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Ammonia, CCUS and hydrogen safety:

Scientific research at the Health and Safety Executive

Simon Gant, Strategic Science Adviser for Net Zero, HSE Science and Research Centre

Presentation to DESNZ staff, London, 12 April 2024

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The main focus of this presentation

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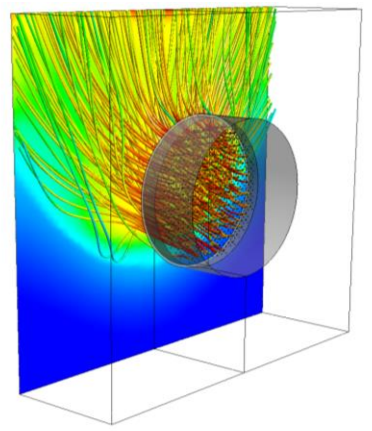
Introduction to HSE

- 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 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

Why use ammonia as an energy vector?

- To transport energy in bulk around the world, it is expensive to use hydrogen

	Hydrogen (H_2)	Ammonia (NH_3)
Boiling point	-253°C	-33°C
Energy density[3] (cryogenic liquid)	9 MJ/litre	16 MJ/litre

30-40% of the energy content of hydrogen is required to liquefy it[2]

- Cheaper to produce ammonia from hydrogen (Haber-Bosch process) and transport liquefied ammonia than it is to transport liquid hydrogen[1]
- Cheaper to import green hydrogen from the Middle East as ammonia than produce green hydrogen in the UK?[2] Blue/green ammonia will also be shipped from elsewhere, e.g. USA
- Ammonia can be cracked to hydrogen and fed into gas grid, or used in fuel cells to produce electricity, with waste nitrogen released to air[4] (cracking ammonia takes >13% of stored energy)[5]
- Ammonia could be used for balancing peak electrical demand when renewable energy sources cannot meet demand and for seasonal energy storage (like LNG peak shaving)[5]
- Ammonia currently handled in large quantities (180 Mt produced globally, 18-20 Mt shipped)[5]
  - Technologies/procedures for bulk handling of ammonia exist from fertilizer/chemical industry, but there are gaps in global ammonia standards for design/operation of future clean energy supply chains

1 https://doi.org/10.1039/D1SE00345C https://doi.org/10.1016/j.isci.2021.102903
2 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/880826/HS420_-_Ecuity_-_Ammonia_to_Green_Hydrogen.pdf
3 https://www.ammoniaenergy.org/articles/ammonia-for-power-a-literature-review/
4 https://www.gencellenergy.com/
5 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf
6 https://www.ics-shipping.org/wp-content/uploads/2021/07/MSC-104-15-9-Development-of-non-mandatory-guidelines-for-safety-of-ships-using-ammonia-as-fuel-Japan-Singapore-ICS-and....pdf

Other possible applications of ammonia?

- Ammonia is seen as the future clean shipping fuel

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

DNV

WHEN TRUST MATTERS

Energy Transition Outlook 2023

MARITIME FORECAST TO 2050

A deep dive into shipping's decarbonization journey

It is hard to identify clear winners among the many different fuel options across all scenarios, but ammonia (electro-based and 'blue') and bio-based methanol are the most promising carbon-neutral fuels in the long run.

https://eto.dnv.com/2021/maritime-forecast-2050/about

Climate Change Committee

The Sixth Carbon Budget

Shipping

- **Options for reducing emissions**. Mitigation options considered include improvements in vessel efficiency (including electricity), and use of zero-carbon fuels (principally ammonia made from low-carbon hydrogen) to displace fossil marine fuels.

https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Shipping.pdf

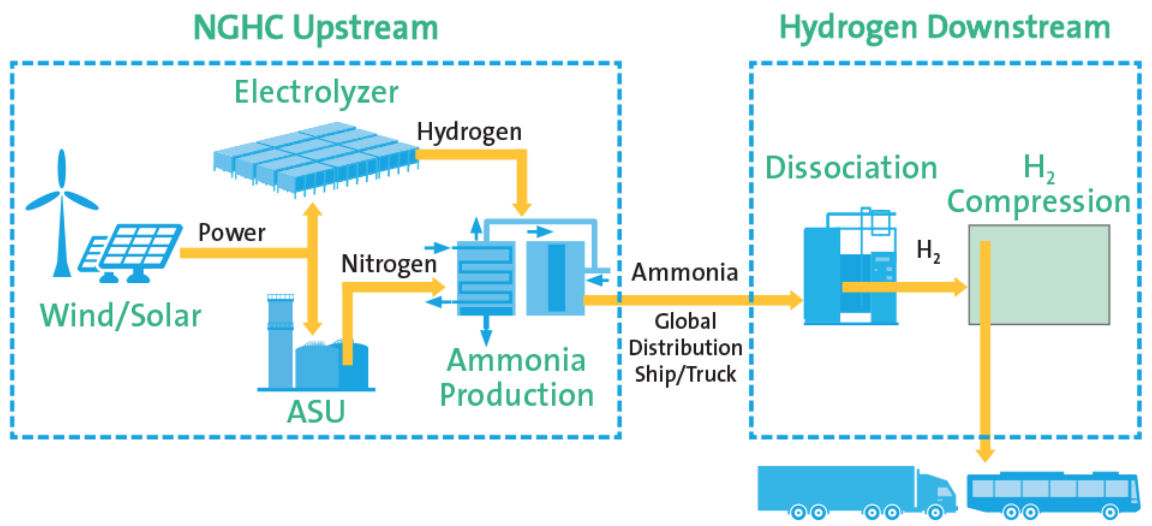
Clean ammonia production projects

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

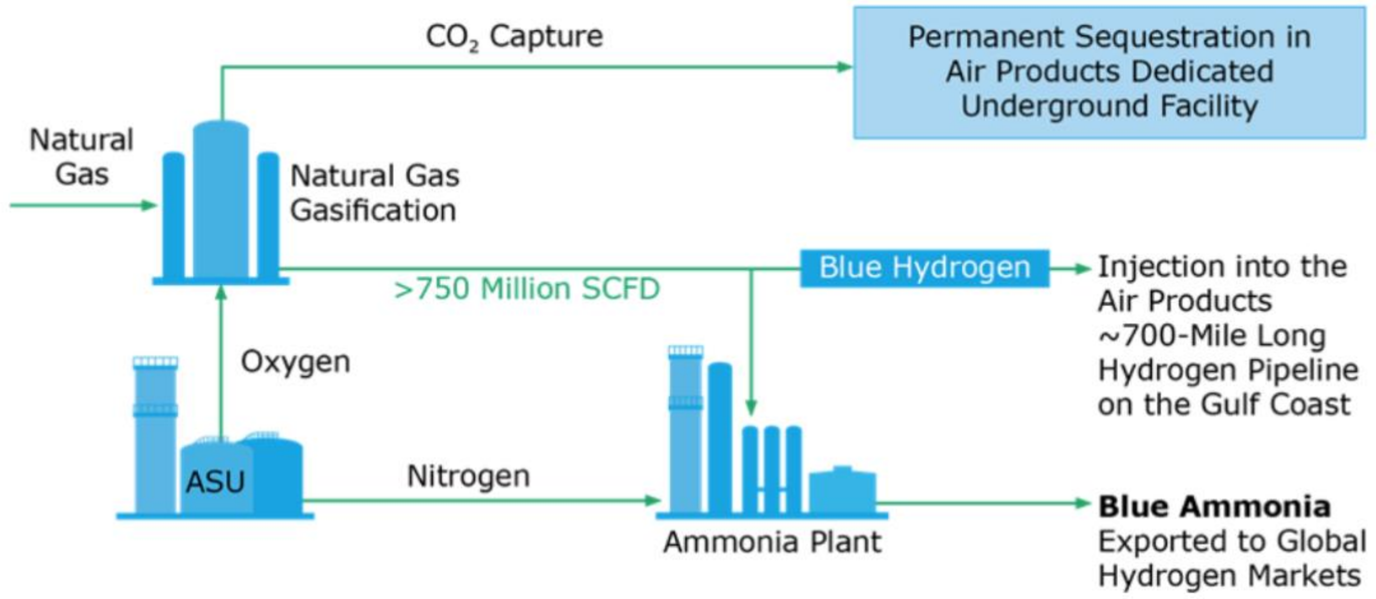


https://www.airproducts.com/news-center

https://www.hydrogeninsight.com/production/interview-neoms-2-2gw-green-hydrogen-and-ammonia-complex-will-meet-high-bar-eu-definition-of-renewable-fuel/2-1-1498120

Air Products Louisiana Clean Energy (USA)

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



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)

Blue hydrogen setback | Europe's largest blue ammonia project in limbo after CCS partner Equinor pulls out

Planned undersea carbon storage facility left without an operator, leaving no clear path forward for EU-subsidised Barents Blue

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

https://www.hydrogeninsight.com/production/blue-hydrogen-setback-europes-largest-blue-ammonia-project-in-limbo-after-ccs-partner-equinor-pulls-out/2-1-1397825

Ammonia-powered ships

Yara “Eyde” container ship

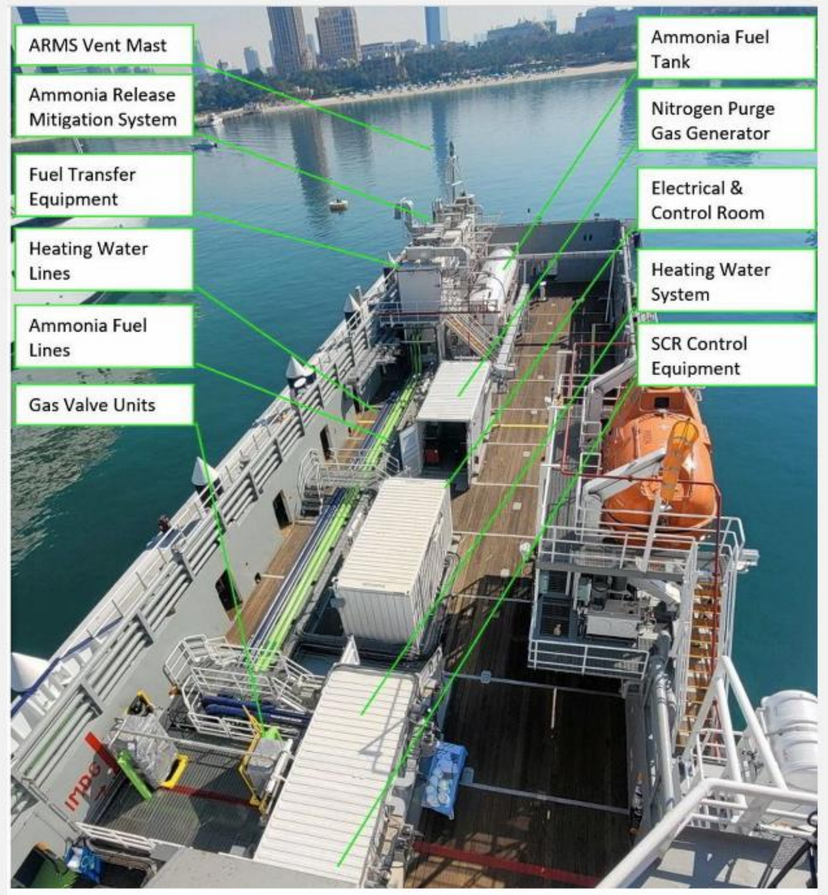
Due to start operating between Norway and Germany in 2026

