PROTECTING PEOPLE AND PLACES FOR 50 YEARS HSE

Summary of research activities on ammonia safety at HSE

Simon Gant, Strategic Science Adviser for Net Zero

Fourth EU+OECD Hydrogen Fuel Risks Webinar, with a focus on ammonia, 11 March 2025

Outline

- Introduction to HSE
- Why are we interested in ammonia safety?
- Quick overview of ammonia safety issues
- Research questions
- Recent activities and ongoing research projects

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
- In 2022-23, HSE investigated over 230 fatal and 5,500 non-fatal incidents
- 2,700 total staff (FTE): £262M annual budget, 66% from Government

- 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

Why is HSE interested in ammonia safety?

- Growth in use of ammonia to meet Net Zero targets
  - Ammonia as a clean energy vector, to transport and store clean hydrogen
  - Ammonia as a decarbonised fuel, especially in the marine industry
- New applications and new users who may be unfamiliar with ammonia risks

By 2025 we expect that:

i. All vessels operating in UK waters are maximising the use of energy efficiency options. All new vessels being ordered for use in UK waters are being designed with zero emission propulsion capability.

ii. Zero emission commercial vessels are in operation in UK waters.

iii. The UK is building clean maritime clusters focused on innovation and infrastructure associated with zero emission propulsion technologies, including bunkering of low or zero emission fuel.

By 2035 we expect that:

iv. The UK has built a number of clean maritime clusters. These combine infrastructure and innovation for the use of zero emission propulsion technologies. Low or zero emission marine fuel bunkering options are readily available across the UK.

July 2019

- Under the assumptions made in the research, ammonia is estimated to be more cost-effective than methanol or hydrogen for most ship types.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf

Published by the previous Conservative UK Government


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Ammonia-powered vessel docks in Southampton

The Singapore-flagged vessel Fortescue Green Pioneer docked at the Port of Southampton on Saturday

2 March 2025

https://www.bbc.co.uk/news/articles/c2er3dv9rj0o

https://www.gov.uk/government/news/worlds-first-dual-fuel-ammonia-powered-vessel-arrives-in-the-uk

Projections for growth in use of ammonia as a shipping fuel

Climate Change Committee

February 2025

The Seventh Carbon Budget

Advice for the UK Government

– By 2040, the Balanced Pathway sees ammonia meet 22% of shipping energy use and synthetic fuels a further 17%, predominantly from synthetic methanol.

- **Ammonia (22% of shipping energy use in 2040).** Low-carbon ammonia is not yet used in ships and enters the shipping energy mix in our pathway from 2028. Ammonia is globally traded today, but it is toxic and requires specific handling skills and storage systems, and is therefore only used on cargo ships in our pathway.[178;179]

- **Ammonia:** given the global nature of the shipping market, shipping fuels are currently predominantly supplied via international bunkering hubs. The Balanced Pathway assumes a continuation of this approach, with ammonia for use in shipping similarly supplied by the international market. This therefore means domestic hydrogen is not required for production of ammonia for use in UK shipping in our pathway.

https://www.theccc.org.uk/publication/the-seventh-carbon-budget/

DNV

WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK UK 2025

A national forecast to 2050

from international ships bunkering in UK ports. In 2021, 85% of maritime energy demand went into international marine bunkers. Maritime energy demand is expected to peak by 2027 (at 5% above today's level) and decline slowly afterwards due to energy efficiency improvements. By 2050, we expect UK maritime energy demand to be 26% less than today.

with ammonia starting to be adopted by 2030. The maritime energy mix will be a lot more varied by 2050 (Figure 3.11) and consist of 25% ammonia, 12% synthetic e-fuels, 11% bioenergy and the remaining share made up of oil, natural gas, and electricity.

https://www.dnv.com/energy-transition-outlook/uk

Ammonia storage at ports

Stanlow
https://www.stanlowterminals.co.uk/stanlow-terminals-at-the-heart-of-global-hydrogen-energy-transition-with-development-of-open-access-green-ammonia-import-terminal/

Immingham
https://imminghamget.co.uk/
https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/TR030008

Shoreham
https://www.shoreham-port.co.uk/need-to-know/news/shoreham-port-and-getech-move-forward-with-five-year-commitment-to-green-energy-hub-partnership-2095/

© Google Maps

Antwerp-Brugge
https://advario.com/driving-europes-hydrogen-strategy-fluxys-and-advario-join-forces-to-develop-a-green-ammonia-import-terminal-at-the-port-of-antwerp-bruges/
https://www.fluxys.com/en/projects/ammonia-antwerp-terminal

Herøya
https://www.yara.com/yara-clean-ammonia/

Esbjerg
https://hoestptxesbjerg.dk/

Brunsbüttel-Hamburg
https://www.ammoniaenergy.org/articles/large-scale-ammonia-imports-to-hamburg-brunsbuttel/
https://www.hafen-hamburg.de/en/port-of-hamburg-magazine/future-energy/clean-ammonia-for-hamburg/

Rotterdam
https://www.ammoniaenergy.org/articles/preparing-the-netherlands-for-large-scale-ammonia-imports/
https://www.gasunie.nl/en/projects/ace-terminal

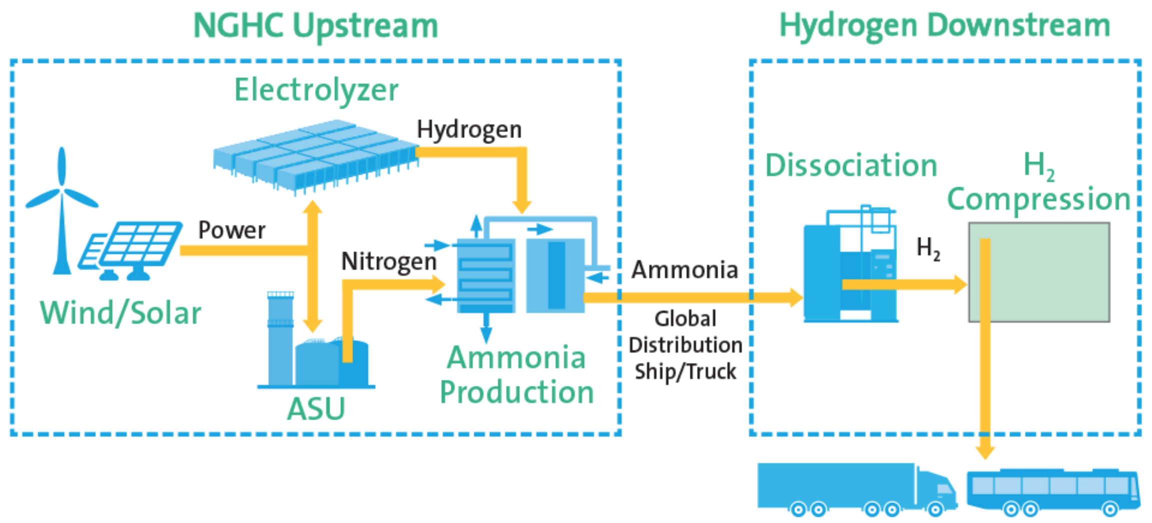
Clean ammonia production facilities

Air Products NEOM (Saudi Arabia)

Green ammonia, due to start operating 2026

Solar/wind farm covering 150 km^2 area

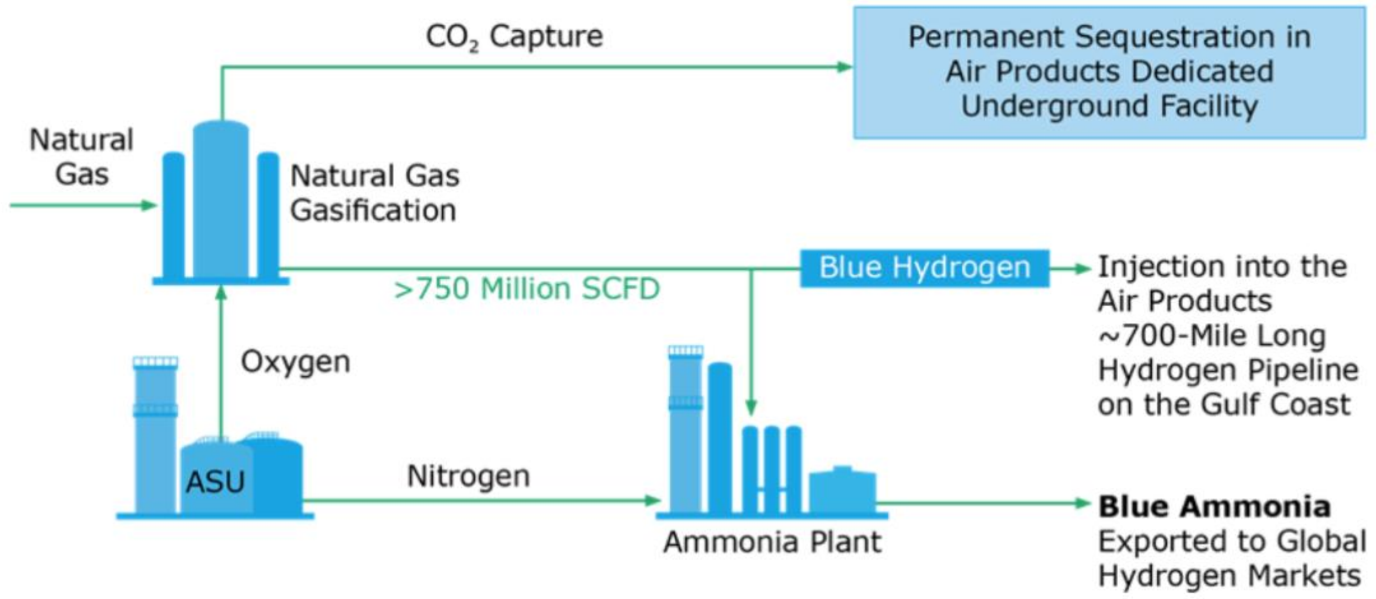
1.2 Mt/yr ammonia to be exported to by ship to Rotterdam, Hamburg and Immingham



https://www.airproducts.com/energy-transition/neom-green-hydrogen-complex

Air Products Louisiana Clean Energy (USA)

$4.5bn investment for blue hydrogen and ammonia, due to start operating in 2026



https://www.airproducts.com/energy-transition/louisiana-clean-energy-complex

HEGRA (Norway)

HErøya GReen Ammonia

Aim to electrify ammonia plant owned by Yara, Aker and Statkraft

https://www.yara.com/yara-clean-ammonia/

HØST PtX Esbjerg (Denmark)

Green hydrogen and ammonia

FID in 2025, operating 2028

https://hoestptxesbjerg.dk

Barents Blue (Norway)

