by HSE
  - Bespoke consultancy on a commercial basis

Dense gas dispersion physics

- Flow generated by density differences
- Plume spreads with increased horizontal and reduced vertical extent (as compared to a passive plume)
- Profiles of concentration in lateral direction are often quite uniform
- Little meandering of plume due to random environmental flow
- Shear between plume and environment induces mixing
- Stably-stratified conditions reduce turbulence
- Inertia of the cloud depends on the density of the released material

Why is HSE interested in dense gas dispersion?

Jack Rabbit II Trial 8 chorine release © DHS S&T CSAC https://www.uvu.edu/es/jack-rabbit/

- Dense gases often fall to the ground, even if they are released from height
- Dispersing clouds of dense gas, spreading along the ground can lead to:
  - High concentrations of toxic gases in our breathing zones
  - Increased chances of flammable clouds reaching ignition sources
- Many of the toxic and flammable substances of interest to HSE produce dense gases

Substances of interest to HSE

Control of Major Accident Hazards (COMAH) regulations

Column 1	CAS number (1)	Column 2	Column 3
Dangerous substances		Qualifying quantity in tonnes of dangerous substances for the application of:	
		Lower tier requirements	Upper tier requirements
35. Anhydrous ammonia	7664-41-7	50	200
36. Boron trifluoride	7637-07-2	5	20
37. Hydrogen sulphide	7783-06-4	5	20
38. Piperidine	110-89-4	50	200
39. Bis(2-dimethylaminoethyl) (methyl)amine	3030-47-5	50	200
40. 3-(2-Ethylhexyloxy)propylamine	5397-31-9	50	200
41. Mixtures of sodium hypochlorite classified as Aquatic Acute Category 1 [H400] containing less than 5 % active chlorine and not classified under any of the other hazard categories in Part 1 of this Schedule, provided that the mixture in the absence of sodium hypochlorite would not be classified as Aquatic Acute Category 1 [H400]	–	200	500
42. Propylamine (see note 21)	107-10-8	500	2,000
43. Tert-butyl acrylate (see note 21)	1663-39-4	200	500
44. 2-Methyl-3-butenenitrile (see note 21)	16529-56-9	500	2,000
45. Tetrahydro-3,5-dimethyl-1,3,5-thiadiazine-2-thione (Dazomet) (see note 21)	533-74-4	100	200

Etc. https://www.hse.gov.uk/pubns/priced/l111.pdf

Planning (Hazardous Substances) Regulations

Named hazardous substances

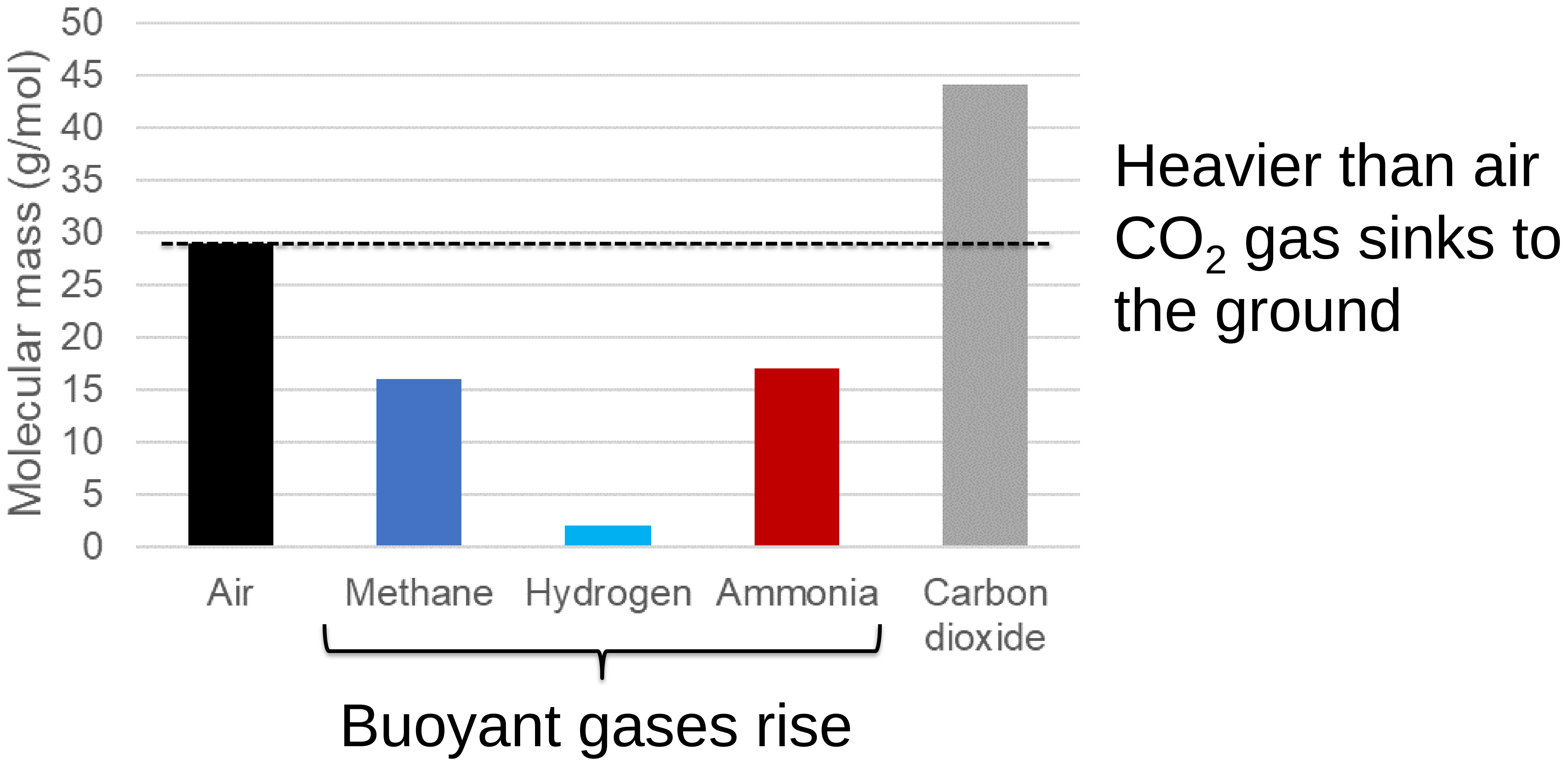
Column 1	*CAS number*[(1)]	*Column 2*
Hazardous substances		*Controlled quantity (tonnes)*
1. Ammonium nitrate (see note 14)	-	5,000
2. Ammonium nitrate (see note 15)	-	1,250
3. Ammonium nitrate (see note 16)	-	350
4. Ammonium nitrate (see note 17)	-	10
5. Potassium nitrate (see note 18)	-	5,000
6. Potassium nitrate (see note 19)	-	1,250
7. Arsenic pentoxide, arsenic (V) acid and/or salts	1303-28-2	1
8. Arsenic trioxide, arsenious (III) acid and/or salts	1327-53-3	0.1
9. Bromine	7726-95-6	20
10. Chlorine	7782-50-5	10

Etc. https://www.legislation.gov.uk/uksi/2015/627/schedule/1/made

Many of these exhibit dense-gas dispersion behaviour

What causes density differences?

Molecular mass of gas relative to air



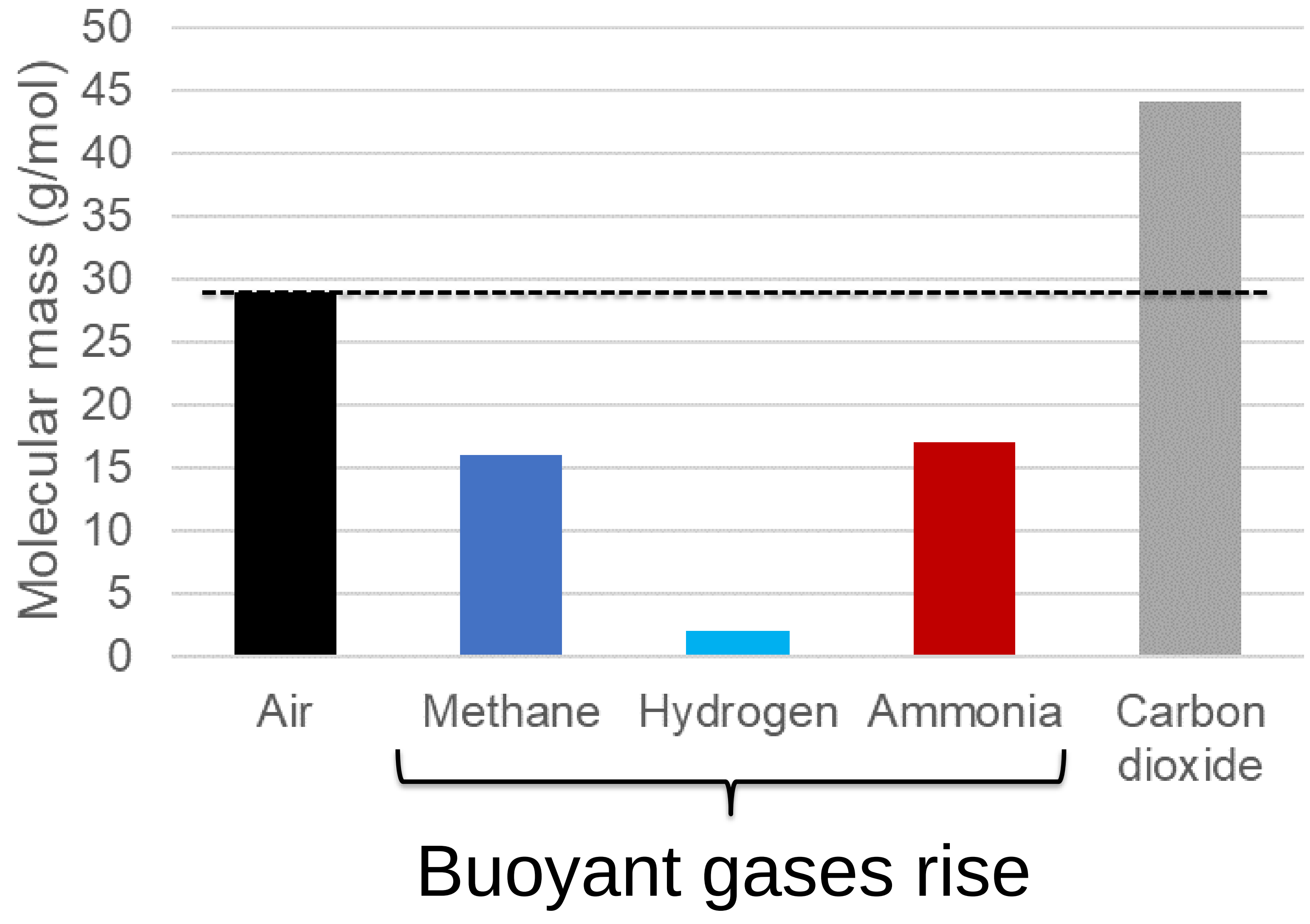
What causes density differences?

Molecular mass of gas relative to air

But…

Temperature and aerosols are also important

Methane, hydrogen and ammonia can all behave as dense gases if they are cold and aerosols are present



Heavier than air CO_2 gas sinks to the ground

Methane (liquefied natural gas)

https://www.tradewindsnews.com/weekly/mol-outlines-lessons-learned-from-lng-ship-cargo-release/1-1-769623

Hydrogen

Experiments at HSE for www.preslhy.eu

Ammonia

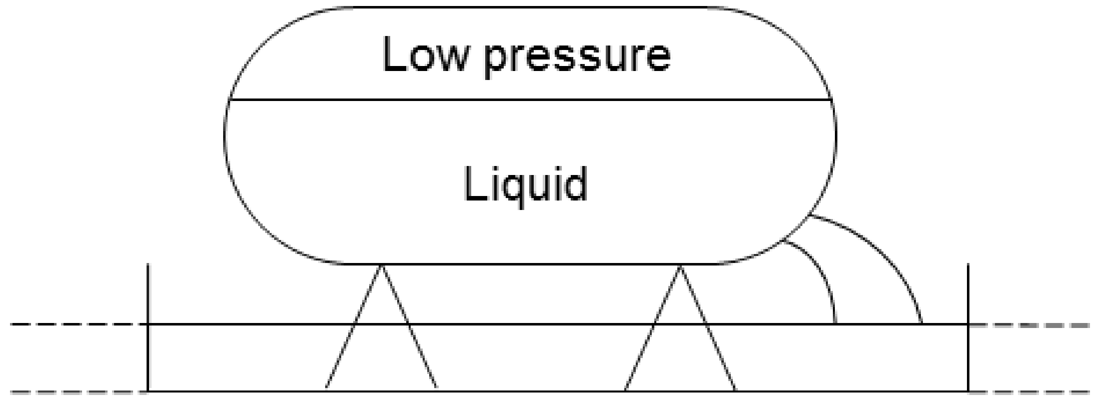
© DHS S&T CSAC www.uvu.edu/es/jack-rabbit/

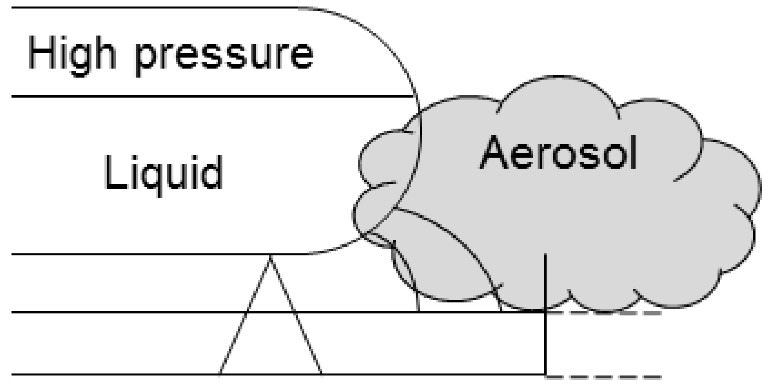
Factors affecting dense gas dispersion

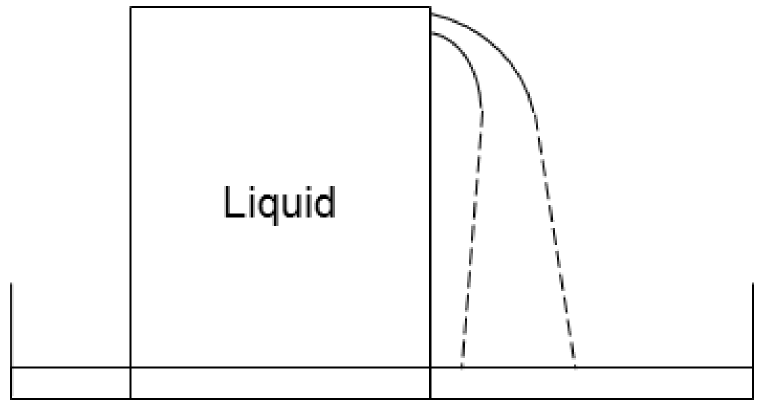
- Source geometry and conditions
- Atmospheric conditions (wind speed, stability, temperature)
- Heat transfer
- Phase changes
- Dry/wet deposition and surface chemical reactivity
- Surface conditions (roughness and obstacles)
- Topography

Source conditions

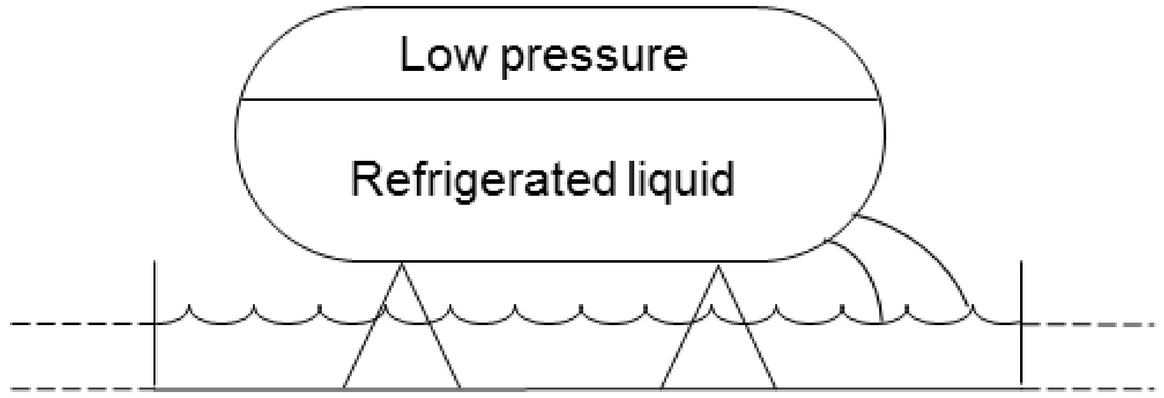
Spills of liquids with boiling point above ambient temperature

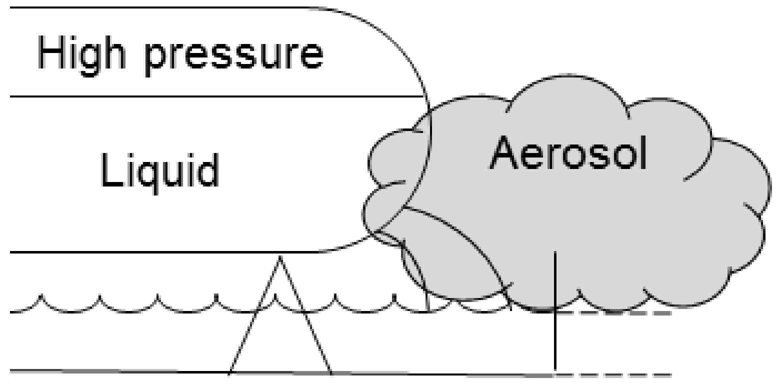




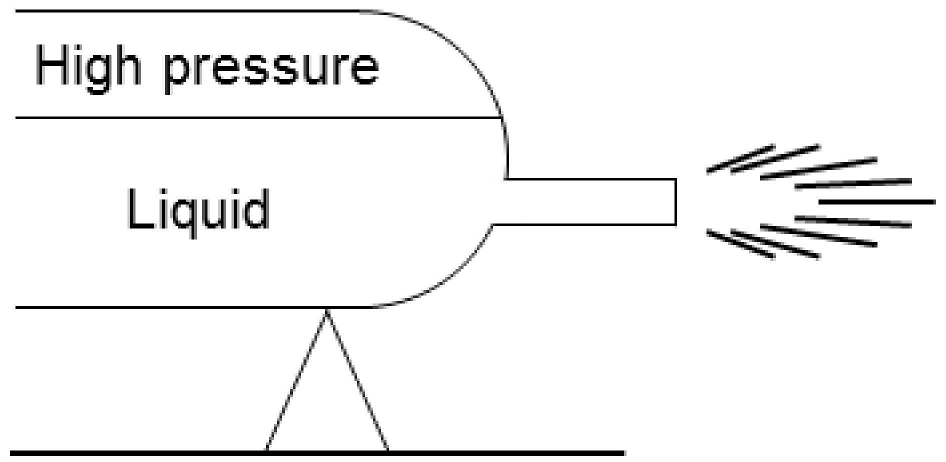


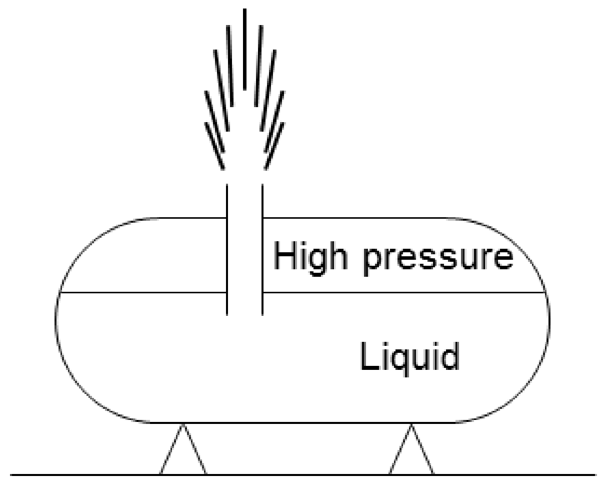
Spills of refrigerated liquids

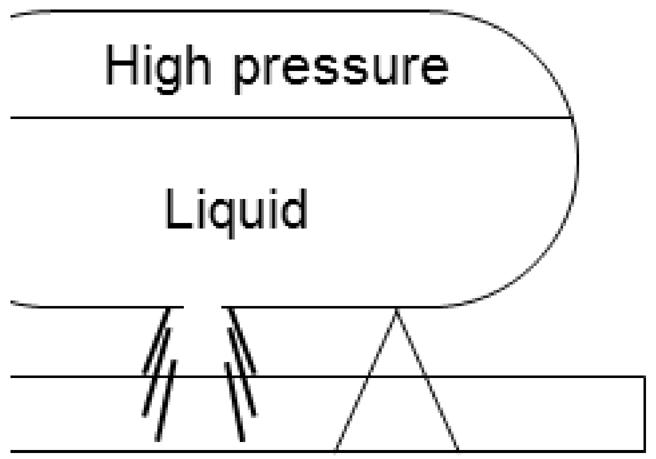


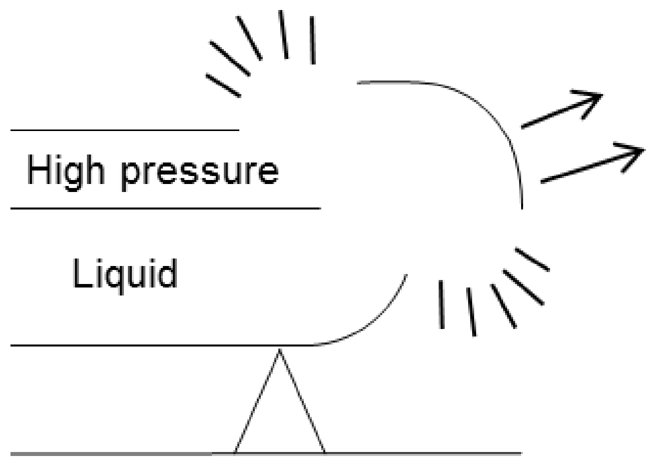


Releases of pressure-liquefied gases









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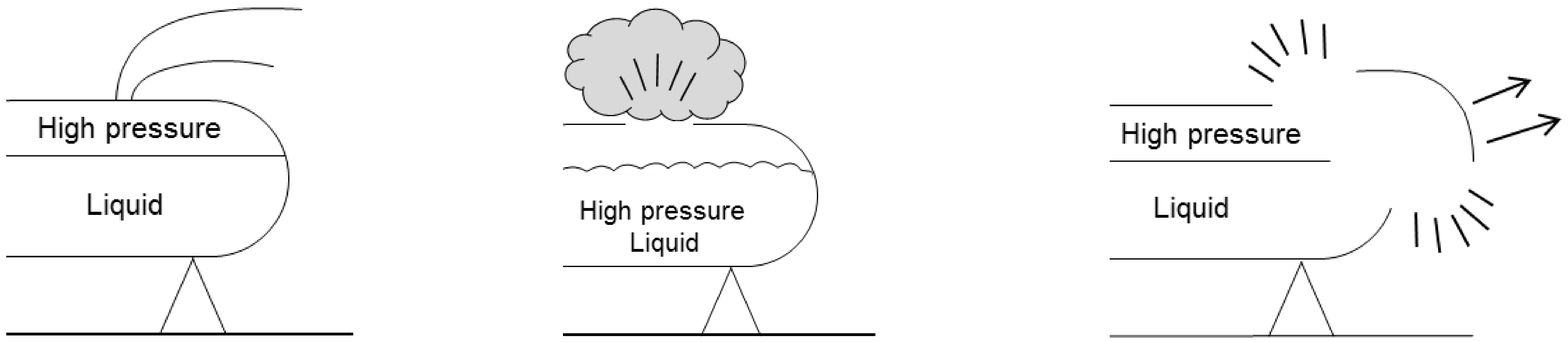
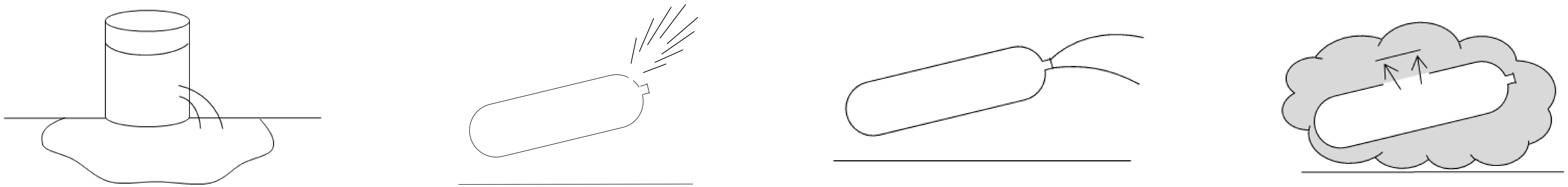
… more source conditions

Releases of pressurised vapour

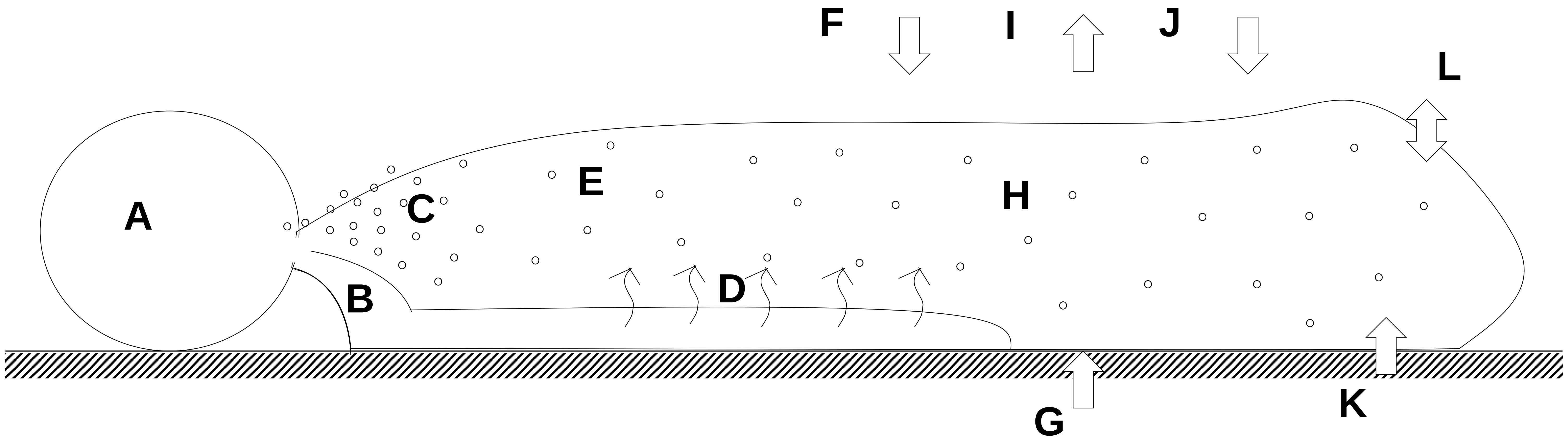


Releases from drums and cylinders



Reactions of some chemicals can also produce dense gases, e.g., acids + hypochlorites = chlorine gas

Heat transfer and phase change



A	Ruptured vessel	G	Ground heat flux to the surface
B	Liquid spill	H	Heat gain/loss due to condensation/ evaporation
C	Cold temperature gas/aerosol mixture	I	Heat loss due to radiation
D	Evaporation and possibly aerosols thrown into the cloud by violent boiling	J	Solar energy input
E	Endothermic or exothermic chemical reactions	K	Convective heat flux from surface to the plume
F	Entrainment of warm ambient air, subsequent condensation of water vapour	L	Heat exchange by convection

(Based on Hanna *et al*., 1996)

Characterisation of dense gas behaviour

- Froude number $Fr = \frac{u}{\sqrt{g'L}}$ or in some references $Fr = \frac{u^2}{g'L}$ $\frac{\text{Inertial forces}}{\text{Gravitational forces}}$

- Richardson number $Ri = \frac{g'L}{u^2}$ where $g' = g\frac{(\rho_g - \rho_a)}{\rho_a}$ is the reduced gravity

3.5 Criteria for Effectively Passive Behaviour

Under what conditions might a release be analysed using correlations from passive dispersion experiments that are widely available, have been well studied and exist in workbook form already (e.g. Turner, 1970; Clarke, 1979)?

For continuous releases of $q_o m^3/s$ we recommend on the basis of Appendix A that the flow will be effectively passive and passive dispersion results may be used when

$$\left(\frac{g_o q_o}{U_{ref}^3}/D\right)^{\frac{1}{3}} \leq 0.15$$

where U_{ref} is the velocity at $z = 10$ m.

For an instantaneous release of $Q_o m^3$ we recommend, also on the basis of Appendix A, that the flow will be effectively passive and passive dispersion results may be used when

$$\frac{(g_o Q_o^{\frac{1}{3}})^{\frac{1}{2}}}{U_{ref}} = \left(\frac{g_o Q_o}{U_{ref}^2}\right)^{\frac{1}{2}} / Q_o^{\frac{1}{3}} \leq 0.2$$

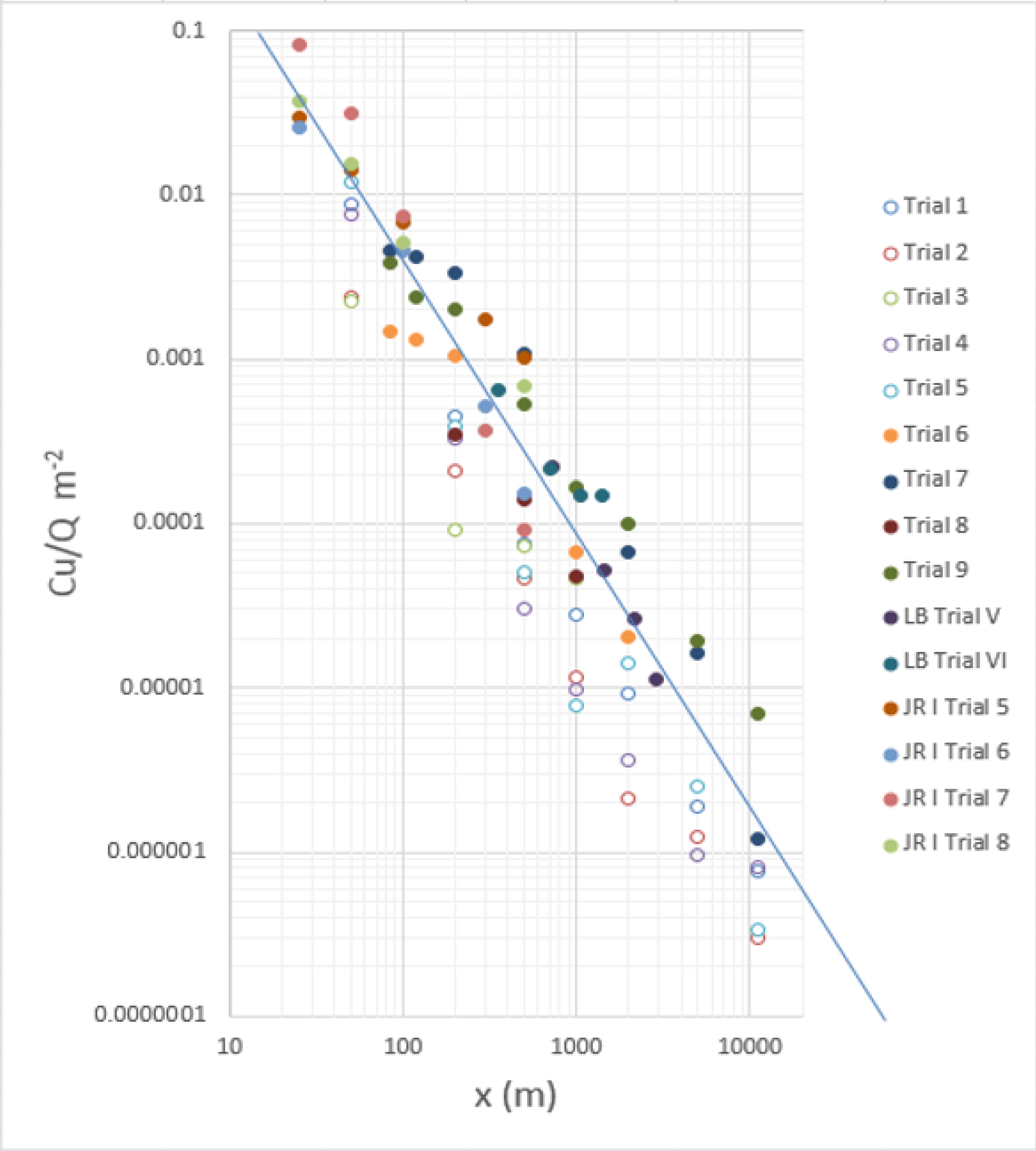
where U_{ref} is again the velocity at $z = 10$ m.