Yara is currently the world’s largest shipper of ammonia
(15 ships, 18 terminals, annual revenue of $24bn)

https://www.yara.com/corporate-releases/the-worlds-first-clean-ammonia-powered-container-ship/

Fortescue “Green Pioneer” former offshore supply vessel

The Green Pioneer moored in Dubai for the COP28 summit. Photo: Paul Peachey/TradeWinds



Green Pioneer deck layout. Photo: Mattison McGellin

https://www.hydrogeninsight.com/transport/in-safe-hands-onboard-the-world-s-first-ammonia-powered-ship-billionaire-andrew-forrest-s-green-pioneer/2-1-1576006 (Dec 2023)

Singapore, 15 March 2024

World’s First Use of Ammonia as a Marine Fuel in a Dual-Fuelled Ammonia-Powered Vessel in the Port of Singapore

Fortescue, with the support from the Maritime and Port Authority of Singapore (MPA) government agencies, research institutes, and industry partners, has successfully conducted the world's first use of ammonia, in combination with diesel in the combustion process, as a marine fuel onboard the Singapore-flagged ammonia-powered vessel, the *Fortescue Green Pioneer*, in the Port of Singapore. The *Fortescue Green Pioneer* was loaded with liquid ammonia from the existing ammonia facility at Vopak Banyan Terminal on Jurong Island for the fuel trial.

https://www.mpa.gov.sg/media-centre/details/world-s-first-use-of-ammonia-as-a-marine-fuel-in-a-dual-fuelled-ammonia-powered-vessel-in-the-port-of-singapore

Ammonia flagged as green shipping fuel of the future

Marine operators are looking to clean up their act

Adaptive behaviour: the Viking Energy supply vessel which is planned to run on ammonia fuel cells

Charlotte Middlehurst MARCH 30 2020

Eidesvik Offshore’s “Viking Energy” supply vessel

Ammonia fuel cell to be installed in 2024

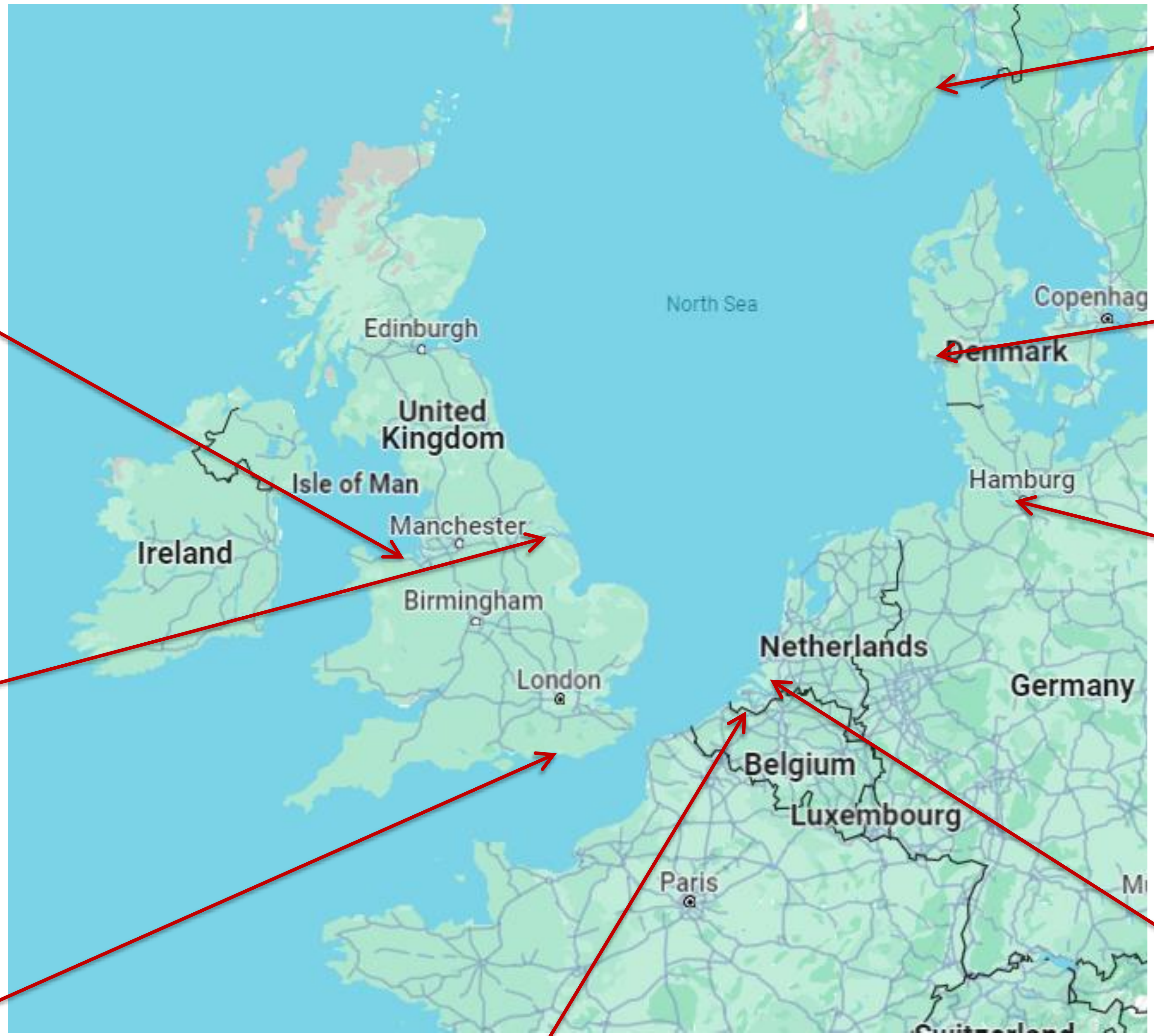
https://eidesvik.no/viking-energy-with-ammonia-driven-fuel-cell/
https://www.ft.com/content/2014e53c-531f-11ea-a1ef-da1721a0541e
https://shipfc.eu/

Clean ammonia storage at ports

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

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/

Esbjerg
https://hoestptxesbjerg.dk/



© Google Maps

Hamburg
https://www.ammoniaenergy.org/articles/large-scale-ammonia-imports-to-hamburg-brunsbuttel/

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

Rotterdam
https://www.ammoniaenergy.org/articles/preparing-the-netherlands-for-large-scale-ammonia-imports/

Shoreham
https://www.ammoniaenergy.org/articles/green-ammonia-port-hubs-in-the-uk-and-australia/

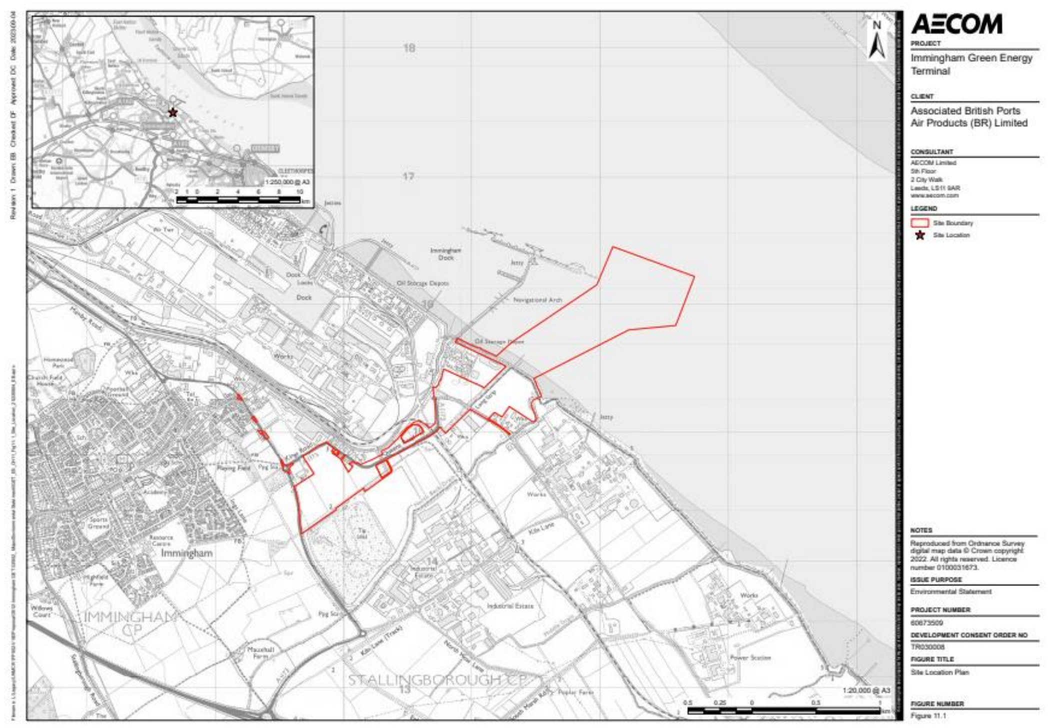
Antwerp-Brugge
https://www.ammoniaenergy.org/articles/advario-new-ammonia-import-capacity-in-belgium/

Ammonia shipping terminals

Immingham Green Energy Terminal DCO NSIP

(Planning examination stage in progress, April 2024)

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



- Ammonia import by ship
- Cracking to hydrogen
- Hydrogen liquefaction
- Future: carbon dioxide ship transport

Yara Clean Ammonia and Azane granted safety permit to build world's first low emission ammonia bunkering terminal

MARCH 25, 2024

https://www.yara.com/corporate-releases/yara-clean-ammonia-and-azane-granted-safety-permit-to-build-worlds-first-low-emission-ammonia-bunkering-terminal/