Commercial progress for the Barents Blue project

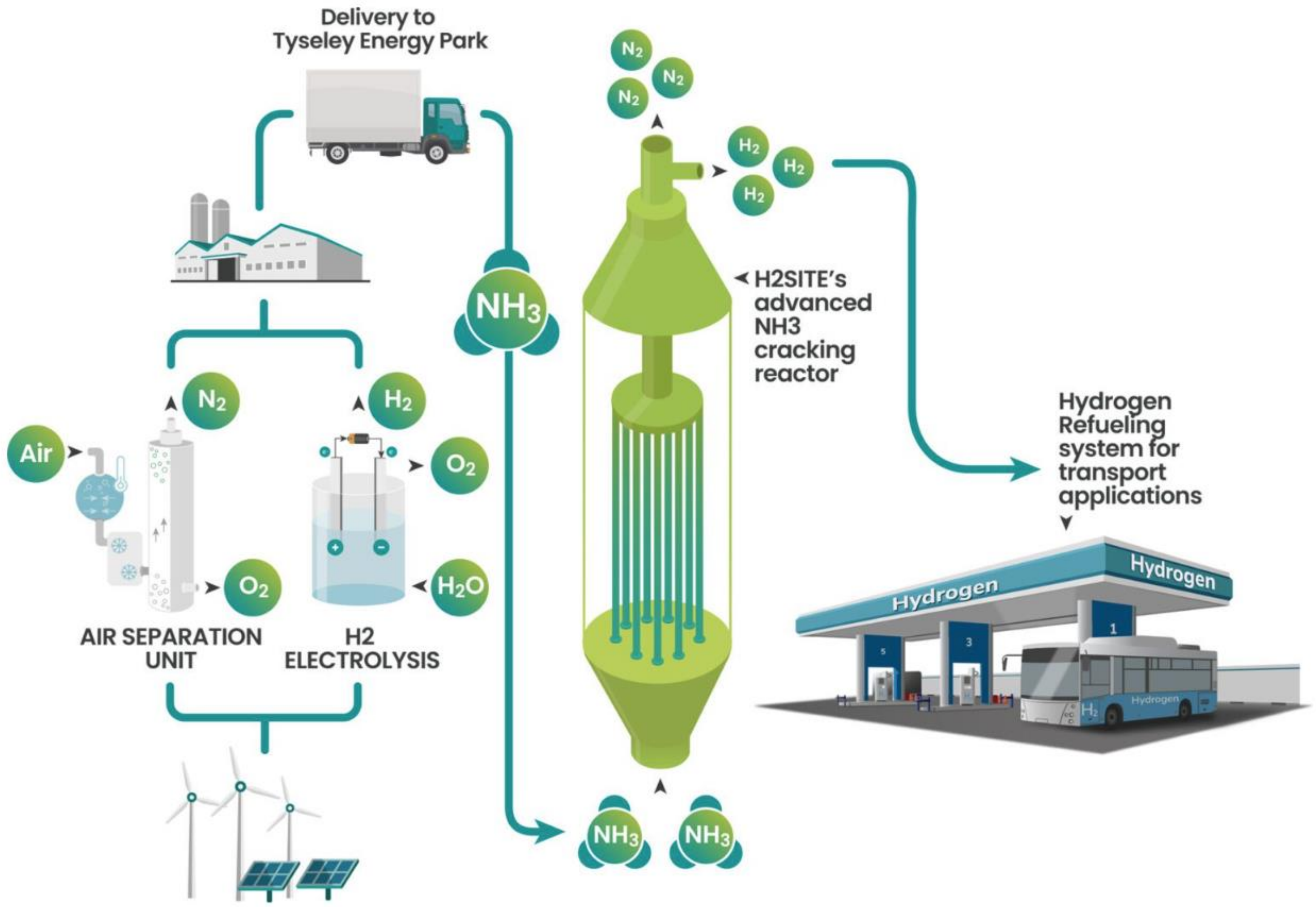
11. February 2025

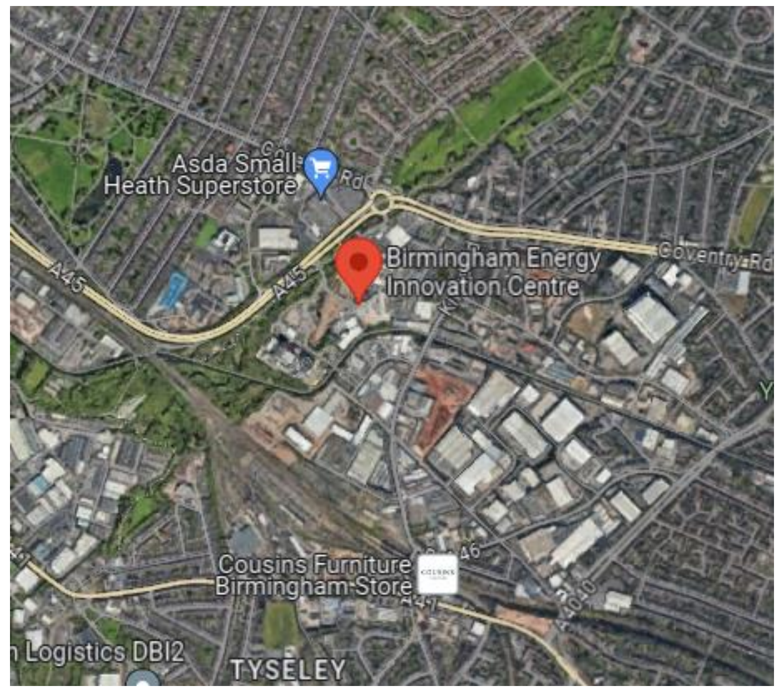
https://horisontenergi.no/projects/barents-blue/

Potential new uses of ammonia

- £6.7 million from the Department for Business, Energy and Industrial Strategy (BEIS)
- Principle: distribute ammonia to local vehicle refuelling stations where it is cracked to hydrogen
- Site was operated from April to December 2024
- Demonstrated successful operation of ammonia cracker
- Ammonia transported to site via road in 530 kg barrels
- Up to 10 tonnes of ammonia storage on site
- 200 kg/day produced hydrogen, which was flared due to issues contracting with hydrogen vehicle refuelling facility
- Scrubber in vent used to remove ammonia slip in vented gases

https://ammogen.co.uk/





Potential new uses of ammonia

AMBURN
https://amburn.co.uk

Amburn: ammonia for heating at commercial/industrial sites not connected to gas network

- Burning ammonia is cheaper than hydrogen
- Biofuels do not offer a long-term, scalable solution
- Direct electrification requires significant grid upgrades, which can be costly and has long lead times
- Heat pumps are unsuitable for high temperature operations (>150 °C)

Amburn partners: Flogas, Enertek, Cardiff University and Element Energy, ERM

Phase 1: feasibility study funded by BEIS, ended 2022

Phase 2: demonstration 1 MW ammonia-fired boiler (awarded £3.4m funding from DESNZ)

Centrica Energy, Bord Gáis Energy and Mitsubishi Power Announce Development of Europe's First Ammonia Fired Power Generation Facility

29 NOVEMBER 2023

Bord Gáis Energy's Whitegate Combined Cycle Gas Turbine (CCGT) power station in Cork, Ireland. Centrica and Mitsubishi Power Europe Limited have signed a Memorandum of Understanding to explore the development, construction, and operation of Europe's first-ever ammonia-fired power generation facility at Bord Gáis Energy's Whitegate Combined Cycle Gas Turbine (CCGT) power station in Cork, Ireland. Photo: Bord Gáis Energy

https://www.centrica.com/media-centre/news/2023/centrica-energy-bord-gais-energy-and-mitsubishi-power-announce-development-of-europes-first-ammonia-fired-power-generation-facility/

https://www.bordgaisenergy.ie/news/20232911

Onshore transport of ammonia

RWE and VTG develop logistics concept for ammonia: from import terminal to customer by rail

- Customers in Germany and the Netherlands can be reached without pipelines or inland ports
- Investigation of supply routes and required filling and transport capacities underway

Essen/Hamburg, 13 February 2023

News on RWE's planned green import terminal for ammonia in Brunsbüttel: RWE plans to use rail transport for the onward journey of this fuel. To this end, the company is working with the global logistics company VTG to deliver the ammonia by tank wagon to customers in Germany and neighbouring countries. The two companies today signed a Memorandum of Understanding (MoU) to this effect.

https://www.rwe.com/en/press/rwe-supply-and-trading/2023-02-13-rwe-and-vtg-develop-logistics-concept-for-ammonia/

wsp | North Sea Port | smart delta resources | Provincie Zeeland

14 November, 2024

Publication of main conclusions of the ammonia network study

Ammonia transmission pipelines in the Netherlands, Belgium and Germany

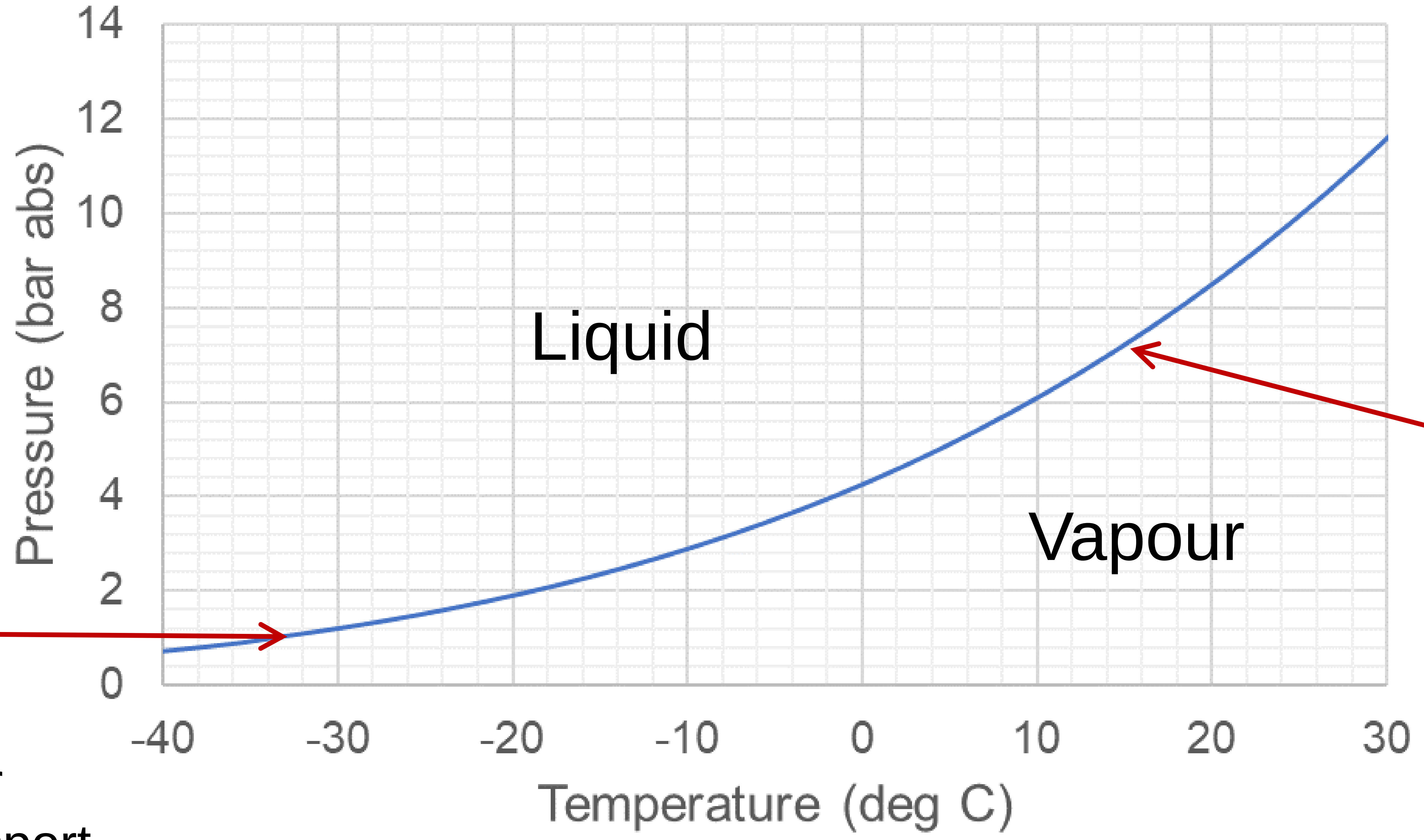
In March 2024, North Sea Port, Smart Delta Resources and the Province of Zeeland decided to conduct a feasibility study into an ammonia network from the port of Vlissingen to the hinterland in Germany, the Netherlands and Belgium. The study shows that transport via pipeline can be done safely and is economically feasible, provided that a number of conditions are met.

https://www.waterstofnet.eu/en/news/feasibility-study-for-ammonia-network-in-north-sea-port
https://www.smartdeltaresources.com/en/node/162

Ammonia storage and transport conditions

At normal atmospheric pressure of 1.01 bar, the boiling point of ammonia is -33°C

Conditions usually used for bulk storage and ship transport



At a typical atmospheric temperature of say 15°C, a pressure of 7.2 bar will liquefy ammonia

Conditions typically used for road, rail and pipeline transport

https://webbook.nist.gov/cgi/cbook.cgi?ID=C7664417&Mask=4#Thermo-Phase

Stull D.R. (1947) *Vapor Pressure of Pure Substances*. Organic and Inorganic Compounds, Ind. Eng. Chem., 39, 4, 517-540, https://doi.org/10.1021/ie50448a022

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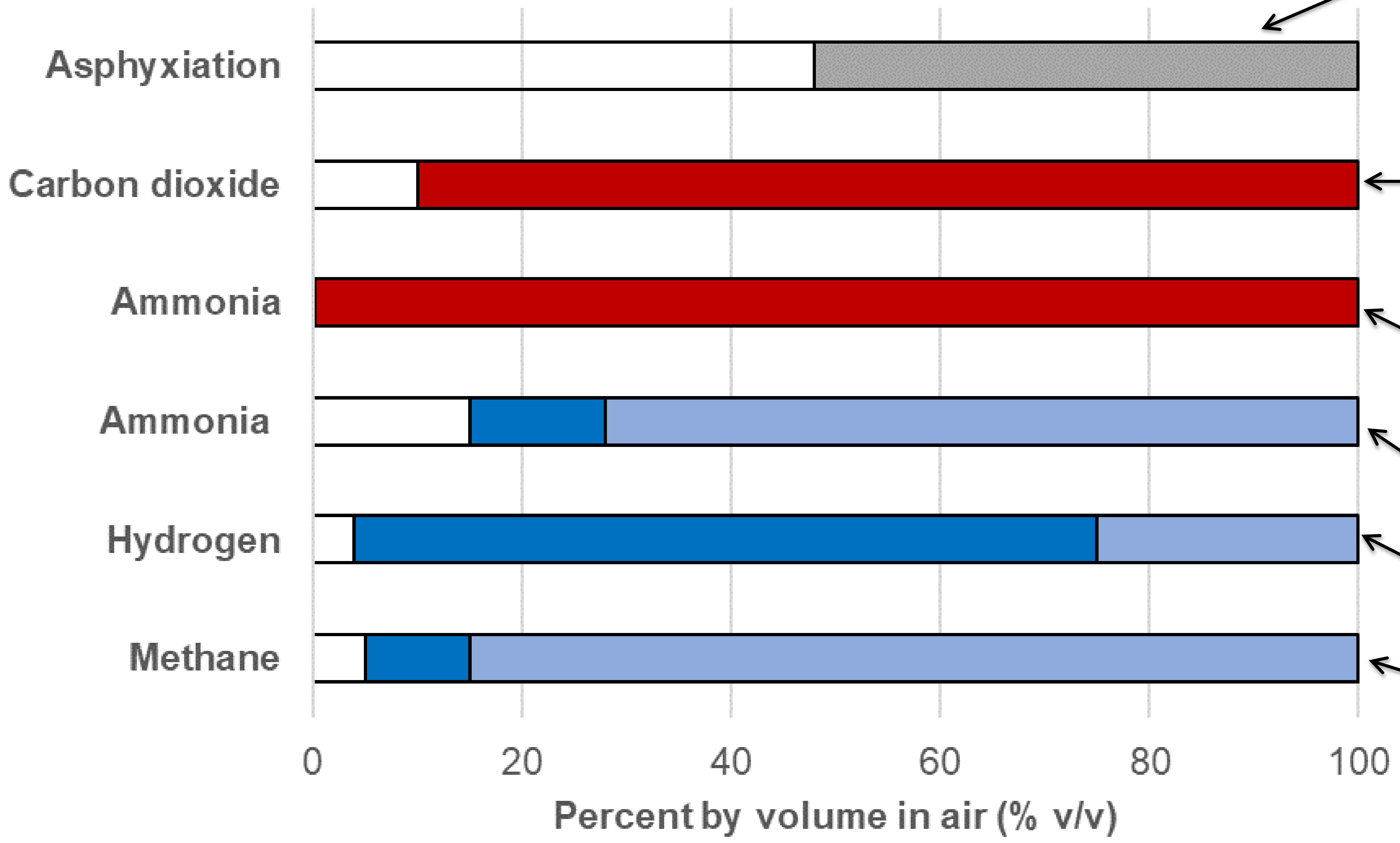
Comparison of ammonia hazard thresholds