1

Source: Britter & McQuaid (1988) “Workbook on the dispersion of dense gases” https://xnet.hsl.gov.uk/fileshare/public/3583/britter-mcquaid-1988-workbook-on-dense-gas-dispersion-crr88017.pdf

Decay of concentration with distance

Arc max Cu/Q versus x for Lyme Bay (LB), Jack Rabbit I (JR I), and Jack Rabbit II (Trials 1 – 9)



The straight line represents the relation $Cu/Q = 8.5x^{-5/3}$, where Cu/Q has units m^{-2} and x has units m

Source: Hanna, Chang & Mazzola (2017) "Analysis of Variations of Concentrations with Downwind Distance and Characteristics of Dense Gas Plume Rise for Jack Rabbit II–2015 and 2016 Chlorine Field Experiments", Harmo-18

https://www.harmo.org/conference.php?id=18

Theoretical basis supporting -5/3 power law decay of concentration by Jeff Weil

In previous work, Hanna et al. (2016b, 2017) found that the chlorine maximum surface concentrations from the 2015 Jack Rabbit II experiments decreased approximately as $C_{max} \propto x^{-5/3}$. This empirical correlation is presented later in the NCAR model comparisons with the Jack Rabbit II data and is derived below based on results from Appendix A.

The maximum concentration for an effective Gaussian distribution is proportional to the puff top-hat concentration C_{th} (Section 4.4), which is estimated from the puff radius R and depth h as $C_{th} \propto Q/(R^2h)$. At long times or far downstream, $R \propto t^{1/2}$ and $h \propto t$ and with $C_{max} \propto C_{th}$, the C_{max} is given by

$$C_{max} \propto Q/t^2 \quad (1)$$

A conversion from t to x as the independent variable can be made using the mean wind profile and the puff entrainment relationship at long times, where $h \propto t$. This h dependence means that the entrainment velocity w_e (= dh/dt) must be constant.

We can also write

$$dh/dx = (dh/dt)/(dx/dt) = w_e / U(h) \quad (2)$$

where the mean wind is evaluated at z = h, and Eq. (2) can be rewritten as

$$U(h)\, dh = w_e\, dx \quad (3)$$

Now instead of using the logarithmic wind profile, we adopt a simple power-law profile of the form

$$U(z) = U_{ref}\, (z/z_{ref})^p \quad (4)$$

where U_{ref} is the reference wind speed at the reference height z_{ref}, and the exponent p is < 1.

By rewriting Eq. (4) as $U(z) = a_1 z^p$ and substituting this along with z = h into Eq. (3), we can integrate the latter to obtain

$$h^{1+p} = [w_e\,(1+p)]/a_1 \cdot x \quad (5a)$$

or

$$h = b_1\, x^{-1/(1+p)} \quad (5b)$$

where $b_1 = f(w_e, p, a_1)$. Far downstream, we have $h = w_e t$ and by using this in Eq. (5b), we find

$$t = (b_1/w_e)\, x^{-1/(1+p)} \quad (6)$$

The above relationship can be substituted into Eq. (1) to obtain

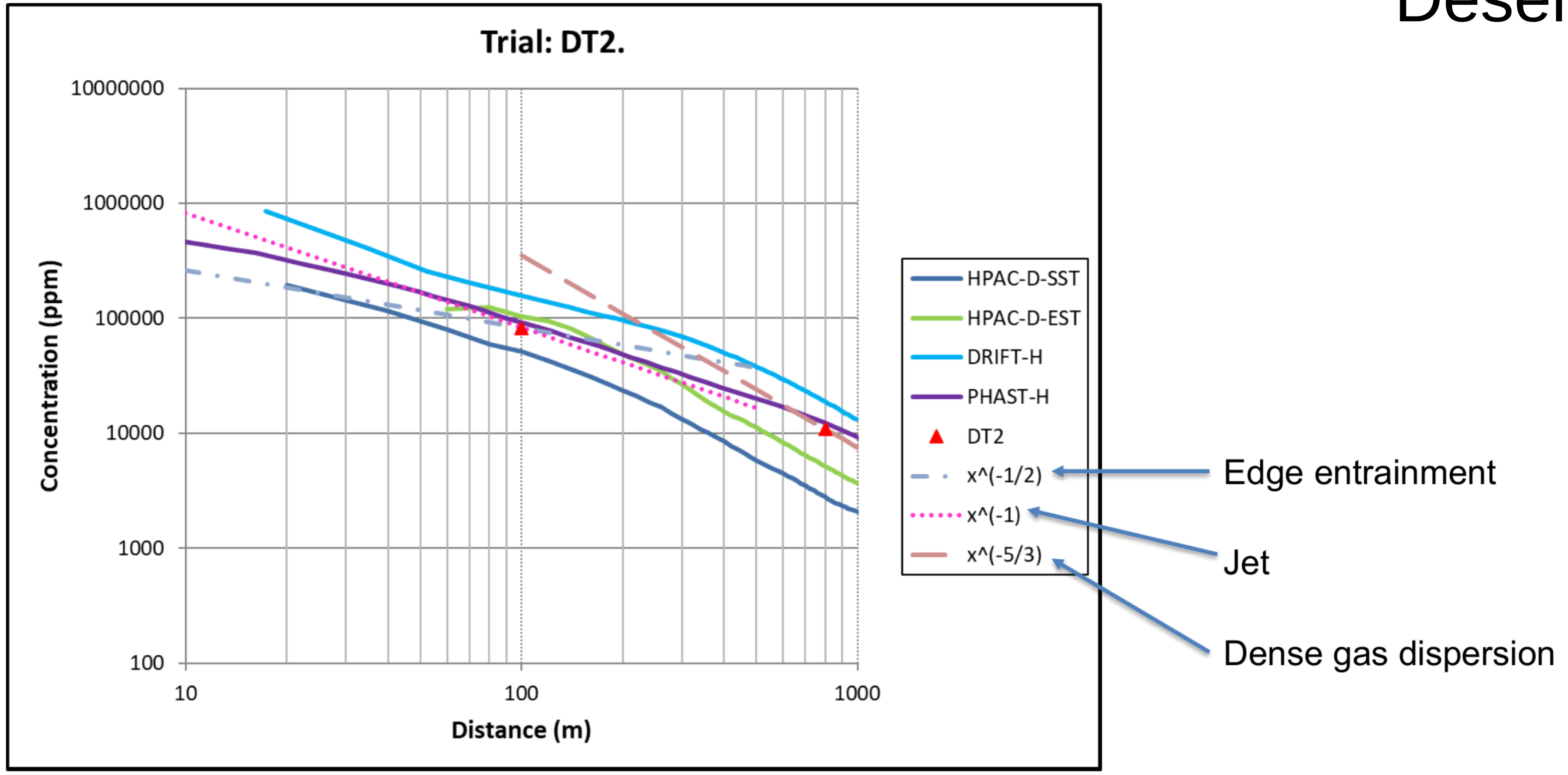
$$C_{max} \propto Q\, x^{-2/(1+p)} \quad (7)$$

For neutral conditions and a typical exponent p = 1/6 (Counihan (1975); Irwin (1979), with z_0 = 0.1 m), the exponent on x is −1.71 and for p = 1/7, it is −1.75. These x exponents are close to the empirically-determined value of −5/3, and for a slightly more stable environment

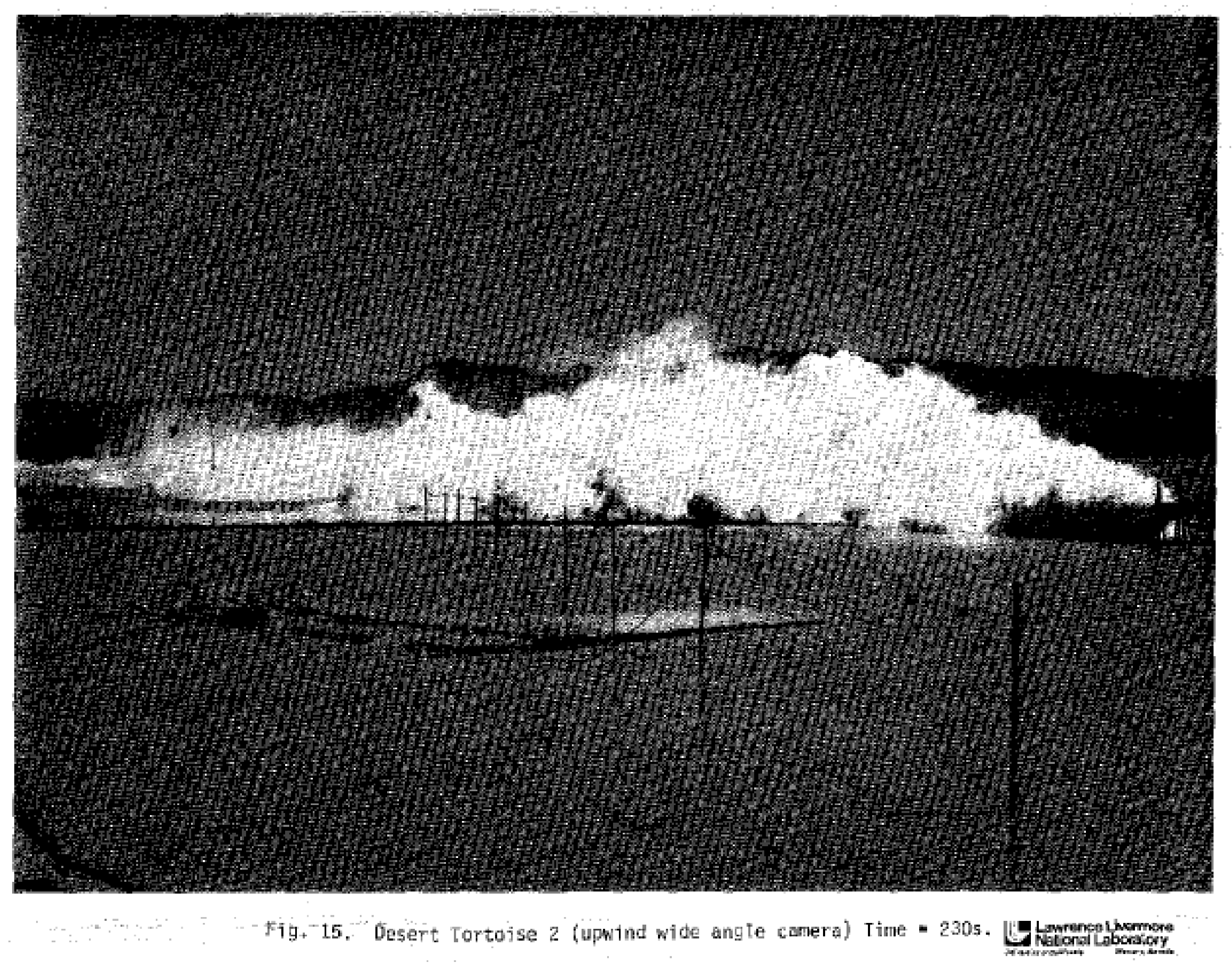
https://doi.org/10.1016/j.atmosenv.2018.08.009

Decay of concentration with distance

Complex behaviour in some dense-gas dispersion experiments with momentum-dominated flow (jetting) and transition from dense to passive dispersion



Desert Tortoise ammonia experiments



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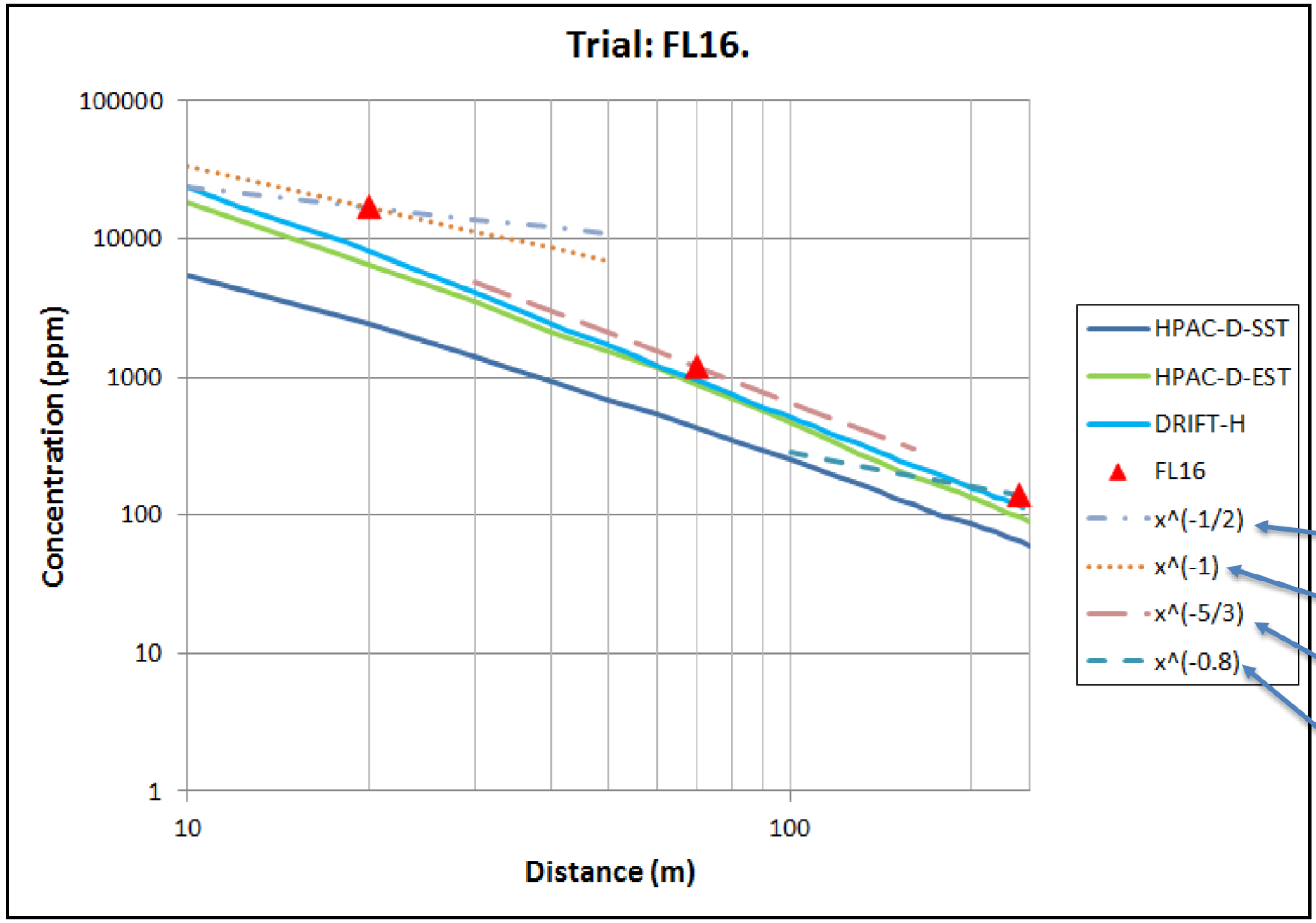


Edge entrainment

Jet

Dense gas dispersion

Passive dispersion

FLADIS ammonia experiments

Nielsen M. and S. Ott, 1996: FLADIS field experiments: final report, Risø-R-898(EN), Risø National Laboratory, Roskilde, Denmark, July 1996

Decay of concentration with distance

For passive dispersion

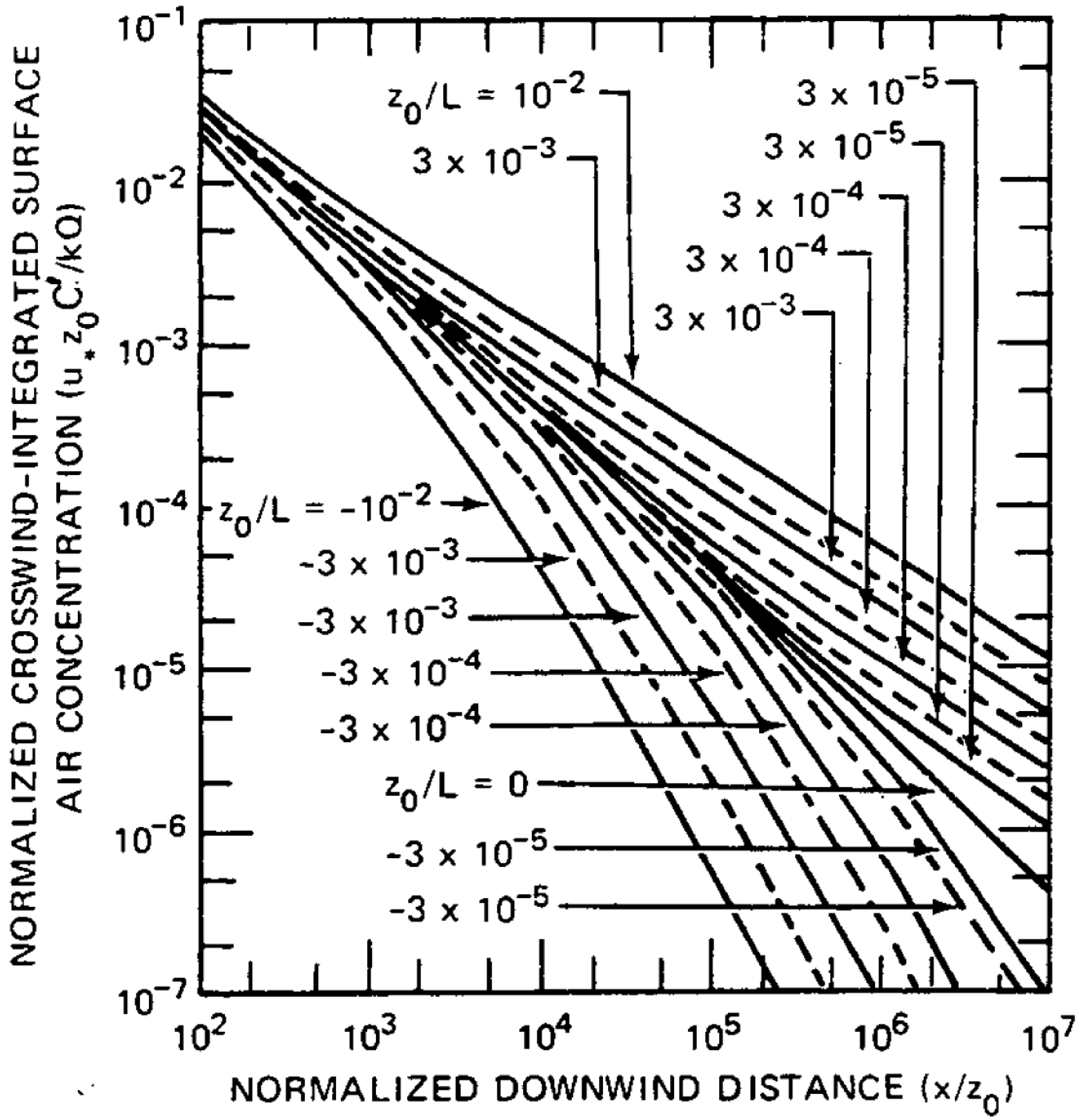


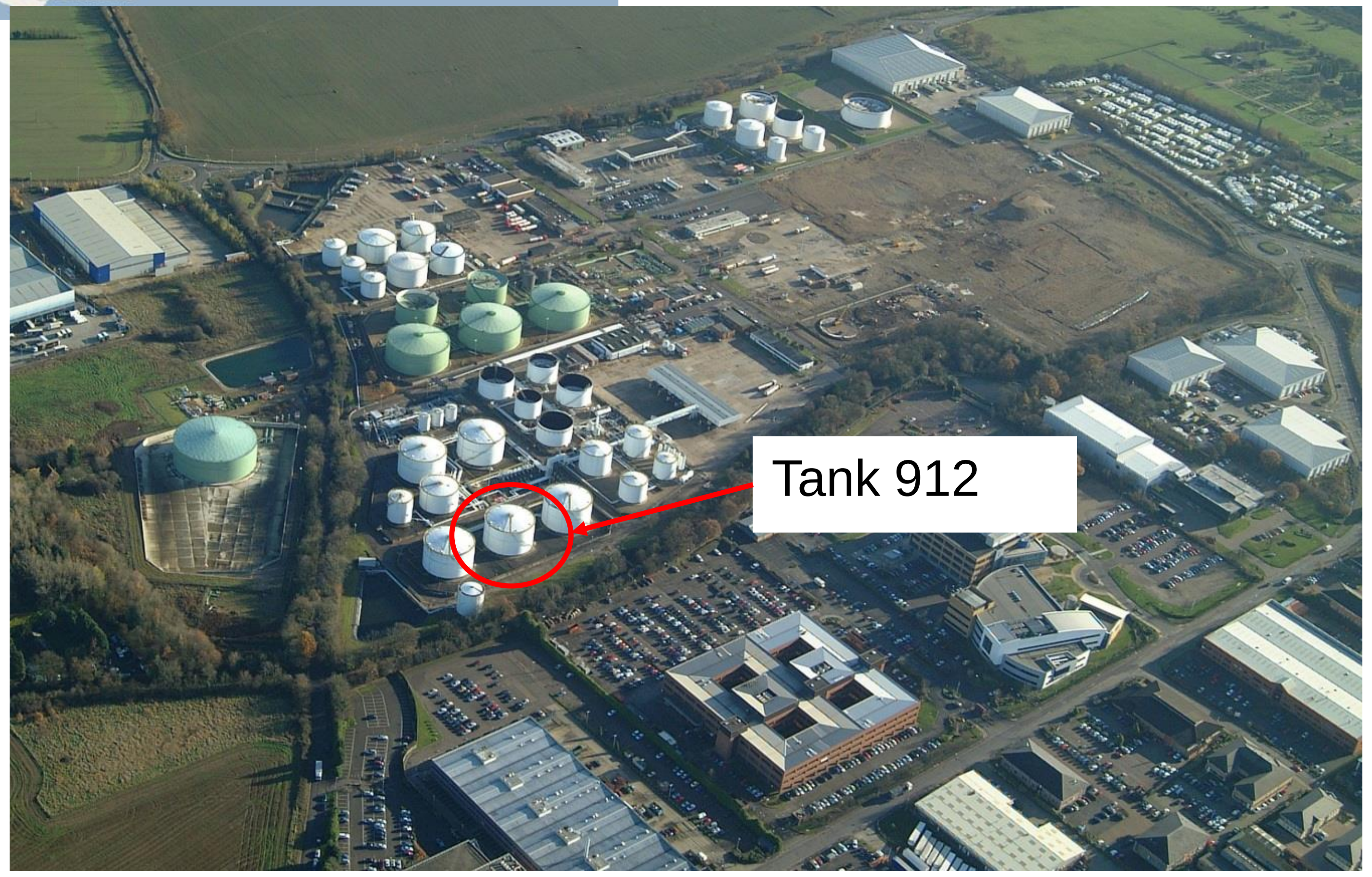
Fig. 7.2 Predicted crosswind-integrated concentration at ground level as a function of downwind distance for various stability conditions. [From T. W. Horst, Lagrangian Similarity Modeling of Vertical Diffusion from a Ground Level Source, *J. Appl. Meteorol.*, 18: 734 (1979).]

Source: Hanna, Briggs & Hosker “Handbook of atmospheric diffusion” https://www.nrc.gov/docs/ML0926/ML092640175.pdf