Recent risk studies on marine applications

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- "**Hydrogen and ammonia infrastructure: safety and risk information and guidance**" by Lloyds Register, May 2020 https://static1.squarespace.com/static/5d1c6c223c9d400001e2f407/t/5eb553d755f94d75be877403/1588941832379/Report+D.3+Safety+and+regulations+Lloyds+Register.pdf
- "**External safety study - bunkering of alternative marine fuel for seagoing vessels, Port of Amsterdam**" by DNV, April 2021 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
- "**Safety and operational guidelines for piloting ammonia bunkering in Singapore**", DNV-led ammonia safety study for Global Centre for Maritime Decarbonisation (GCMD), April 2023 https://www.gcformd.org/ammoniabunkeringreportdownload
- "**Ammonia as a marine fuel**", Maritime Energy & Sustainable Development (MESD) and Nanyang Technological University (NTU), October 2022 https://www.ntu.edu.sg/mesd-coe/publications
- "**Recommendations for design and operation of ammonia-fueled vessels based on multi-disciplinary risk analysis**" by Lloyds Register for Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, June 2023 https://www.zerocarbonshipping.com/publications/recommendations-for-design-and-operation-of-ammonia-fueled-vessels-based-on-multi-disciplinary-risk-analysis/
- **ITOCHU** Joint Study Framework on Ammonia as an Alternative Marine Fuel – any progress? https://www.itochu.co.jp/en/news/news/2022/220406.html

Rail transport and power applications

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/

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/

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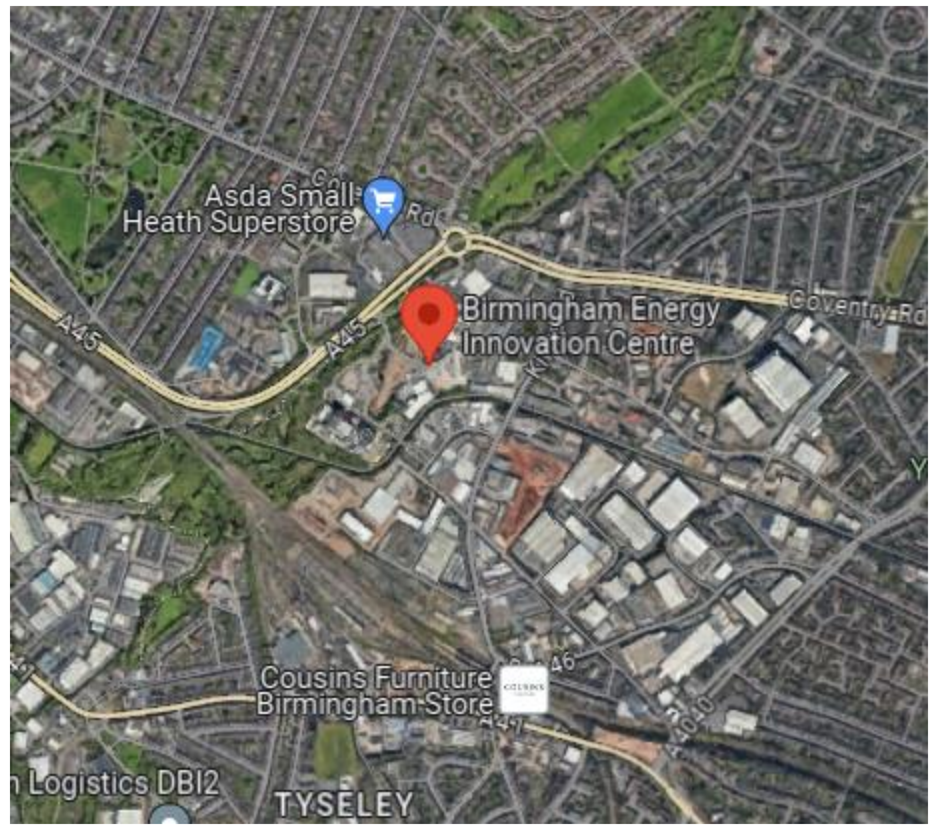
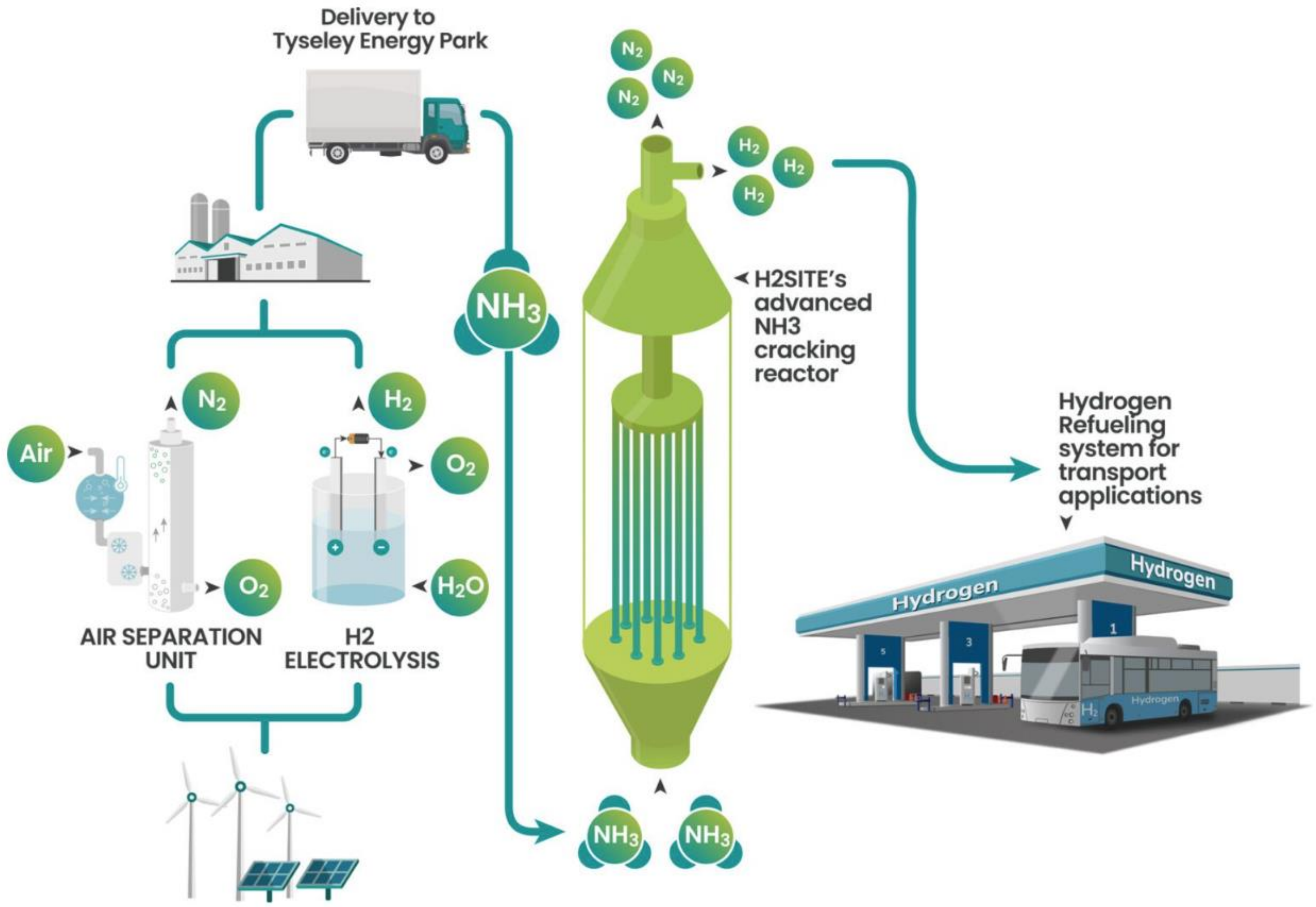
Ammonia distribution for vehicle refuelling

- £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
- Ammonia storage and vaporization units arrived on site in Sept 2023
- Commissioning in Jan 2024
- https://ammogen.co.uk/





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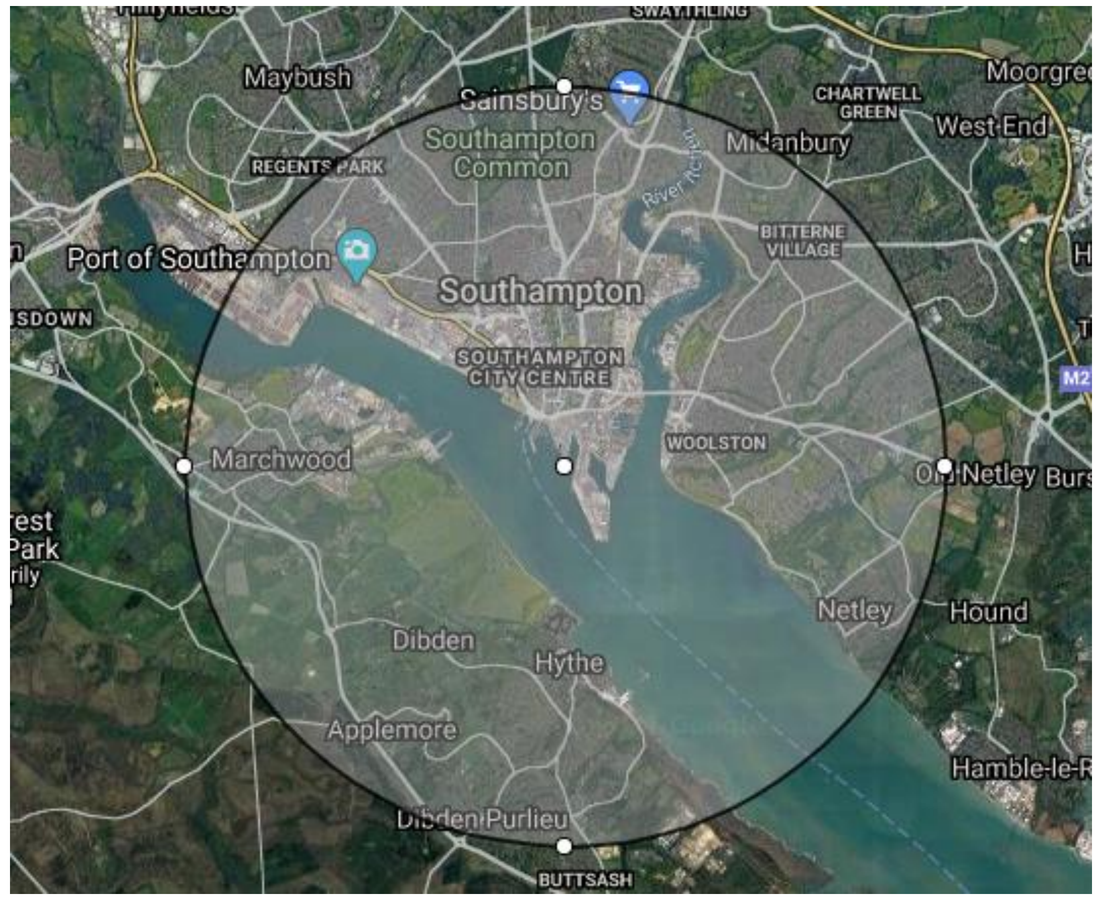
What are the important safety issues?