Asphyxiation: possibility of fainting within a few minutes without warning and risk of death with < 11% v/v oxygen (which equates to > 48% v/v of an inert gas) https://www.eiga.eu/ct_documents/doc044-pdf



Carbon dioxide has lethal effects with CO_2 concentrations > 10% v/v
https://www.eiga.eu/uploads/documents/SI024.pdf
https://www.rivm.nl/sites/default/files/2018-11/20091002_Evaluation_toxicity_CO2.pdf

Ammonia AEGL-3 (10-minute exposure) is 2,700 ppm or 0.27% v/v
https://www.epa.gov/aegl/ammonia-results-aegl-program

Ammonia flammable range 15 – 28% v/v

Hydrogen flammable range 4 – 75% v/v

Methane flammable range 5 – 15% v/v
https://www.osti.gov/biblio/7355338/

Too dilute to burn | Flammable | Too rich to burn (but could ignite if diluted) | Toxic (AEGL-3) or equivalent life-threatening health effects or death

Ammonia is detectable by smell at ~ 17 ppm
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/290981/scho0307bmkt-e-e.pdf

See AIHA for alternative occupational exposure levels www.aiha.org

Ignition of ammonia and hazardous area classification

	Methane, CH_4	Hydrogen, H_2	Ammonia, NH_3	Carbon Dioxide, CO_2
Boiling point[†a] (°C)	-161	-253	-33	-78
Dynamic viscosity[*a] (μPa.s)	11	8.7	9.7	14
Specific heat capacity at constant pressure[*a] (kJ/kg.K)	2.2	14	2.2	0.8
Burning velocity[b] (m/s)	0.37	3.2	?	–
Detonation cell size[c] (mm)	250 – 310	15	?	–
Autoignition temperature[bc] (°C)	595	560	651	–
Minimum ignition energy[bc] (mJ)	0.26	0.01	680	–
Minimum quenching distance[b] (mm)	2.0	0.5	?	–
Maximum experimental safe gap[d] (MESG) (mm)	1.1	0.29	3.2	–
Minimum Igniting Current[d] (MIC) ratio	1.0	0.25	6.9	–
Temperature Class[d]	T1	T1	T1	–
Equipment Group[d]	IIA	IIC	IIA	–

† Sublimation temperature for CO_2
* Properties given at 15°C and ambient pressure

a https://encyclopedia.airliquide.com
b Drysdale (1998)
c Babrauskas (2003)
d BS EN 60079-20-1:2010 (BSI, 2010)

Ignition of pools of refrigerated liquid ammonia

- Experiments undertaken on ignited pools of cryogenic liquid ammonia in the 1960s by Phillips 66
- Found it difficult to sustain a pool fire
- Water sprayed onto pool increased the ammonia evaporation rate and increased the fire intensity
- Combustion was incomplete: toxic ammonia hazard persisted downwind from burning pool

https://www.youtube.com/watch?v=TezJ82GuUuw

Presented at the Air Separation and Ammonia Plant Safety Symposium at the 1963 San Juan meeting of the A.I.ChE

HAZARD OF LIQUID AMMONIA SPILLS FROM LOW PRESSURE STORAGE TANKS

H. W. Husa and W. L. Bulkley
American Oil Co.
Whiting, Ind.

After a few minutes, the boiling subsided and near steady-state conditions were established. An ignited railway fusee was then passed through the vapor above the liquid surface and through the vapor cloud rolling over the downwind lip of the pan. All areas of the pan were probed from the surface of the liquid upward for several inches. No sustained flame was observed. Brief local flashes occurred when the flare was brought near the liquid surface. Touching the liquid with the fusee tip did not intensify or extend the flame. Submerging the tip extinguished the flare.

Spillage to surroundings

A portion of the liquid in the pan was spilled onto the surrounding slag where it boiled vigorously. Moving the flare into the vapor cloud resulted in ignition. The vapor burned with a colorless flame which persisted after the flare was removed. The flame was stable in the brisk wind, and some tongues of fire were 10 ft. long. Radiation from the flame could be felt, but its intensity was considerably less than that from a hydrocarbon fire of comparable size.

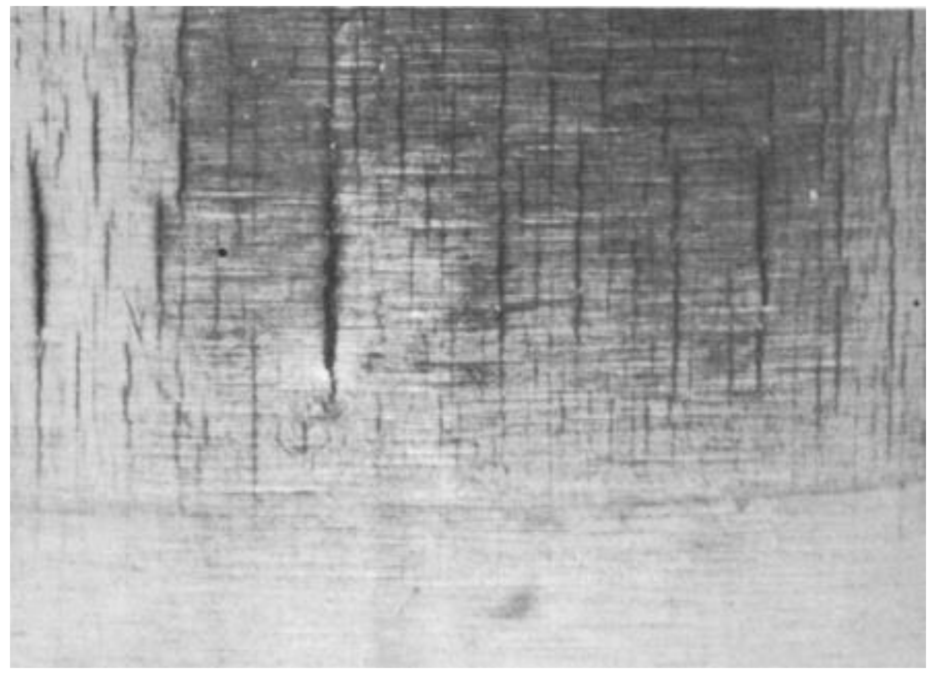
Burning ceased when boiling stopped. With the addition of liquid ammonia, the fire could be rekindled, but it was smaller. With each successive addition of ammonia, the fire diminished in size and eventually degenerated into a wisp of flame in the lee of the pan lip. The ammonia-wetted slag was quite cold to the touch.

When water was sprayed onto the cold ammonia-wetted slag, vigorous boiling occurred. The vapor burned and the flames were stable in the wind. The burning sequence was repeated with spills onto fresh slag. However, at no time could the flame be made to propagate back into the liquid ammonia pool in the pan.

Although the ammonia flames were noticeably less intense than hydrocarbon flames, subsequent tests demonstrated that ammonia flames can ignite hydrocarbon-air mixtures and readily combustible solids such as paper and wood splinters.

Asset integrity issues

- Stress Corrosion Cracking (SCC) sometimes experienced in ammonia transport and storage tanks
- Depends on type of steel, ammonia impurities and stresses in the material
- Mainly occurs in welds and heat-affected zones
- Uncommon in cryogenic tanks operating at -33°C
- Addition of 0.2% water to ammonia acts as corrosion inhibitor
- Water-inhibited tanks can still suffer SCC in vapour space
- Primary cracking promoter is oxygen (just 0.5 ppm can lead to SCC)
- Lunde & Nyborg (1987) found that maximum SCC rates occurred with 3-10 ppm oxygen and up to 100 ppm water
- Zinc, copper and copper-based alloys are susceptible to SCC and should not be used with ammonia* ("season cracking" https://www.corrosionpedia.com/definition/1012/season-cracking)



L. Lunde and R. Nyborg (1987) Stress Corrosion Cracking of Different Steels in Liquid and Vaporous Ammonia, Corrosion 43 (11): 680–686 https://doi.org/10.5006/1.3583849

* HSG30 Storage of anhydrous ammonia under pressure in the United Kingdom, Health and Safety Executive (also CGA G-2.1-2023)

Asset integrity issues

- Embrittlement at low operating temperature of -33°C
  - Need to use suitable grades of steel and/or heat treatment
- Corrosion under insulation
  - Caused by water trapped underneath insulation in contact with steel pipework
  - For further details, see: https://www.hse.gov.uk/foi/internalops/hid_circs/technical_general/spc_tech_gen_18.htm
- Non-metallic materials*
  - Nitrile and neoprene rubber parts are suitable within their temperature limitations
  - Butyl and ethylene propylene rubbers should only be used in ammonia vapour systems
  - PTFE, polypropylene, polyethylene and nylon are relatively unaffected by ammonia
  - Most other rubbers and plastics are unsuitable, fluoro-elastomers are badly affected
- See also ammonia standards and guidance, e.g.
  - PGS-12 https://publicatiereeksgevaarlijkestoffen.nl/publicaties/online/pgs-12/2023/0-1-fase-1-december-2023
  - ANSI/CGA G-2.1 https://webstore.ansi.org/standards/cga/ansicga2014
  - https://www.fertilizerseurope.com/
  - https://www.icheme.org/media/11771/hazards-26-paper-34-review-of-global-regulations-for-anhydrous-ammonia-production-use-and-storage.pdf

* Source: HSG30 Storage of anhydrous ammonia under pressure in the United Kingdom, Health and Safety Executive

COMAH regulations

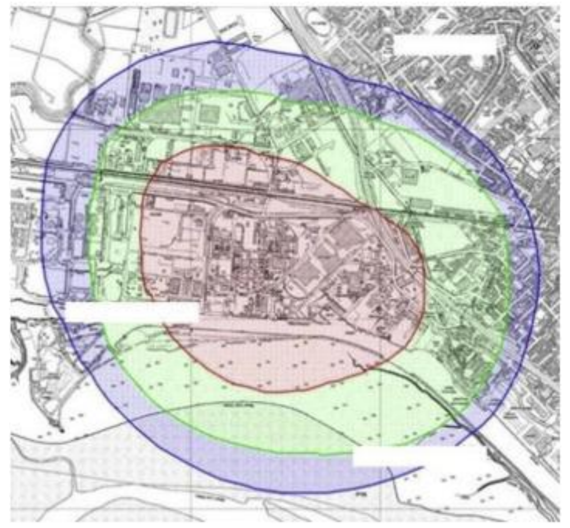
- Control of Major Accident Hazards (COMAH) Regulations 2015
- Implements the majority of the Seveso III Directive (2012/18/EU) in Great Britain
- Competent authority: HSE, Environment Agency (EA, SEPA, NRW), ONR
- All sites: reduce risks to As Low As Reasonably Practicable (ALARP)
- Adopt relevant good practice as a minimum (ACOPs, ISO, CEN, API etc.)
- Quantified Risk Assessment (QRA) not always necessary to demonstrate ALARP
- Two thresholds: lower and upper tier COMAH sites
- Additional duties for upper tier sites: safety report, major accident prevention policy, test external emergency plan, provide public information
- Aggregation rules for multiple different hazardous substances stored on the same site

	Lower Tier	Upper Tier
Hydrogen	5 t	50 t
Ammonia	50 t	200 t

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

Land-use planning requirements

- Seveso land-use planning requirements are implemented in GB by the Planning (Hazardous Substances) Regulations 2015
- New sites handling substances above controlled quantity are required to seek land-use planning consent
- Process led by planning authority, HSE is statutory consultee
- HSE assesses residual risks to people using combination of risk and consequence-based calculations, e.g., models such as DRIFT for dispersion
- HSE advises local planning authority, who makes decision to grant permission or not
- If consent is granted against HSE's advice: potential for HSE to call for review
- For existing consented sites: HSE provides public safety advice to developers and planning authorities via web app https://www.hse.gov.uk/landuseplanning/planning-advice-web-app.htm