Contents

Buncefield, UK (2005): Gasoline vapour

- Incident caused by overfilling a gasoline bulk storage tank

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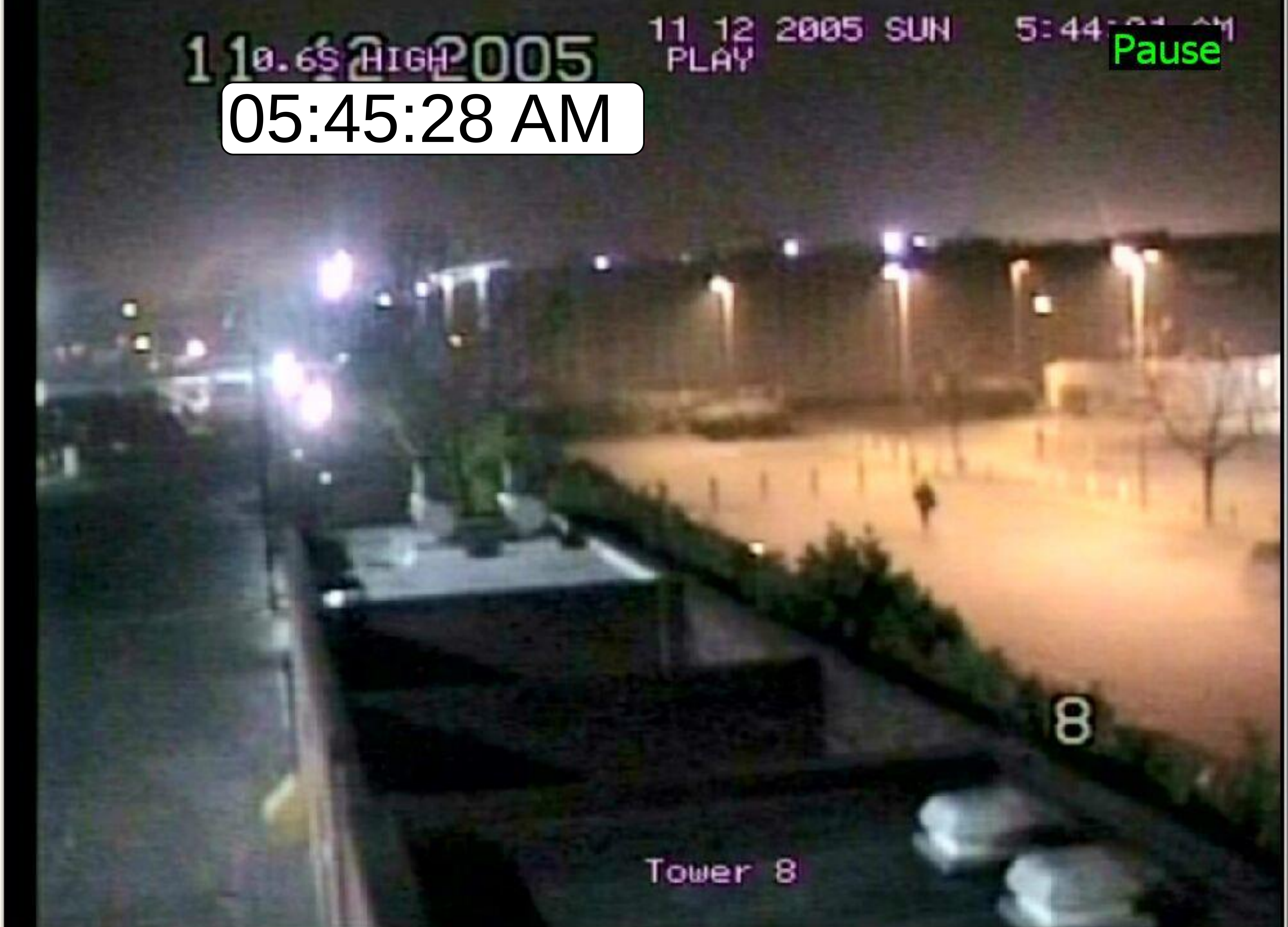
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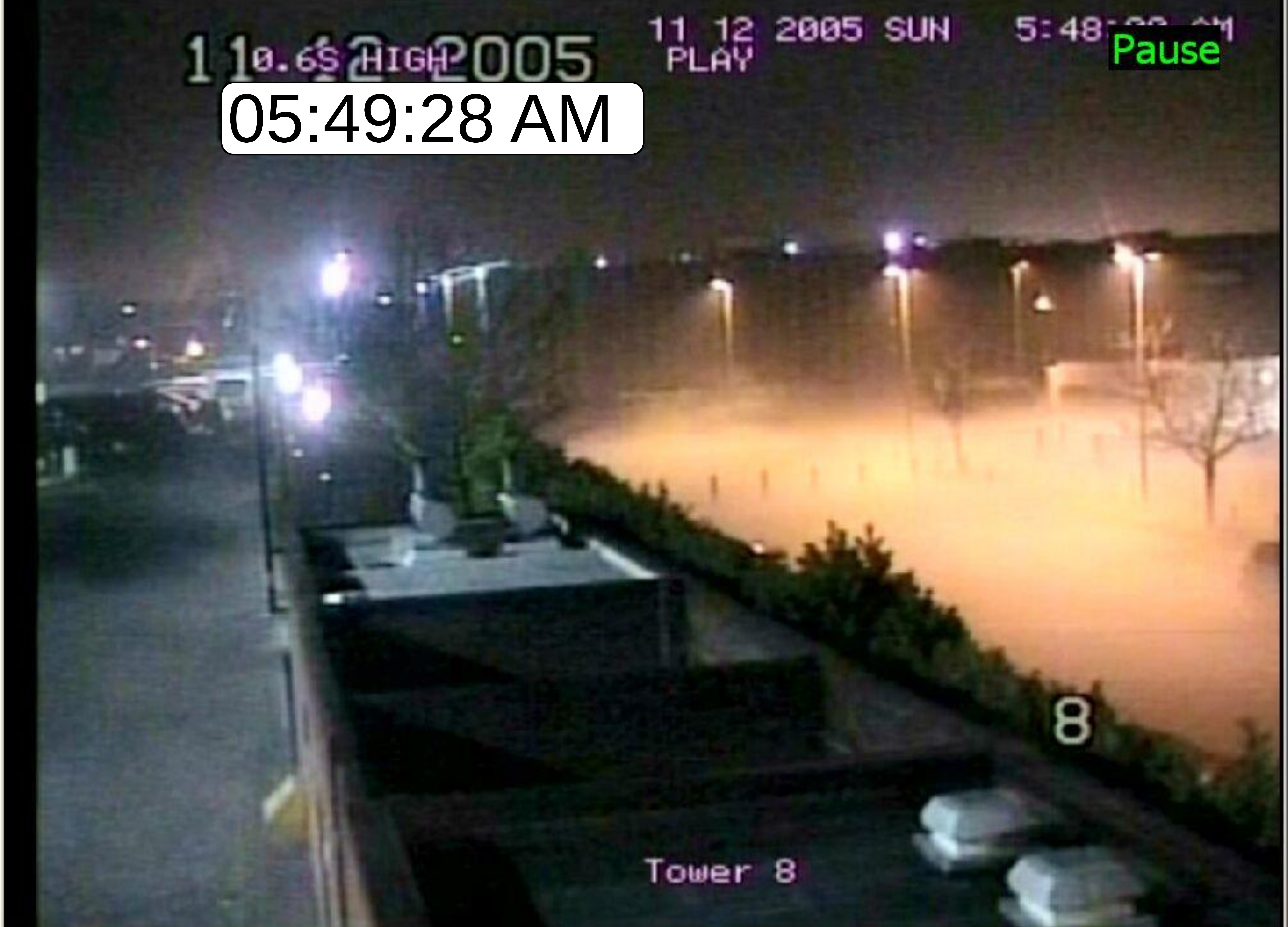
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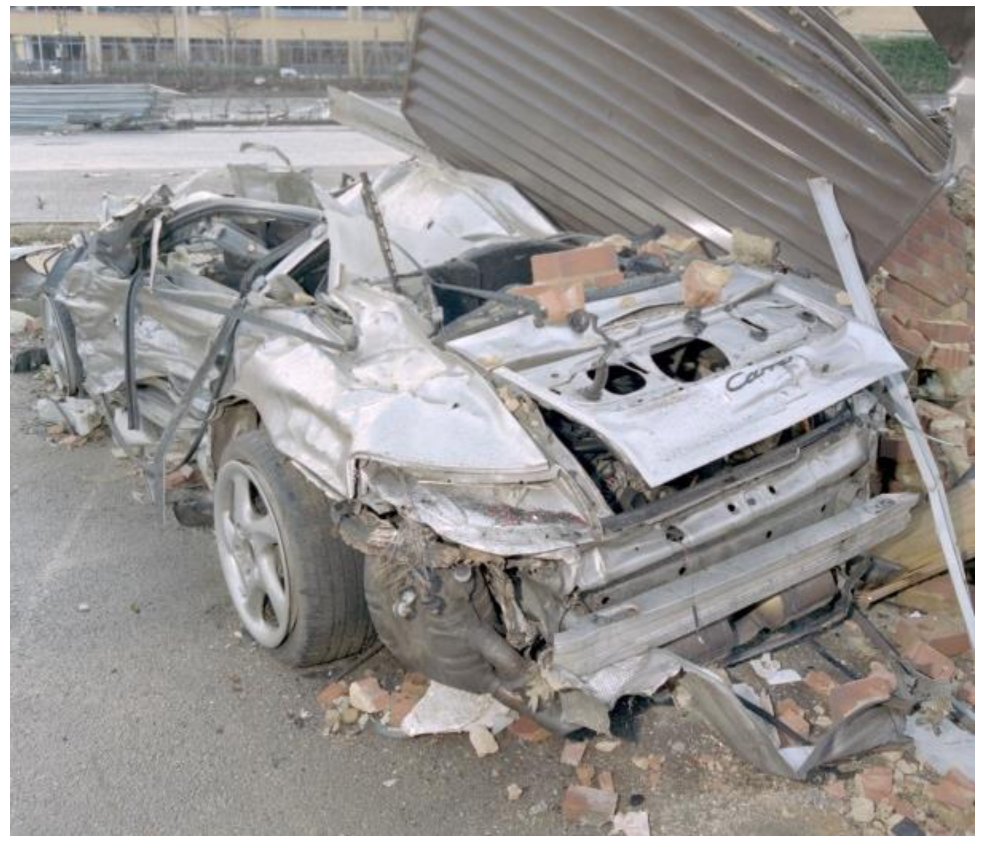
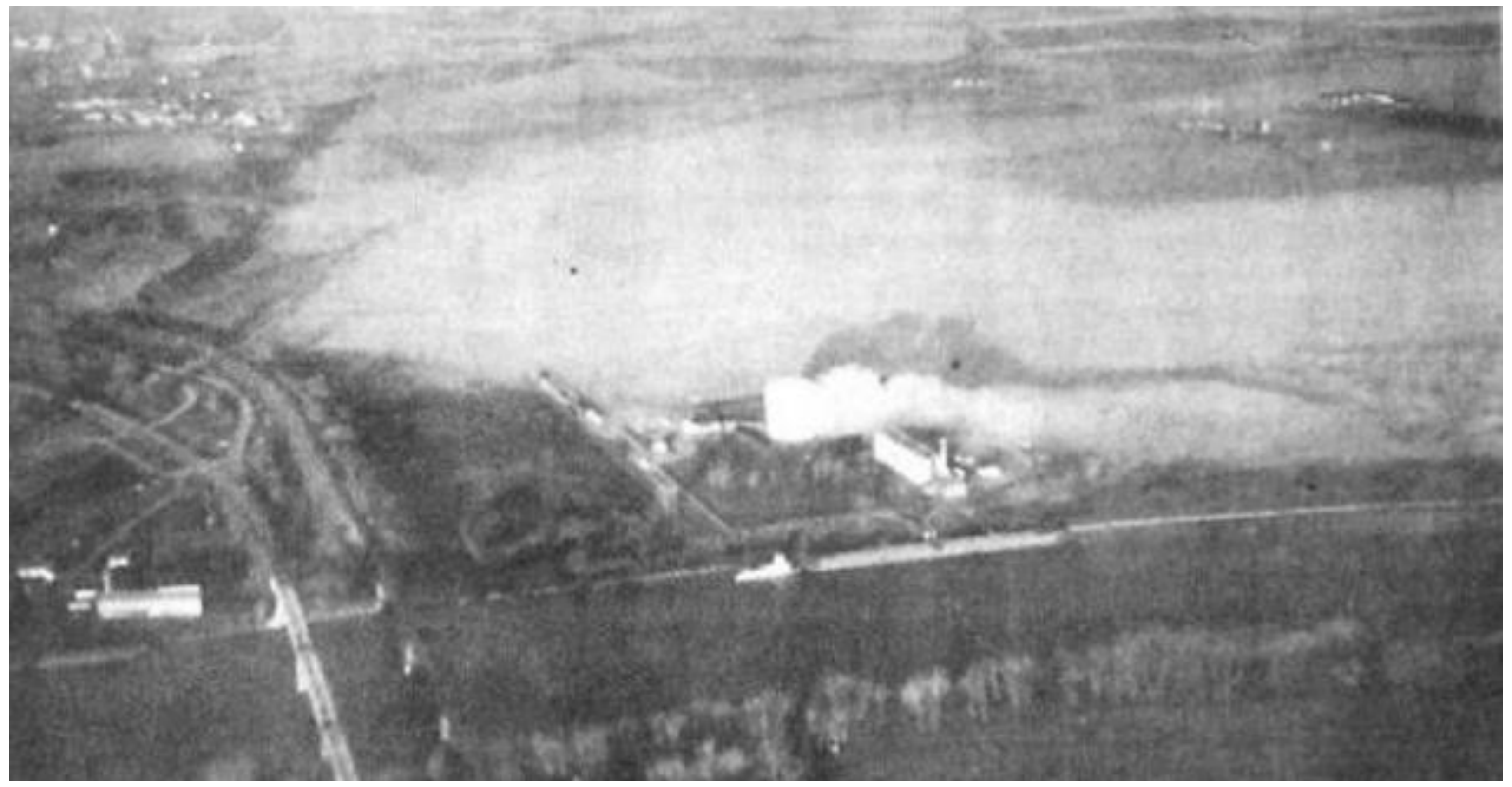
Buncefield, UK (2005): Gasoline vapour



Blair, Nebraska (1970): Ammonia

- Overflow of ammonia from 36,000 t refrigerated storage tank
- Tank levels not carefully monitored, alarm and shut-down system failed to operate
- Overflow discharge valve failed to operate at the set pressure, so that the liquid level in the tank rose until it reached the roof, at which point the overflow valve did open
- Discharge continued for 2.5 h, producing a dense vapour cloud that blanketed the surrounding area, 10 m thick and extending to a distance of 2.7 km
- Cloud eventually dispersed and avoided populated areas, three people hospitalised

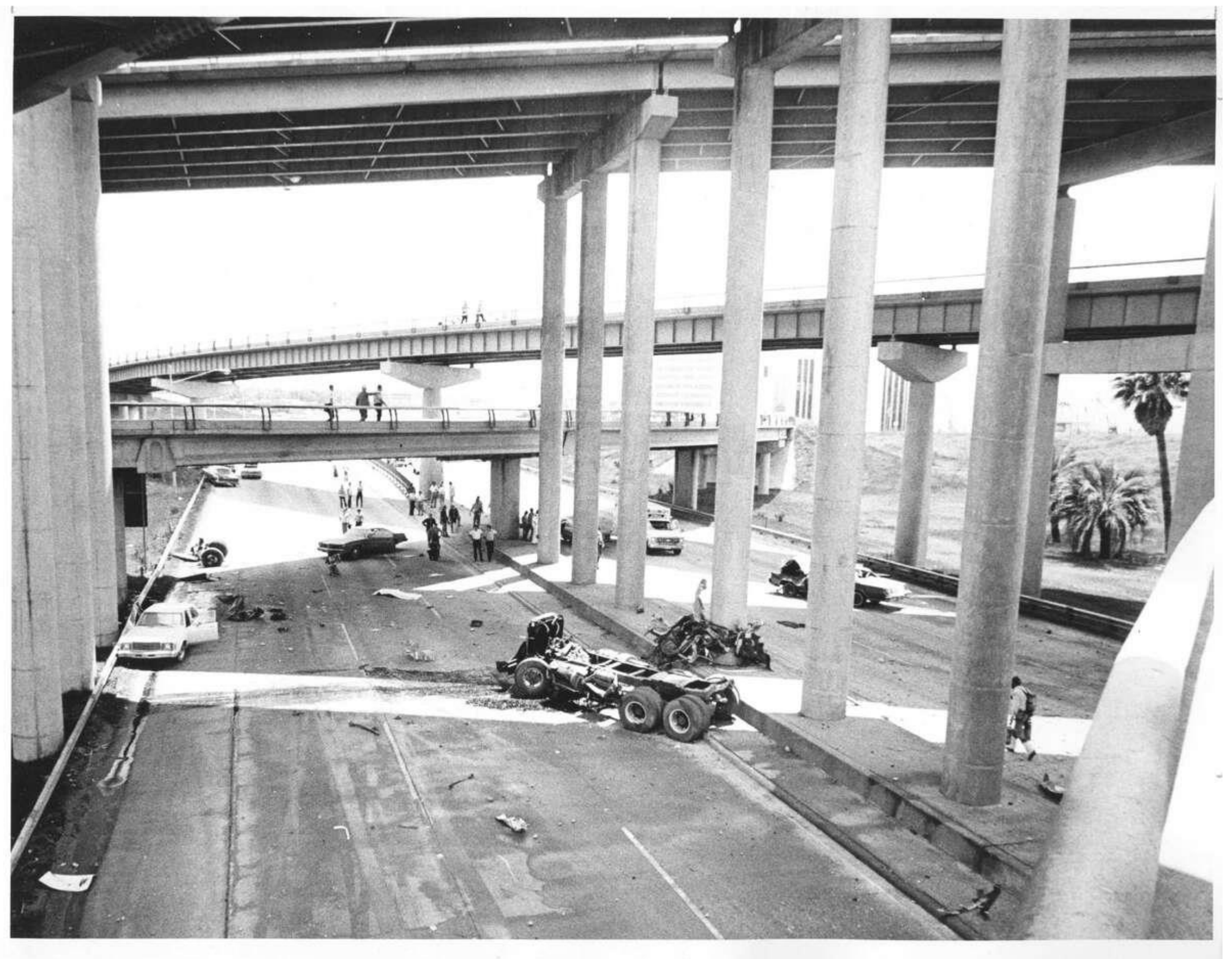


The Enterprise newspaper, 1 October 2004, www.blairnebraska.com

Photos kindly provided by Steven Hanna (originally from Rex Britter)
See also: Lees Loss Prevention, ISBN: 978-0-12-397189-0

Houston, Texas (1976): Ammonia

- Road tanker crashed through highway bridge rail at intersection
- Vessel holding 19 t of pressure-liquefied ammonia ruptured on impact
- Dense cloud of ammonia vapour covered an area of 300 m x 600 m
- 100 people injured, 6 deaths

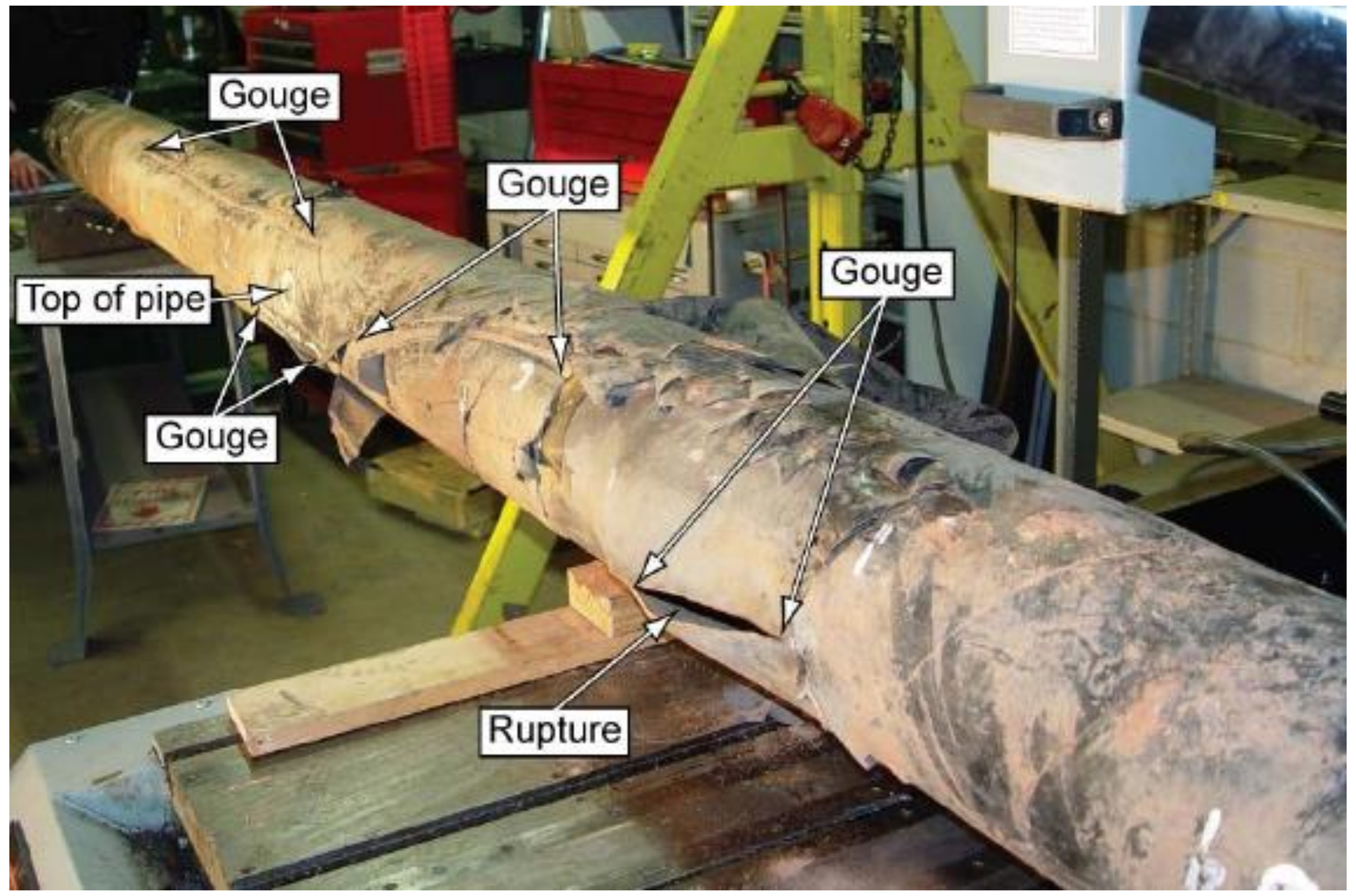


https://www.houstonchronicle.com/news/houston-texas/houston/article/In-1976-an-ammonia-truck-disaster-claimed-the-12906732.php

Photograph taken by Texas Air Control Board
© Texas Commission Environmental Quality copyright 1976

Kingman, Kansas (2004): Ammonia

- 8-inch diameter Magellan pipeline ruptured and released 480 t of ammonia
- Visible vapour cloud 0.5 miles wide and 1.5 miles long
- Four families evacuated, no injuries
- Analysis showed pipeline rupture was caused by damage from digging equipment, either during construction or later agricultural activities



https://www.ntsb.gov/investigations/AccidentReports/Reports/PAB0702.pdf

Beach Park, Illinois (2019): Ammonia

- Release of 1.5 t of ammonia from faulty coupling on two 1,000-gallon nurse tanks being towed by a tractor in farming area
- Vapour dispersed in dense cloud: 1 mile shelter-in-place order imposed
- 83 people taken to hospital, 14 admitted, 8 in intensive care unit, no deaths

https://www.ntsb.gov/investigations/AccidentReports/Reports/HZIR2201.pdf

https://www.cbsnews.com/chicago/news/ammonia-spill-beach-park/

https://www.chicagotribune.com/suburbs/lake-county-news-sun/ct-lns-ammonia-spill-no-charges-st-0626-20190625-ikztowsrhfhwhgym3lryjk4v2m-story.html

Festus, Missouri (2002): Chlorine

- 20 t of chlorine released due to failure of a transfer hose from railcar
- 63 people sought medical attention, 3 hospitalised, no fatalities

KTVI-TV, St. Louis, Missouri

KTVI–TV, St. Louis, Missouri

https://www.csb.gov/dpc-enterprises-festus-chlorine-release/

Jordan Aqaba Port (2022): Chlorine

- Catastrophic failure of chlorine storage tank dropped during a lifting operation

Video broadcast by state-owned AlMamlaka TV showed the dock engulfed in a cloud of yellow gas

https://www.bbc.co.uk/news/world-middle-east-61950965

https://www.youtube.com/watch?v=DfR1K9c6lUA

Chelyabinsk, Russia (2011): Bromine

- 24-50 litres of bromine released from glass containers damaged during movement of railway carriages
- 47 people received medical treatment

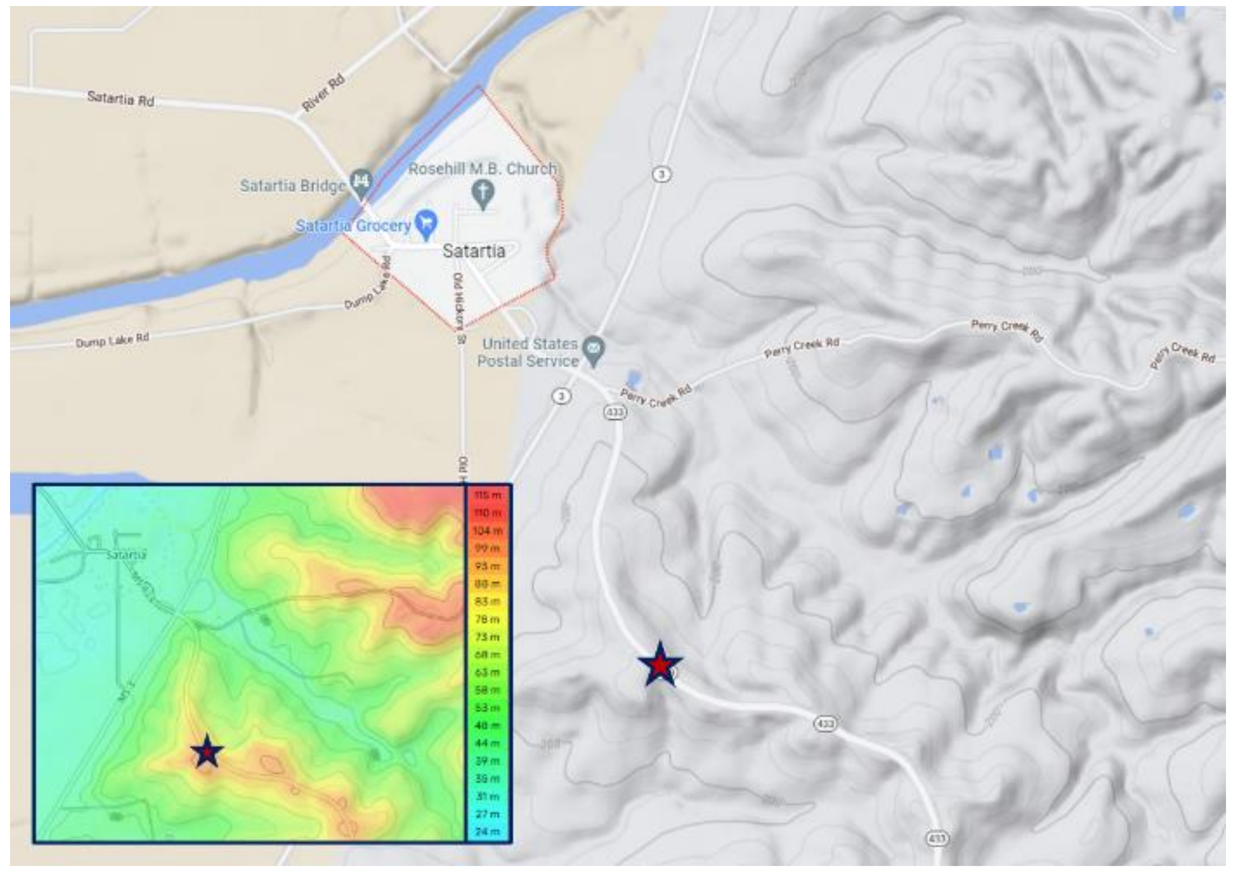
https://www.youtube.com/watch?v=OszlK-1xxuA

https://www.bbc.co.uk/news/world-europe-14755874

Satartia, Mississippi (2020): Carbon dioxide

- 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

Lake Nyos, Cameroon (1986): Carbon dioxide

- Release of 100kt -300kt of carbon dioxide from lake within volcanic crater
- Dense cloud rolled down valley and killed 1,746 people

https://www.atlasobscura.com/places/lake-nyos-the-deadliest-lake-in-the-world

https://www.voanews.com/a/survivors-1986-lake-nyos-disaster-cameroon/3474673.html

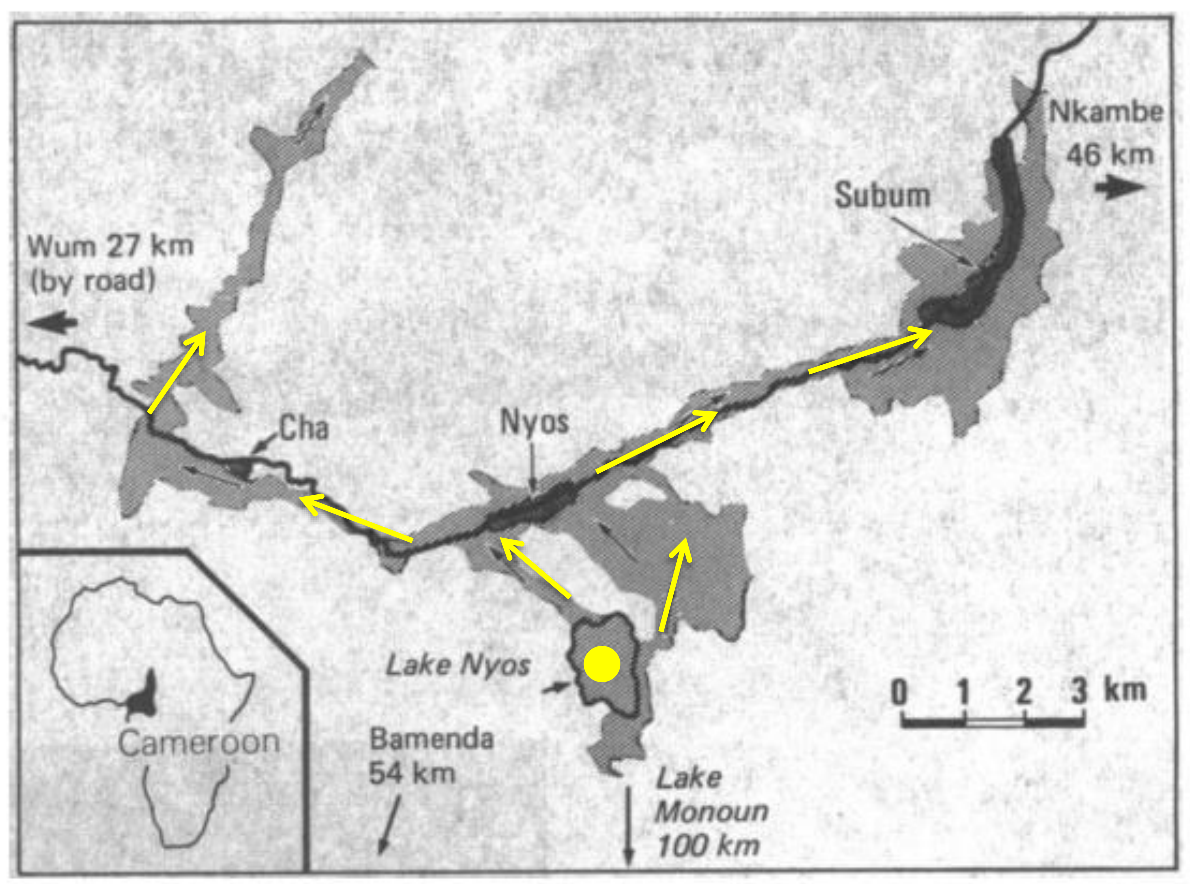


FIG 1—*Direction of flow of gas (arrows; stippled area) from Lake Nyos into adjacent valleys*

Baxter et al. (1989), © BMJ Publishing Group Ltd.

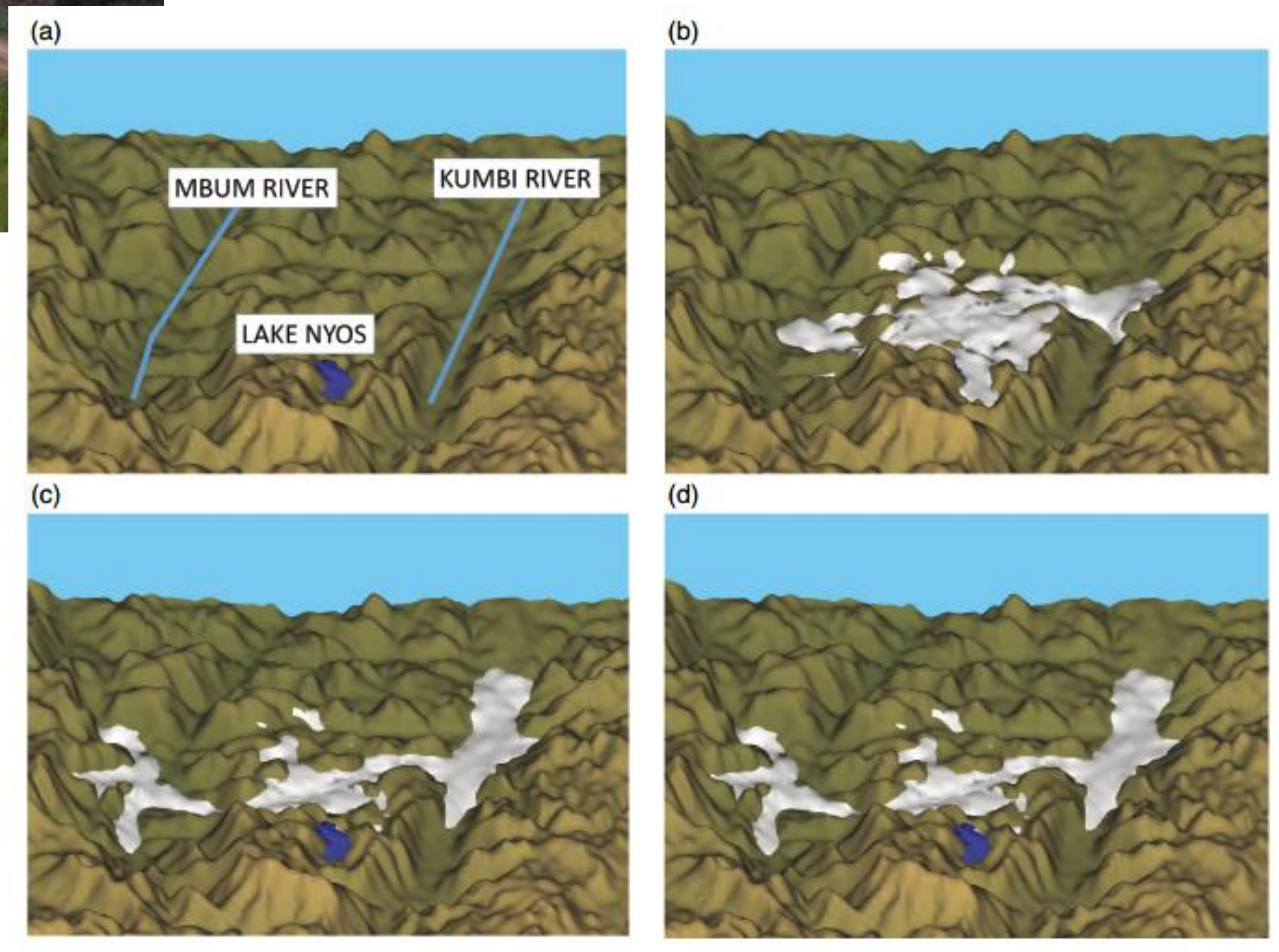


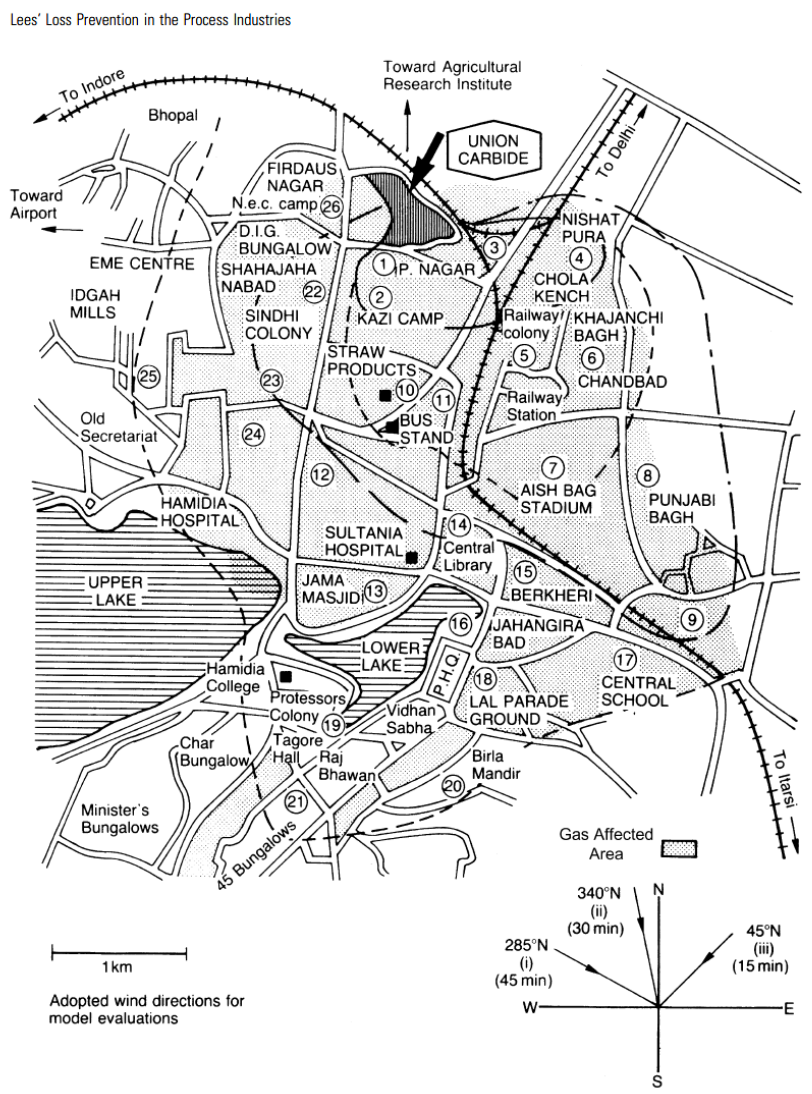
Figure 8. Three-dimensional visualization of the simulated spread of CO_2 from Lake Nyos. (a) Before eruption and (b) 20, (c) 40 and (d) 60 min after eruption. The 5% CO_2 concentrations in all plots represent the threshold level where the onset of laboured breathing occurs. The plots are designed to simulate a viewpoint from an elevated position, looking due north.