- Increased transport, storage and use of ammonia is highly likely in coming decade
  - New operators and emergency responders unfamiliar with safety of bulk ammonia transport and storage
  - Change of risk profile
- Regulatory considerations for bulk ammonia storage at ports
  - Ports often located near populated areas
  - Onshore bunkering and/or floating barges?
  - Onshore/subsea pipeline connection to single mooring point?
  - Multiple stakeholders: Site operators, Health and Safety, Environment, Security, Port Authorities, Local Authorities, Coastguard, Emergency Services
- Risk assessment
  - Need to build confidence and trust in risk assessments for ammonia and ensure underlying models are robust and validated
    - Includes source models, atmospheric transport and dispersion models, waterborne hazard models
- Emergency planning and response
  - Advice to emergency responders on cordon distances and protective actions



2.8 mile radius for ammonia railcar release

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2020-08/ERG2020-WEB.pdf

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Useful reviews for further reading

Ammonia:
zero-carbon fertiliser, fuel and energy store

POLICY BRIEFING

THE ROYAL SOCIETY

- Royal Society policy briefing on green ammonia, 2020
  https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf

- International Power-to-X Hub reports, 2024
  - Ammonia, nitrogen and green hydrogen production and purification
    https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-nitrogen-and-green-hydrogen-production-and-purification.pdf
  - Ammonia transport and storage
    https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-transport-and-storage.pdf

- Ammonia roadmap journal paper, 2023 https://dx.doi.org/10.1088/2515-7655/ad0a3a

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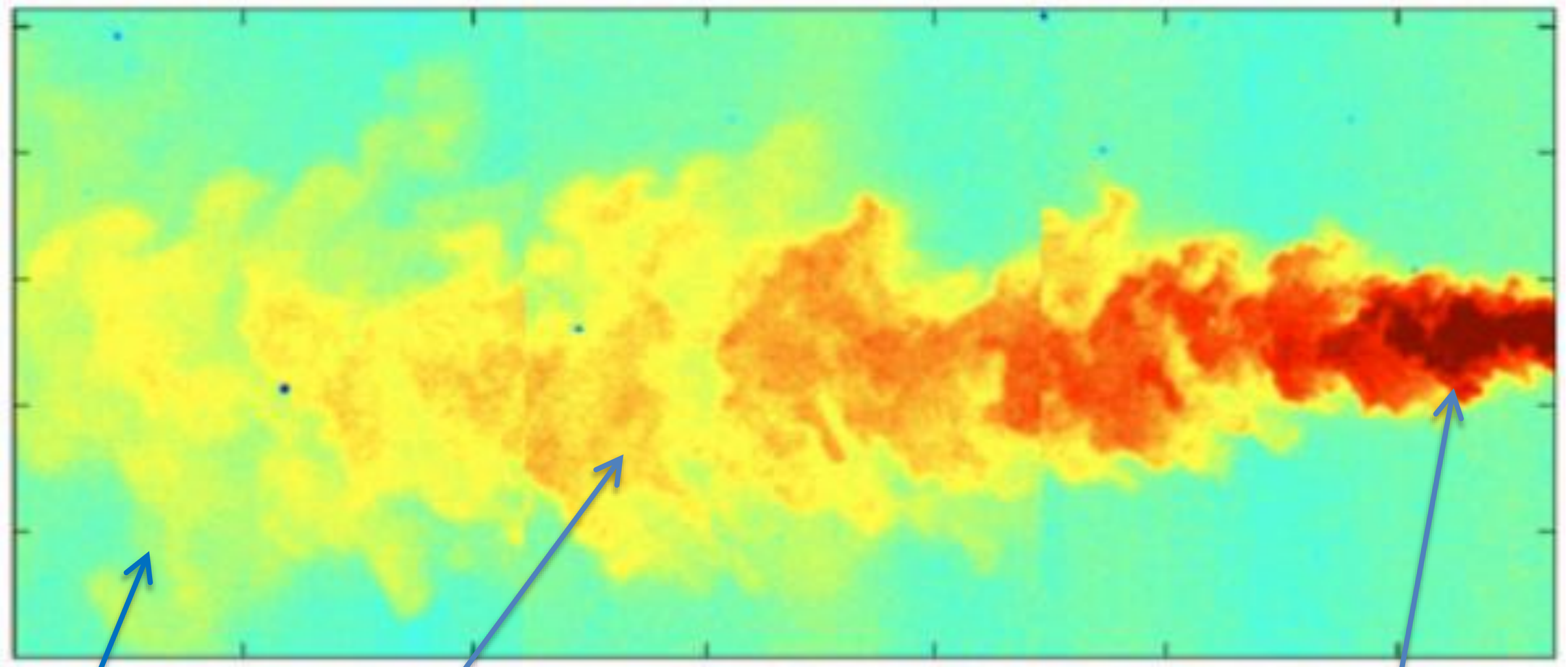
Flammability and toxicity

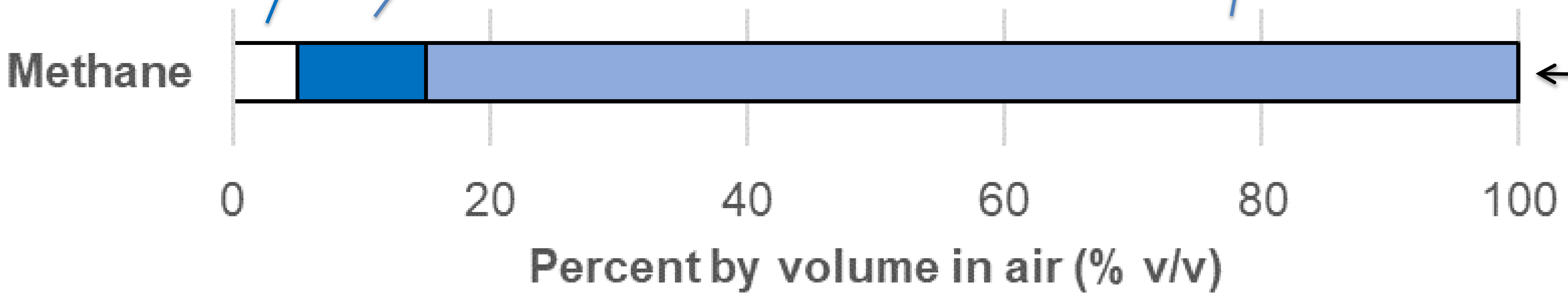


Plume image source: http://www.hysafe.org/science/eAcademy/docs/4thesshs/presentations/ESSHS2009KellerJ1.pdf

Low concentrations on edge of plume, too dilute to burn

Plume is flammable where concentrations are between 5% and 15% v/v

High concentrations in core of plume, too rich to burn



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

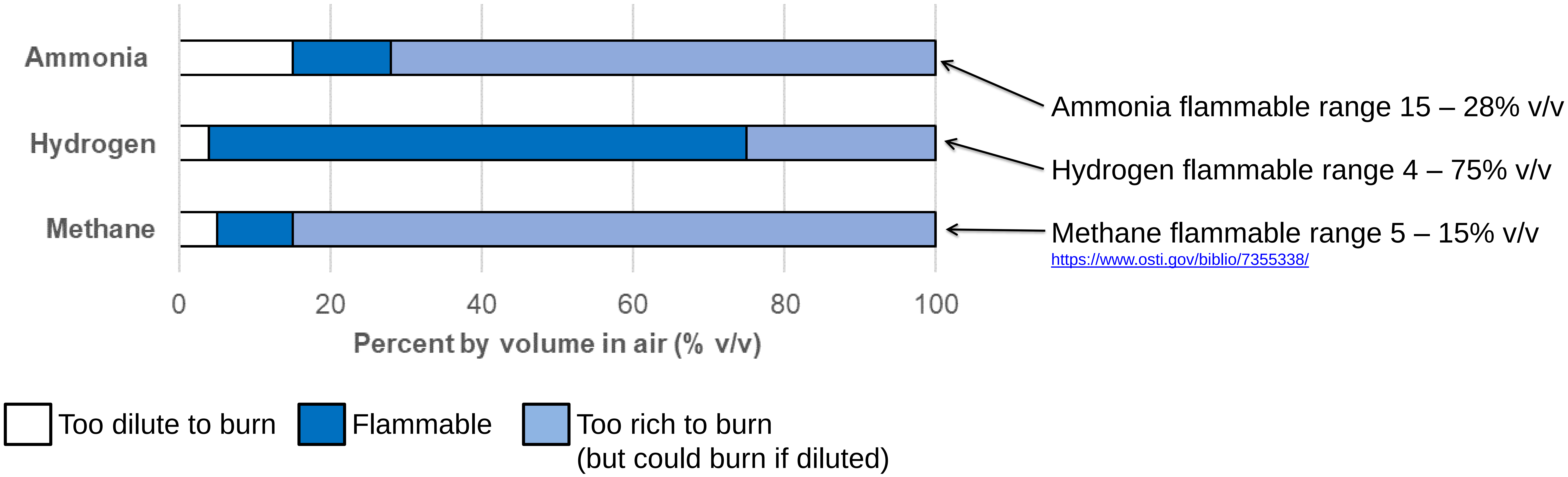
Too dilute to burn | Flammable | Too rich to burn (but could burn if diluted)

Flammability and toxicity

Hydrogen has a wide flammable range, i.e., it is possible to ignite and burn a large proportion of the plume

Ammonia has a relatively narrow flammable range (needs to be richer than methane to burn)