	Consent threshold
Hydrogen	2 t
Ammonia	50 t

Lower than COMAH lower tier threshold

https://www.hse.gov.uk/landuseplanning/about.htm

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

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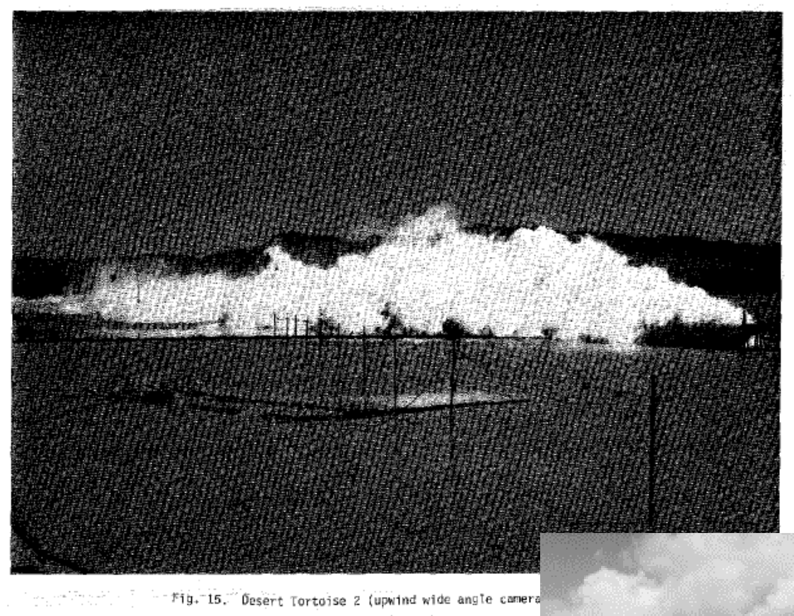
Research questions

- Understanding the complex dispersion behaviour of ammonia
  - Ammonia clouds can be buoyant or heavier than air, depending on presence of aerosols and temperature
  - Behaviour is affected by release mechanism: pressure- or temperature-liquefied ammonia source, size of release, catastrophic vessel failure or jet, impinging, evaporating pool characteristics etc.
  - Ammonia reacts with moisture and releases heat in the process
  - Ammonia reacts with surfaces (e.g., vegetation, soil), which may reduce airborne concentrations

- Knowledge of ammonia dispersion behaviour is limited to relatively few experiments
  - Desert Tortoise, USA (1983)
    - 10 – 41 tonnes of ammonia released, largest tests to date
    - Dispersion measurements at 100 m and 800 m
    - Lack of data in far field to determine size of hazardous cloud
  - FLADIS, Sweden (1993-4)
    - Release rates of 0.25 – 0.55 kg/s
    - Dispersion measurements at 20 m, 70 m and 240 m
    - Releases too small to exhibit full range of dense-gas effects



© LLNL
https://www.osti.gov/biblio/6393901

© Risø National Laboratory

Research questions

- Other ammonia experiments
  - Mourmelon (Resplandy, 1969)
  - A.D.Little (Raj *et al*., 1974)
  - ICI (Reed, 1974)
  - Unie van Kunstmestfabrieken (Blanken, 1980)
  - Landskrona (Nyrén and Winter, 1983)
  - Ecole des Mines D'Ales (Bara & Dussere, 1997)
  - INERIS (Bouet, 1999)
  - Jack Rabbit I (Fox & Storwold, 2011)
  - Red Squirrel (Dharmavaram *et al.*, 2023)

Red Squirrel test http://dx.doi.org/10.1002/prs.12454

Figure 11: RS-3F refrigerated, pressurized ammonia release

- Hanna *et al*. (2021) and Batt (2021) reviewed the experimental data and identified limitations
  - Lack of reliable data for catastrophic vessel failure, two-phase jets, cryogenic releases, spills of ammonia on water, issues of scale, instrumentation, quantification of rainout and deposition, experimental uncertainties etc.

Hanna *et al*. (2021) Gaps in toxic industrial chemical model systems Improvements and changes over past 10 years, https://dx.doi.org/10.1002/prs.12289
Batt (2021) Review of dense-gas dispersion for industrial regulation and emergency preparedness and response, https://admlc.com/publications/

Research questions

- Only one experimental waterborne liquid ammonia spill dataset produced to date, by Raj *et al*. (1974)
- Maximum release size in experiments: 50 US gallons (~200 litres) of ammonia, spilled into a lake
- Review by Griffiths (1977) was strongly critical of their interpretation of the experimental data

PREDICTION OF HAZARDS OF SPILLS OF ANHYDROUS AMMONIA ON WATER

PREPARED FOR COAST GUARD

ARTHUR D. LITTLE, INCORPORATED

MARCH 1974

Raj, P.K., Hagopian, J., and Kalelkar, A.S.

The vapor puff formed is very buoyant and rises into the air as it travels downwind. The rate of rise depends on the wind velocity. Under low wind conditions the cloud forms a characteristic mushroom cloud before dispersing. The path of the cloud can be estimated with reasonable accuracy by existing plume theories. Because of the rapid rise in low wind, the toxic hazard at ground level is smaller for low wind than for high wind.

https://apps.dtic.mil/sti/pdfs/AD0779400.pdf

Griffiths, R F (1977). Critical review of the USCG report by RAJ et al (1974) on spills of liquid anhydrous ammonia on to water, with an alternative assessment of the experimental results, SRD R67

This report is principally devoted to a criticism of experiments performed by Raj et al (Reference 10) in which it was demonstrated that spills of LNH_3 (liquid anhydrous ammonia) on to water from refrigerated storage tanks result in releases of ammonia to the atmosphere. Raj et al concluded that such releases are adequately described in terms of a buoyant plume rise model, in which it is assumed that the ammonia is released as a pure undiluted vapour.

This conclusion is challenged on the grounds that it is incompatible with the experimental measurements. An alternative interpretation of the data is proposed which is shown to be consistent with the observed behaviour. In this scheme the ammonia is considered to be released as a plume containing both vapour and liquid droplet aerosol, by virtue of which it is rendered non-buoyant.

The difficulties inherent in providing a rigorous description of such a release are circumvented by use of a simplified model of the dispersion behaviour, which is used to calculate downwind ground level concentrations (GLC) of ammonia vapour. Comparison calculations are performed to demonstrate that the hazard ranges for a given consequence are significantly greater if the release is non-buoyant.

It is concluded that the study performed by Raj et al does not provide the information needed to perform hazard assessments for LNH_3 releases on to water, and that further experimental studies are required.

https://admlc.com/safety-and-reliability-directorate-srd-series-reports/

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Recent activities and ongoing research projects

- Review of ammonia incidents, operational experience and emergency response
  - Joint presentation by HSE, Star Refrigeration and Ricardo/NCEC at the FABIG Technical Meeting, London, UK, 23-24 October 2024
  - Immediate causes of incidents: brittle fracture of vessel, fatigue cracking, incompatible material for hoses, tank over-pressurization, third-party activity, vehicle collision, connection failure etc.
  - Slides available on request simon.gant@hse.gov.uk

Ammonia pipeline release, Kingman, Kansas (2004)
https://www.ntsb.gov/investigations/AccidentReports/Reports/PAB0702.pdf

Ammonia storage tank overfilling, Blair, Nebraska (1970)
Photos kindly provided by Steven Hanna (originally from Rex Britter)
See also: Lees Loss Prevention, ISBN: 978-0-12-397189-0

Recent activities and ongoing research projects

- Presentation at AIChE meeting in Sept 2024 by Rory Hetherington (HSE)
  https://www.aiche.org/conferences/annual-safety-ammonia-plants-and-related-facilities-symposium/2024

Analyzing Ammonia Dispersion Under Varying Atmospheric Conditions Using DRIFT

Atmospheric conditions, such as ambient temperature and relative humidity, can influence dispersion of toxic chemicals. Ammonia is hygroscopic and therefore has complex interactions with water vapor present in the atmosphere. The integral model DRIFT has been utilized to predict ammonia dispersion and downwind concentrations for a range of temperatures and humidities. We have simulated ammonia dispersion for two types of release: (i) long-duration, typical of a leak from a hole in a vessel; (ii) instantaneous release, typical of a catastrophic vessel failure.

The two cases studied in this paper are somewhat idealized representations of what can happen during loss of containment. However, both release scenarios contribute knowledge to how a release of ammonia interacts with the environment, and how this affects downwind dispersion.

Rory Hetherington, Alison McGillivray, Simon Gant
Health and Safety Executive

Gemma Tickle
GT Science & Software

Recent activities and ongoing research projects

- Health and safety workshop at the Second Symposium on Ammonia Energy, Orléans, France, 11-13 July 2023 https://ammonia-energy.sciencesconf.org/
  - Attendees include ship certification authorities, ammonia engine testing experts, safety professionals, academics
  - Workshop discussions summarised in journal paper http://dx.doi.org/10.18573/jae.30

- Annual George Mason University (GMU) Conference on Atmospheric Transport and Dispersion Modeling, Fairfax, Virginia, USA http://camp.cos.gmu.edu/
  - Meeting place for discussions about Jack Rabbit III ammonia project
  - Examples from GMU 2024 conference include:
    - Matt Rowley: Jack Rabbit III ammonia chamber studies at Battelle Institute, Ohio, USA
    - Tom Spicer: Jack Rabbit III ammonia dry deposition experiments at University of Arkansas

Recent activities and ongoing research projects

- 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/

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

RESEARCH AND GUIDANCE FROM HSE

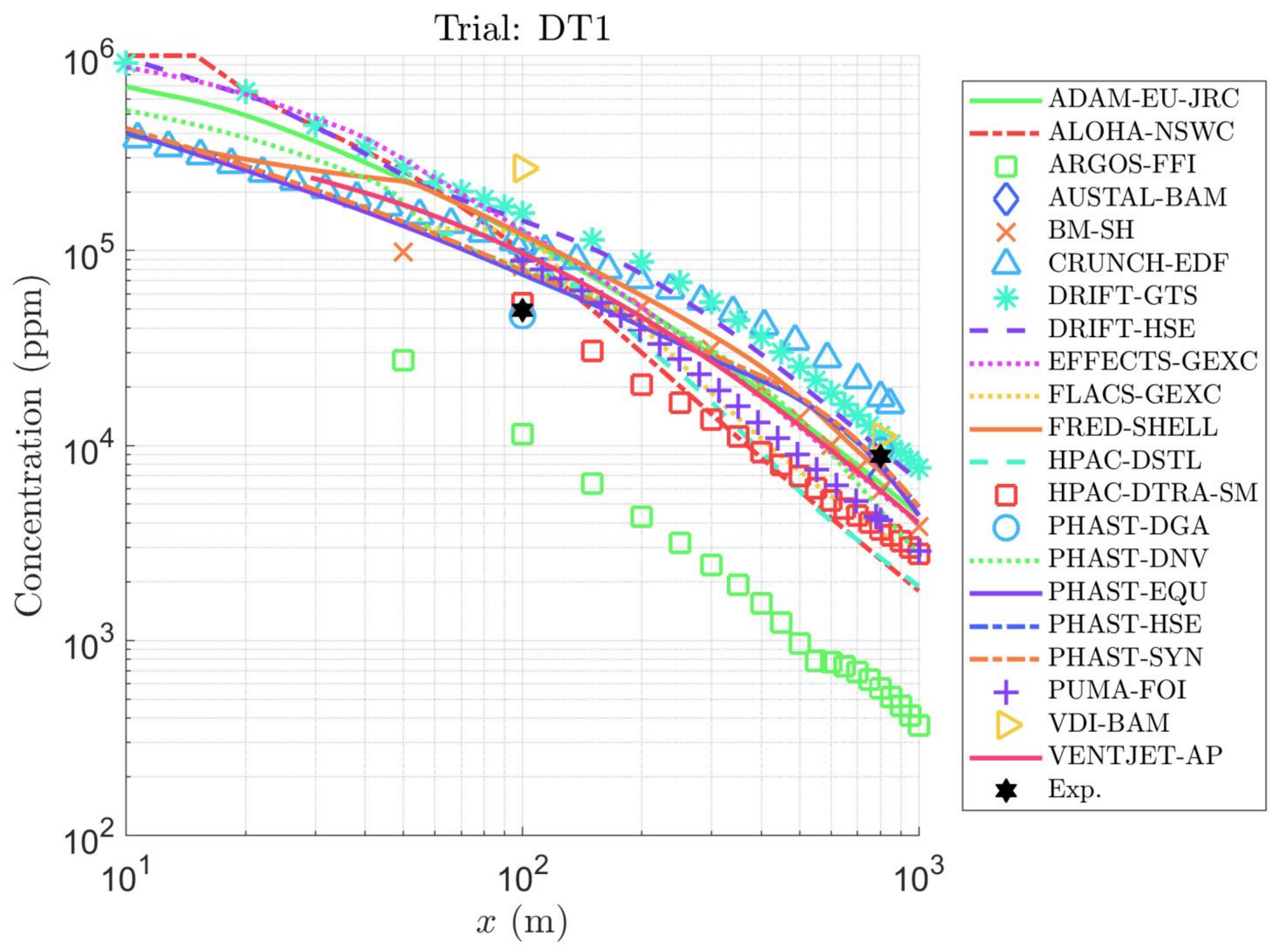
Participants in the JRIII Initial Modeling Exercise