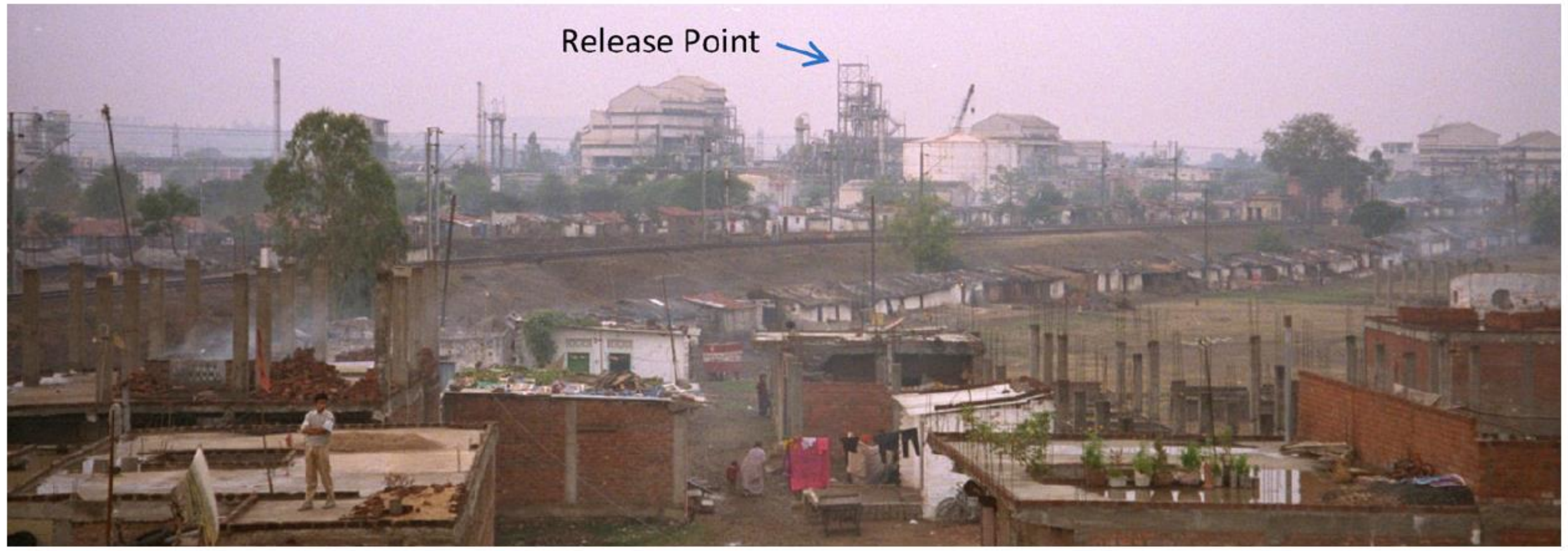
http://dx.doi.org/10.1002/met.1603

Bhopal, India (1986): MIC

- Pressure relief valve released highly toxic methyl isocyanate (MIC) from chemical plant
- Cloud of MIC gas dispersed into housing and shantytowns close to the site
- Release occurred at night: light wind, stable inversion, toxic cloud hung around the area for the entire next day (AEGL-3 is just 0.4 ppm for 30 mins exposure)*
- To date: 25,000 people died, 150,000 people with chronic illnesses
- Initial gas density ranges from 2.4 to 4.3 kg/m^3 in different assessments

https://www.bhopal.net/





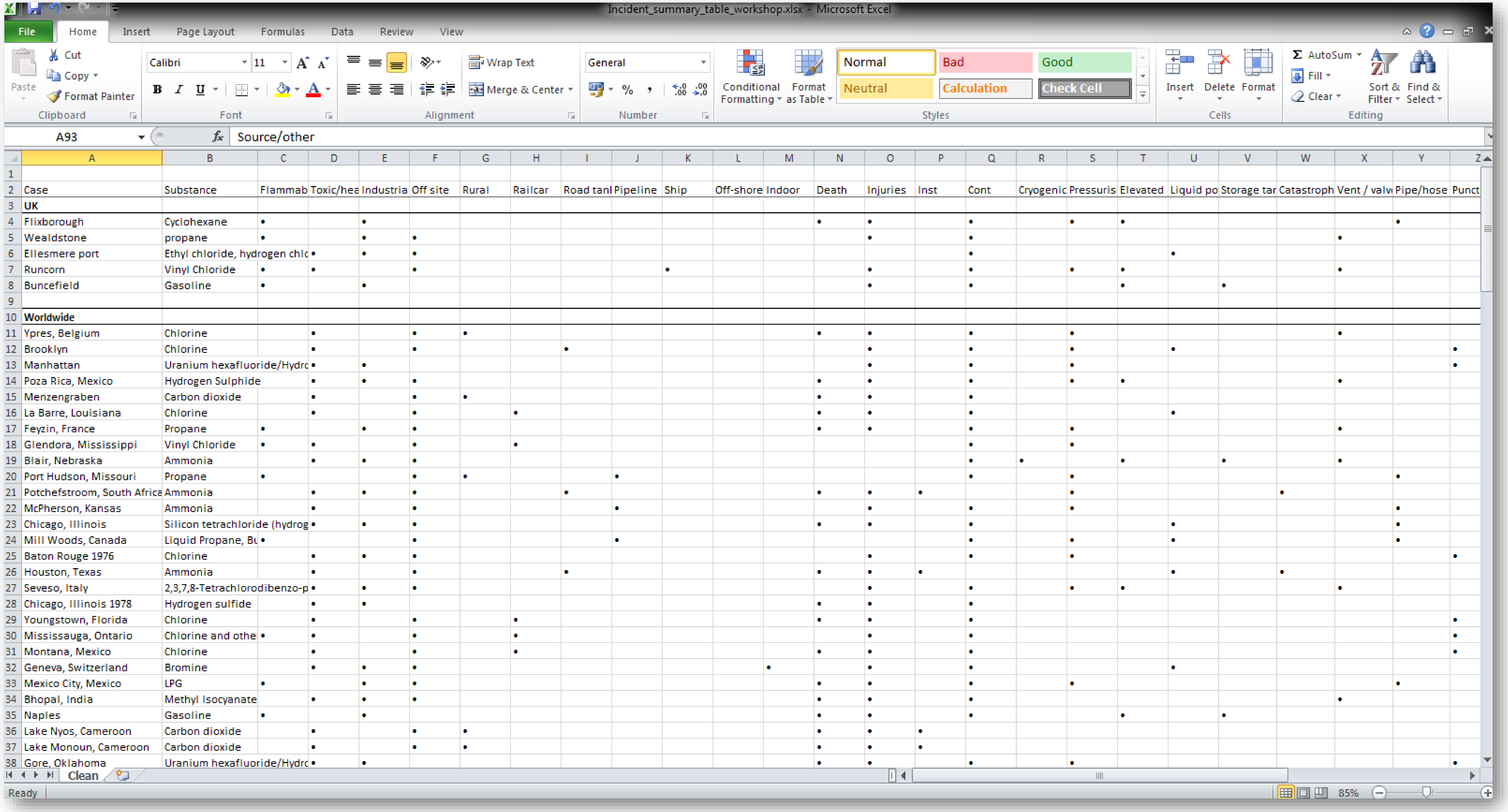
Photograph by Jerry Havens – International Medical Commission to Bhopal,1994.

http://dx.doi.org/10.1016/j.jhazmat.2012.06.055
http://dx.doi.org/10.1016/j.atmosenv.2015.06.038

* https://www.ncbi.nlm.nih.gov/books/NBK201335/

Review of dense gas incidents by Rachel Batt (2021)

Name
Substance
Flammable
Toxic/health
Industrial
Off-site
Rural
Railcar
Road tanker
Pipeline
Ship
Off-shore
Indoor
Death
Injuries
Instantaneous
Continuous
Pressurised
Elevated

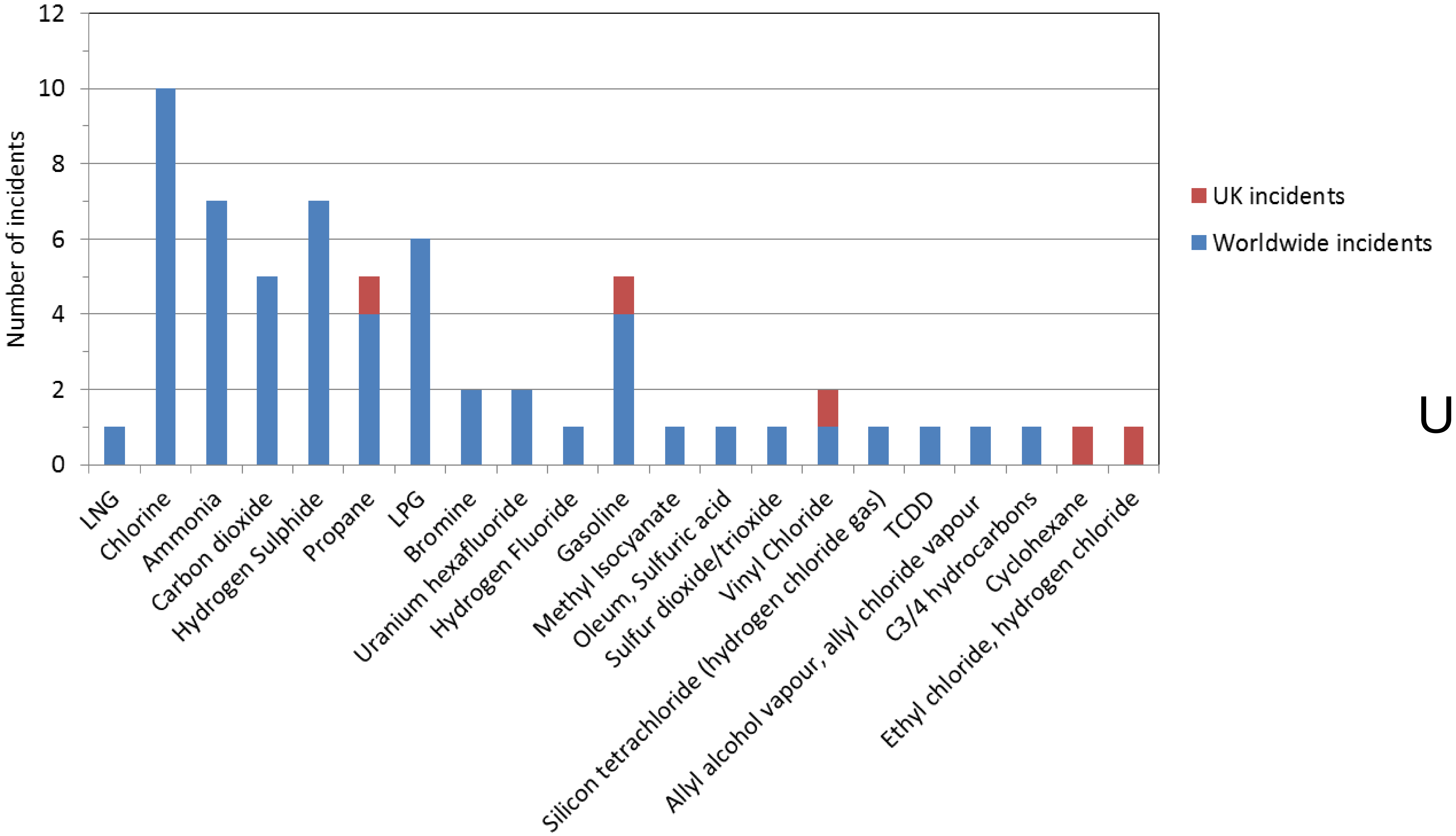


	Case	Substance	Flammab	Toxic/hea	Industria	Off site	Rural	Railcar	Road tanl	Pipeline	Ship	Off-shore	Indoor	Death	Injuries	Inst	Cont	Cryogenic	Pressuris	Elevated	Liquid po	Storage tar	Catastroph	Vent / valv	Pipe/hose	Punct
3	**UK**																									
4	Flixborough	Cyclohexane	•		•									•	•		•		•	•					•	
5	Wealdstone	propane	•		•	•									•		•							•		
6	Ellesmere port	Ethyl chloride, hydrogen chlc		•	•	•											•				•					
7	Runcorn	Vinyl Chloride	•	•		•					•				•		•		•	•				•		
8	Buncefield	Gasoline	•		•										•		•			•		•				
9																										
10	**Worldwide**																									
11	Ypres, Belgium	Chlorine		•		•	•							•	•		•		•					•		
12	Brooklyn	Chlorine		•		•			•						•		•		•		•					•
13	Manhattan	Uranium hexafluoride/Hydrc		•	•										•		•		•							•
14	Poza Rica, Mexico	Hydrogen Sulphide		•	•	•								•	•		•		•	•				•		
15	Menzengraben	Carbon dioxide		•		•	•							•	•		•									
16	La Barre, Louisiana	Chlorine		•		•		•						•	•		•				•					
17	Feyzin, France	Propane	•		•	•								•	•		•		•					•		
18	Glendora, Mississippi	Vinyl Chloride	•	•		•		•									•		•							
19	Blair, Nebraska	Ammonia		•	•	•											•	•		•		•		•		
20	Port Hudson, Missouri	Propane	•			•	•			•							•		•						•	
21	Potchefstroom, South Africa	Ammonia		•	•	•			•					•	•	•			•				•			
22	McPherson, Kansas	Ammonia		•		•				•					•		•		•						•	
23	Chicago, Illinois	Silicon tetrachloride (hydrog		•	•	•								•	•		•				•				•	
24	Mill Woods, Canada	Liquid Propane, Bu	•			•				•							•		•		•				•	
25	Baton Rouge 1976	Chlorine		•	•	•									•		•		•							•
26	Houston, Texas	Ammonia		•		•			•					•	•	•					•		•			
27	Seveso, Italy	2,3,7,8-Tetrachlorodibenzo-p		•	•	•									•		•		•	•				•		
28	Chicago, Illinois 1978	Hydrogen sulfide		•	•									•	•		•									
29	Youngstown, Florida	Chlorine		•		•		•						•	•		•									•
30	Mississauga, Ontario	Chlorine and othe	•	•		•		•							•		•									•
31	Montana, Mexico	Chlorine		•		•		•						•	•		•									•
32	Geneva, Switzerland	Bromine		•	•	•							•		•		•				•					
33	Mexico City, Mexico	LPG	•		•	•								•	•		•		•						•	
34	Bhopal, India	Methyl Isocyanate		•	•	•								•	•		•							•		
35	Naples	Gasoline	•		•									•	•		•			•		•				
36	Lake Nyos, Cameroon	Carbon dioxide		•		•	•							•	•	•										
37	Lake Monoun, Cameroon	Carbon dioxide		•		•	•							•	•	•										
38	Gore, Oklahoma	Uranium hexafluoride/Hydrc		•	•									•	•		•		•							•

Liquid pool
Storage tank overfilling
Catastrophic failure
Vent/valve
Pipe/hose
Puncture/crack/hole
Obstructions
Topography
Nil/low wind
Concentration data
Ingress
Mitigation
ER/safety reg ignored/failed
Previous model validation
Potential model validation
Source description

Excel spreadsheet available here: https://admlc.com/publications/

Substances involved in dense gas incidents



Top five substances worldwide:

- Chlorine
- Ammonia
- Hydrogen sulphide
- LPG
- CO_2, propane & gasoline

UK incidents

- Propane
- Gasoline
- Vinyl chloride
- Cyclohexane
- Ethyl chloride / hydrogen chloride

Other examples of gravity currents in nature

https://wallpapercave.com/avalanche-nature-wallpapers

https://education.nationalgeographic.org/resource/pyroclastic-flow/

https://mymodernmet.com/arizona-dust-storm-news-helicopter/

Also:

- Sea-breeze fronts
- Storm gust fronts
- Atmospheric bores
- Katabatic flows

Modelling approaches

- Empirical correlations and nomograms
- Integral
- Gaussian puff
- Lagrangian
- Computational Fluid Dynamics (CFD)
- Shallow layer
- Lattice-Boltzmann
- Smooth particle hydrodynamics

Empirical nomograms

17/1988

HSE Health & Safety Executive

NOT TO BE TAKEN AWAY

HSE CONTRACT RESEARCH REPORT No. 17/1988

WORKBOOK ON THE DISPERSION OF DENSE GASES

R E Britter
Department of Engineering
University of Cambridge

J McQuaid
Research and Laboratory Services Division
Health and Safety Executive
Sheffield

Price £35.00

[redacted]

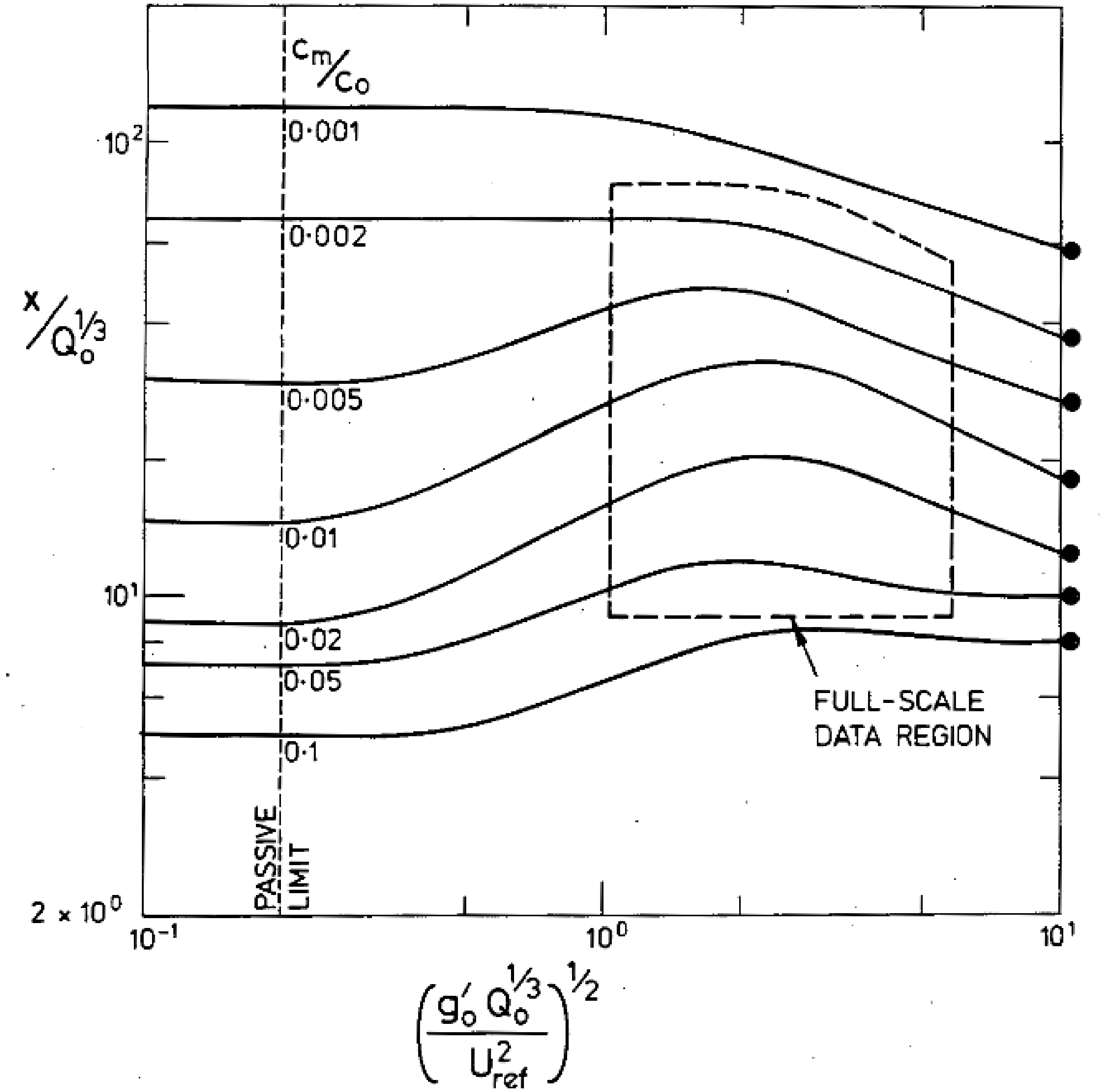
Contents

https://xnet.hsl.gov.uk/fileshare/public/3583/britter-mcquaid-1988-workbook-on-dense-gas-dispersion-crr88017.pdf

Britter & McQuaid (1988) workbook

- Downwind distance to a particular concentration, for instantaneous releases

Q_o	source volume (m^3)
x	downwind distance (m)
g_o	reduced gravity at source (m/s^2)
U_{ref}	reference wind speed (m/s)
C_o	source concentration
C_m	ground-level concentration on plume axis



German VDI 3783 Part 2 guidelines

DK/UDC 502.55(203): 551.510.4: 551.511: 523.31-852-125
502.572: 620.26: 614.878: 628.395
351.777.078.33
614.71/75(083,132)

VDI-RICHTLINIEN

Juli 1990
July 1990

VEREIN DEUTSCHER INGENIEURE	Umweltmeteorologie Ausbreitung von störfallbedingten Freisetzungen schwerer Gase — Sicherheitsanalyse Environmental Meteorology Dispersion of Heavy Gas Emissions by Accidental Releases — Safety Study	VDI 3783 Blatt 2 / Part 2 Ausg. deutsch/englisch Issue German/English

A gas in the sense of this Guideline is to be considered as "heavy" if the following criteria apply (see also Appendix A):

- the relative density excess of the gas at the place of release $\Delta\varrho_0/\varrho_a$ amounts to more than 0.16,
- simultaneously, for instantaneous release, the source volume V_0 amounts to more than 0.1 m^3, or, for continuous release, the source volume flow rate $\dot{V}_0$ is larger than $1 \cdot 10^{-3}$ m^3/s.

If both criteria are not fulfilled simultaneously, the procedure described in Guideline VDI 3783 Part 1 is to be applied. The same holds if it can be reasonably excluded, on the basis of the source conditions, that the gas can disperse near the ground.

The following definitions hold:

$$\Delta\varrho_0/\varrho_a = (\varrho_0 - \varrho_a)/\varrho_a$$

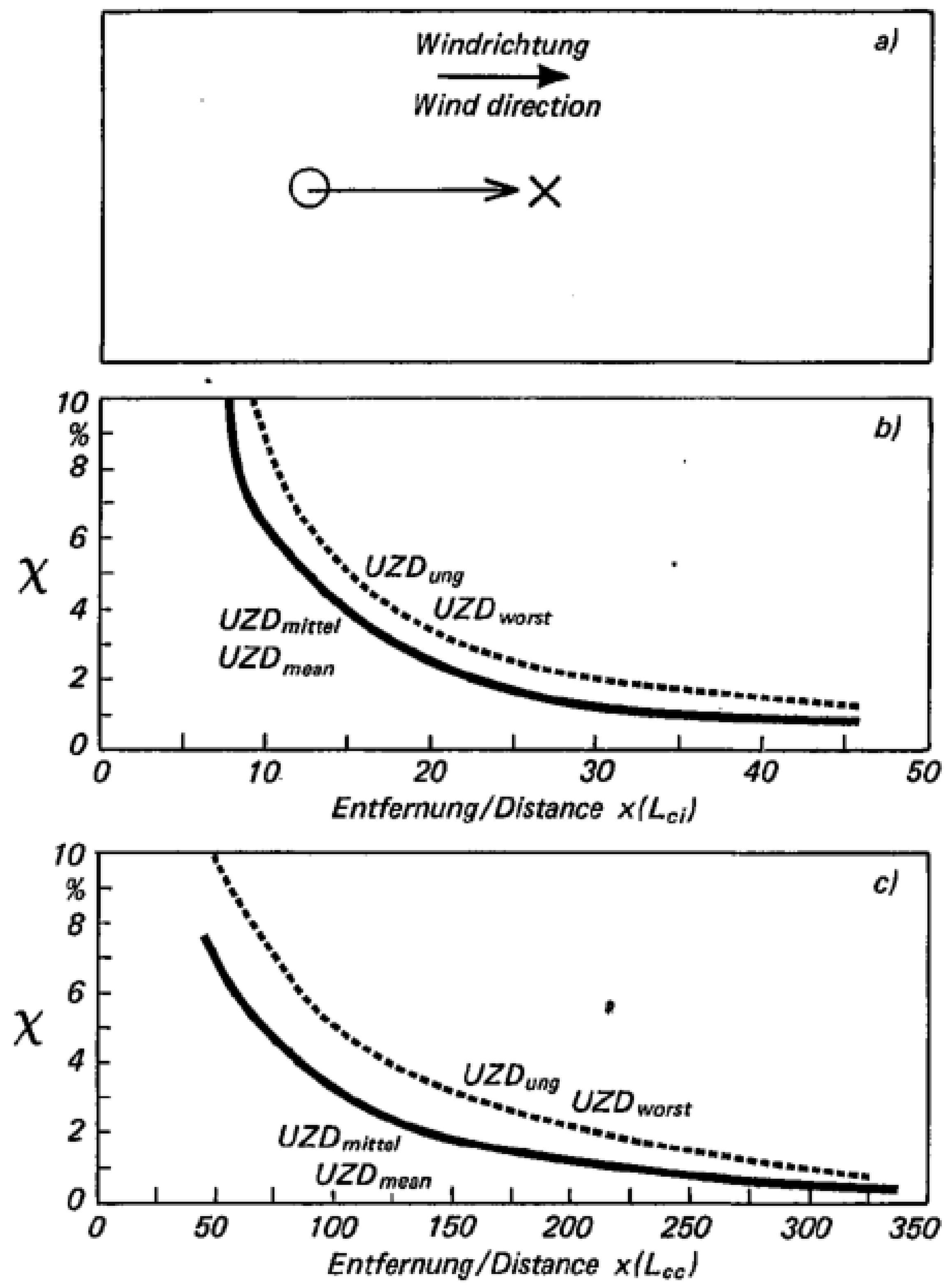
relative density difference of the gas at the source, with

ϱ_0 density of the gas at the source according to Section 3.1 in kg/m^3. If the gas has been diluted with air before the release, the density of the gas mixture is to be used in divergence of Section 3.1.

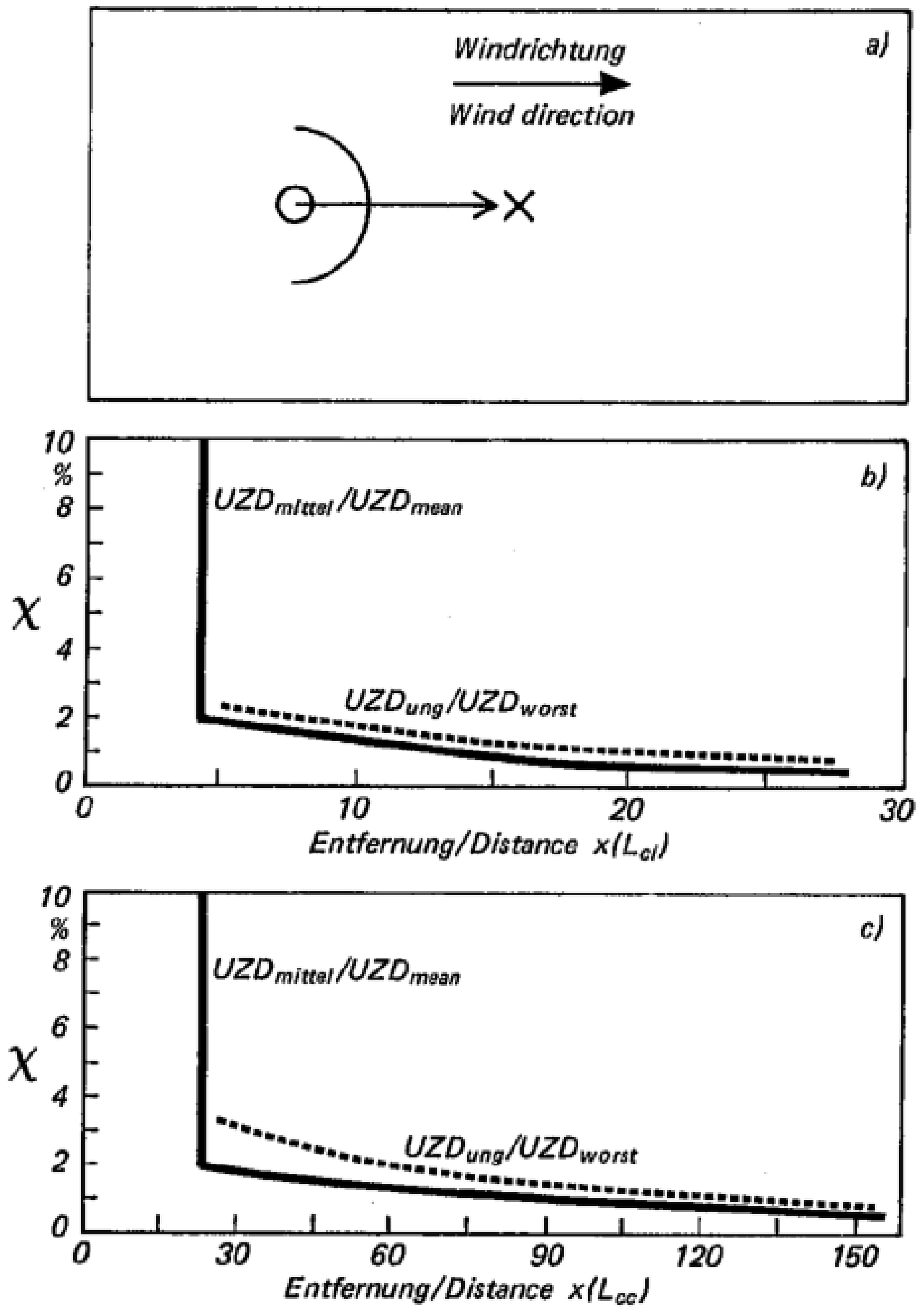
ϱ_a density of the ambient air at source height in kg/m^3 (It is recommended to calculate with $\varrho_a = 1.2$ kg/m^3.)