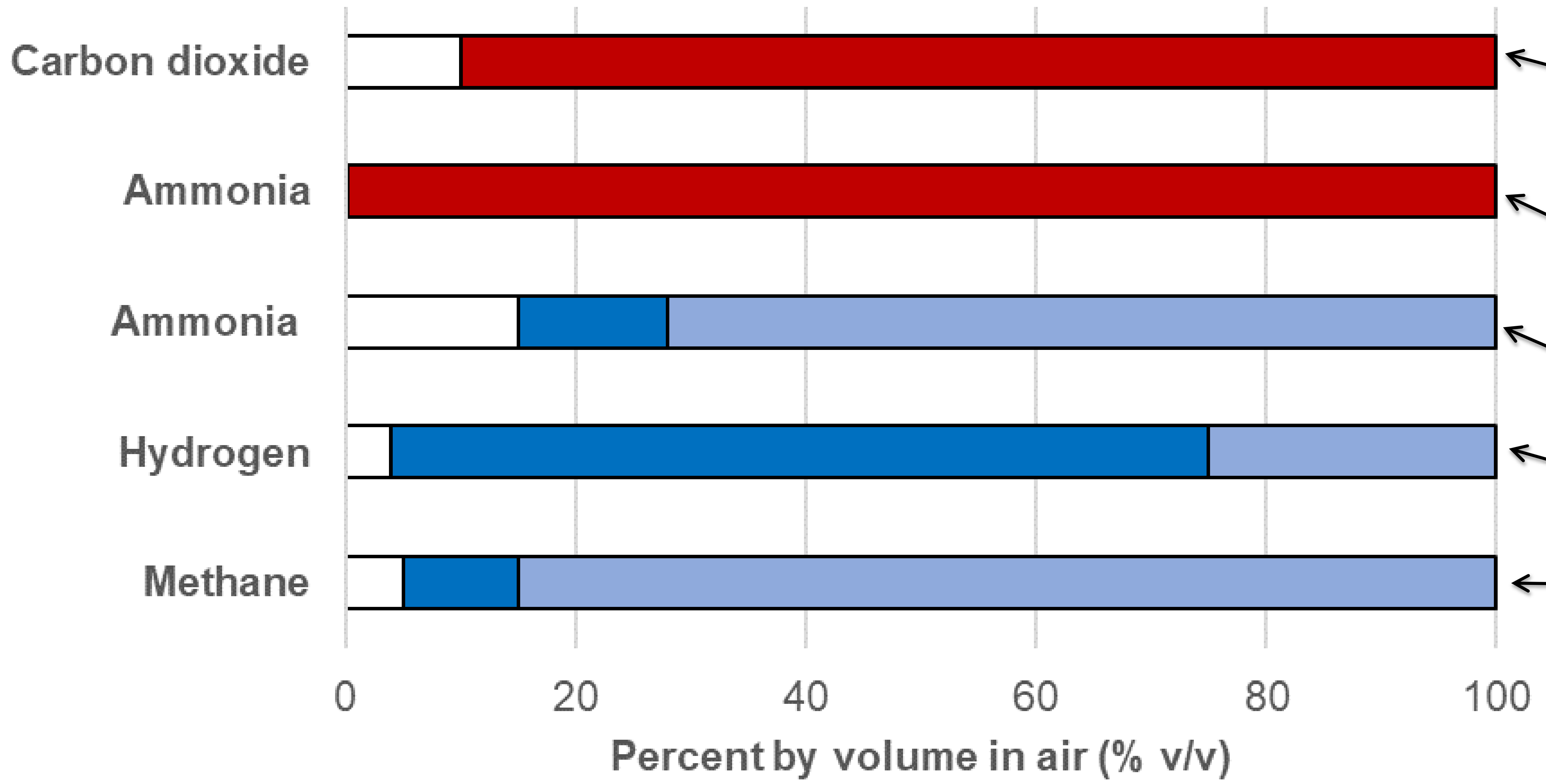
Ammonia is also difficult to ignite (its minimum ignition energy is over a thousand times that of hydrogen)



Flammability and toxicity

Ammonia is toxic at lower concentrations than when it is flammable (also detectable by smell at ~17 ppm)
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/290981/scho0307bmkt-e-e.pdf

Carbon dioxide is toxic at a similar concentration to common hydrocarbon flammable limits



Carbon dioxide is not just an asphyxiant
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

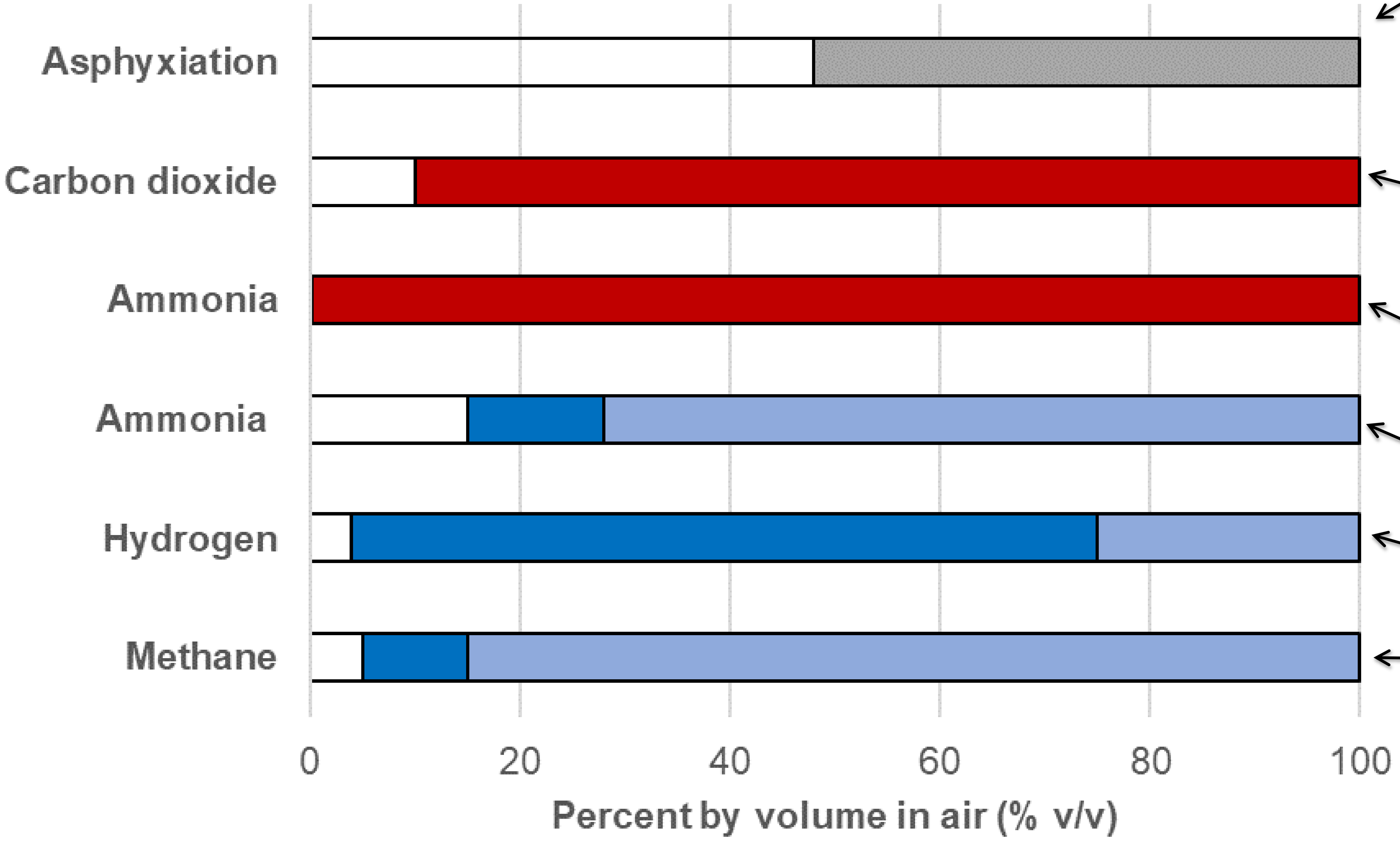
Hydrogen flammable range 4 – 75% v/v

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

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

Flammability and toxicity



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 is not just an asphyxiant
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

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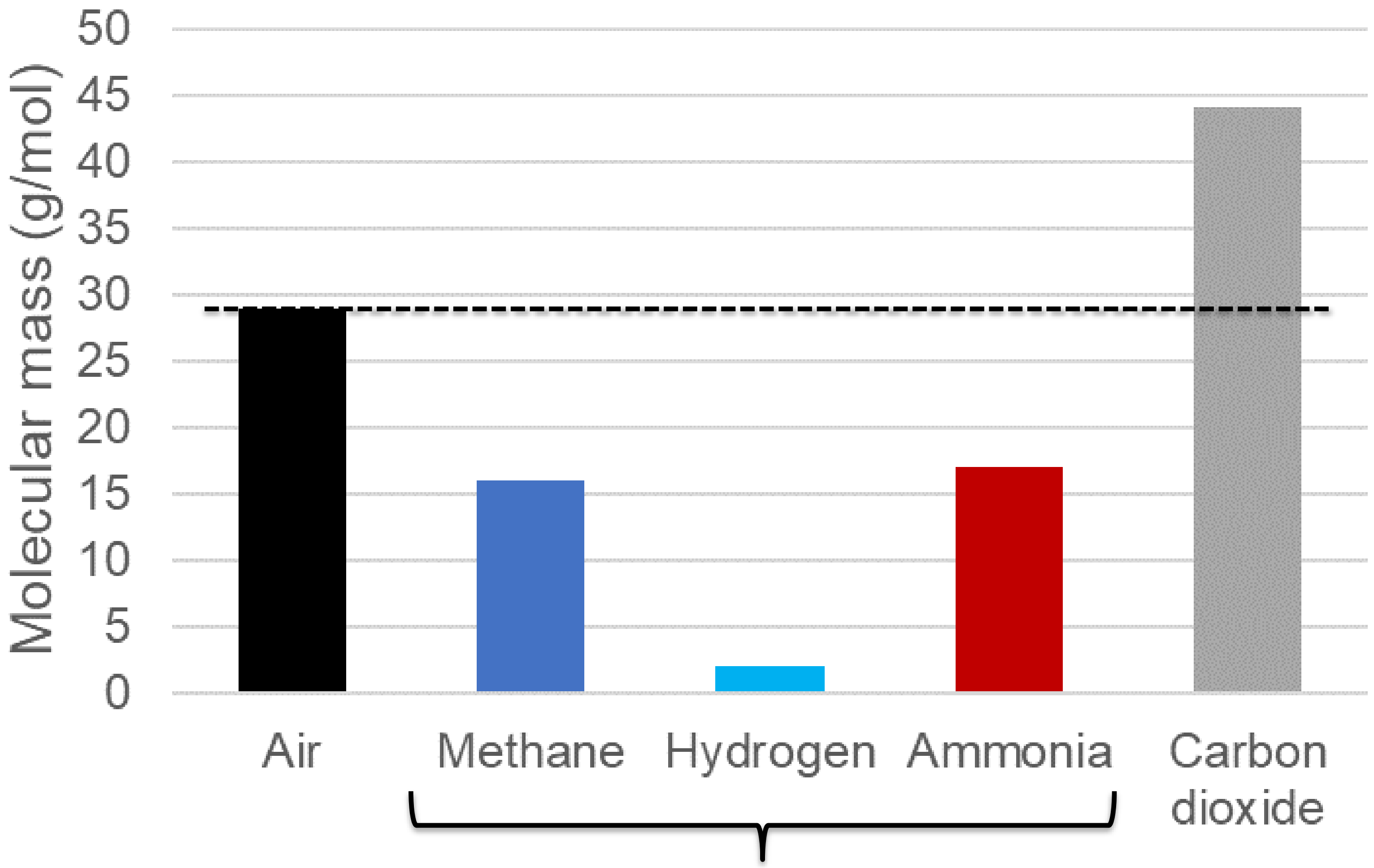
Is ammonia heavier or lighter than air?