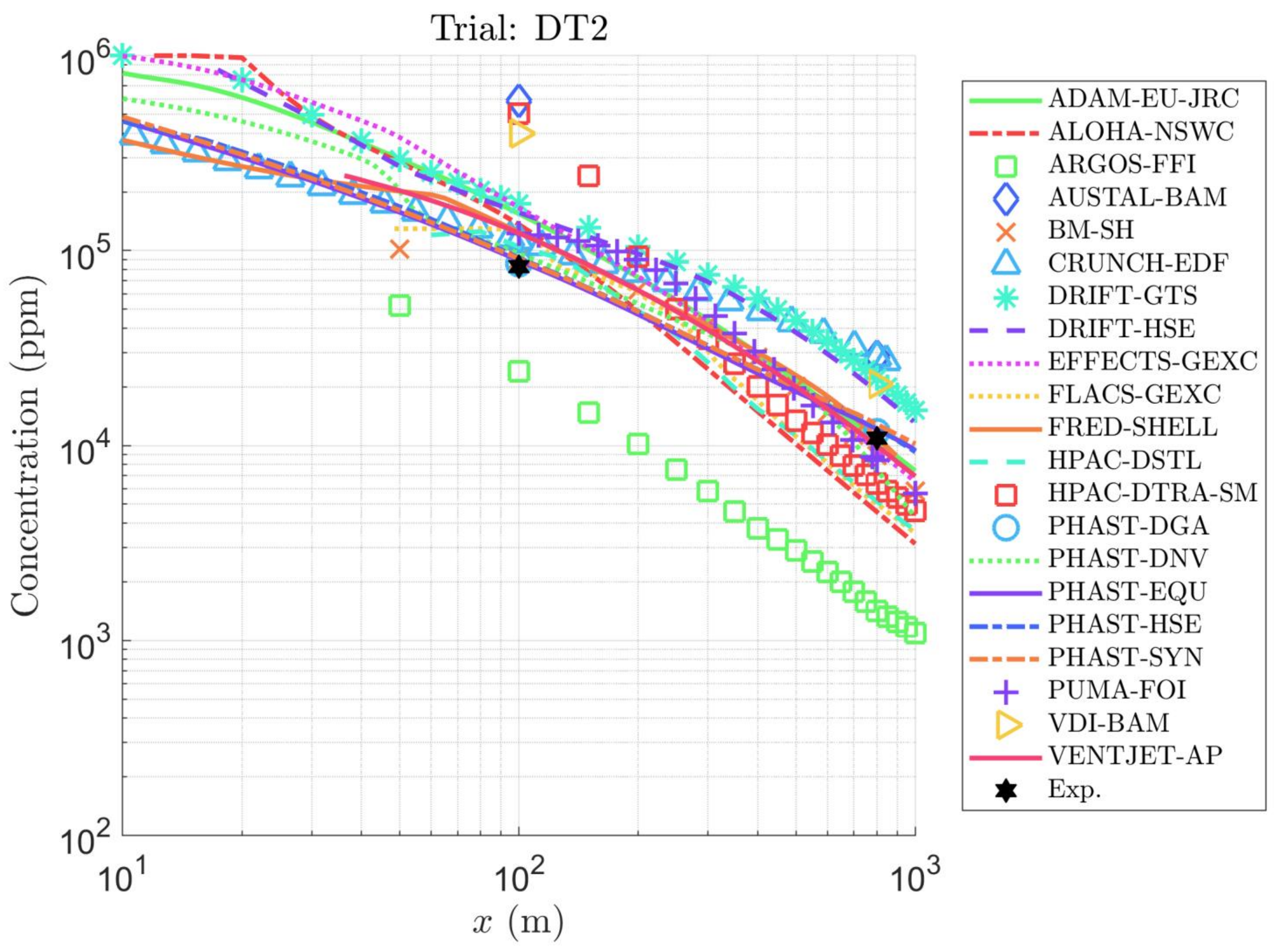
#	Organization	Model	Model Type				Desert Tortoise			FLADIS		
			Empirical nomogram/ Gaussian plume	Integral	Gaussian Puff/ Lagrangian	CFD	1	2	4	9	16	24
1	Air Products, USA	VentJet		■			■	■	■	■	■	■
2	BAM, Germany	AUSTAL			■		■	■	■	■	■	■
3		VDI	■				■	■	■	■	■	■
4	DGA, France	PHAST v8.6		■			■	■	■	■	■	■
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		■			■	■	■	■	■	■