V_0 source volume of the gas according to Section 3.2 in m^3

$\dot{V}_0$ source volume flow rate of the gas according to Section 3.2 in m^3/s



The normalized concentration χ is defined as the ratio of the local volume concentration to the volume concentration at the source, and it is indicated in %. The distance from the source x is indicated in the characteristic length scales L_{ci} (for instantaneous release according to Section 3.3) resp. L_{cc} (for continuous release according to Section 3.3).



b) Continuous release (according to Section 3.3)

$L_{cc} = (\dot{V}_0^2/g_e)^{1/5}$ characteristic length scale in m

https://www.vdi.de/en/home/vdi-standards/details/vdi-3783-blatt-2-environmental-meteorology-dispersion-of-heavy-gas-emissions-by-accidental-releases-safety-study

Integral models

- Commercial software and/or freely-available integral models
  - Arkansas University DEGADIS (also ALOHA) www.epa.gov/scram/air-quality-dispersion-modeling-alternative-models#degadis
  - CERC GASTAR www.cerc.co.uk/environmental-software/GASTAR-model.html
  - DNV PHAST www.dnv.com/software/services/plant/consequence-analysis-phast
  - ESR DRIFT www.esrtechnology.com/safety-risk/what-we-do/software/drift/
  - JRC ADAM adam.jrc.ec.europa.eu/en/adam/content
  - LLNL SLAB www.epa.gov/scram/air-quality-dispersion-modeling-alternative-models
  - Shell HEGADAS www.hgsystem.com
  - Shell FRED www.gexcon.com/software/shell-fred/
  - TNO EFFECTS www.gexcon.com/software/effects/

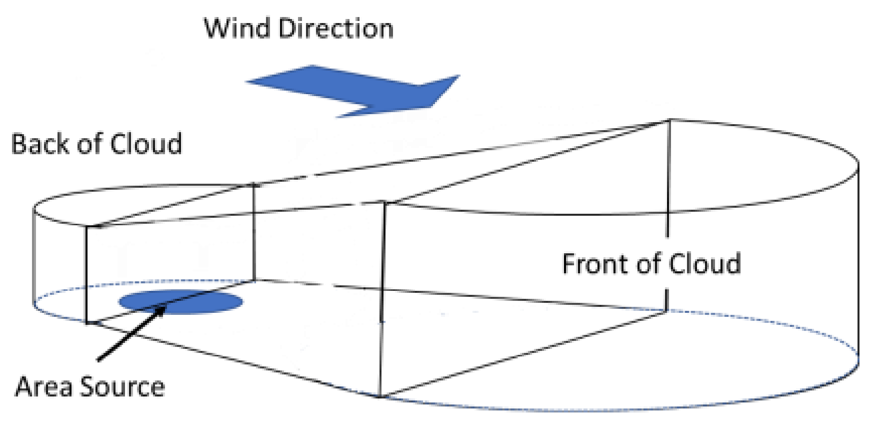


Figure 3. Schematic diagram of DRIFT's area source option

https://doi.org/10.1016/j.atmosenv.2020.117717

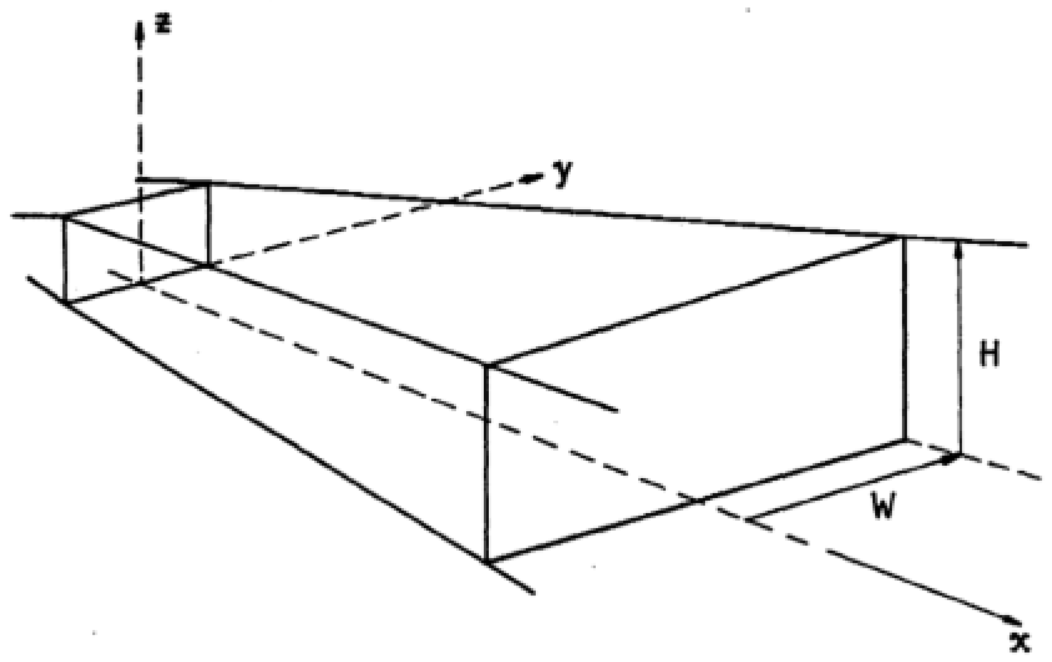


FIG. 3 A REPRESENTATION OF THE CLOUD

https://admlc.com/wp-content/uploads/2023/09/webber_jones_tickle_wren_1992_implementation_drift_model_continuous_releases_srd_r587.pdf

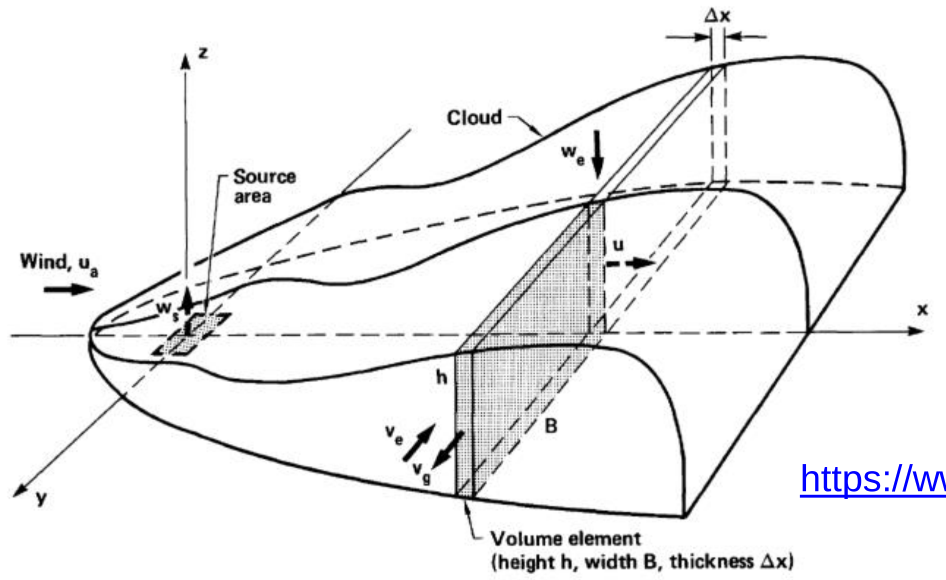


Figure 1. Depiction of a dispersing cloud of heavy gas and air as assumed by the SLAB model, so named because of the slab-shaped volume element.

https://www.osti.gov/biblio/6271522

- Future talk to Met Office/HSE by Gemma Tickle (DRIFT developer) on integral models

Integral models

- Examples of integral model predictions

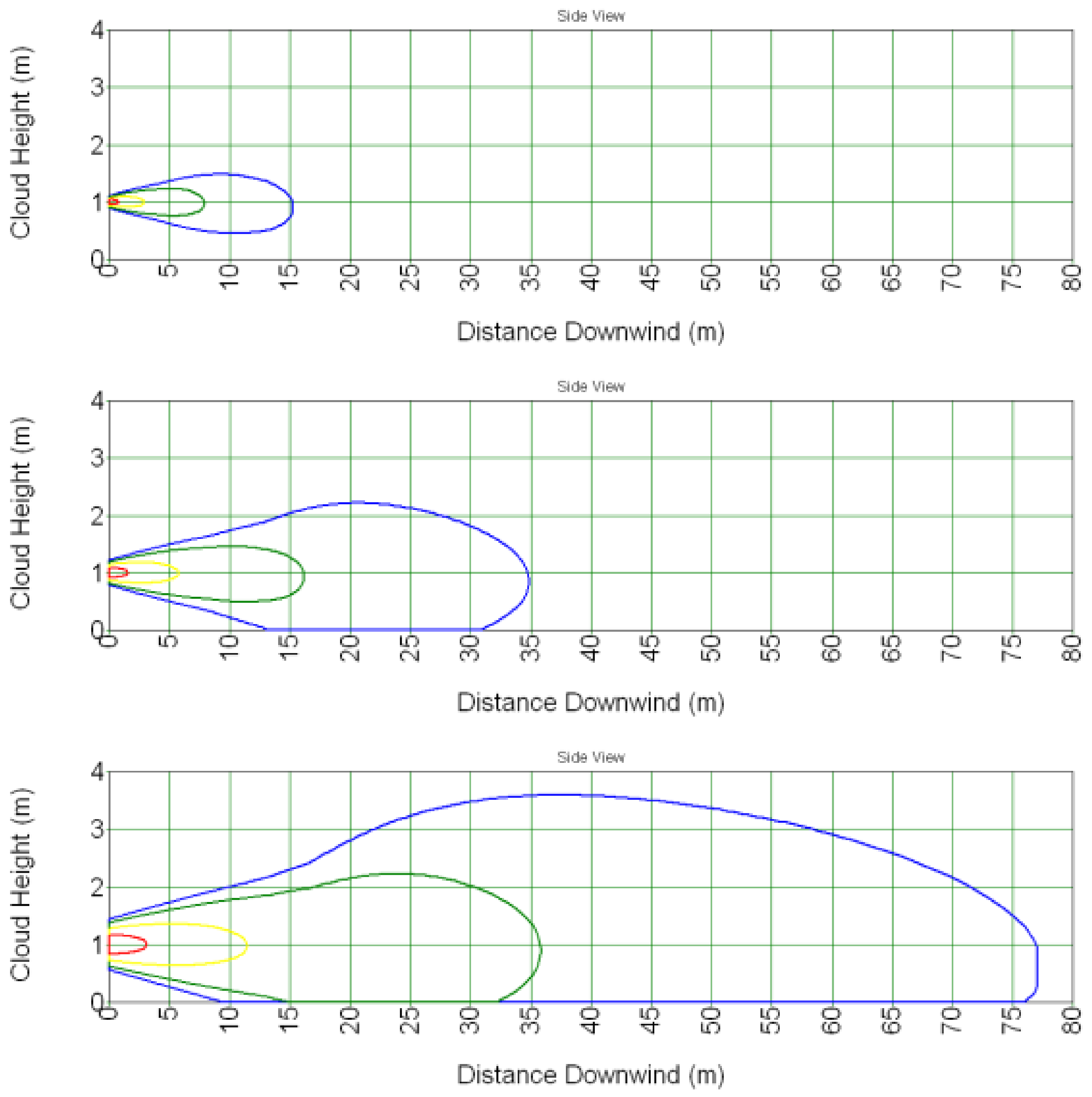
PHAST

Orifice Diameter

½ inch

1 inch

2 inch



http://gant.org.uk/research/Gant_LP2013a.pdf

DRIFT

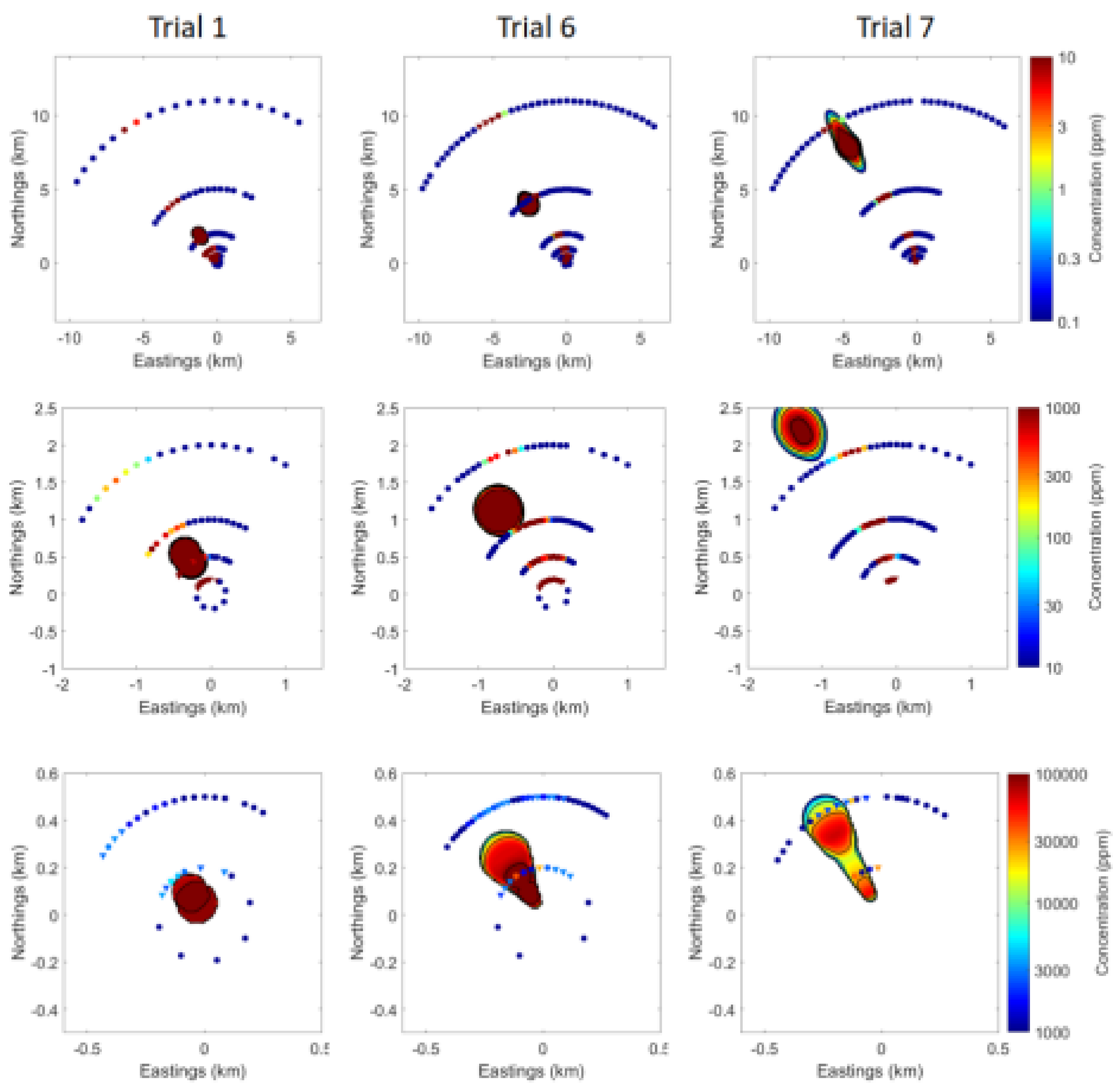


Figure 10 DRIFT1 predicted concentration contours for Trials 1, 6 and 7, at three locations: near, mid and far-field (shown in the bottom, middle and top plots, respectively). Coloured symbols show measured maximum concentrations (over all time), whereas contours show a snapshot of the predicted concentration at the time intervals of 120 s, 600 s and 1800 s in the near, mid and far-field, respectively. Triangular symbols indicate the sensor saturated, whereas round symbols indicate the sensors were unaffected by saturation issues. Both the contours and symbols use the same colour scales. Predicted concentrations below lower limit of the colour scale (e.g. 1,000 ppm in the near-field plots) are not shown, i.e. contour limits are clipped to this lower bound so that the background appears white, not blue.

https://doi.org/10.1016/j.atmosenv.2020.117717

Integral models

- Capabilities
  - Fast to compute: typically seconds or minutes on a standard laptop
  - Different sources: vessels, pipelines, small holes, catastrophic ruptures
  - Single and two-phase releases (assuming homogenous equilibrium)
  - Liquid rainout and pool evaporation
  - Initial jet dispersion and later transition to passive plume (in addition to dense gas dispersion)
  - Different release directions relative to wind direction (up/down/sideways)
  - Condensation of atmospheric moisture and latent heat effects
  - Complex reactions, e.g., oligomerization of hydrogen fluoride, water-reactive substances

Only some integral models have these complex features

- Limitations
  - Flat terrain (or continuous uniform slopes) with uniform roughness
  - Steady atmospheric conditions (single wind profile and atmospheric stability)

Gaussian puff, Lagrangian and Röckle models

- ARGOS https://pdc-argos.com/
- AUSTAL http://austal.de
- FOI PUMA and LPELLO https://doi.org/10.1016/j.atmosenv.2020.117521
- LANL QUIC https://www.lanl.gov/projects/quic/
- Riskaware UDM https://www.riskaware.co.uk/wp-content/uploads/HASP-Suite-UDM.pdf
- SCIPUFF (also HPAC) https://github.com/epri-dev/SCICHEM/releases
- SUEZ-ARIA Micro SWIFT/SPRAY

- Compute times: typically minutes to hours
- Capable of simulating buildings, obstacles, and (in principle) complex terrain
- Some models (e.g., HPAC) have a range of in-built complex source models

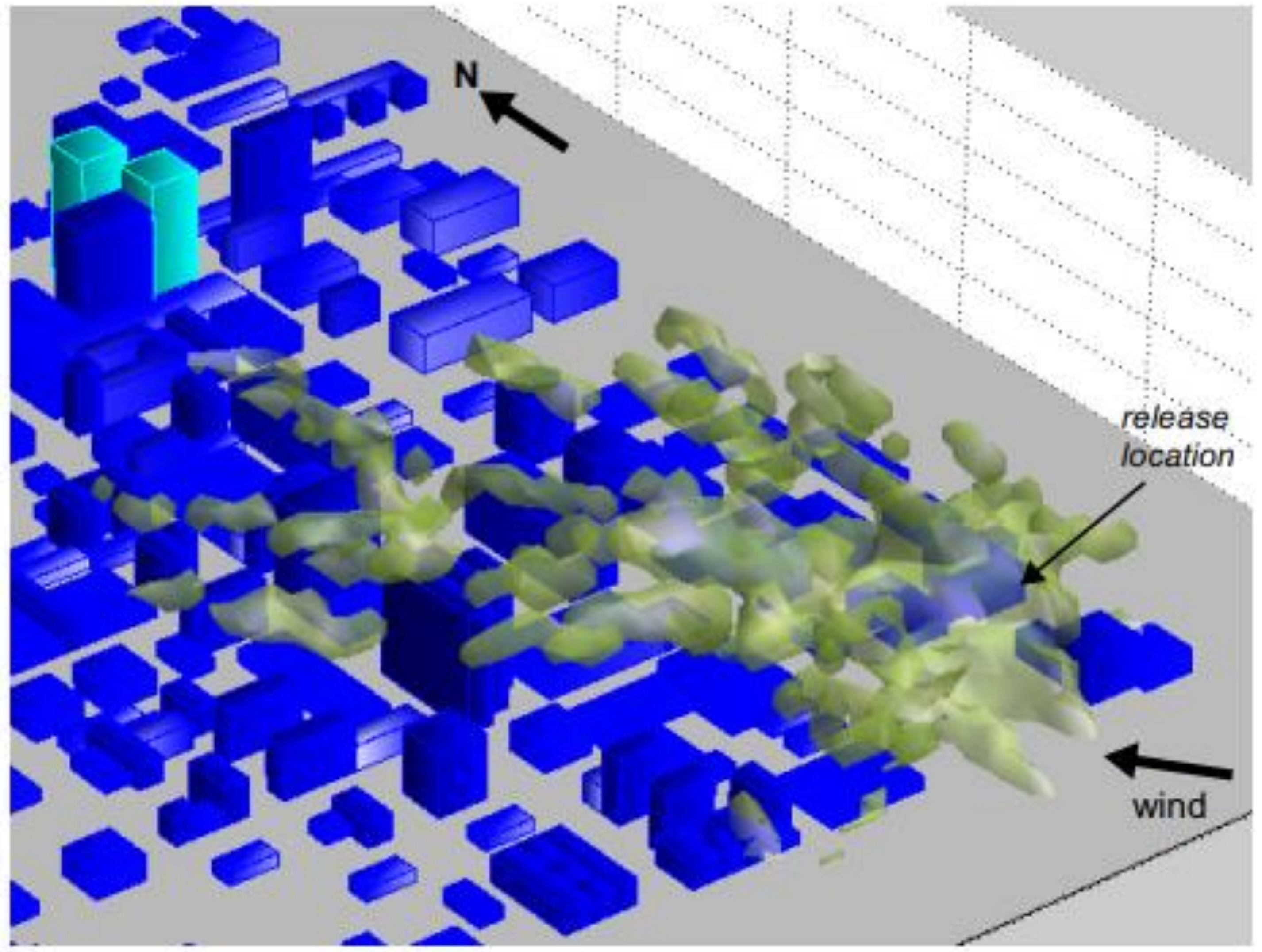
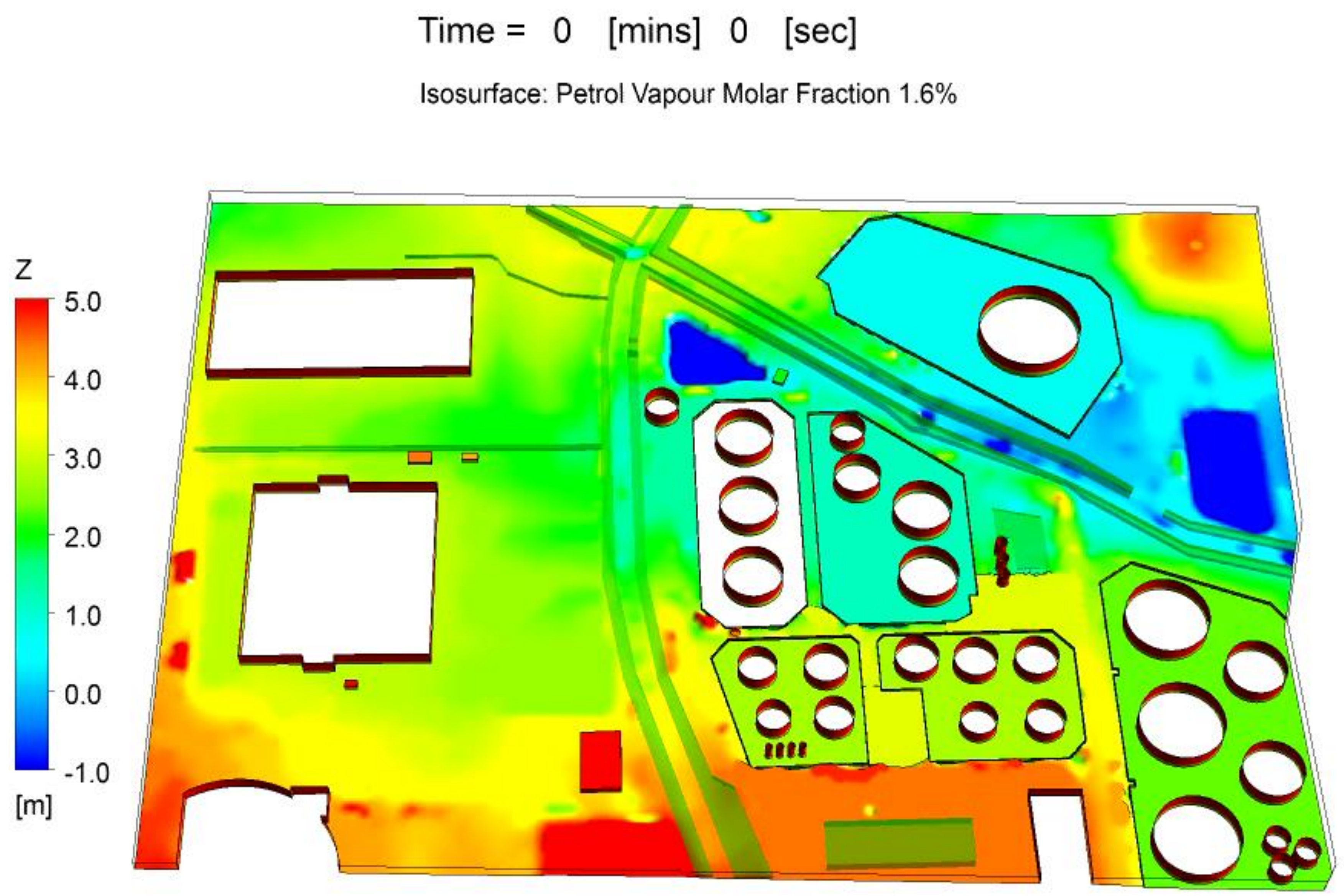


Figure 2. QUIC-PLUME simulation of CB agent transport and dispersion in downtown Salt Lake City. The agent cloud is quickly lofted into the air due to the presence of tall buildings. The inflow wind is from the southeast.

https://www.lanl.gov/projects/quic/open_files/QUIC_factsheet.pdf

Computational Fluid Dynamics (CFD)

- ANSYS Fluent/CFX https://www.ansys.com/
- Demokritos ADREA-HF https://doi.org/10.1016/j.ijhydene.2010.01.002
- DNV KFX https://www.dnv.com/services/cfd-simulation-kfx-110662
- EDF Code-Saturne https://www.code-saturne.org/
- OpenFOAM https://www.openfoam.com/
- Gexcon FLACS https://www.gexcon.com/software/flacs-cfd/
- Siemens Star-CCM+ https://plm.sw.siemens.com/en-US/simcenter/fluids-thermal-simulation/star-ccm/



- Computing times: hours to days on high-performance computers
- Complex physics: evaporation, condensation, two-phase flows, pool evaporation etc.
- Flexible geometry: terrain, buildings, obstacles
- Atmospheric boundary layers are challenging to model in CFD (see https://doi.org/10.1504/IJEP.2018.093026)

Shallow layer, lattice-Boltzmann, SPH etc.