Molecular mass indicates the buoyancy of the gas in air
(assuming that they are at the same temperature and there are no aerosols)



Buoyant gases rise

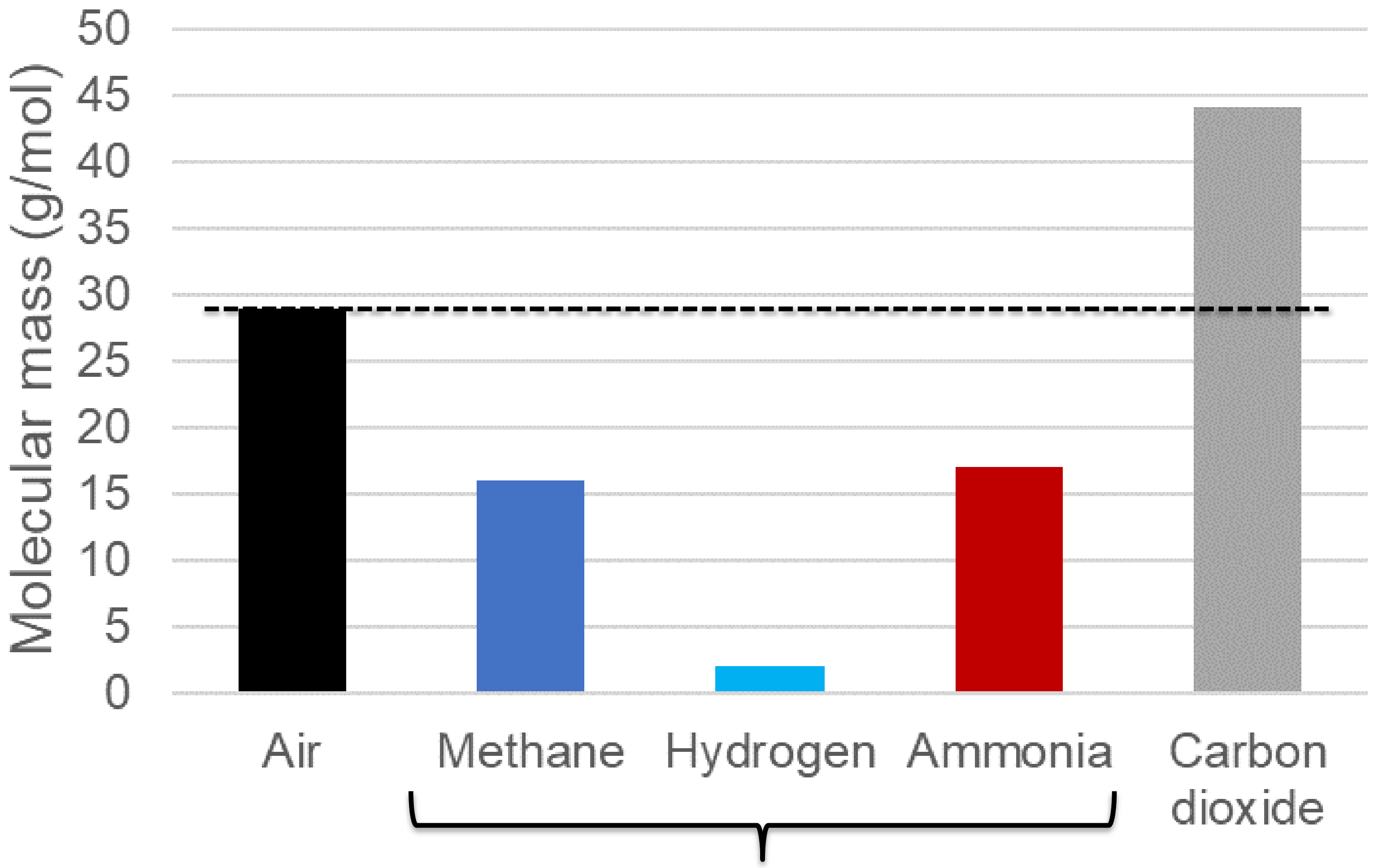
Heavier than air CO_2 gas sinks to the ground

Is ammonia heavier or lighter than air?

Molecular mass indicates the buoyancy of the gas in air
(assuming that they are at the same temperature and there are no aerosols)

But…

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



Buoyant gases rise

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

Liquid hydrogen release experiments at HSE for www.preslhy.eu

Ammonia

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

See Haddock & Williams (1978) https://admlc.com/safety-and-reliability-directorate-srd-series-reports/

Other properties

	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	–

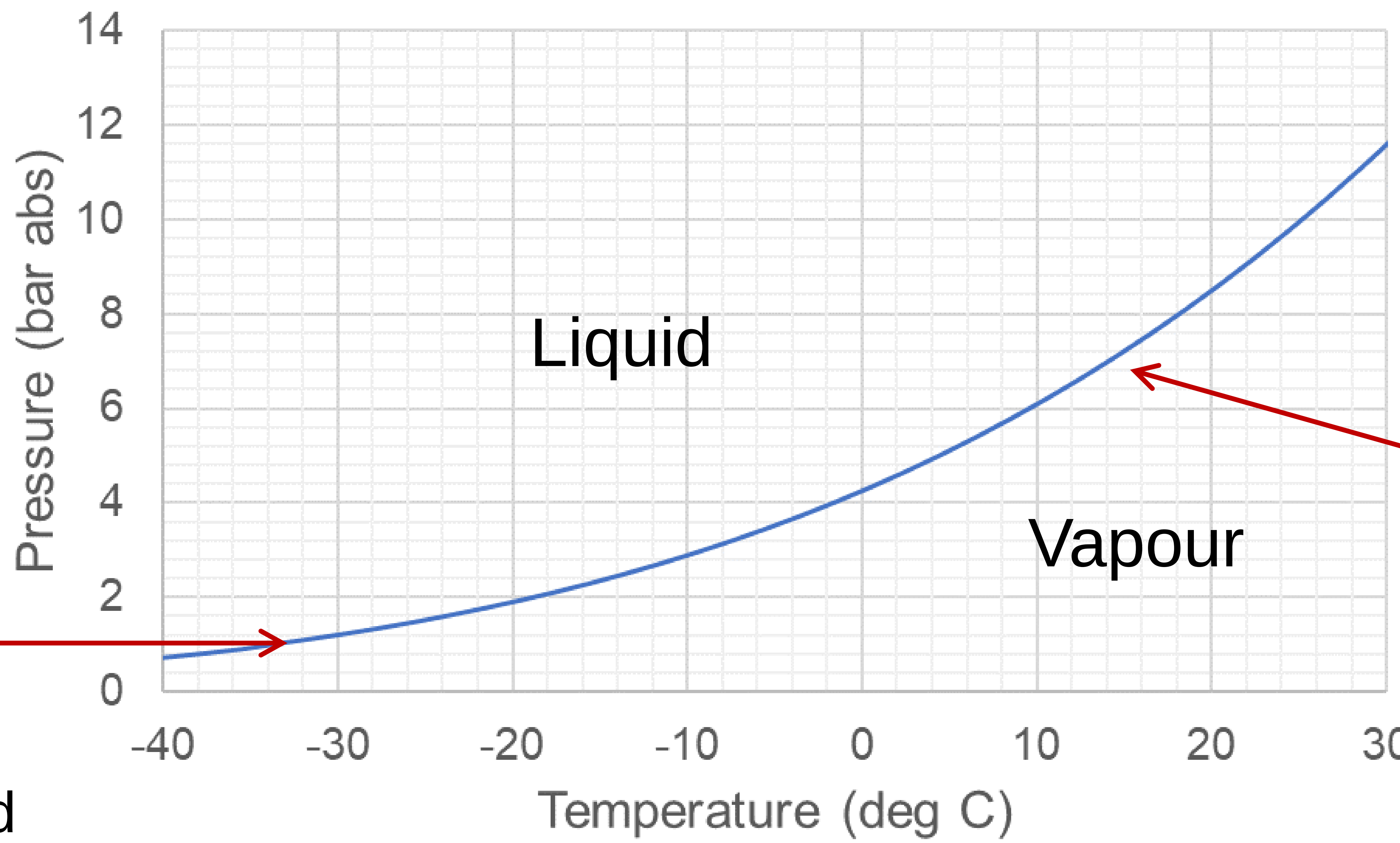
† Sublimation temperature for CO_2
* Properties given at 15°C and ambient pressure

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

Ammonia phase diagram

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 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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Liquid ammonia pools: flammability

- Experiments undertaken on ignited pools of cryogenic liquid ammonia in the 1960s
- 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 hydro-carbon-air mixtures and readily combustible solids such as paper and wood splinters.