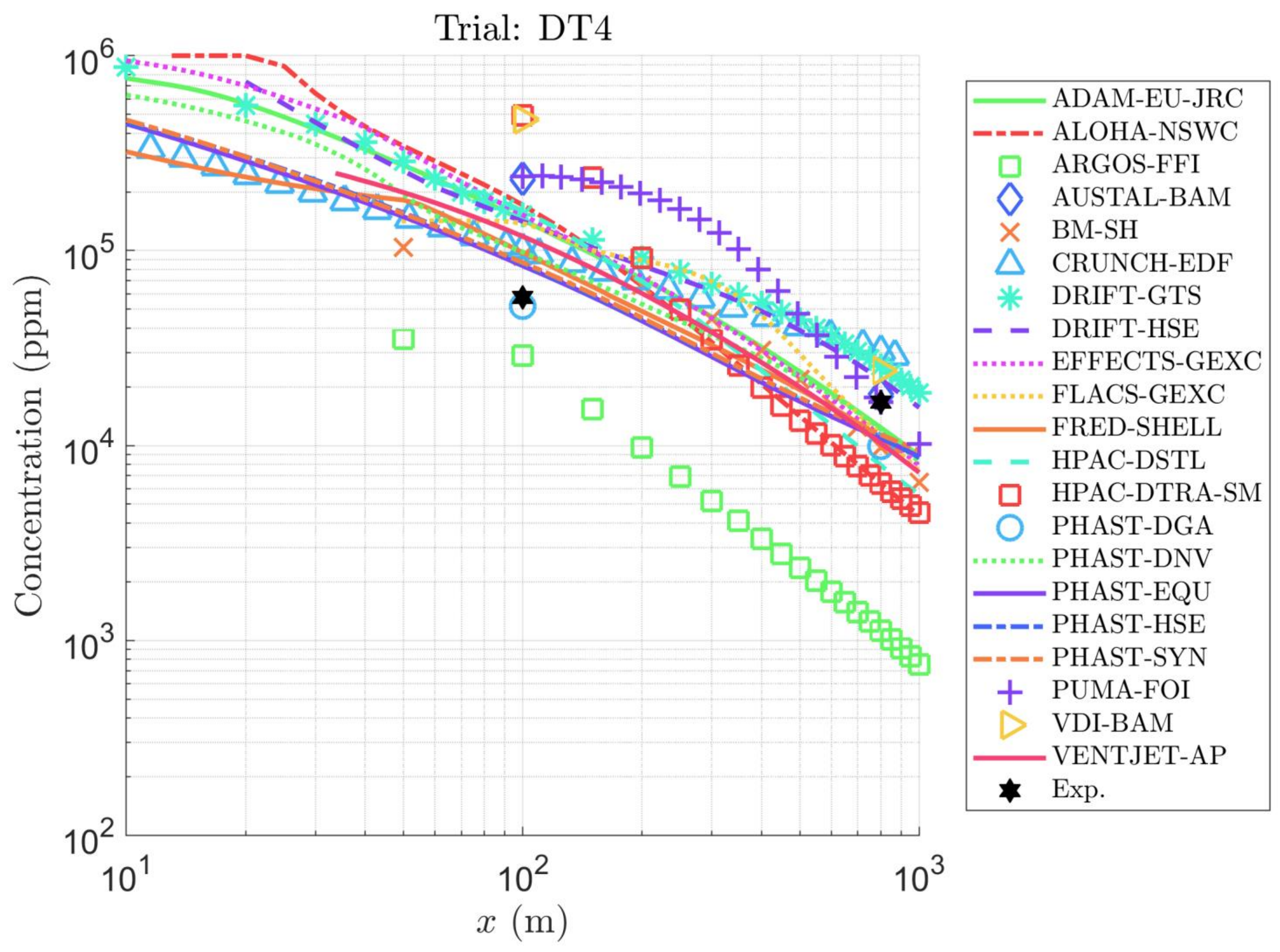
RAND CORPORATION

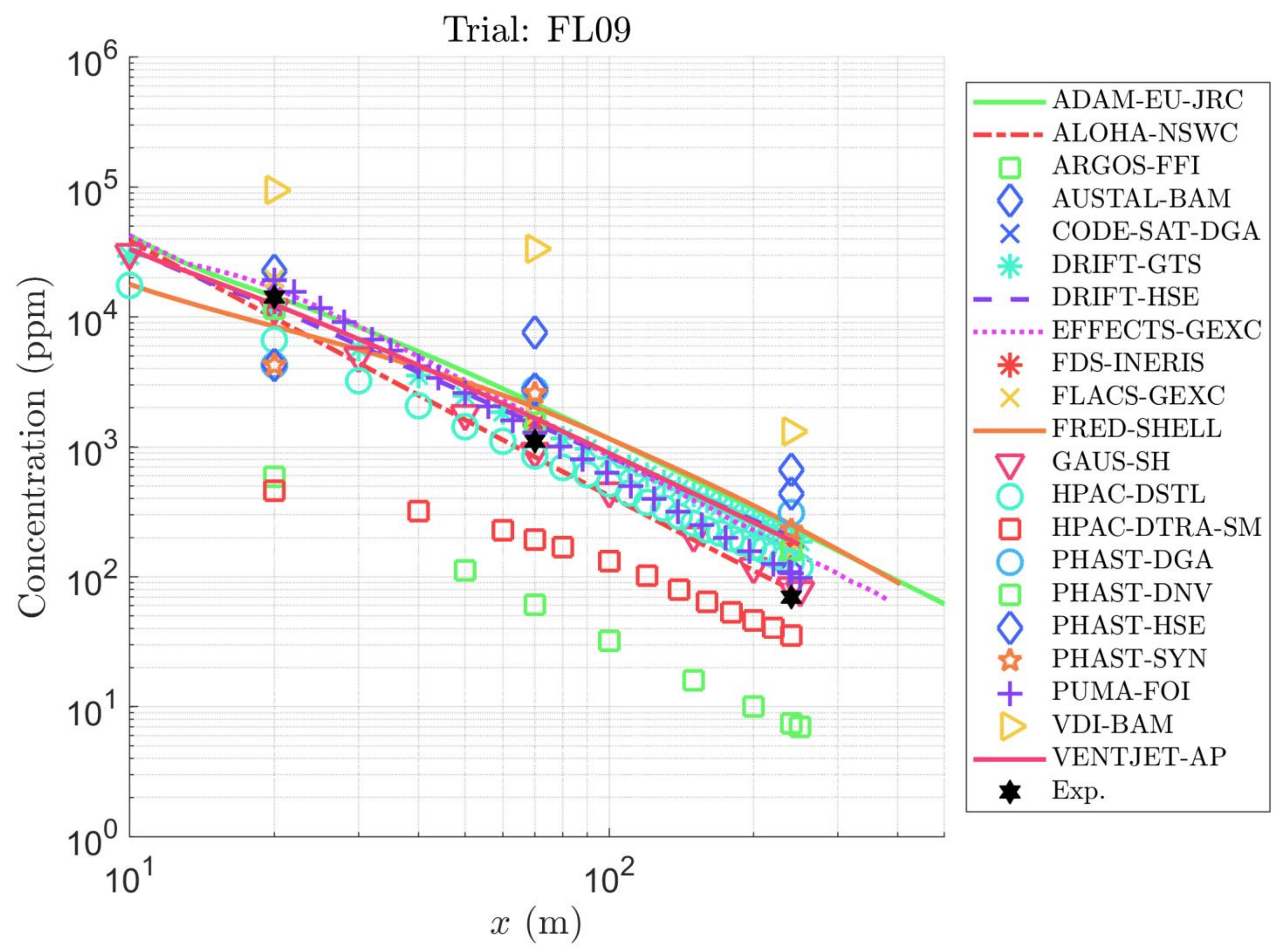
RESEARCH AND GUIDANCE FROM HSE

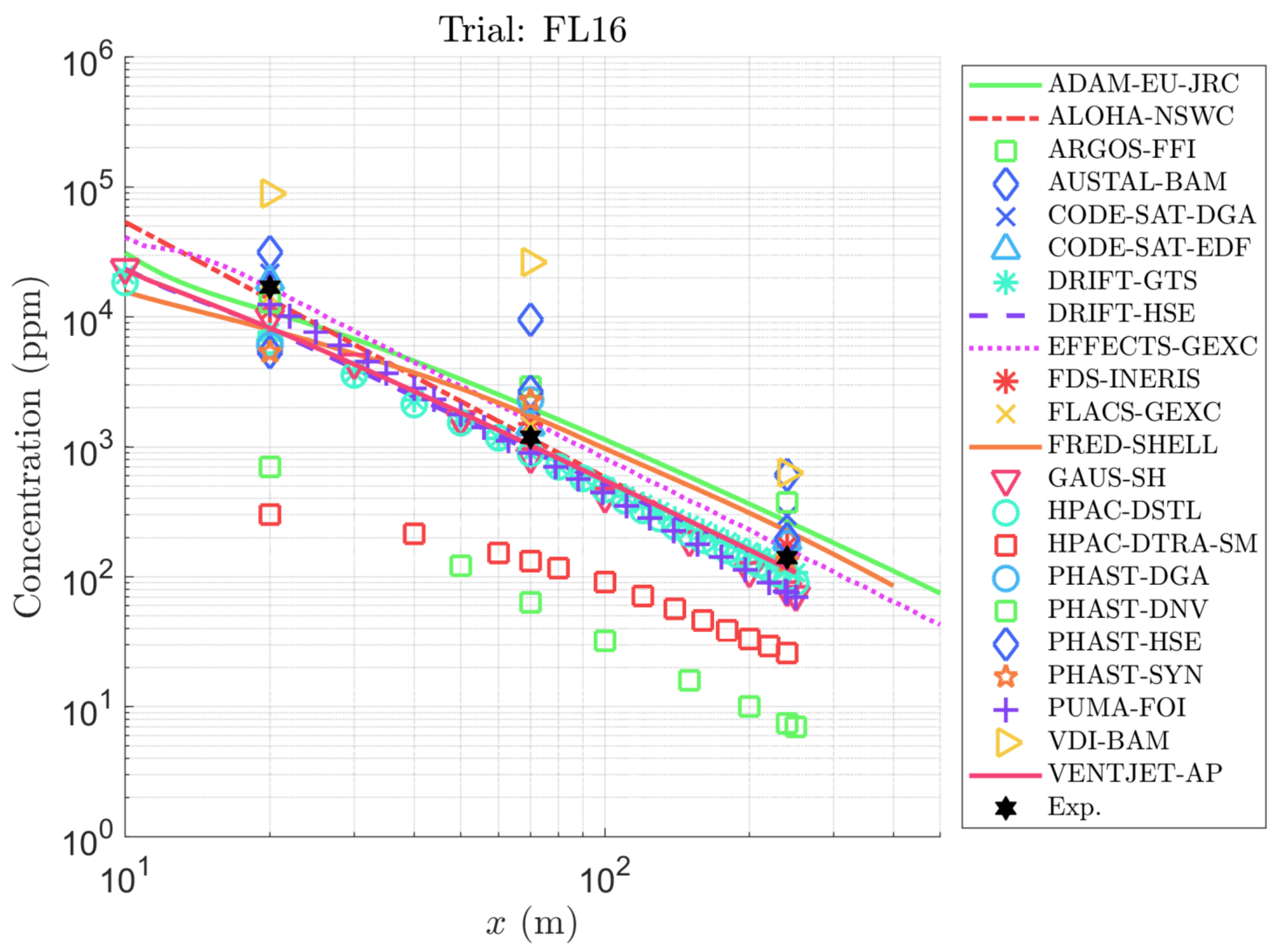
All Model Results

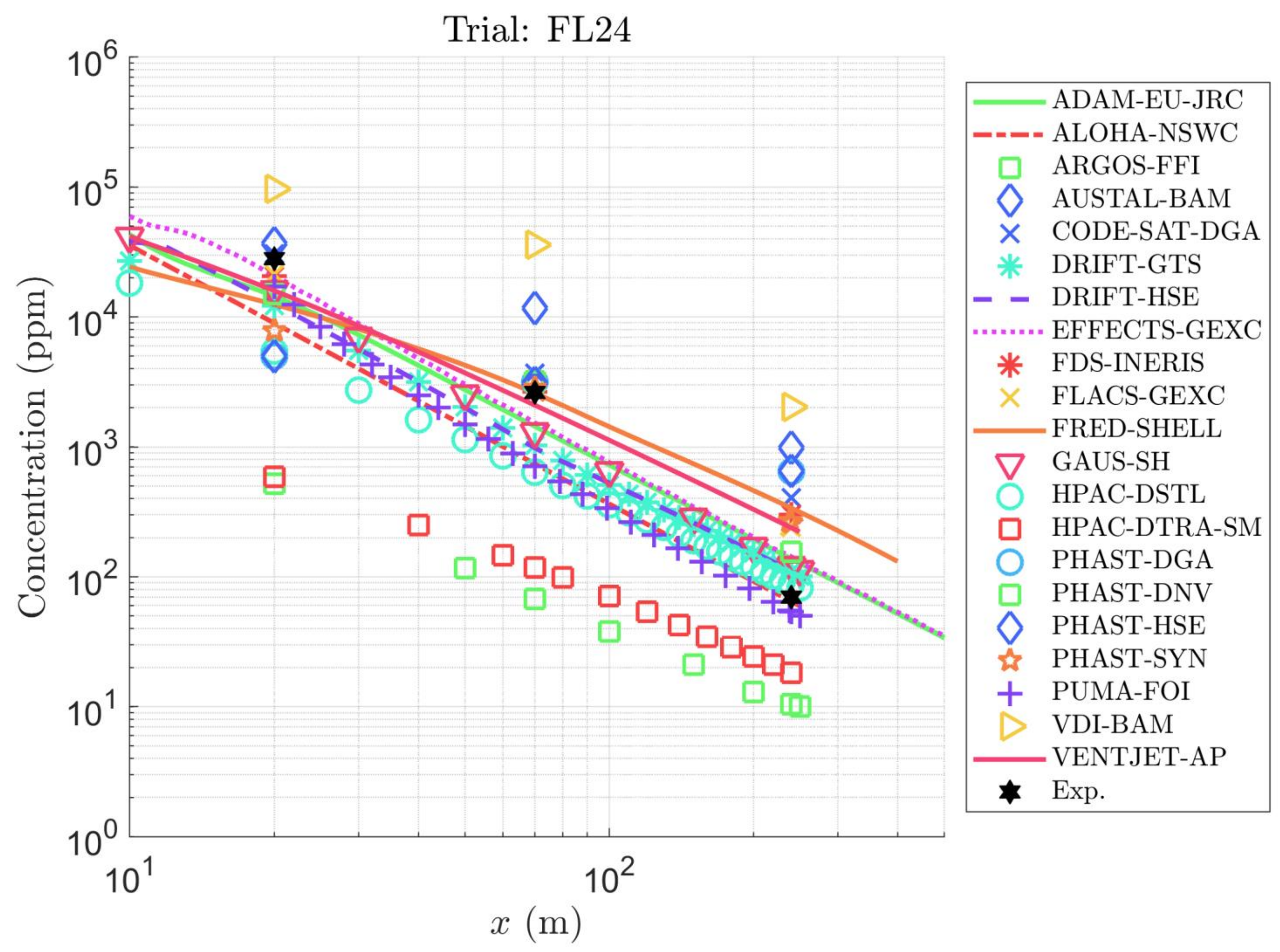










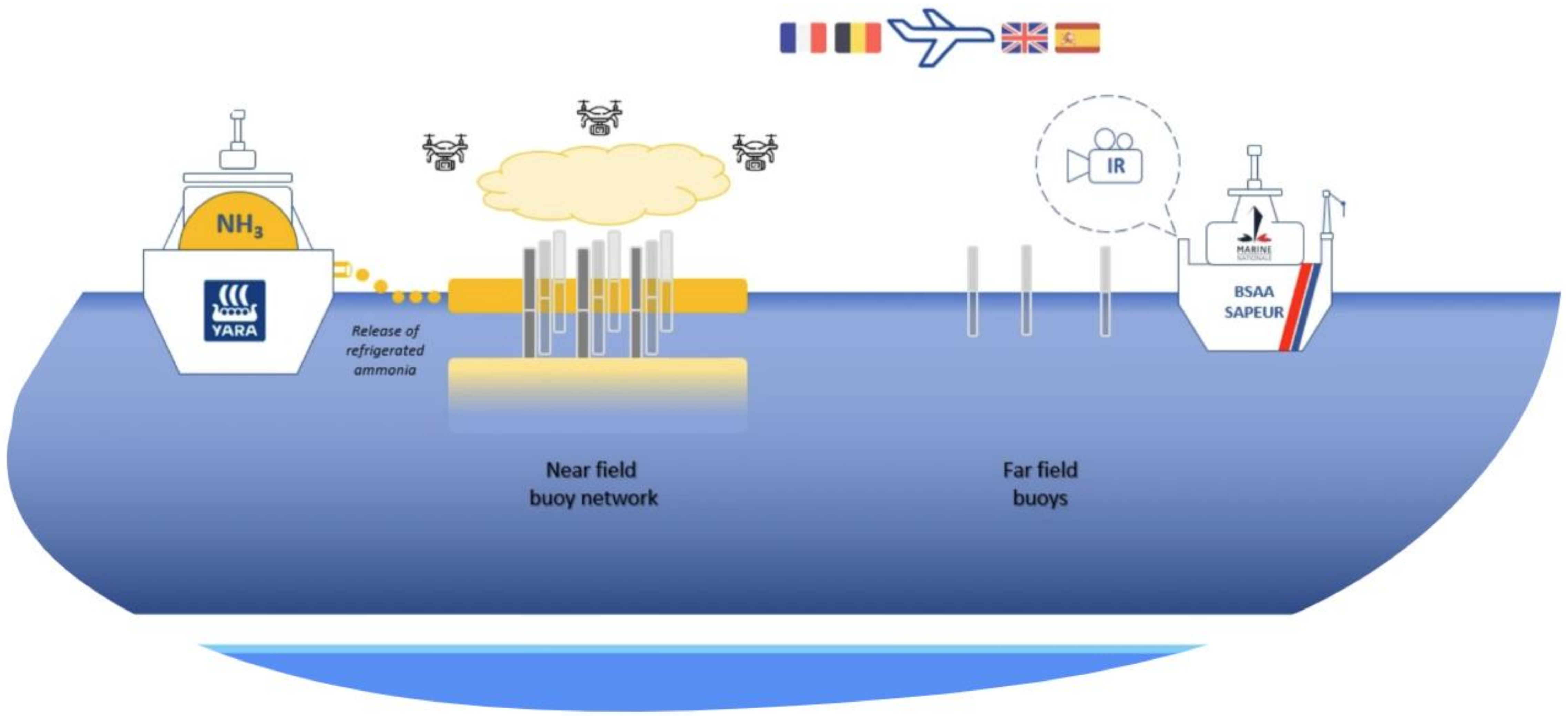


Recent activities and ongoing research projects

- 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 2025
- Contact: Laurent.Ruhlmann@yara.com

ARISE
Ammonia Response In Sea Emergencies

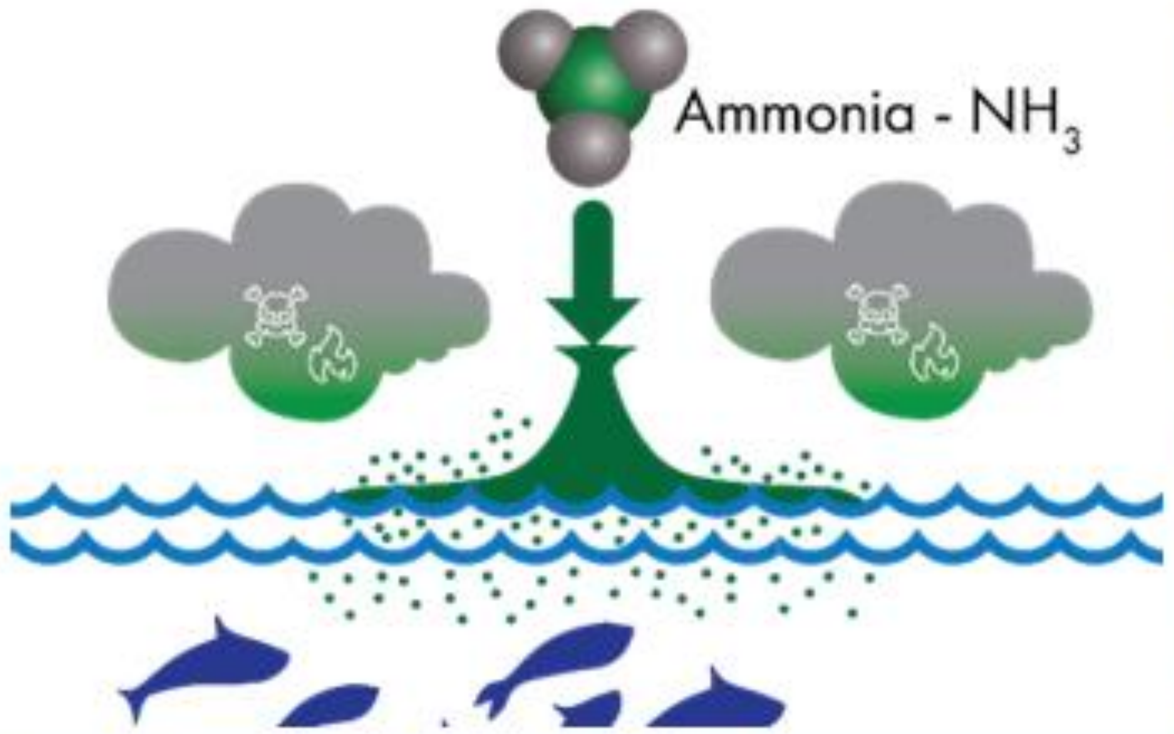
www.arise-partnership.org



INERIS · Cedre · Yara Clean Ammonia · ONERA · museum Royal Belgian Institute of Natural Sciences · HSE Health and Safety Executive · INERIS Développement · IMT Mines Alès · SINTEF

SafeAm

Increased Safety of Ammonia Handling for Maritime Operations



Consortium of 21 partners led by SINTEF

LOWEMISSION, Sjøfartsdirektoratet Norwegian Maritime Authority, Havtil, KYSTVERKET, HSE Health & Safety Executive, DNV, TotalEnergies, WÄRTSILÄ, amon MARITIME, YARA, NTNU, USN University of South-Eastern Norway, equinor, ConocoPhillips

BACKGROUND

- Ammonia (NH_3) is deemed by many as a promising energy carrier to reduce carbon dioxide (CO_2) emissions from transport and a viable solution for global H_2 transport
- Although NH_3 has been safely transported as a chemical in dedicated carriers for decades, the potential large-scale implementation and handling by different users, introduces emerging risks and a potential need for stricter requirements

OBJECTIVE Accelerate the implementation of new value chains for NH_3 as a zero-emission fuel and energy carrier by improving safety systems design and procedures for handling of LNH_3 spills on and into water.