- Shallow layer models
  - TWODEE
  - SPLOT
  - DISPLAY
  - KLAM (katabatic flows) https://admlc.com/events/

Smoothed Particle Hydrodynamics (SPH)

https://www.spheric-sph.org/

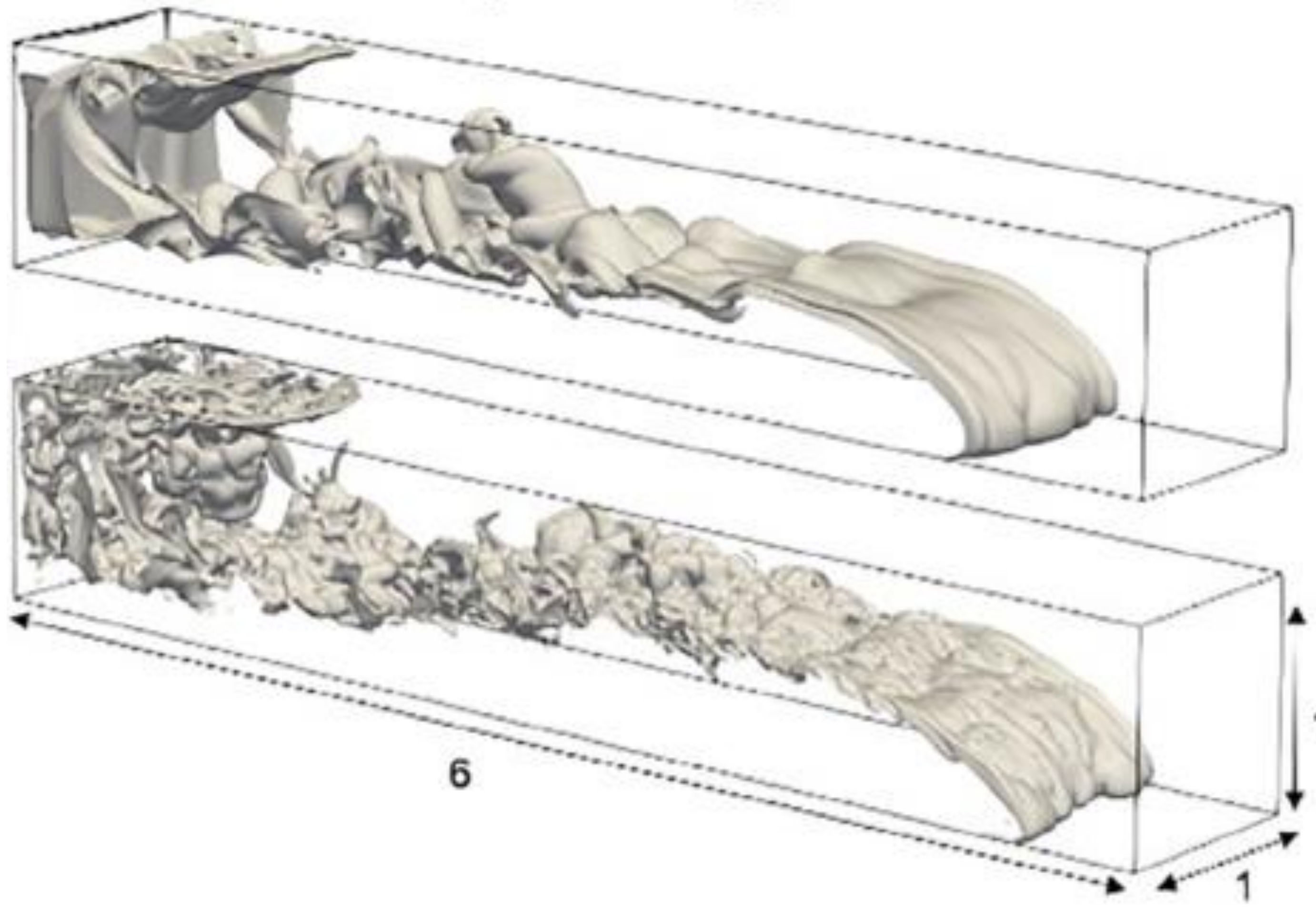
Physics of Fluids ARTICLE scitation.org/journal/phf

Graphics processing unit accelerated lattice Boltzmann method simulations of dilute gravity currents

Cite as: Phys. Fluids **34**, 046602 (2022); doi: 10.1063/5.0082959
Submitted: 20 December 2021 · Accepted: 7 February 2022 ·
Published Online: 7 April 2022

Damilola Adekanye,[1,a)] Amirul Khan,[2] Alan Burns,[3] William McCaffrey,[4] Martin Geier,[5] Martin Schönherr,[5] and Robert Dorrell[6]

d) Case 8 - $Re_b = 30000$:



RESEARCH AND GUIDANCE FROM HSE

Summary of results from the Jack Rabbit III international model inter-comparison exercise on Desert Tortoise and FLADIS

Simon Gant[1] , Joseph Chang[2], Sun McMasters[3], Ray Jablonski[3], Helen Mearns[3], Shannon Fox[3], Ron Meris[4], Scott Bradley[4], Sean Miner[4], Matthew King[4], Steven Hanna[5], Thomas Mazzola[6], Tom Spicer[7], Rory Hetherington[1], Alison McGillivray[1], Adrian Kelsey[1], Harvey Tucker[1], Graham Tickle[8], Oscar Björnham[9], Bertrand Carissimo[10], Luciano Fabbri[11], Maureen Wood[11], Karim Habib[12], Mike Harper[13], Frank Hart[13], Thomas Vik[14], Anders Helgeland[14], Joel Howard[15], Veronica Bowman[15], Daniel Silk[15], Lorenzo Mauri[16], Shona Mackie[16], Andreas Mack[16], Jean-Marc Lacome[17], Stephen Puttick[18], Adeel Ibrahim[18], Derek Miller[19], Seshu Dharmavaram[19], Amy Shen[19], Alyssa Cunningham[20], Desiree Beverley[20], Matthew O'Neal[20], Laurent Verdier[21], Stéphane Burkhart[21], Chris Dixon[22]

[1]Health and Safety Executive (HSE), [2]RAND Corporation, [3]Chemical Security Analysis Center (CSAC), Department of Homeland Security (DHS), [4]Defense Threat Reduction Agency (DTRA), [5]Hanna Consultants, Inc., [6]Systems Planning and Analysis, Inc. (SPA), [7]University of Arkansas, [8]GT Science and Software, [9]Swedish Defence Research Agency (FOI), [10]EDF/Ecole des Ponts, [11]European Joint Research Centre (JRC), [12]Bundesanstalt für Materialforschung und -prüfung (BAM), [13]DNV, Stockport, [14]Norwegian Defence Research Establishment (FFI), [15]Defence Science and Technology Laboratory (DSTL), [16]Gexcon, [17]Institut National de l'Environnement Industriel et des Risques (INERIS), [18]Syngenta, [19]Air Products, [20]Naval Surface Warfare Center (NSWC), [21]Direction Générale de l'Armement (DGA), [22]Shell

21st International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

27-30 September 2022

Methodology

- Simulate 3 trials each from the Desert Tortoise and FLADIS pressure-liquefied ammonia field trials
- Desert Tortoise
  - Tests conducted in 1983 at DOE Nevada Test Site
  - Release rates of 81 – 133 kg/s
  - 10 – 41 tonnes of ammonia released
  - Dispersion measurements at 100 m and 800 m
  - Largest tests to date on ammonia
- FLADIS
  - Tests conducted in 1993-4 at Landskrona, Sweden
  - Release rates of 0.25 – 0.55 kg/s
  - Dispersion measurements at 20 m, 70 m and 240 m (transition from dense to passive dispersion)

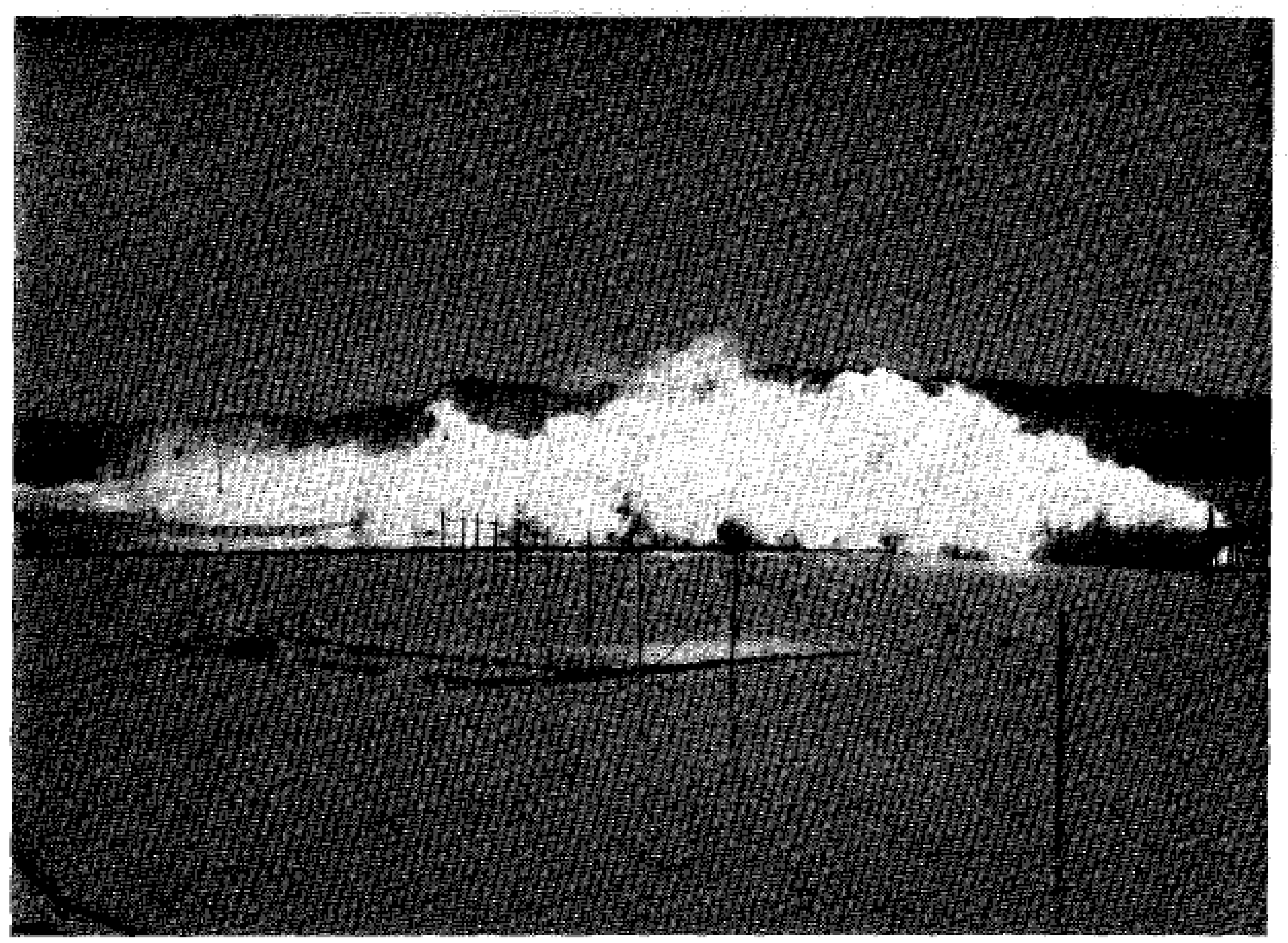
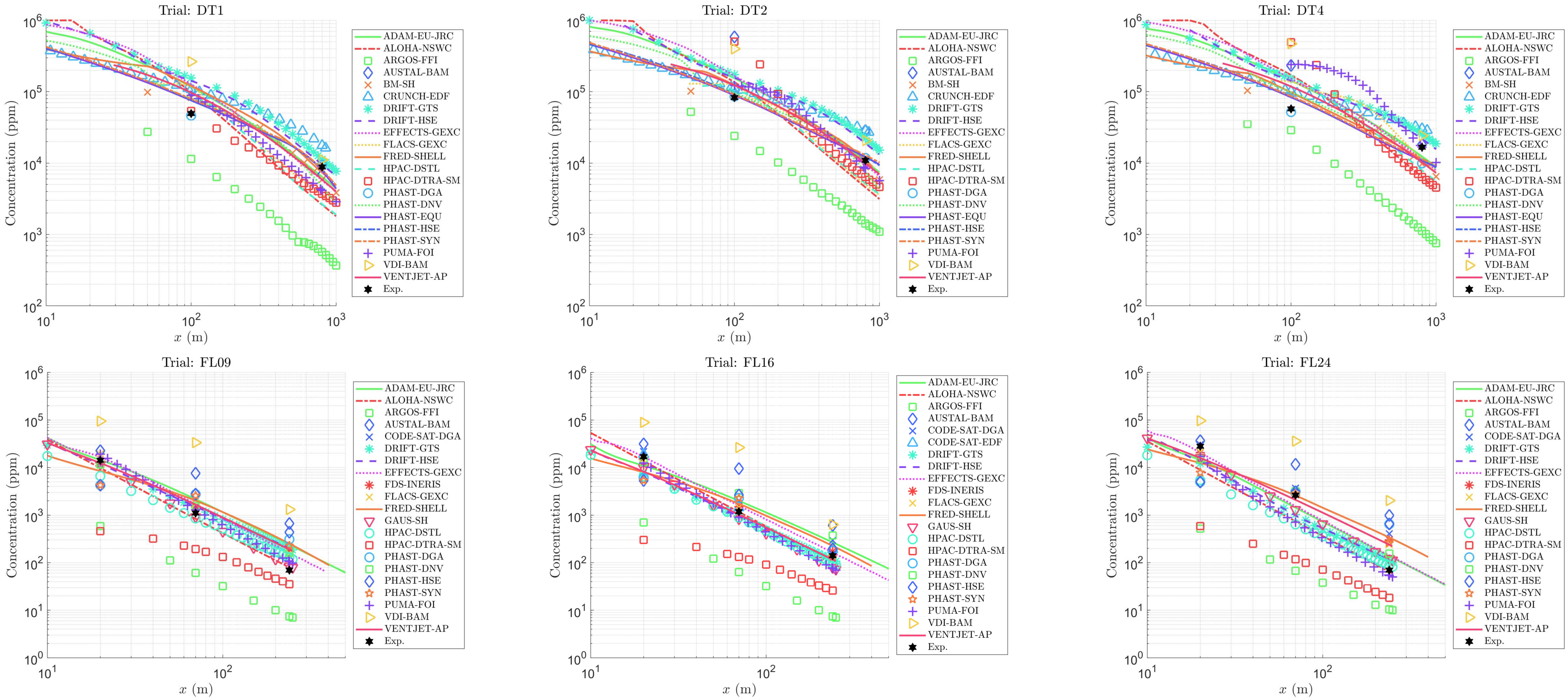


Fig. 15. Desert Tortoise 2 (upwind wide angle camera) Time = 230s. Lawrence Livermore National Laboratory

Participants in the JRIII initial modeling exercise

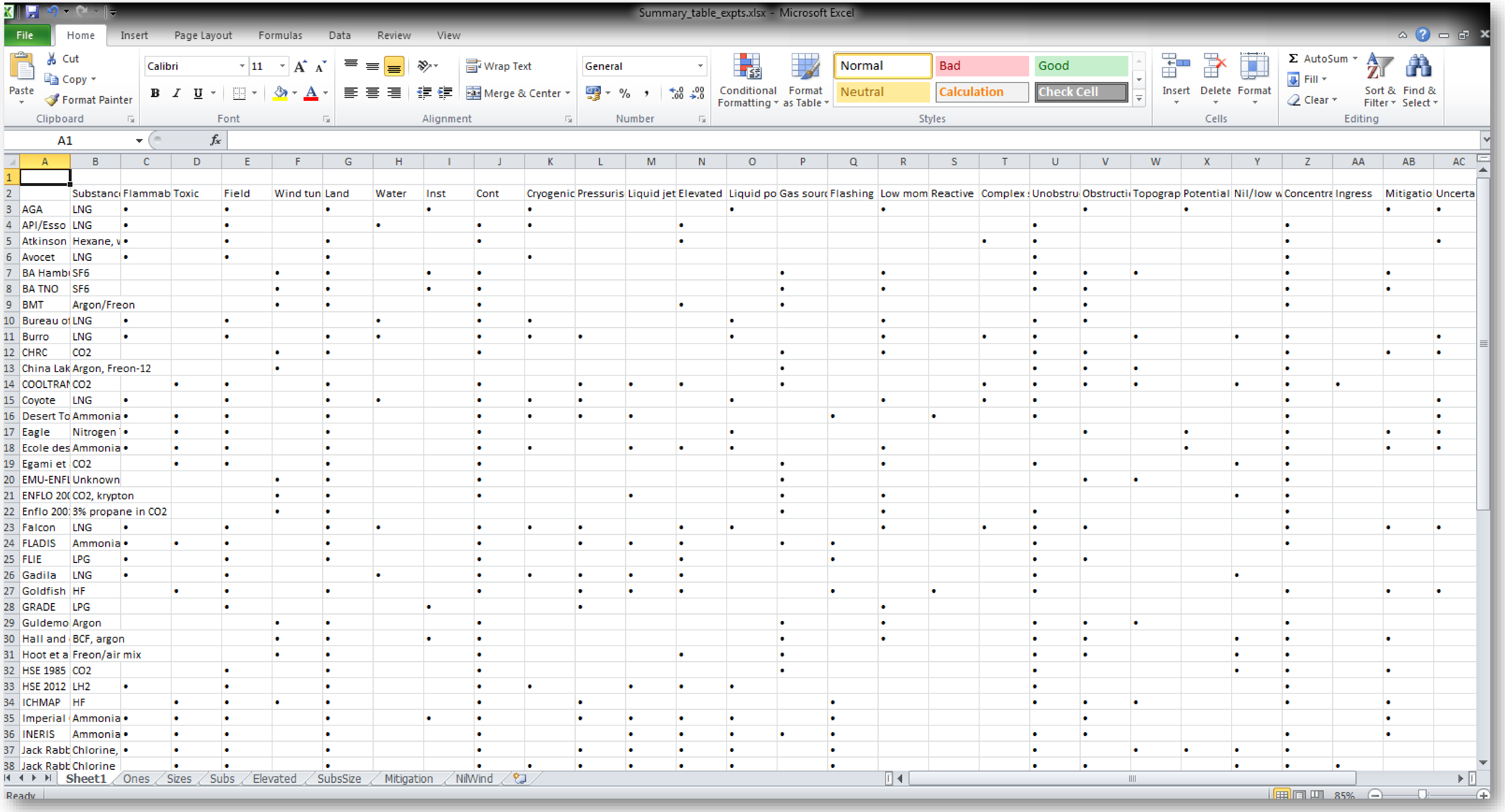
#	Organization	Model	Model Type				Desert Tortoise			FLADIS		
			Empirical nomogram/ Gaussian plume	Integral	Gaussian Puff/ Lagrangian	CFD	1	2	4	9	16	24
1	Air Products, USA	VentJet		■			■	■	■	■	■	■
2	BAM, Germany	AUSTAL			■		■	■	■	■	■	■
3		VDI	■				■	■	■	■	■	■
4	DGA, France	PHAST v8.6		■			■	■	■	■	■	■
5		Code-Saturne v6.0				■				■	■	■
6	DNV, UK	PHAST v8.61		■			■	■	■	■	■	■
7	DSTL, UK	HPAC v6.5			■		■	■	■	■	■	■
8	DTRA, ABQ, USA	HPAC v6.7			■		■	■	■	■	■	■
9	DTRA, Fort Belvoir, USA	HPAC			■		■	■	■	■	■	■
10	EDF/Ecole des Ponts, France	Code-Saturne v7.0				■					■	
11		Crunch v3.1		■			■	■	■			
12	Equinor, Norway	PHAST v8.6		■			■	■	■	■	■	■
13	FFI, Norway	ARGOS v9.10			■		■	■	■	■	■	■
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 v3.7.12		■			■	■	■	■	■	■
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	Syngenta, UK	PHAST v8.61		■			■	■	■	■	■	■

All model results



Summary of dense gas experiments by Rachel Batt (2021)

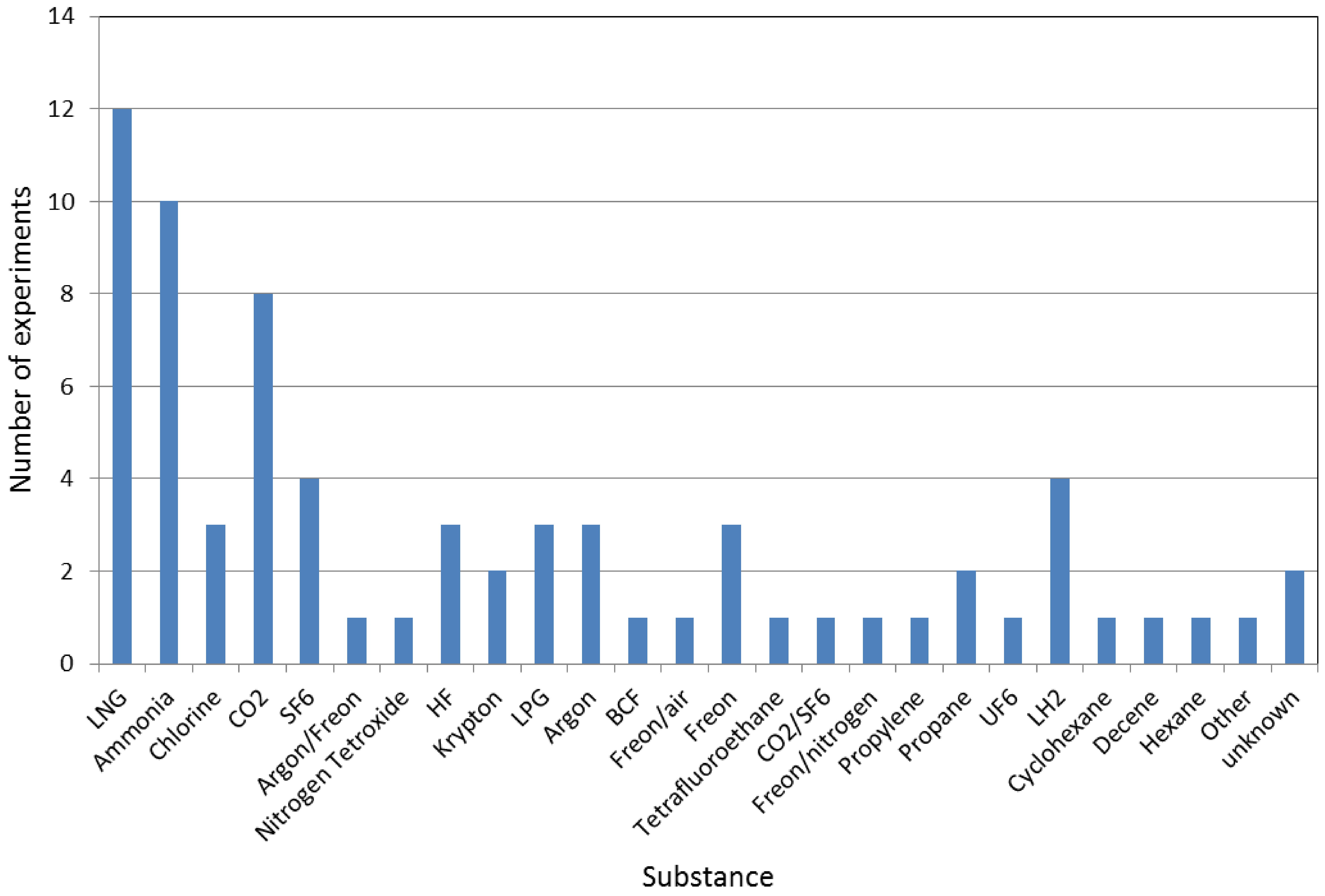
Name
Substance
Flammable
Toxic/health
Field
Wind tunnel
Land
Water
Instantaneous
Continuous
Cryogenic
Pressurised
Liquid jet
Gas source
Flashing
Low momentum
Reactive
Complex source



Unobstructed
Obstructed
Topography
Potential porosity effects
Nil/ low wind/ stably stratified
Concentration data
Ingress
Mitigation
Uncertainties
Previous model validation
Potential model validation
Reference

Excel spreadsheet available here: https://admlc.com/publications/

Substances used in experiments



Top five substances in exps:

- Liquefied Natural Gas (LNG)
- Ammonia
- Carbon dioxide (CO_2)
- Sulphur hexafluoride (SF_6)
- Liquid hydrogen (LH_2)

Top five substances in dense-gas incidents worldwide:

- Chlorine
- Ammonia
- Hydrogen sulphide
- LPG
- CO_2, propane and gasoline

Dense gas dispersion datasets

- Modelers Data Archive (MDA)
  - run by Joe Chang and Steve Hanna

Data Sets Included in MDA

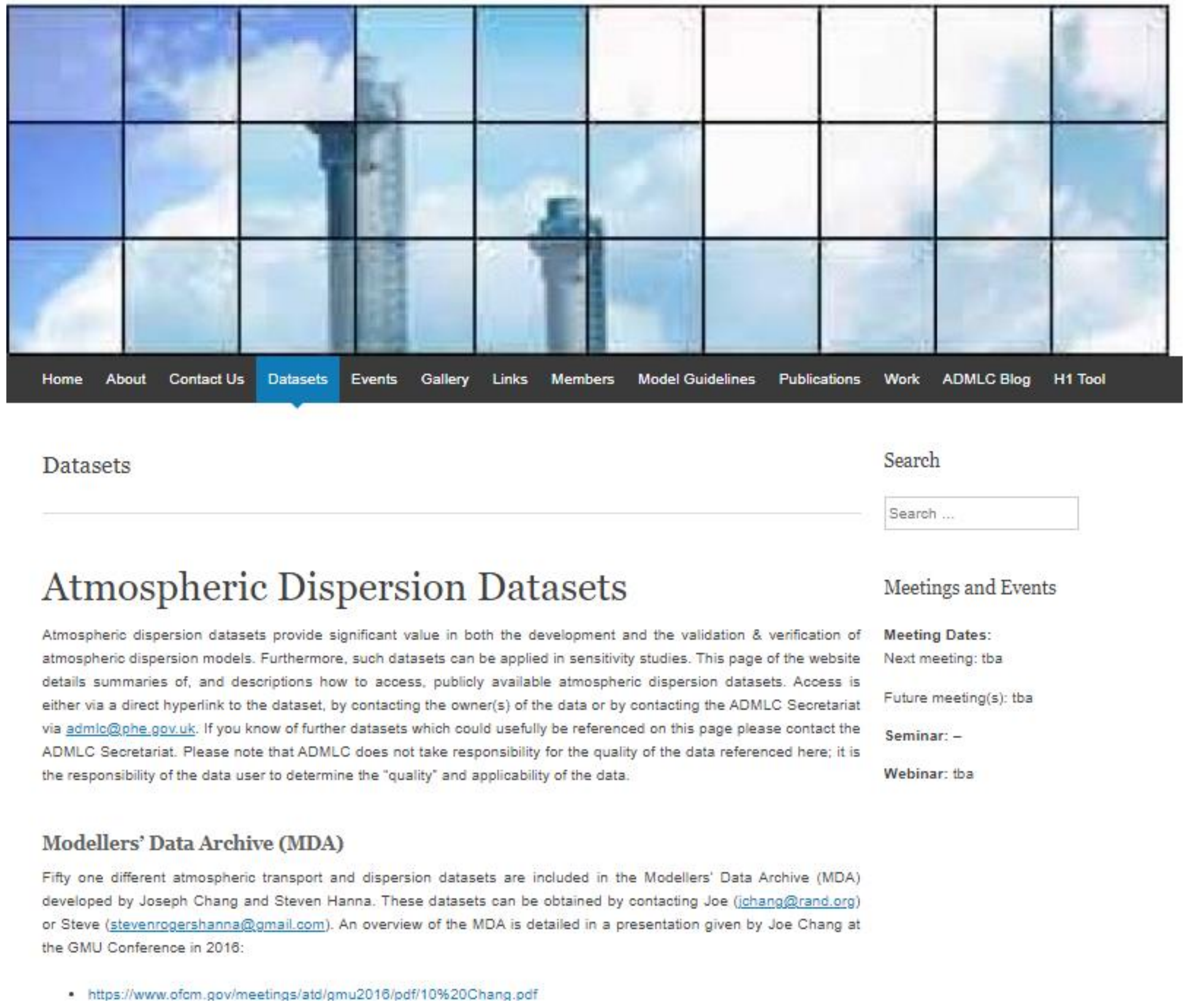
1. Dense Gas MDA (including Burro, Coyote, Desert Tortoise, Goldfish, Lyme Bay, Maplin Sands, and Thorney Island)
2. Prairie Grass
3. Hanford Kr^{85}
4. Ocean Breeze
5. Dry Gulch
6. Green Glow
7. Kit Fox
8. EPA CO_2
9. DSWA Phase I
10. DP26 (Dipole Pride 26)
11. OLAD (Overland Alongwind Dispersion)
12. MVP (Model Validation Program)
13. Ventura
14. Pismo Beach
15. Cameron
16. Carpinteria
17. LROD (Long-Range Overwater Diffusion)
18. MADONA (Meteorology And Diffusion Over Non-Uniform Areas)
19. ACURATE (Atlantic Coast Unique Regional Atmospheric Tracer Experiment)
20. ANATEX (Across North America Tracer Experiment)
21. METREX (Metropolitan Tracer Experiment)
22. CAPTEX (Cross Appalachian Tracer Experiment)
23. ETEX (European Tracer Experiment)
24. INEL74
25. OKC80
26. Birmingham
27. Urban 2000 (Salt Lake City)
28. Joint Urban 2003 (Oklahoma City)*
29. Madison Square Garden 2005*
30. Midtown Manhattan 2005*
31. MUST (Mock Urban Setting Test)
32. EMU (Evaluation of Model Uncertainty)
33. DPG Barrel
34. LA 2001
35. Barrio Logan (San Diego)
36. Porton Down 1977
37. Macdonald (water tunnel)
38. SMEDIS (Scientific Model Evaluation of Dense Gas Dispersion Models)
39. TRAPOS (Optimization of Modeling Methods for Traffic Pollution in Streets)
40. REDIPHEM (Review and Dissemination of Physical Effects Models)
41. FLADIS (Research on the Dispersion of Two-Phase Flashing Releases)
42. Kincaid
43. Bull Run
44. Indianapolis
45. Clifty Creek
46. Tracy
47. Martins Creek
48. Westvaco
49. SARMAP (San Joaquin Valley Air Quality Study, Regional Meteorological and Air Pollution)
50. LMOS (Lake Michigan Ozone Study)
51. OTAG (Ozone Transport Assessment Project)

Need to be requested from DoD

6

https://www.icams-portal.gov/meetings/atd/gmu2016/pdf/10%20Chang.pdf

www.admlc.com/datasets



Knowledge gaps exercise

Collaborative exercise run in 2020 to identify topics for further research in Jack Rabbit III

Staged approach:

1. **Pose open questions to gather information**
   - What is the issue?
   - Why are we interested?
   - What testing is needed?
   - Example: Dry deposition
     - Some models predict it could have a significant effect on the hazard range
     - Lack of experimental data for dry deposition rates
     - Tests would involve measurements with different soil/vegetation samples downwind from large realistic release

Knowledge Gaps Exercise

2. **Group common issues identified in the responses into topics and sub-topics**
   - Five topic headings:
     - Source terms
     - Dispersion
     - Physicochemical effects
     - Mitigation
     - Outcomes
3. **Contributors vote on their top three sub-topics**
   - For example, sub-topics in dispersion:
     - Obstacle effects
     - Terrain effects
     - Stable atmospheres
     - Internal boundary layers
     - Low wind speeds
     - Transition from dense to passive
     - Persistence in wakes/hollows
     - Detailed turbulence
   - Contributors also asked which topics should not be studied

Knowledge Gaps Exercise

4. **Collate responses from all contributors**
   - Votes summed to find highest-priority research topics
   - Specific research questions identified within the top five highest-priority sub-topics
   - Findings circulated for feedback from the contributors prior to finalising these slides

Findings presented at 24th Annual George Mason University Conference on Atmospheric Transport and Dispersion Modeling, 8-10 December 2020
http://camp.cos.gmu.edu/