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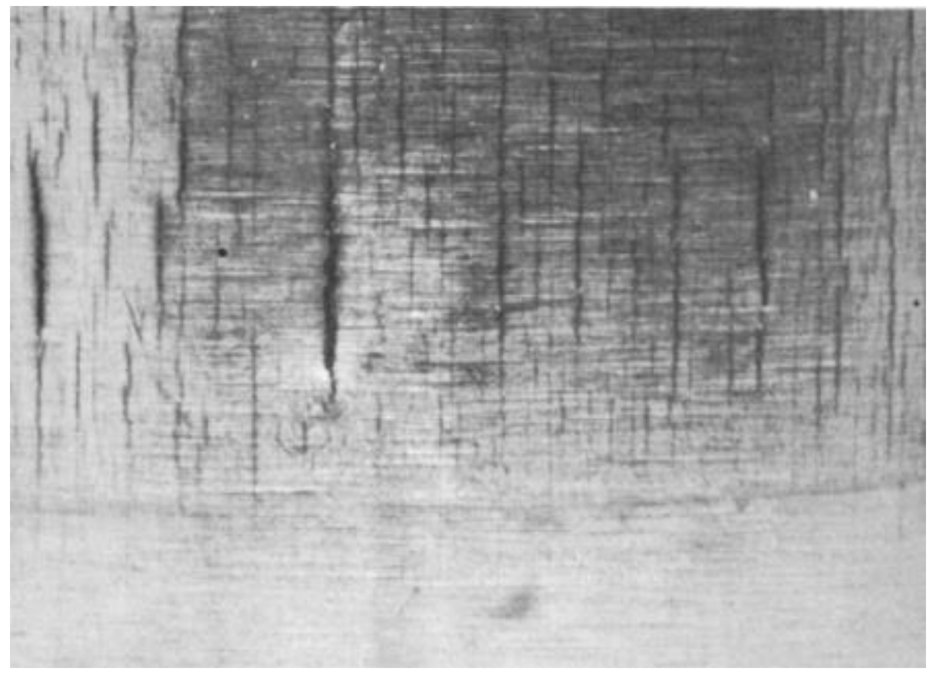
Effects of ammonia on materials

- 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 vapor 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* (see "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)

Effects of ammonia on materials

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- 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 guidance given in ammonia standards and guidance – later slides

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Contents

Ammonia is not Ammonium Nitrate

- Beirut explosion was ammonium nitrate, not ammonia

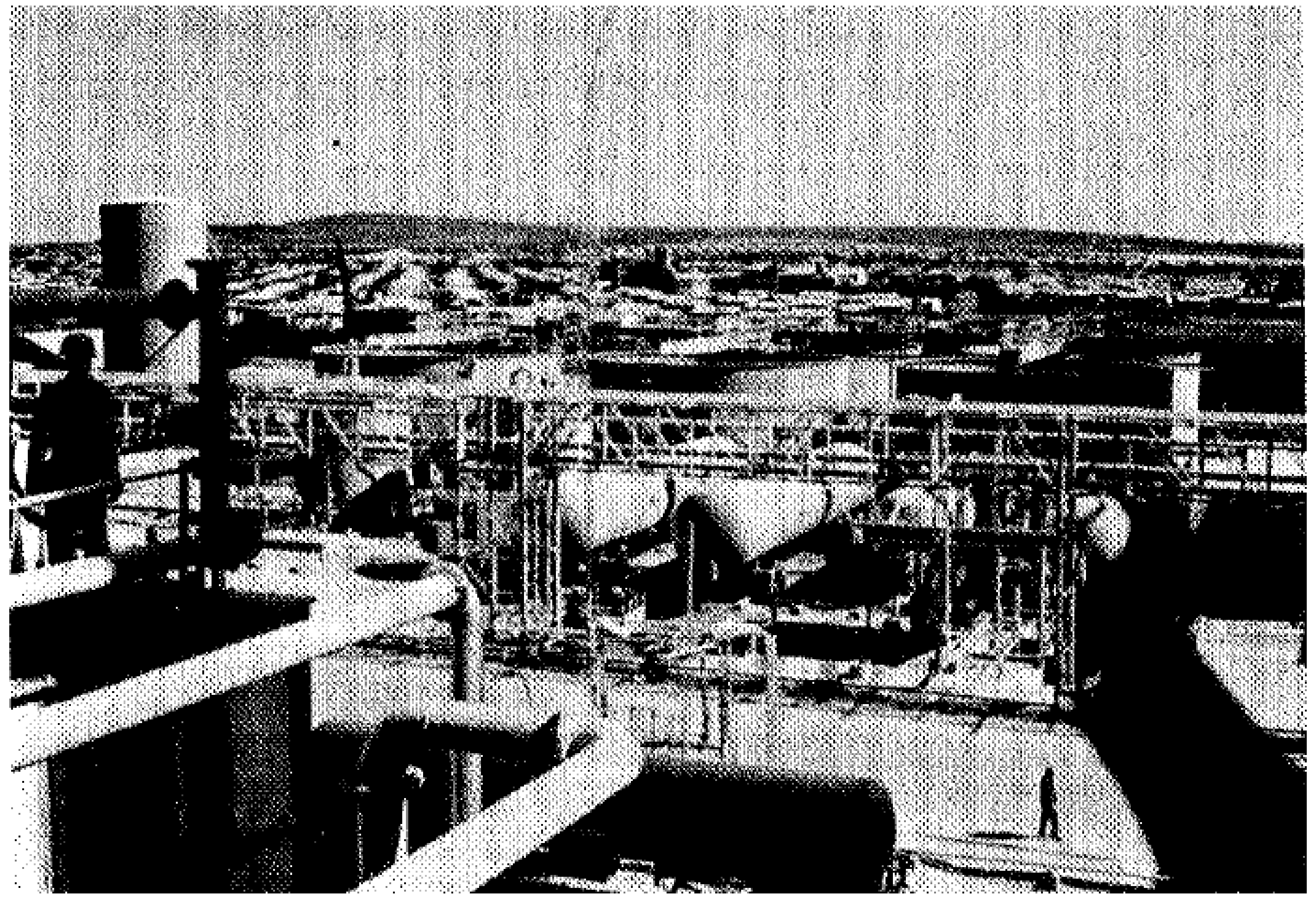
https://www.nytimes.com/video?src=vidm

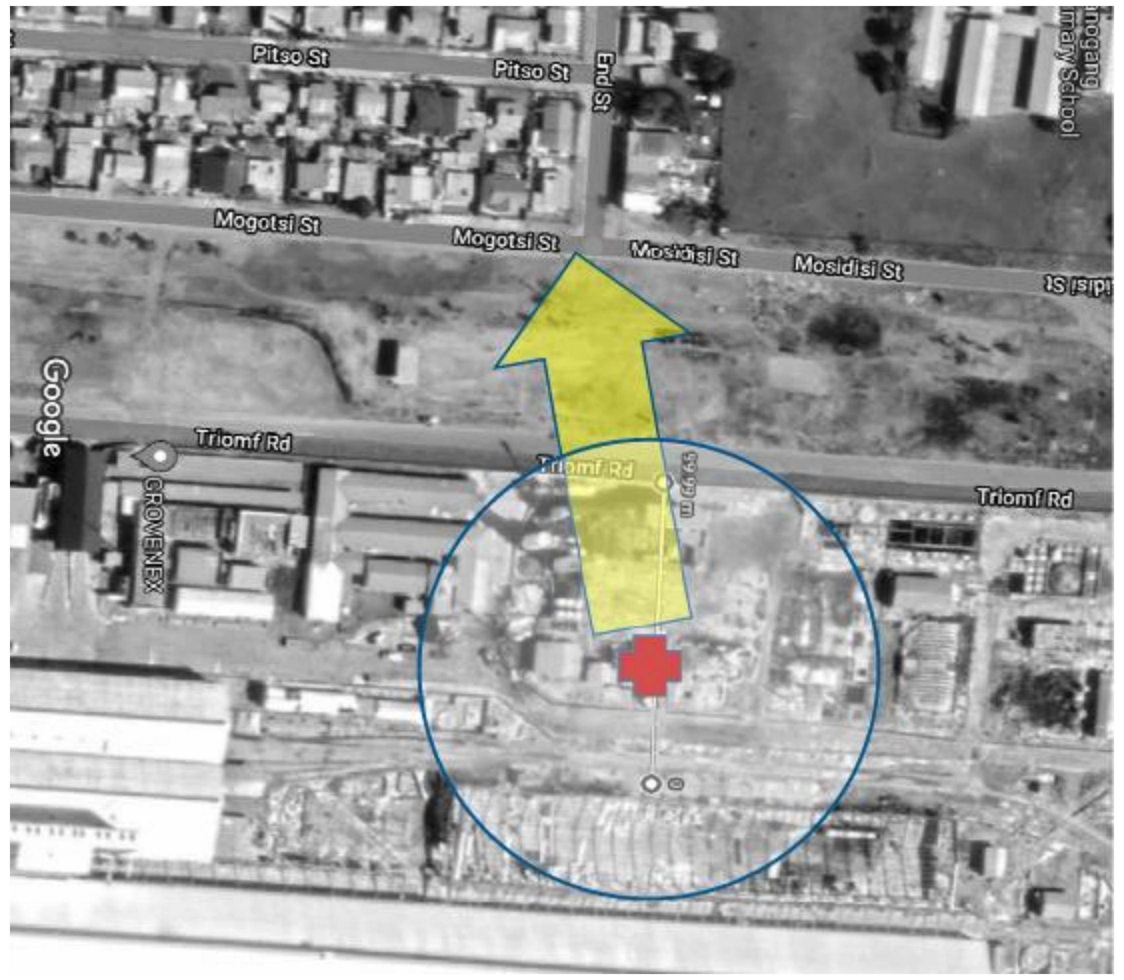
Incidents with pressure-liquefied ammonia

Ambient temperature, pressure > 7 bar

Potchefstroom, South Africa (1973)

- One of four 50 t storage tanks ruptured while being filled with pressure-liquefied ammonia from a railroad car
- Tank failed due to brittle fracture of a dished end of the vessel
- Subsequent investigation found issues with material properties of steel tank
- 30 tons of ammonia released from tank, plus 8 tons from the railcar
- 65 people hospitalized and 18 deaths





Lonsdale, H. Ammonia tank failure-South Africa, Ammonia Plant Safety 17: 126-131, 1975, and analysis by Doug Sommerville for US Department of Homeland Security