APPROACH AND EXPECTED OUTCOMES

- Experiments on NH_3 spills on and into water (evaporation, dissolution, mixing dynamics)
- Thermophysical modelling of NH_3_water interface, Rapid Phase Transition model, partition ratio model (PIRATE)
- Safety and environmental risk analysis (trade-offs, case studies, input to standards and regulations)

Total budget ca. 18 MNOK
For info: marta.bucelli@sintef.no (project manager)

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

SH_2IFT II

- Safe hydrogen fuel handling and use for efficient implementation 2
- Project funded by Research Council of Norway and industry sponsors, 2021 – 2025
- Aim: study explosive and toxic atmospheres of hydrogen and ammonia, respectively, in ventilated enclosed spaces (includes dispersion, fire and explosion tests and modelling)
- Partners: SINTEF, RISE Fire Research, Gexcon, Universities of Southeast Norway, NTNU, Stavanger, Bergen, Demokritos and Karlsruhe Institute of Technology
- Two blind modelling exercises announced in late 2023 on dispersion of hydrogen and ammonia in a confined geometry with active ventilation, with or without congestion
  - Hydrogen results deadline 4 March 2024
  - Ammonia results deadline 11 March 2024
- Exercises coordinated by Trygve Skjold (University of Bergen)
- HSE participated in providing results for the ammonia study using the CFD model Fluent

https://sh2ift-2.com/sh2ift-2-second-blind-prediction-study

Proposed future research project on ammonia pipelines

- Discussions have been held between RIVM and HSE on ammonia pipeline safety over the last 6 months, related to proposals for ammonia pipelines from European ports to inland industrial centres
- Jointly developed an outline scope of work for a future desktop study of ammonia pipeline safety
  - Review ammonia pipeline operational experience and planned future developments
  - Identify relevant regulations/standards/guidelines on risk assessment, e.g. PD 8010, 49 CFR 195
  - Survey ammonia pipeline incidents, e.g., Magellan (2004, 2016), Tampa Bay (2007)
  - Review physics of ammonia pipeline releases: crater formation, flashing jets, pool formation etc.
  - Assess capabilities/limitations of consequence and risk assessment models (flammable & toxic)
  - Compare risks of ammonia pipelines to natural gas pipelines for range of credible cases
  - Identify any areas where further research is needed

- If you share an interest in this topic, particularly as a potential co-sponsor or contractor, please get in touch with simon.gant@hse.gov.uk and mark.spruijt@rivm.nl

Conclusions

- Use of ammonia is forecast to increase in coming decades, especially in the marine sector (with the associated need for ammonia bulk storage at ports)
- Long history in safe ammonia production, transport and use, but future developments will see some novel applications and new users, who may be unfamiliar with the risks
- Several ongoing and planned scientific research initiatives that aim to improve our understanding of ammonia hazards, particularly in terms of atmospheric dispersion
- Developments in scientific research useful to inform safety regulation and policymaking

Thank you

Any questions?

simon.gant@hse.gov.uk

- 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

Waterborne Ammonia Spill Experiments, 1974

Raj, P.K., Hagopian, J., and Kalelkar, A.S.

The vapor puff formed is very buoyant and rises into the air as it travels downwind. The rate of rise depends on the wind velocity. Under low wind conditions the cloud forms a characteristic mushroom cloud before dispersing. The path of the cloud can be estimated with reasonable accuracy by existing plume theories. Because of the rapid rise in low wind, the toxic hazard at ground level is smaller for low wind than for high wind.

R. F. Griffiths

This conclusion is challenged on the grounds that it is incompatible with the experimental measurements. An alternative interpretation of the data is proposed which is shown to be consistent with the observed behaviour. In this scheme the ammonia is considered to be released as a plume containing both vapour and liquid droplet aerosol, by virtue of which it is rendered non-buoyant.

Concentration

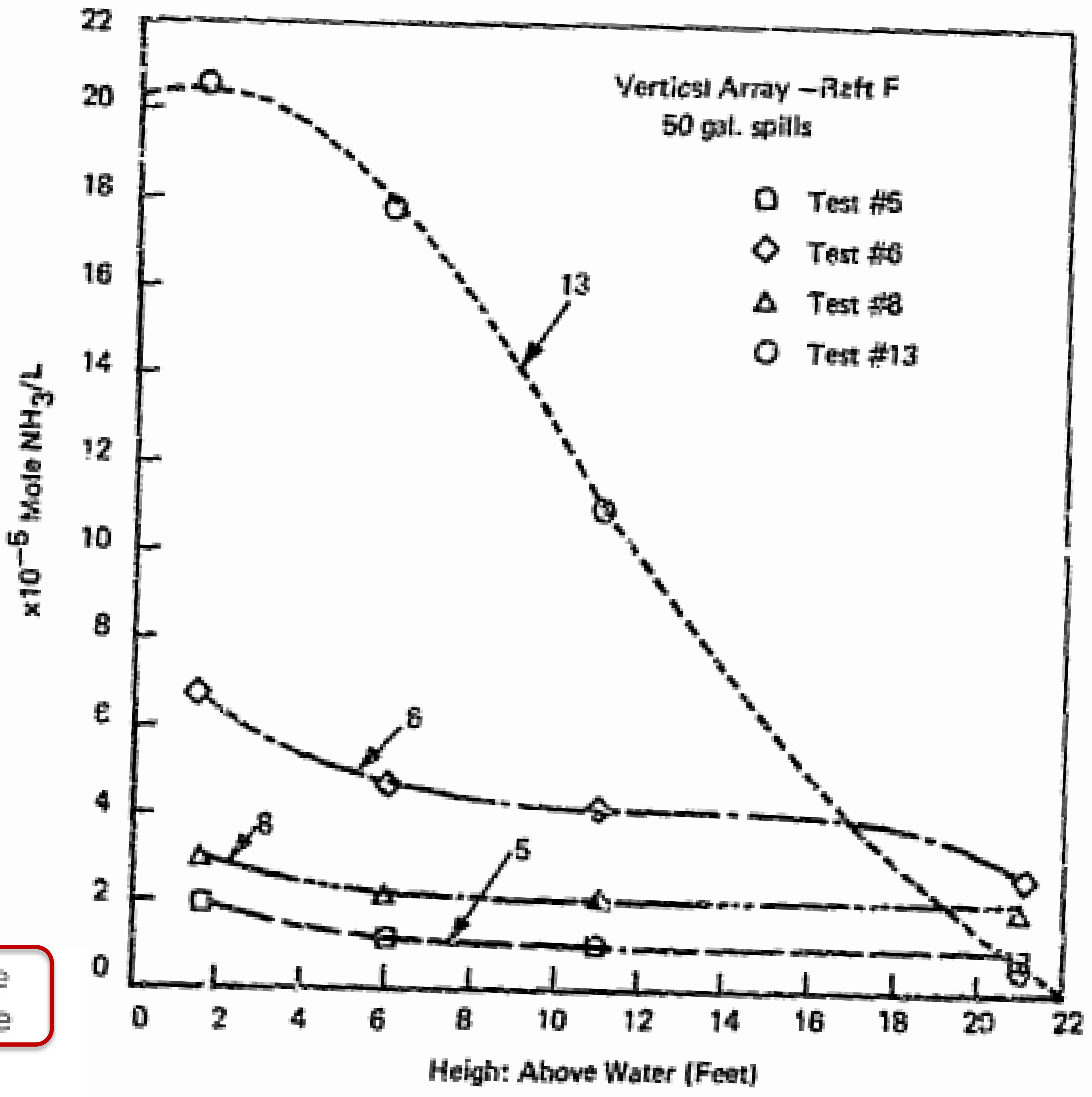


FIGURE 5–9b VERTICAL ARRAY IMPINGER DATA FOR SECOND ROW RAFT (C)

Height

Concentration

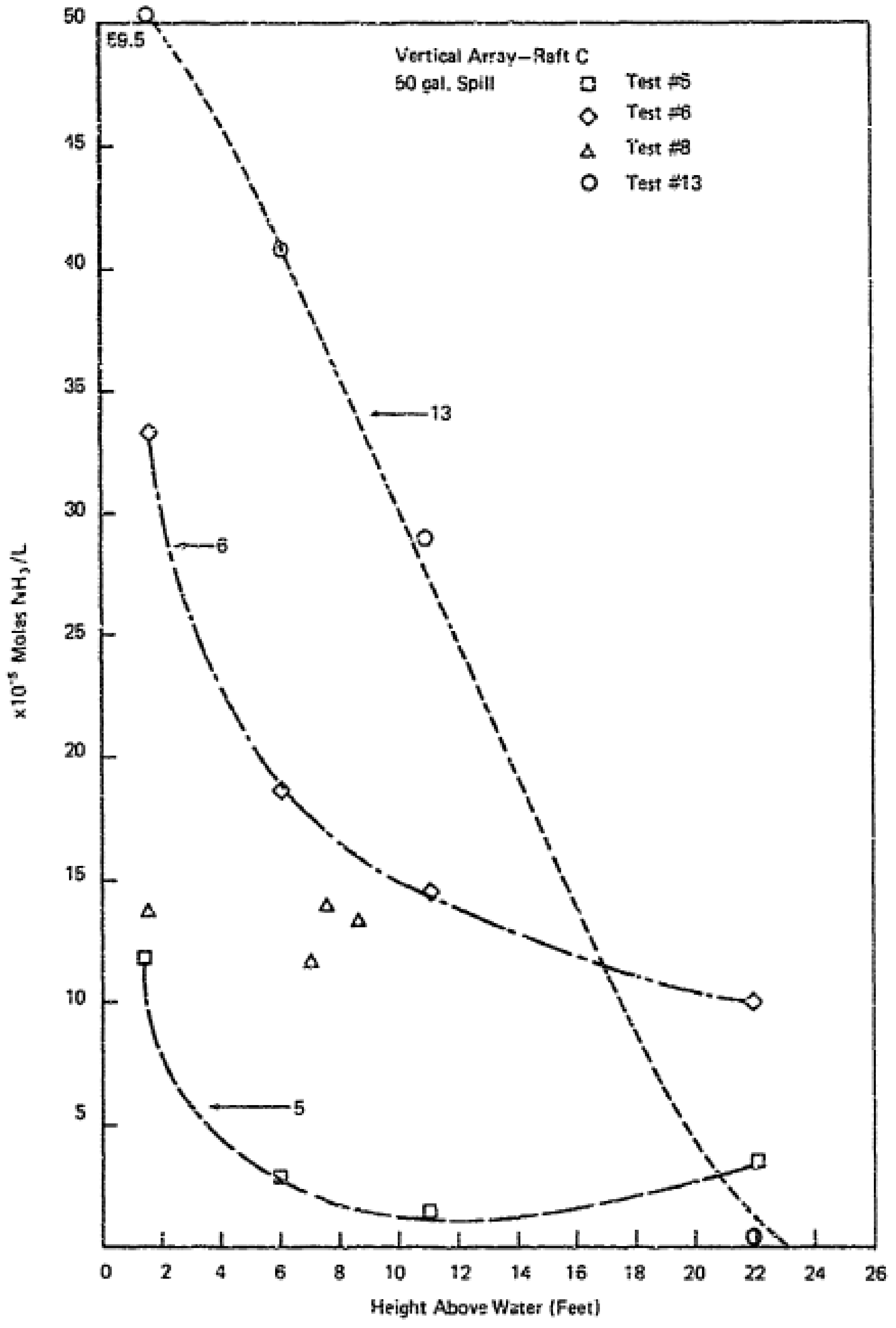


FIGURE 5–10b VERTICAL ARRAY IMPINGER DATA FOR THIRD ROW RAFT (F)