Contributors

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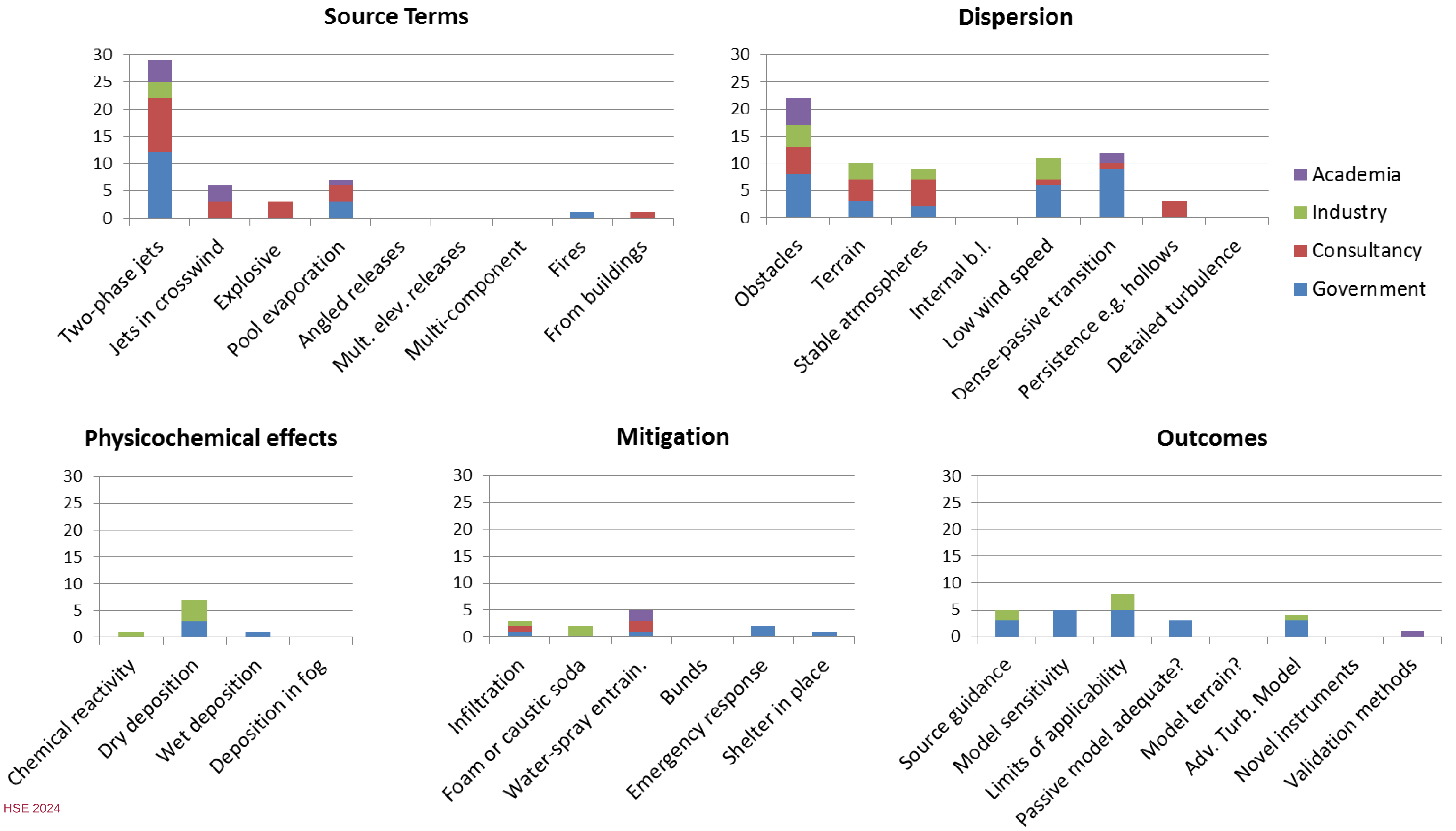
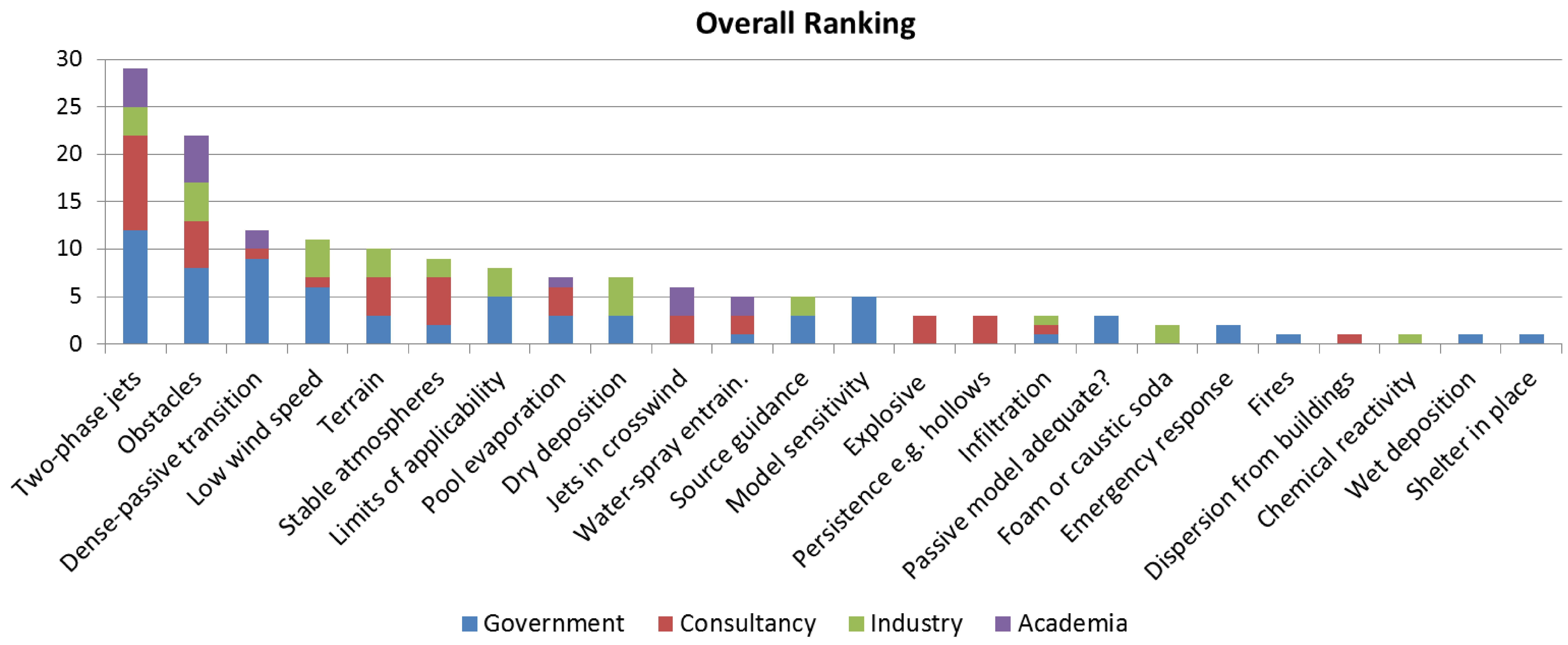
18. Andreas Mack and Mark Spruijt, the Netherlands
19. Claire Witham and Susan Leadbetter, **Met Office**, UK
20. James Stewart-Evans, Public Health England (**PHE**), UK
21. Eelke Kooi and Bert Wolting, **RIVM**, the Netherlands
22. Chris Dixon, **Shell**, UK
23. Stephen Puttick, **Syngenta**, UK
24. John Zevenbergen, **TNO**, the Netherlands
25. Delphine Laboureur and Sophia Buckingham, von Karman Institute for Fluid Dynamics (**VKI**), Belgium

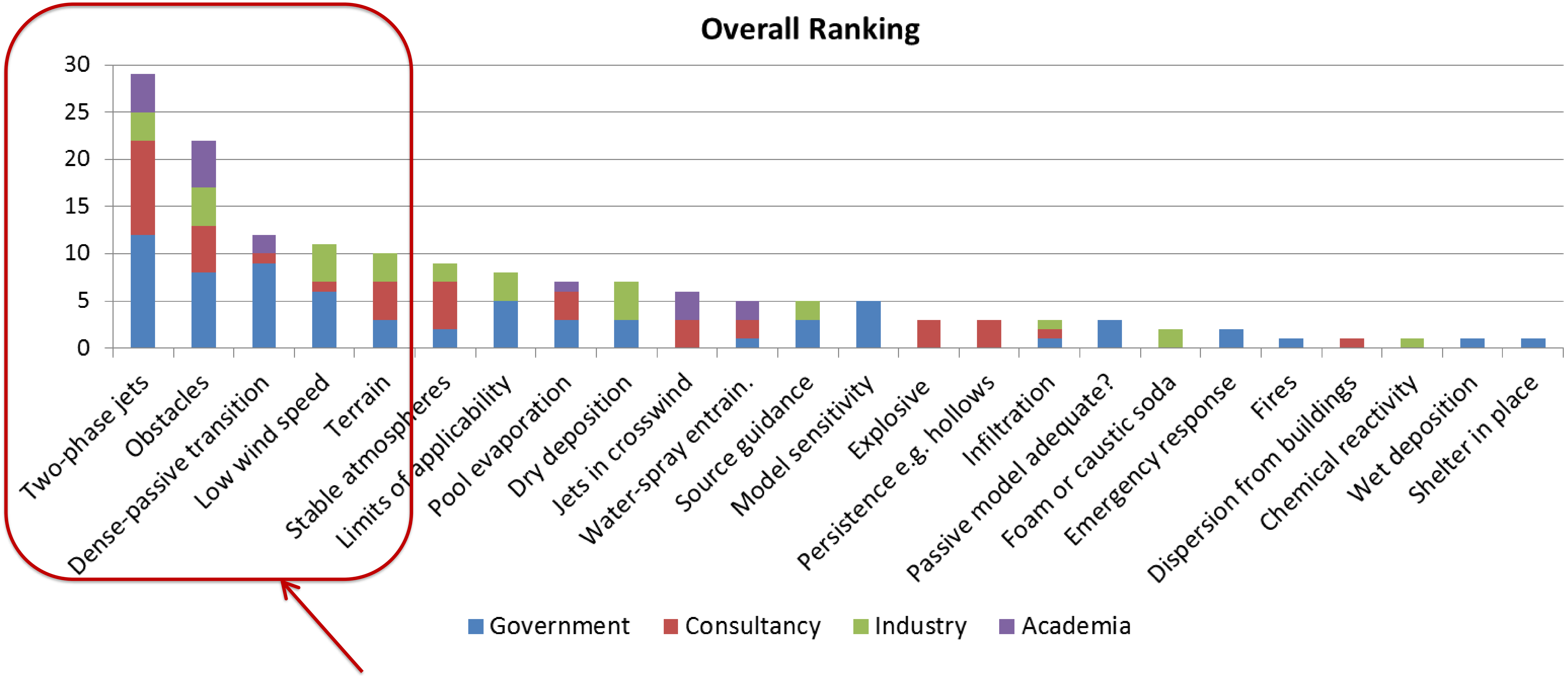
Knowledge gaps: Results from votes



Knowledge gaps: Results from votes



Knowledge gaps: Results from votes



Next slides focus on top five sub-topics

1. Two-phase jets

- Critical issue studied in several previous projects (see later review)
- Lack of data for partitioning between airborne aerosol and liquid pool (i.e. rainout fraction)
- Validity of rainout approaches in operational models is uncertain
- Rainout fraction can have significant influence on dispersion, particularly in the near field
- Rainout is scale-specific: depends on geometry and release size
- Useful to consider range of conditions: hole sizes, release orientations, impinging, short releases (e.g. catastrophic vessel failure), long duration releases (e.g. pipeline)
- Uncertainty in post-expansion source conditions: jet velocity and liquid fraction (metastable or homogeneous equilibrium) – could be studied in laboratory-scale tests?
- Uncertainty in behaviour inside vessel (champagne effect)

2. Obstacles

- Limited field-scale data available for dense-gas dispersion with realistic obstacles
- At what size do obstacles become important such that they need to be taken account of in modelling?
- Are dense gas dispersion models for flat and rough terrain still applicable to built-up environments?
- Which is better: a building-resolved passive model or a dense gas model with surface roughness?
- How much do isolated or small obstacles affect dispersion?
- What is the impact of obstacles on persistence of the cloud?
- How effective are vapour barriers for mitigation?
- Do wakes from isolated tall buildings in city environments have a significant affect? Is it important to model them?

3. Transition from dense-gas to passive dispersion

- When is it necessary to use a dense-gas model instead of a passive model?
  - Is the current rule of thumb that says a dense-gas model should be used for releases of 1 ton or more accurate?
- Can testing determine if there is a threshold release size when a passive model is adequate?
- How rapid is the mixing between the dense cloud and the atmosphere that produces a passive cloud?
- Does near-field dense gas behaviour matter far downwind?
- How does the transition from dense to passive affect turbulence levels and toxic dose (non-linear toxic response to concentration)?
- What are the implications for infiltration into buildings, e.g. draining of dense clouds into basements?

4. Dispersion in low/zero wind speeds

- Lack of experimental data for large dense-gas releases in low/zero wind speeds
  - But there are examples of several severe incidents involving flammable dense-gas releases in low/zero wind, e.g. Buncefield and San Juan fuel storage depots
- How do obstacles and terrain influence the dispersion behaviour when the wind speed approaches zero?
- What are the implications of low/zero wind speeds for emergency response?
  - ERG provides protective action distance in downwind direction
  - ERG for ammonia has three wind speeds (low, moderate, high) for (<10 km/h, 10-20 km/h, >20 km/h)
  - What is the advice for very low or zero wind? Which direction is downwind? Are the ERG distances still valid?

5. Terrain effects

- Lack of experimental data for large dense-gas releases with terrain
  - Indications from incidents that even moderate slopes could have significant effect in low/zero wind
- At what scale does terrain become important for dispersion?
- What is the combined effect of the wind, the release direction and terrain on dense-gas releases?
  - Useful to have range of tests: e.g. releases upslope, downslope and cross-winds for a range of release sizes and slopes
  - Also elevated releases, e.g. for rooftop-mounted ammonia refrigeration tanks

Knowledge gaps

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DOI: 10.1002/prs.12289

PROCESS SAFETY PROGRESS

ORIGINAL ARTICLE

Gaps in toxic industrial chemical model systems: Improvements and changes over past 10 years

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Funding information
Defense Threat Reduction Agency; Department of Homeland Security, Grant/Award Number: N/A; Health and Safety Executive

Abstract

To assess the hazards of the releases of toxic industrial chemicals (TICs) to the atmosphere, comprehensive model systems are often used, which begin with the scenario definition and end with an estimate of health risk. In 2008 and 2010, the US Department of Homeland Security and Defense Threat Reduction Agency sponsored reports that identified knowledge gaps in TIC modeling. The current paper discusses which of the knowledge gaps were satisfactorily resolved in the past 10 years by new theoretical and experimental research, such as the 2010 and 2015–2016 Jack Rabbit field experiments. For example, the linked source emissions and transport and dispersion (T&D) models have been shown, in comparisons with Jack Rabbit II observations, to not have large mean biases. Consequently, the T&D models are less likely to be the cause of model system overpredictions of casualties observed after large TIC accidental releases, such as the Festus, Macdona, and Graniteville chlorine railcar incidents. It may be that the deposition models and/or the health effects models still need improvement. In addition to comments on the knowledge gaps identified 10 years ago, a few new knowledge gaps are addressed, such as indoor T&D and deposition, and estimating the magnitude of the saturation deposition value for various substrates and chemicals.

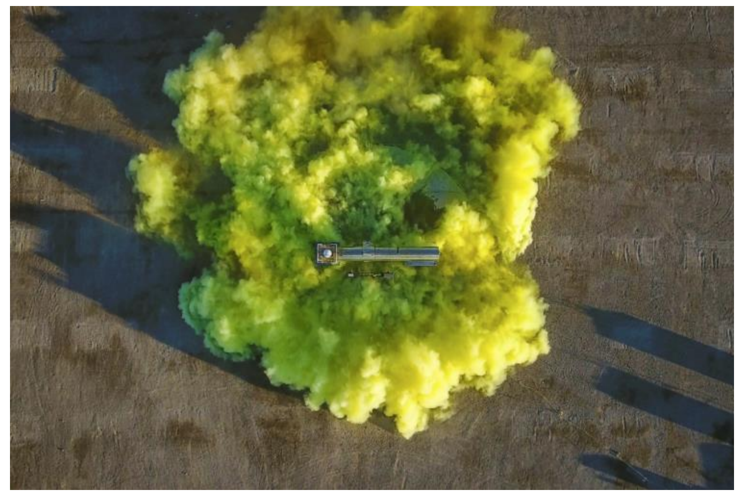
KEYWORDS
anhydrous ammonia, chlorine, dense gas dispersion, hazards analysis, health risk, Jack Rabbit II field experiment, TIC

http://dx.doi.org/10.1002/prs.12289

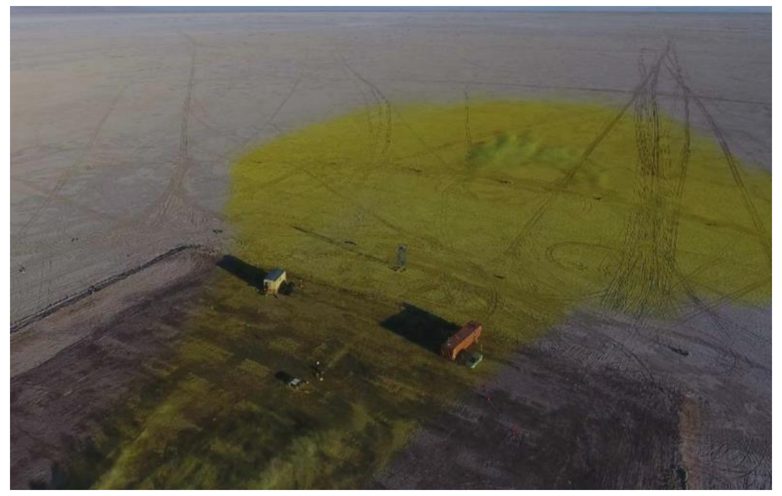
Ongoing HSE research activities

- 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

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

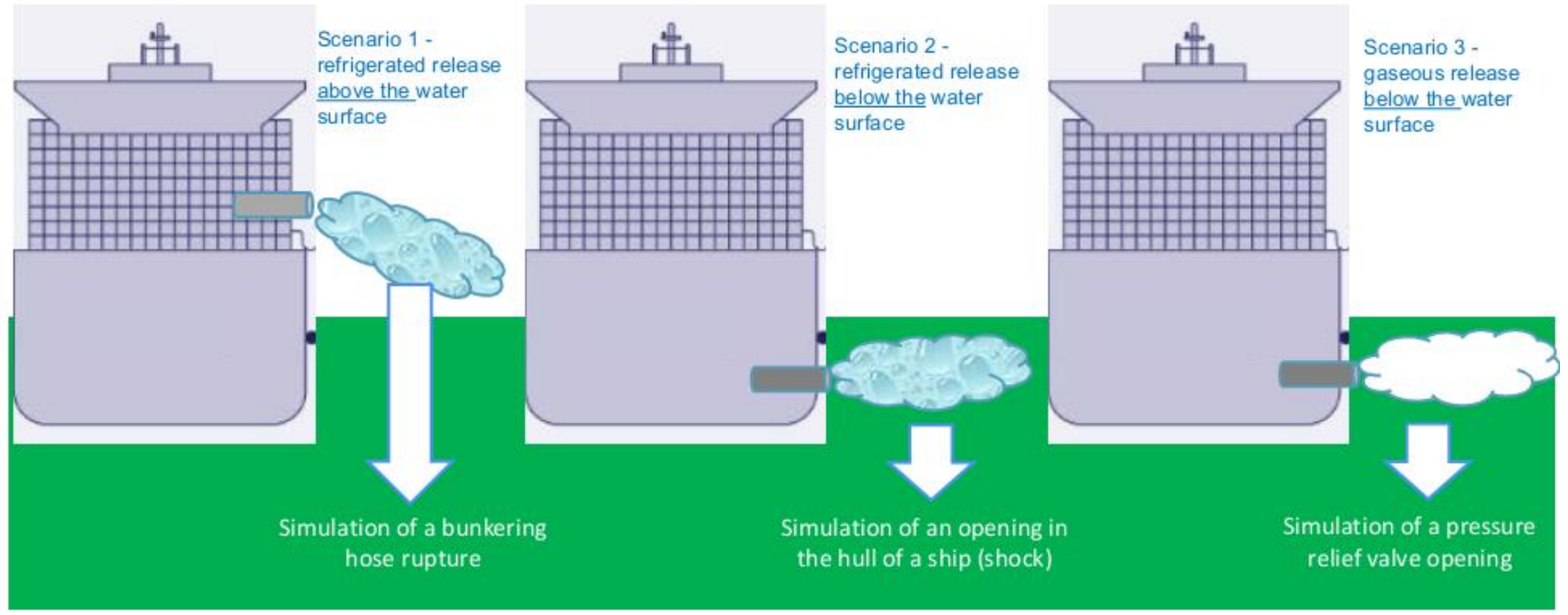





Images © DHS S&T CSAC and Utah Valley University
https://www.uvu.edu/es/jack-rabbit/

Ongoing HSE research activities

- HSE is partner in the ARISE Joint Industry Project led by INERIS, Cedre and Yara
- 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
- Tests planned for 2024-2025
- Contact: Laurent.Ruhlmann@yara.com



ARISE
Ammonia Response In Sea Emergencies

Skylark CO_2 Dispersion Project

Simon Gant, Zoe Chaplin and Rory Hetherington (Health and Safety Executive, UK)
Daniel Allason, Karen Warhurst, Ann Halford, Mike Harper, Jan Stene and Gabriele Ferrara (DNV)
Tom Spicer (University of Arkansas, USA)
Ed Sullivan (National Chemical Emergency Centre, UK)
Justin Langridge and Matthew Hort (Met Office, UK)
Steven Hanna (Hanna Consultants, USA)
Joe Chang (RAND Corporation, USA)
Gemma Tickle (GT Science and Software, UK)

API Pipeline Conference, Salt Lake City, Utah, USA, 6-8 May 2024

Dense gas Terrain Modelling (DTM) project

- **Aim**: to develop a fast-running dense gas dispersion model that can simulate CO_2 pipeline releases in complex terrain, for use in risk assessment and emergency response

Motivation

The development of Carbon Capture and Storage (CCS) infrastructure in the UK requires that new operational capabilities for dense-gas dispersion modelling be developed. For HSE, this capability is needed for the purpose of providing public safety advice on land-use planning to local authorities along the proposed routes of CO_2 pipelines and, potentially, around fixed installations, such as CO_2 capture plants. The Met Office delivers advice to emergency responders dealing with airborne hazards, such as potential future large-scale CO_2 accidents. Currently, the Met Office operate the CHEMET service using their NAME model for this purpose, but this model cannot simulate dense clouds, and an additional modelling capability would be needed to deliver such a service

RISKAWARE
ESR Technology Engineering, Safety & Risk
GT Science & Software
Met Office
HSE
[dstl]

Deliverable

The model developers Riskaware, ESR Technology and GT Science & Software will deliver:

- Dispersion models that have been configured to simulate CO_2 releases from pipelines in complex terrain, with facilities to import UK terrain data.
- Documentation including a description of the underpinning physics, a software user guide and results from their model validation.

HSE, the Met Office and Dstl will deliver an evaluation of the models. This will consider the performance of the models (in terms of accuracy and speed) and the steps needed to integrate the models within their own systems.

Ultimately, the two models may prove to be complementary, with one model providing a quick solution for scoping studies and the other providing more granular detail of the CO_2 dispersion behaviour at higher computational cost. This will only become clear through the course of the project.

Timescale

The DTM modelling project will run alongside the Skylark experimental project. It will start in Summer 2024 and run for three years until Summer 2027.

Outline costs

ROM costs are currently estimated as £2-3 million, spread over three-year project duration.

Thank you

<Play Thorney Island videos>

https://xnet.hsl.gov.uk/fileshare/public/3586/thorney-island-selection-v1-wmv.wmv
https://xnet.hsl.gov.uk/fileshare/public/3587/em00067-thorney-island-full-programme-edit-1982.mp4

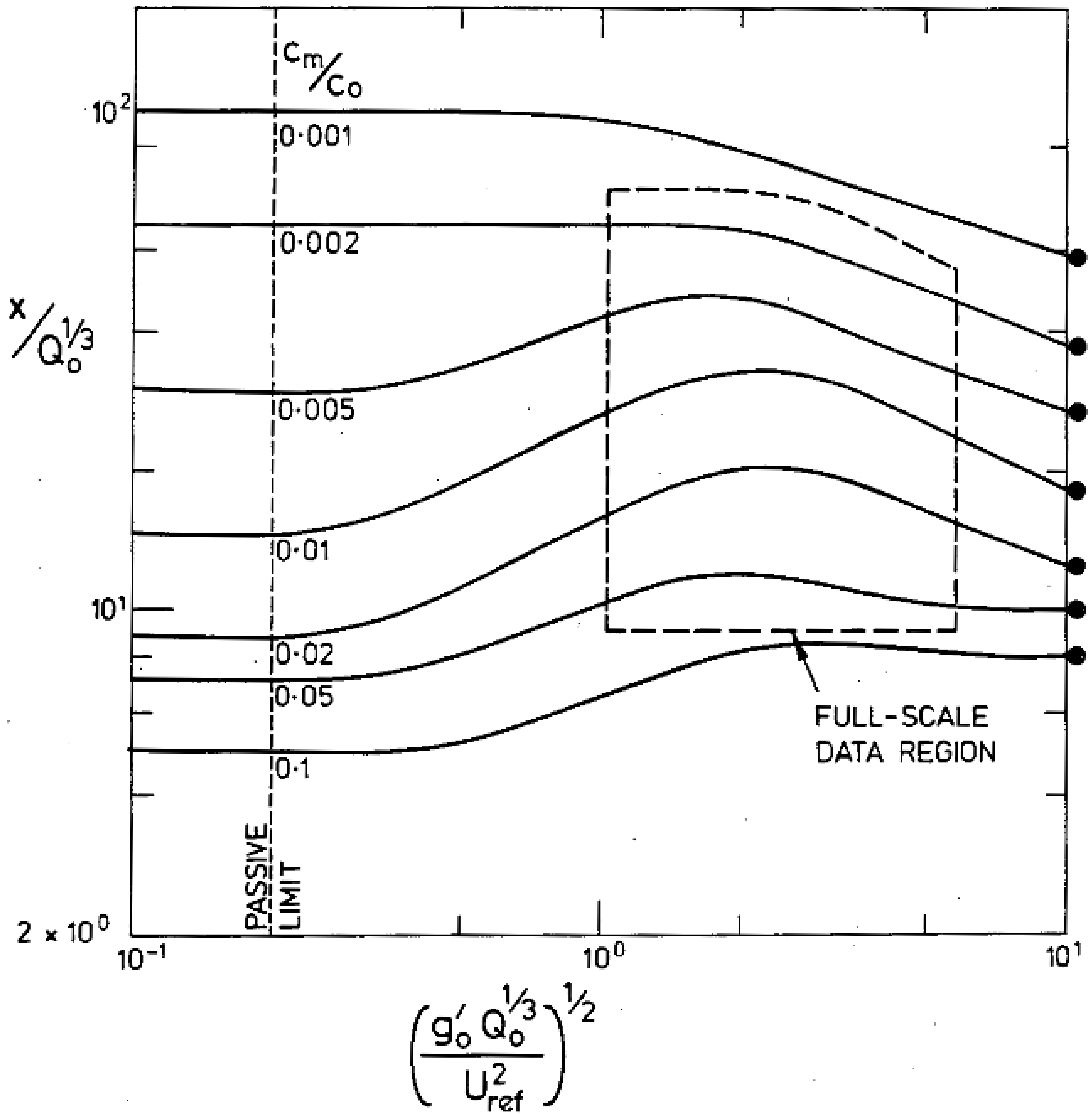
- The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy
- Contact information: simon.gant@hse.gov.uk

Extra material

Britter and McQuaid (1998)

Investigating issues with the vertical axis scale Figure 11

Simon Gant, 29 May 2019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10^2
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$x/Q_o^{1/3}$
PASSIVE LIMIT
FULL-SCALE DATA REGION
10^{-1}
10^0
10^1
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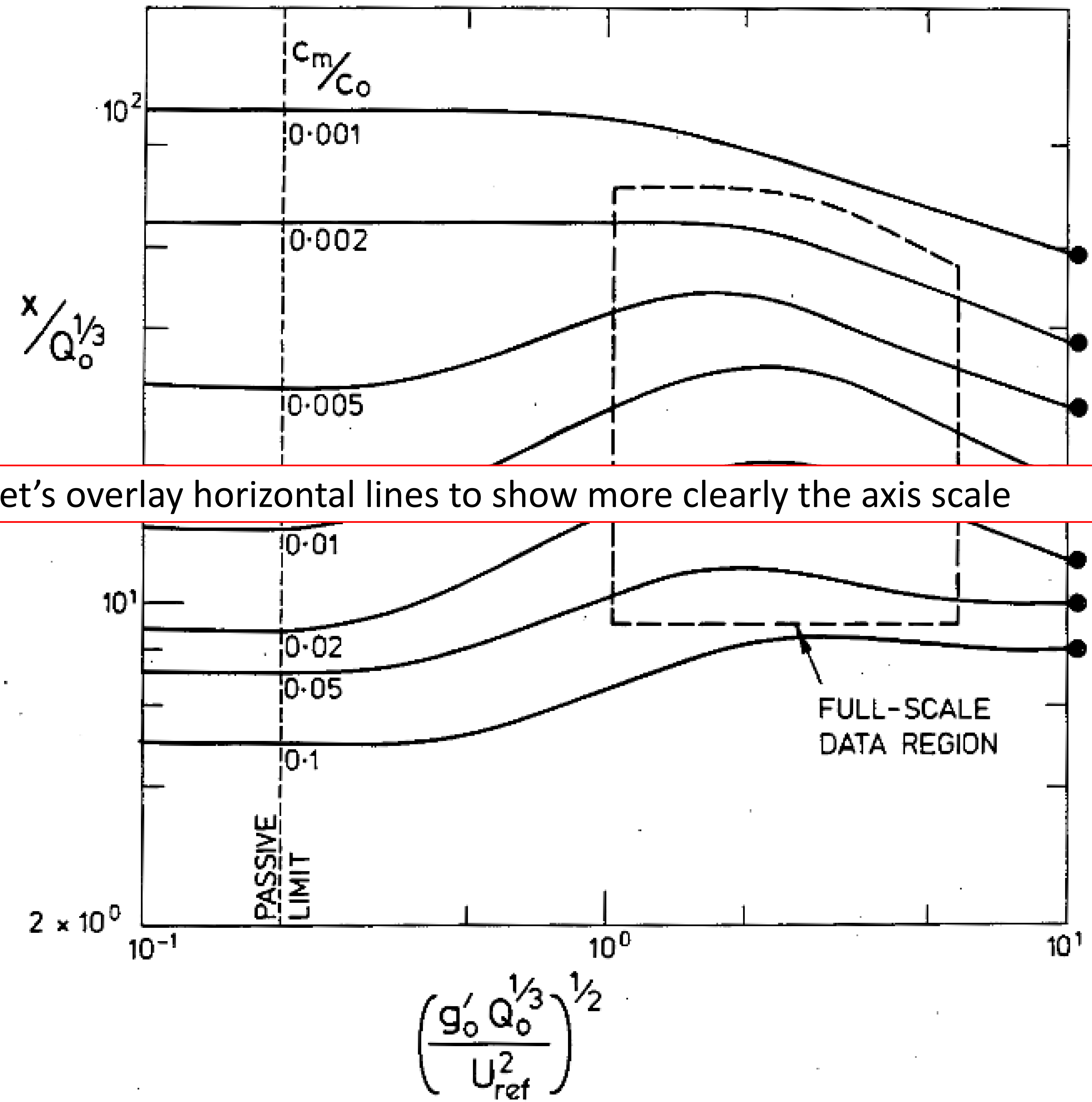
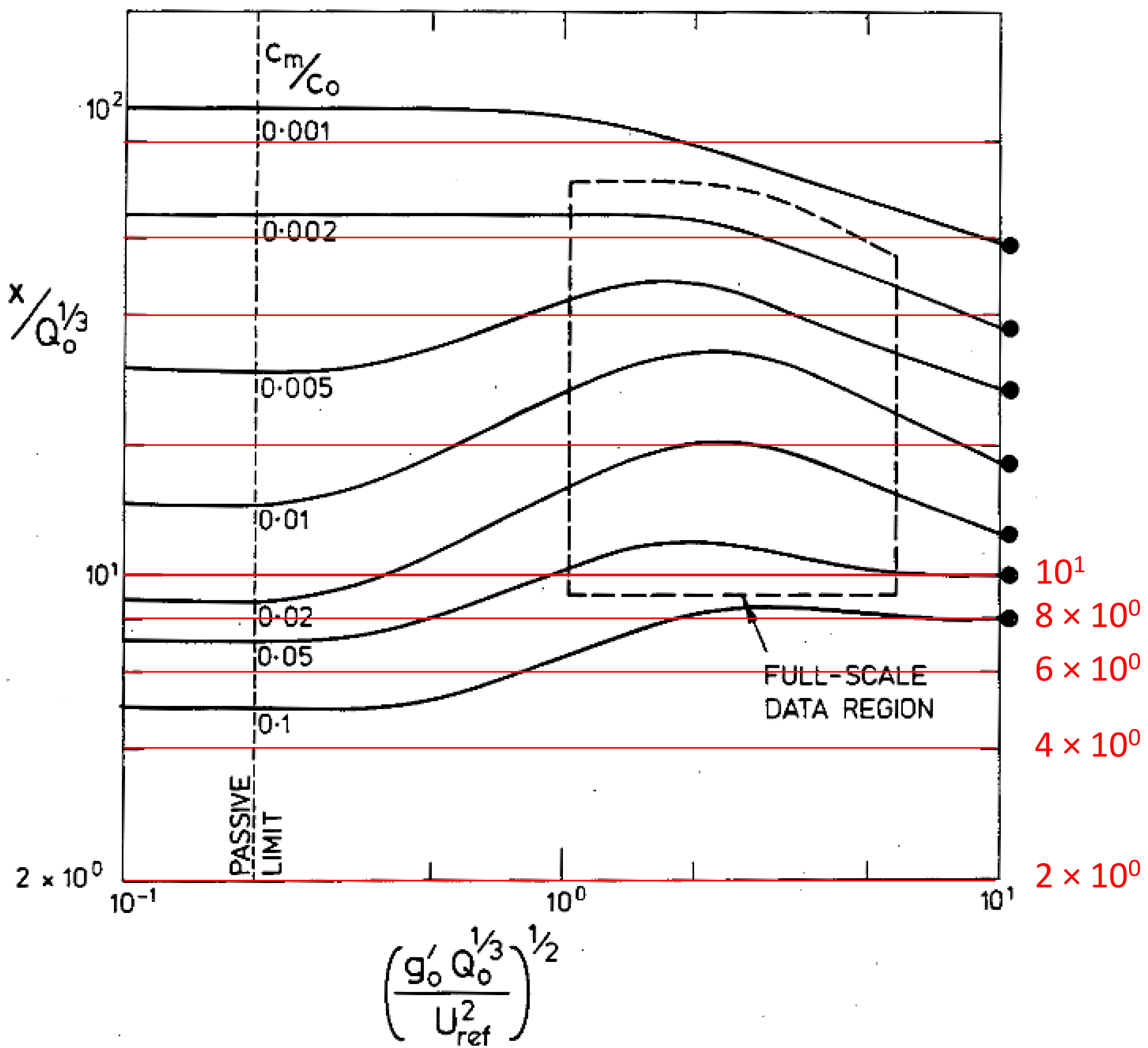