Height

PROTECTING PEOPLE AND PLACES FOR 50 YEARS HSE

Haifa Ammonia Storage Tank Study, 2018

THE TIMES OF ISRAEL

HEZBOLLAH CHIEF LAST YEAR THREATENED TO TARGET FACILITY WITH MISSILES IN NEXT WAR

Hundreds of thousands of lives in danger from Haifa ammonia operation: report

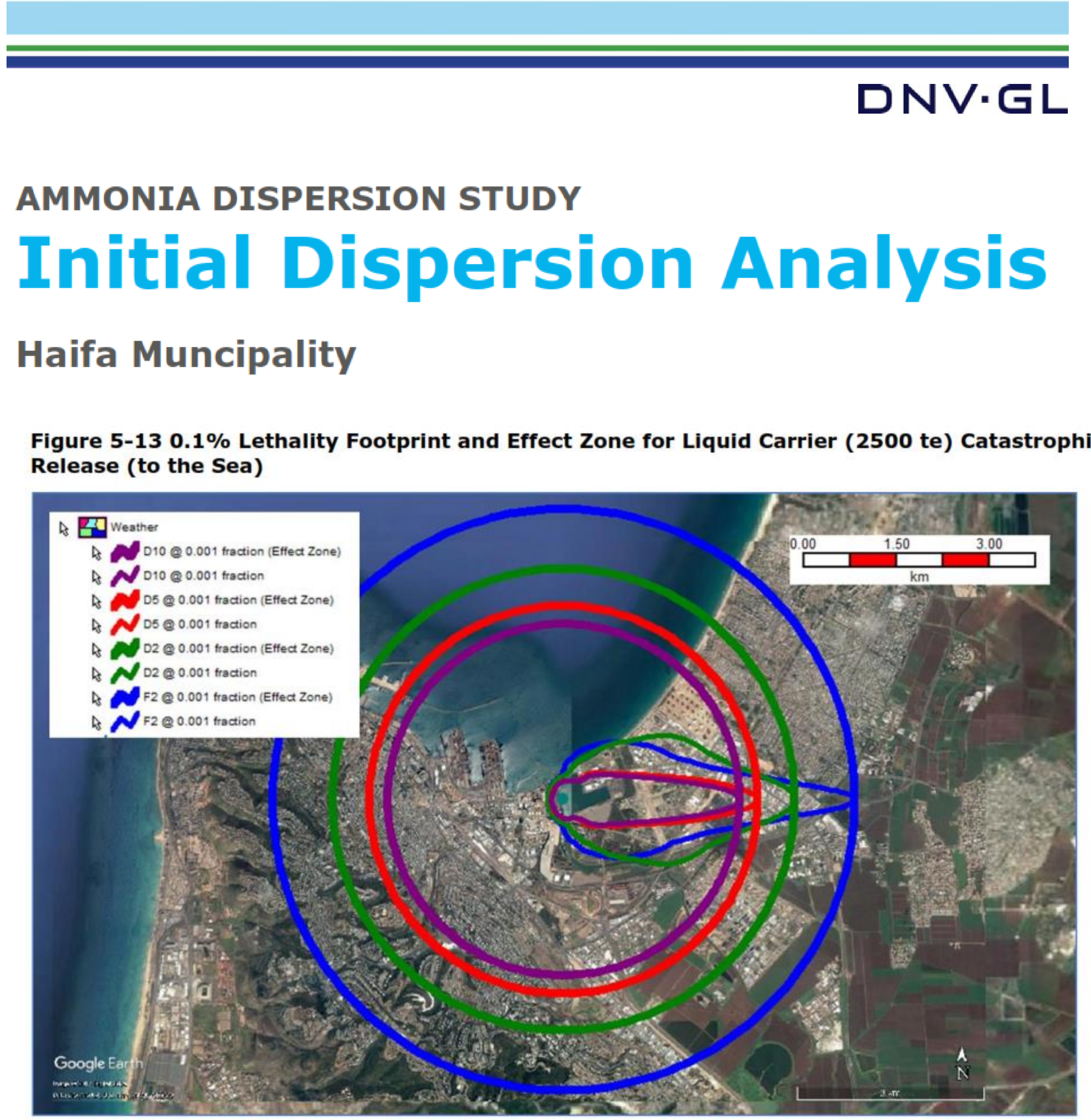
12,000-ton storage container could 'fall apart tomorrow' or be attacked in a war, expert warns, creating a toxic suffocating cloud; managing company dismisses 'fear-mongering'

By STUART WINER

31 January 2017, 7:22 pm | 0

23 shares

Haifa's industrial zone. The ammonia tank is visible on the jetty jutting into the sea at the right. (Shay Levy/Flash90)



DNV·GL

AMMONIA DISPERSION STUDY

Initial Dispersion Analysis

Haifa Muncipality

Figure 5-13 0.1% Lethality Footprint and Effect Zone for Liquid Carrier (2500 te) Catastrophic Release (to the Sea)

https://www.davar1.co.il/wp-content/uploads/2018/03/DNV-Ammonia-Dispersion-Rev-3.1.18%D7%93%D7%95%D7%97-%D7%A1%D7%95%D7%A4%D7%99.pdf

Lloyds Register: ammonia and hydrogen risks, 2020

Lloyd's Register

Working together for a safer world

Hydrogen and Ammonia Infrastructure

Safety and Risk Information and Guidance

Report for:
Ocean Hyway Cluster

Arena Ocean Hyway Cluster

Table 5.1 – Coarse assessment of risk outside fence from simulated releases

Hazard distance	Fatality potential			Injury potential		
Scenario	Full bore	10%	1%	Full bore	10%	1%
Refrigerated NH_3	25m	25m	10m	280m	250m	220m
Compressed NH_3	~2,000m	270m	30m	>10,000m	~2,000m	200m
Liquid H_2	~300m	25m	N/A	~1,000m	300m	N/A
Compressed H_2	~30-40m	20m	N/A	~300m	200m	50m
LNG	>200m	35m	N/A	>200m	35m	N/A

Report no: PRJ11100256122r1 Rev: 00

Date: 7 May 2020

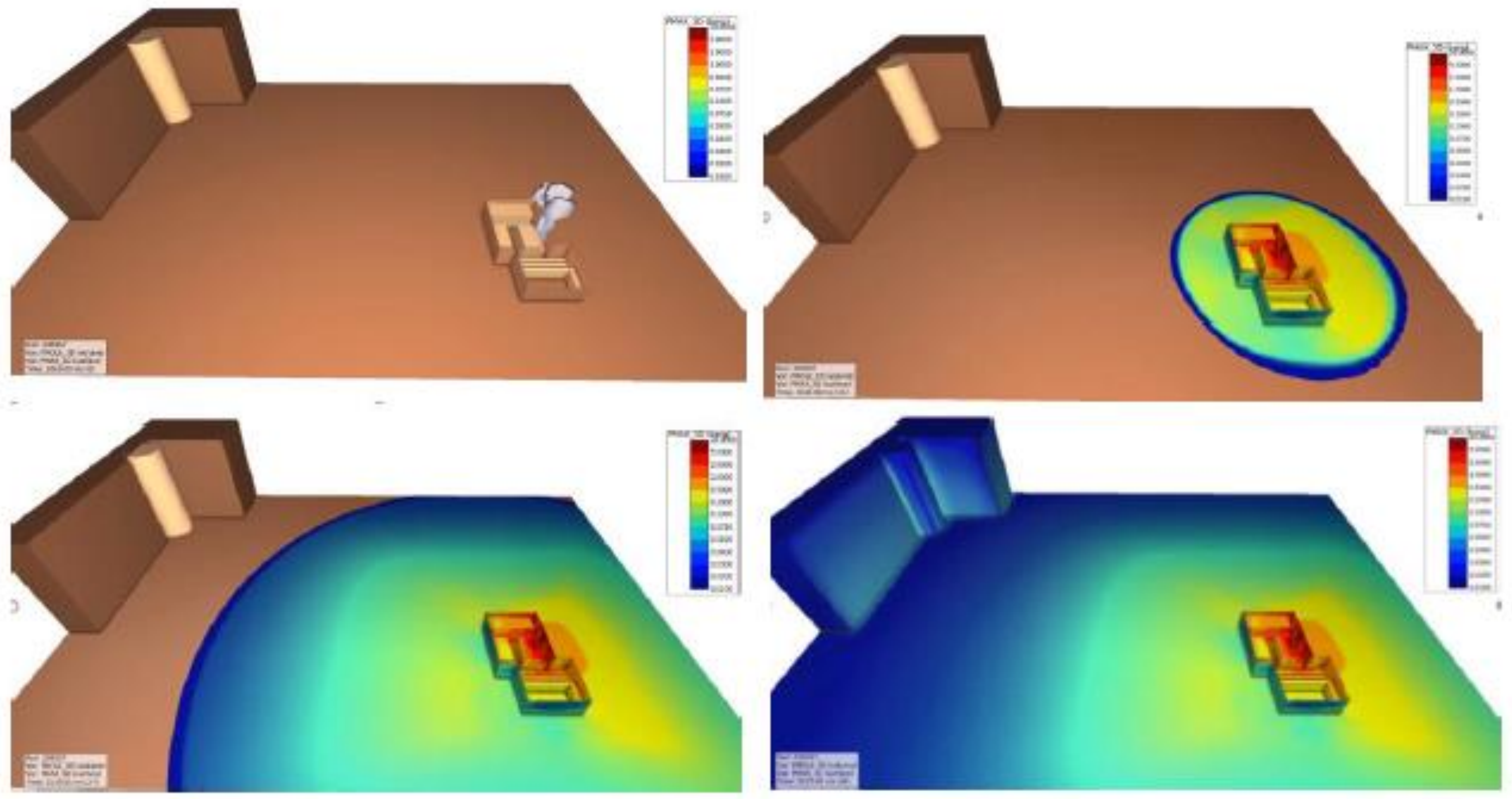
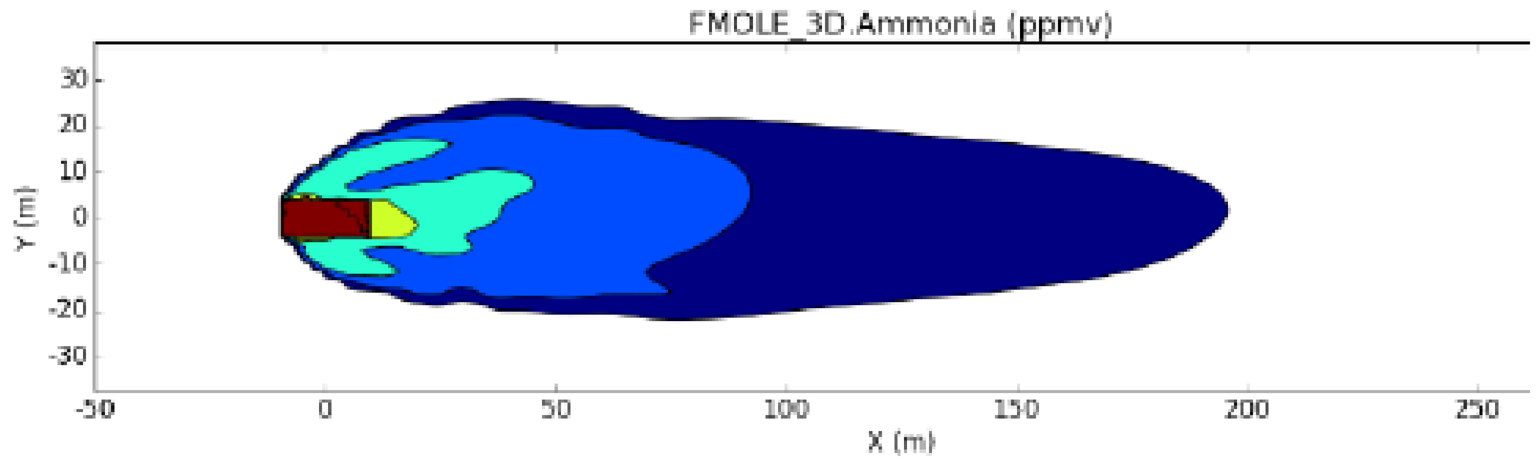


Figure 4-5– CFD-simulation of assumed hydrogen release and detonation [Hansen, 2019] in the Kjørbo accident, first frame shows predicted hydrogen cloud (>15%) at ignition, the other frames show maximum received blast pressures after 45ms, 130ms and 275ms.



Hazard range for ammonia extends further than for hydrogen or LNG (how was the refrigerated NH_3 spill modelled?)

https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/5eb553d755f94d75be877403/1588941832379/Report+D.3+Safety+and+regulations+Lloyds+Register.pdf

DNV Safety Study for Port of Amsterdam, 2021

External safety study - bunkering of alternative marine fuel for seagoing vessels

Port of Amsterdam

Report No.: 10288905-1, Rev. 0
Document No.: 11J5ON0R-1
Date: 2021-04-19

Recent study jointly developed by the Port of Amsterdam and DNV emphasises important spacial safety considerations when designing zero carbon fuel bunkering infrastructure at city ports

Focus areas

Focus areas are areas that visualise where without additional measures, people are insufficiently protected indoors against the consequences of accidents involving hazardous substances. In the new Environmental and Planning Act 2022, a distinction will be made between three types of focus areas:

- Fire focus area;
- Explosion focus area;
- Toxic cloud focus area.

Table 0-2: Maximum distance from bunker hose to focus area boundary

Fuel	Flow rate	Focus area distance (m)		
		Fire	Explosion	Toxic
LNG	400 m³/h (-146 °C)	249	274	- [1]
LNG	400 m³/h (-159 °C)	330	295	- [1]
Methanol	400 m³/h	102	- [1]	22
Ammonia (refrigerated)	400 m³/h	- [1]	- [1]	1446
Ammonia (pressurized)	400 m³/h	- [1]	- [1]	1478
Hydrogen (liquid)	400 m³/h	239	283	- [1]
Hydrogen (gaseous)	3 t/h	87	- [1]	- [1]
Hydrogen (gaseous)	700 bar (60 g/s)	55	- [1]	- [1]
Hydrogen (gaseous)	1000 bar (60 g/s)	55	- [1]	- [1]
LNG	1000 m³/h	448	229	- [1]
Methanol	1000 m³/h	154	- [1]	34
Ammonia (refrigerated)	1000 m³/h	- [1]	- [1]	2624
Ammonia (pressurized)	1000 m³/h	- [1]	- [1]	2060
Hydrogen (liquid)	1000 m³/h	324	338	- [1]

[1] The justification as to why no distances are calculated can be found under Table 7-3 in Section 7.2

https://sustainableworldports.org/wp-content/uploads/DNV-POA-Final-Report_External-safety-study-bunkering-of-alternative-marine-fuels-for-seagoing-vessels_Rev0_2021-04-19.pdf

Other Ammonia Safety Studies

- Ongoing ITOCHU Joint Study Framework on Ammonia as an Alternative Marine Fuel

https://www.itochu.co.jp/en/news/press/2021/210611.html

- DNV-led study for Global Centre for Maritime Decarbonisation (Singapore)
  https://www.gcformd.org/
  https://www.dnv.com/news/gcmd-completes-study-and-readies-stakeholders-for-first-ship-to-ship-pilot-to-transfer-ammonia-in-singapore-242876/
  https://www.gcformd.org/wp-content/uploads/2024/03/Executive-summary.pdf