Let’s overlay horizontal lines to show more clearly the axis scale



c_m/c_o
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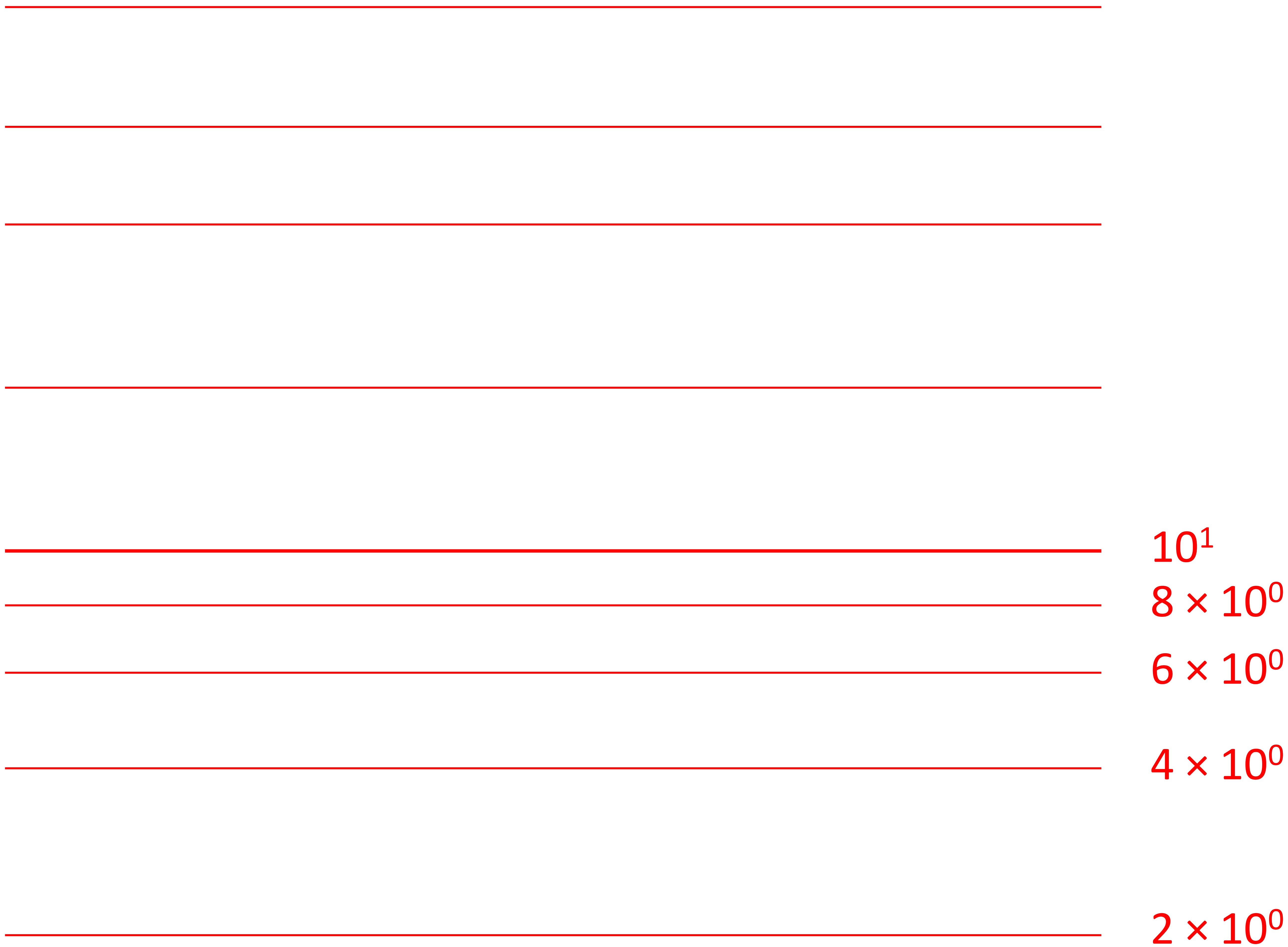
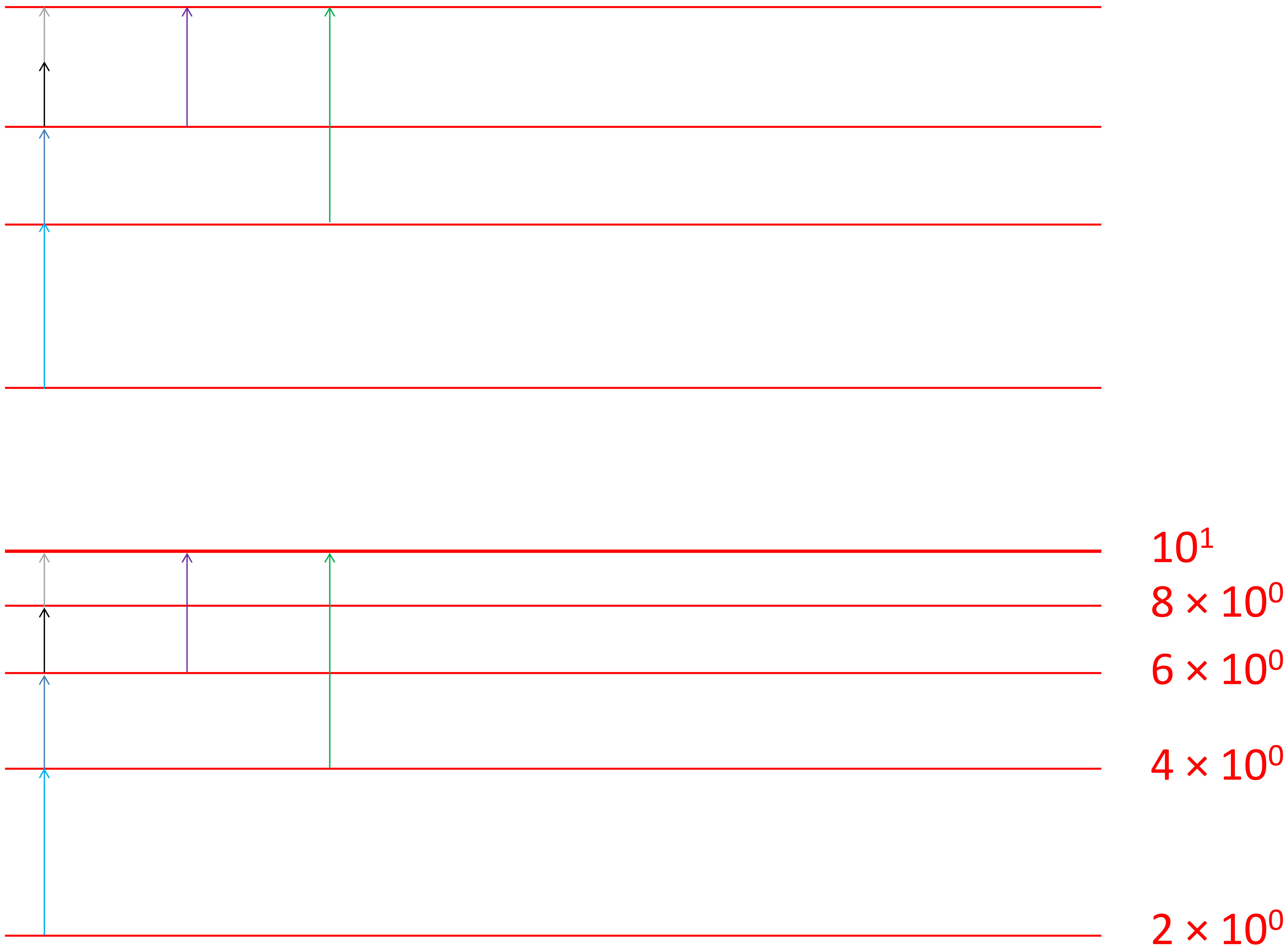
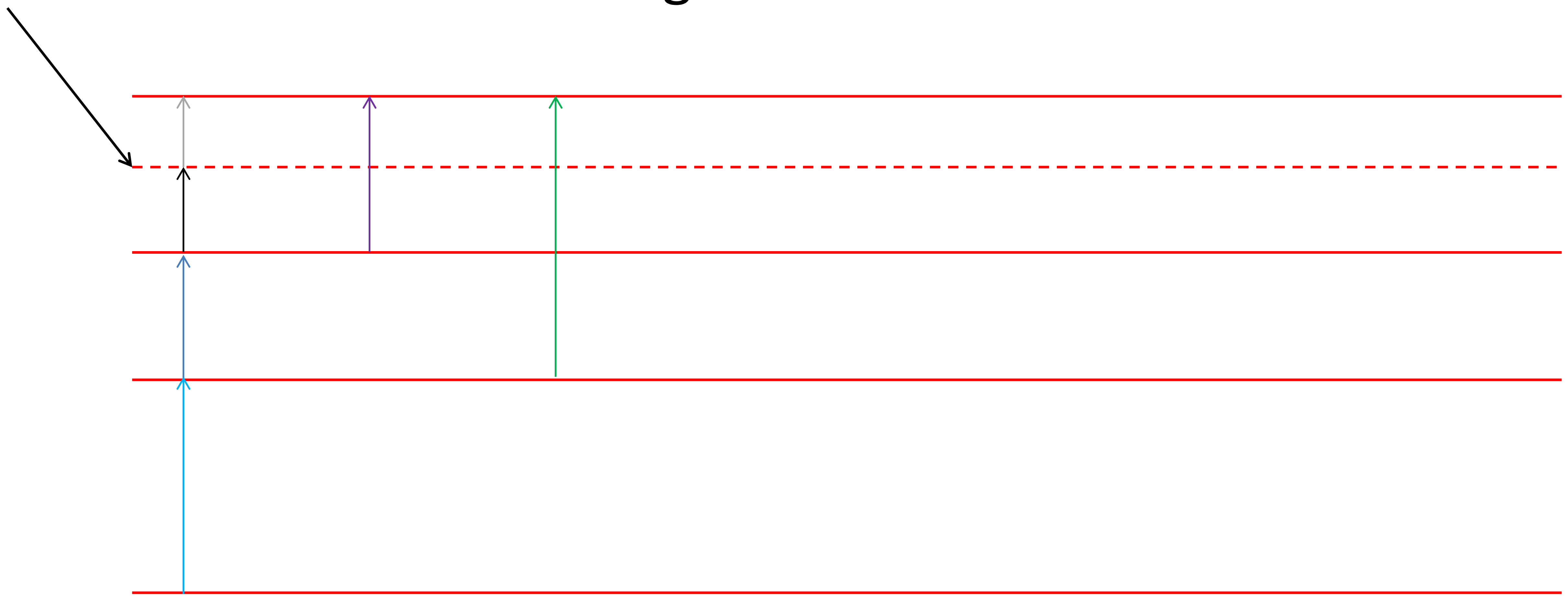
$\left(\frac{g_o' Q_o^{1/3}}{U_{ref}^2}\right)^{1/2}$
PASSIVE LIMIT
FULL-SCALE DATA REGION

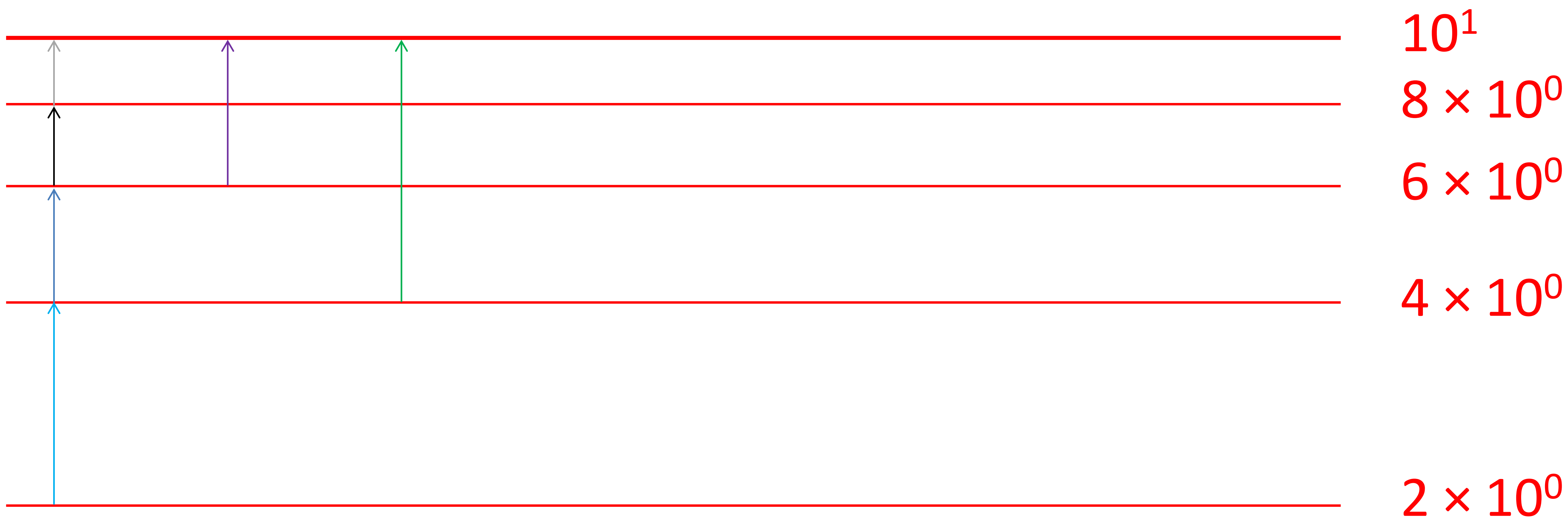


Let’s measure distances between these lines and compare the lower range from 2×10^0 to 10^1 with the upper range

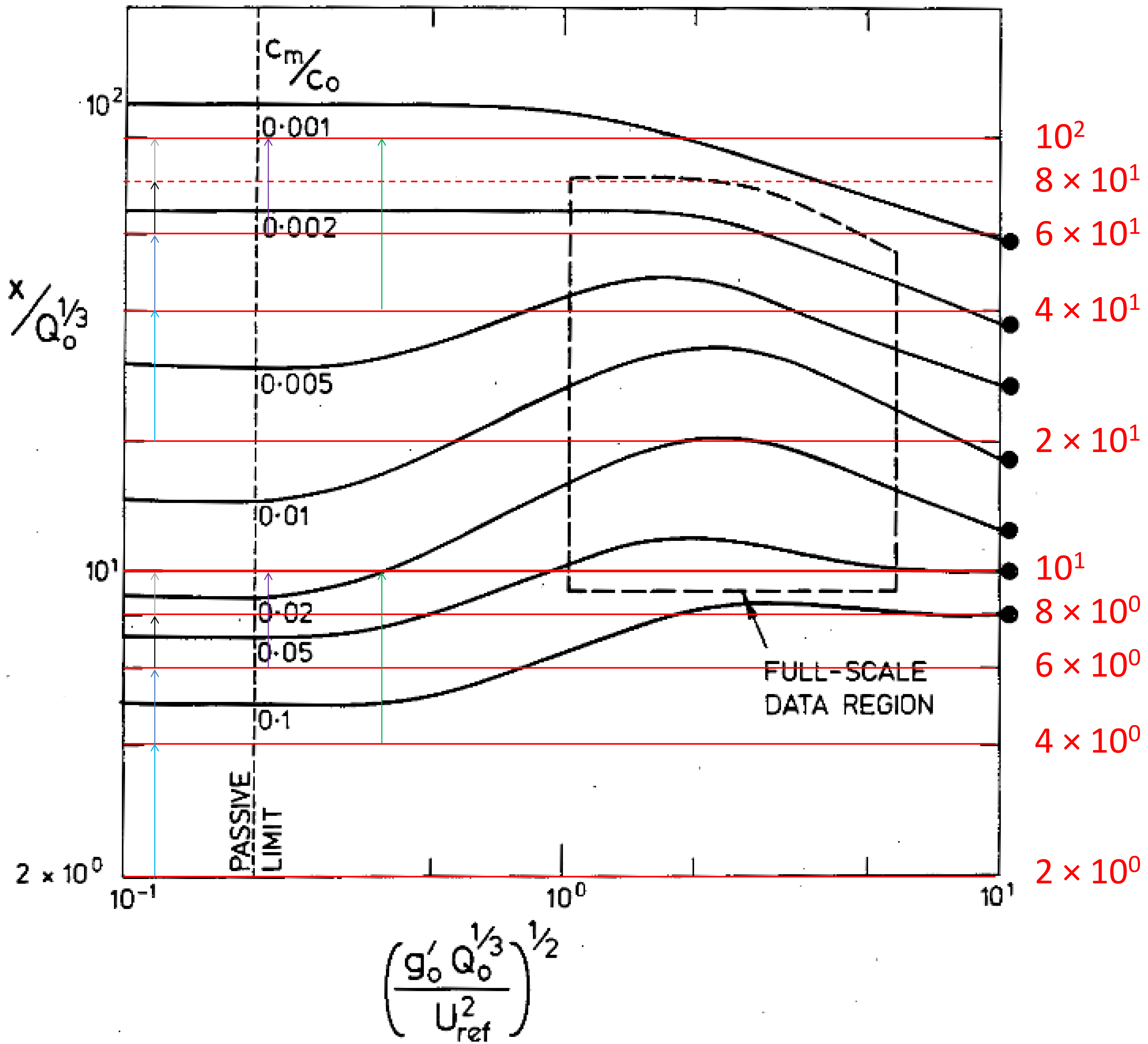

10^1
8×10^0
6×10^0
4×10^0
2×10^0

It looks like this dashed line is missing…





Let’s superimpose that back on the Britter and McQuaid figure



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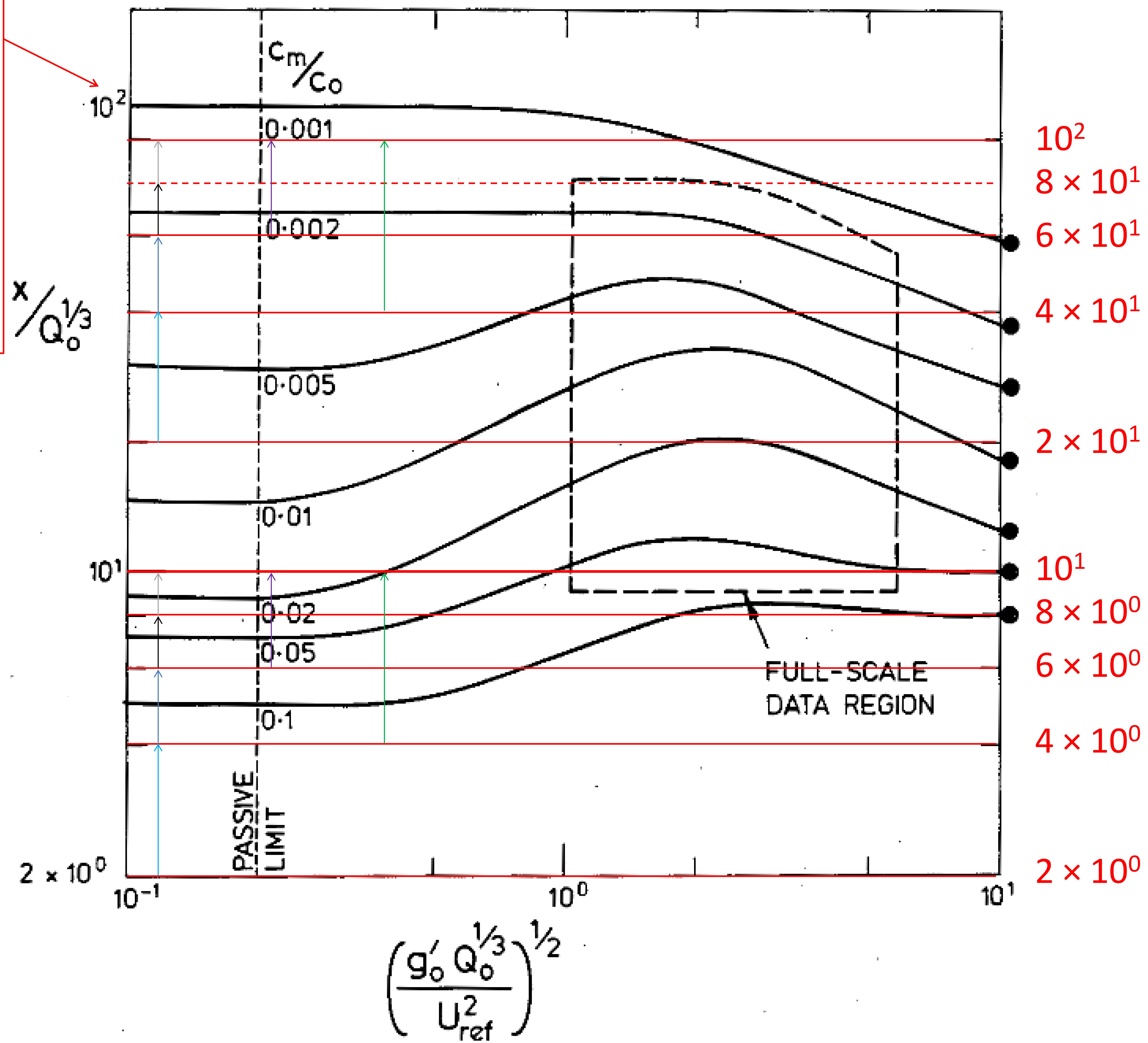
10^1
2×10^0
10^{-1}
10^0
10^1
$\left(\frac{g'_o Q_o^{1/3}}{U_{ref}^2}\right)^{1/2}$
PASSIVE LIMIT
FULL-SCALE DATA REGION
10^2
8×10^1
6×10^1
4×10^1
2×10^1
10^1
8×10^0
6×10^0
4×10^0
2×10^0

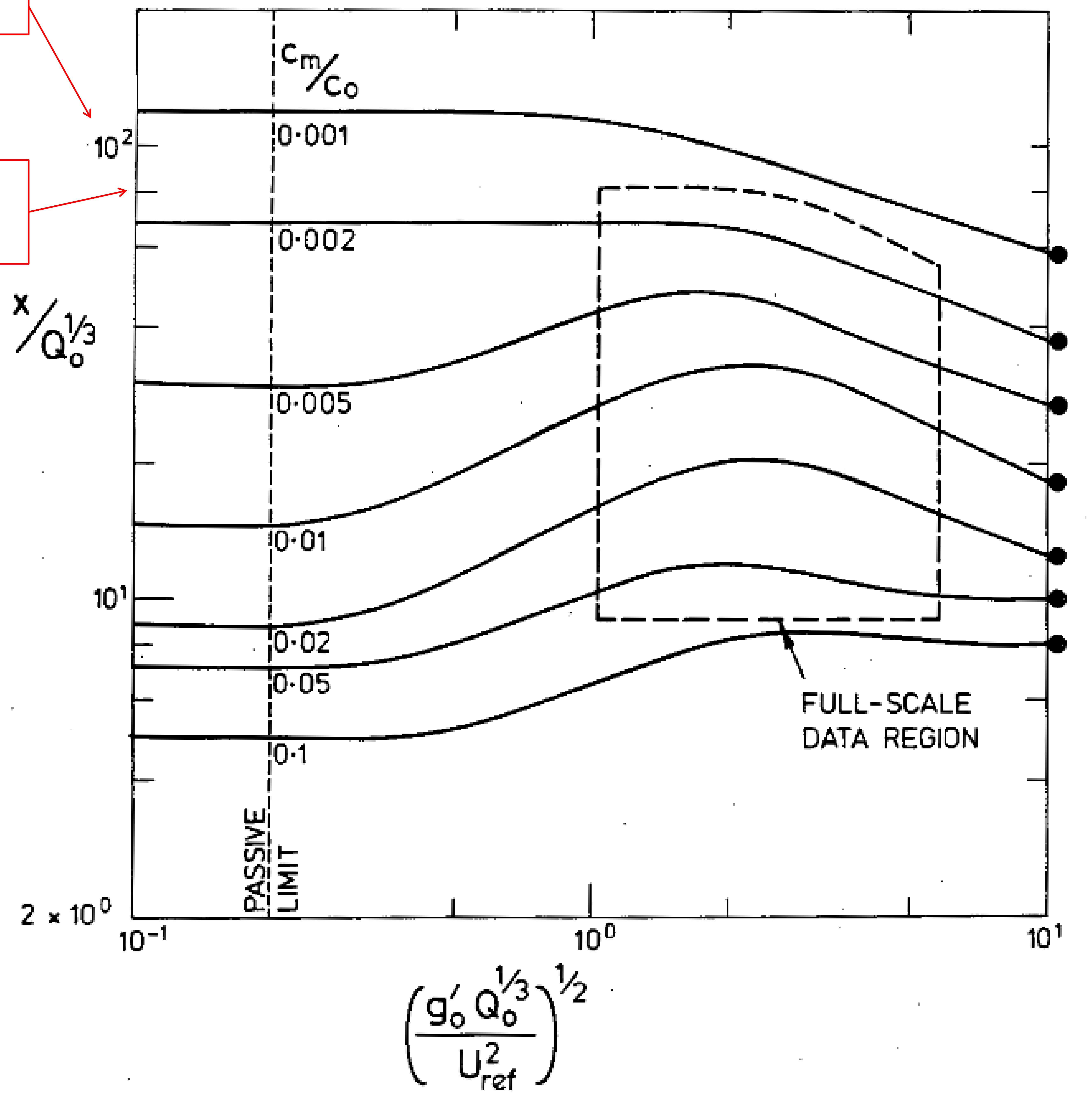
This text "10^2" should be moved down to the nearest tick mark below

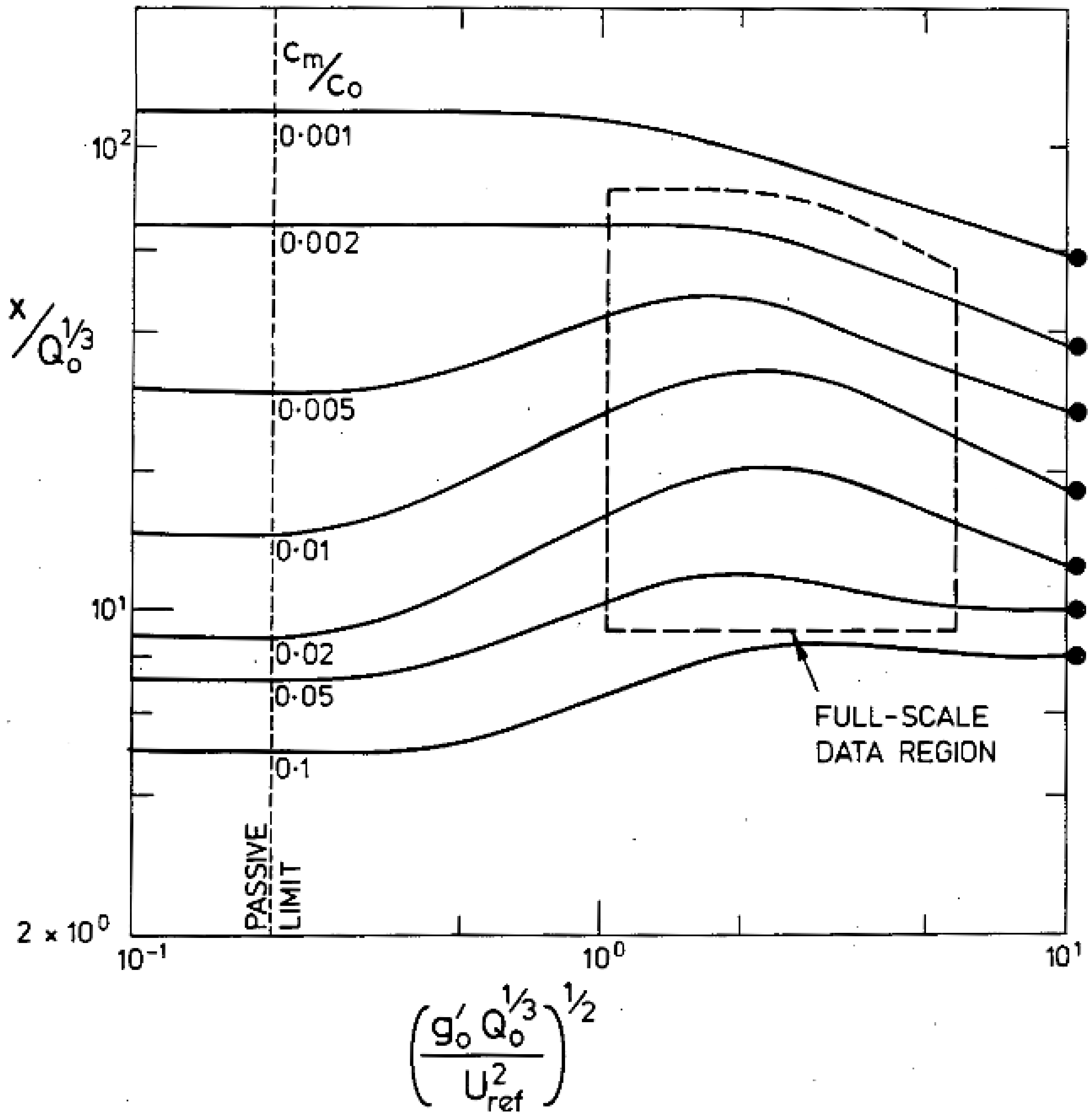


Corrected version

“10^2” moved

Missing tick added





c_m/c_o
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0·005
0·01
0·02
0·05
0·1
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10^1
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10^{-1}
10^0
10^1
$x/Q_o^{1/3}$
$\left(\frac{g'_o Q_o^{1/3}}{U_{ref}^2}\right)^{1/2}$
PASSIVE LIMIT
FULL-SCALE DATA REGION