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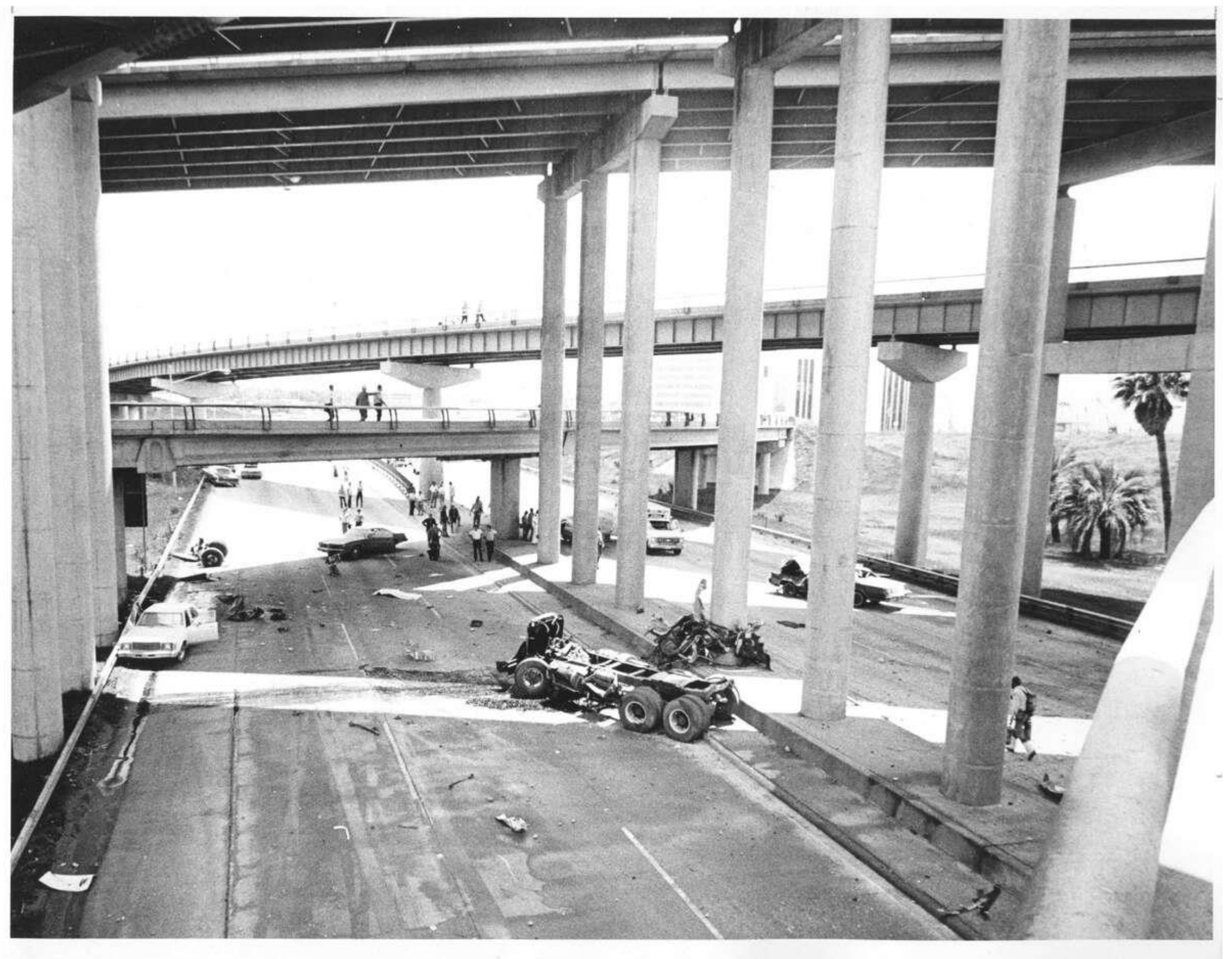
Houston, Texas (1976)

- 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

Houston, Texas (1983)

- Leak from ammonia refrigeration equipment in basement of Borden's building
- Vapour accumulated and found ignition source, producing a vapour cloud explosion
- Fire fighters set to enter building in breathing apparatus at time of explosion
- Incident occurred on early Sunday morning, no serious injuries
- Demonstrated that if ammonia vapour is confined, explosion can be severe

Photo by John Steiger

Rubble litters the streets outside the Borden ice cream plant downtown where a blast triggered by an ammonia leak occurred Sunday morning.

Firefighters almost caught in explosion

By TUPPER HULL
Post Reporter
12-12-83

An ammonia leak at a downtown Houston ice cream plant triggered a massive explosion that left much of the block-square building in ruins and barely missed killing a group of firefighters.

The firefighters were preparing to enter the Borden Inc. ice cream plant at 1900 Milam when it suddenly exploded with a force that shattered surrounding windows and hurled bricks like missiles. One brick punctured the door of a fire truck.

Firefighters were summoned to what dispatchers described as an ammonia leak at the plant about 9 a.m.

Ed Hauck, acting chief of the fire department's District and one of the first to arrive at the building, said about five firefighters "were putting on our air packs and getting ready to go down there. We could hear the ammonia escaping down in the basement. Just as we were about to go in the whole building blew up. If we had been a minute earlier we'd have been blown up, too," Hauck said.

The explosion also set fire to the building and released a cloud of deadly ammonia gas wafting across the nearly deserted downtown business district.

"It was lucky it was a Sunday and no one was down there," said a fire department spokesman.

There were no serious injuries but a fire department official predicted some firemen probably would require treatment because they breathed the poisonous ammonia vapors.

The explosion left the streets surrounding the plant covered in blankets of glass, bricks, ice cream cartons and small wooden Popsicle sticks.

Borden employee Melvin Machart was the only worker inside the plant when ammonia suddenly began leaking from high pressure lines.

"I was down there in the basement when I heard a boom. I ran outside and shut off the ammonia valves and called the fire department," said Machart. He said the first explosion was followed by the devastating major blast about half an hour later.

Ninety firefighters and 35 pieces of firefighting equipment responded to the blast, said fire department officials.

Borden officials said the ammonia was used in 15 compressors to refrigerate the ice cream while it was being made and to store it.

"It doesn't take much ammonia to get a pretty good explosion," said spokesman Donald Kraus. "Once it gets out and vaporizes it goes all through the building. Then all it takes is a spark."

https://ashraehouston.org/downloads/Historian/borden_s_icecream_factory_explosion_1983.pdf#:~:text=This%20was%20disastrously%20indicated%20by%20the%20December%2011%2C,traffic%20to%20be%20exposed%20to%20the%20explosion%20results.

Dakar, Senegal (1992)

- Ammonia storage vessel with capacity of 17.7 t ruptured due to overfilling with more than 22 t of pressure-liquefied ammonia
- Vessel had previously cracked and been repaired
- Vessel fractured violently into two parts
- Visible cloud reported to distances of around 250 m
- 1,150 people injured, 129 deaths
- Later analysis using dispersion model indicated a potential for fatalities up to a distance of 1 km, and injuries up to 4 or 5 km downwind



https://www.aria.developpement-durable.gouv.fr/wp-content/files_mf/A3485_ips03485_002.pdf
https://www.aiche.org/sites/default/files/cep/20230747.pdf
https://www.aiche.org/resources/publications/cep/2023/december/process-safety-beacon-learning-worst-ammonia-accident

Minot, North Dakota (2002)

- Train derailment caused rupture of 5 ammonia tank cars and 350 t release
- Ammonia cloud gradually expanded 5 miles downwind of the accident site and over a population of about 11,600 people
- 322 people sustained minor injuries, 11 sustained serious injuries, 1 death
- Cause: poor maintenance of joint bars in continuous welded rail and insufficient tank car crashworthiness

https://www.ntsb.gov/investigations/AccidentReports/Reports/RAR0401.pdf

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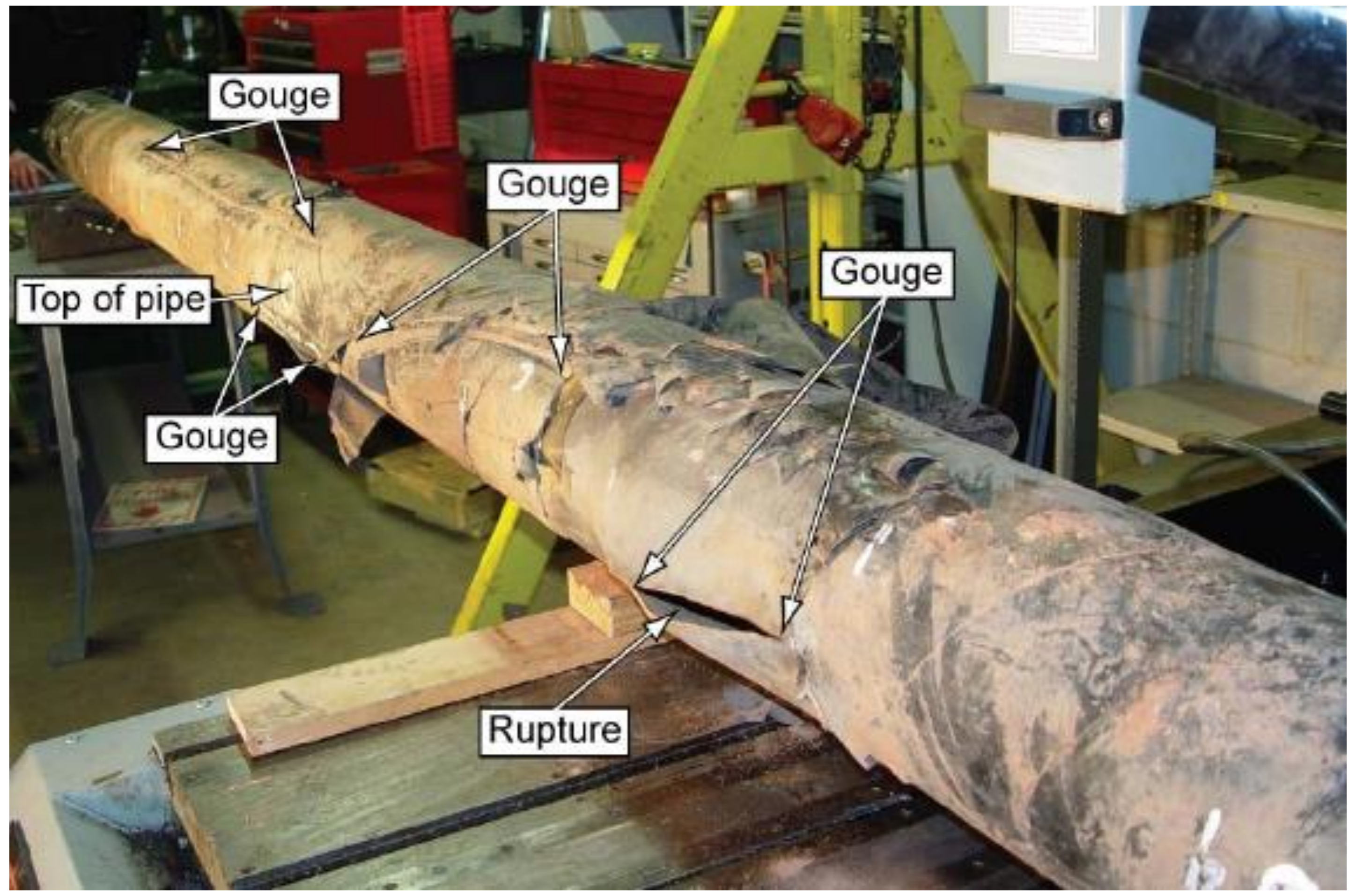
Kingman, Kansas (2004)

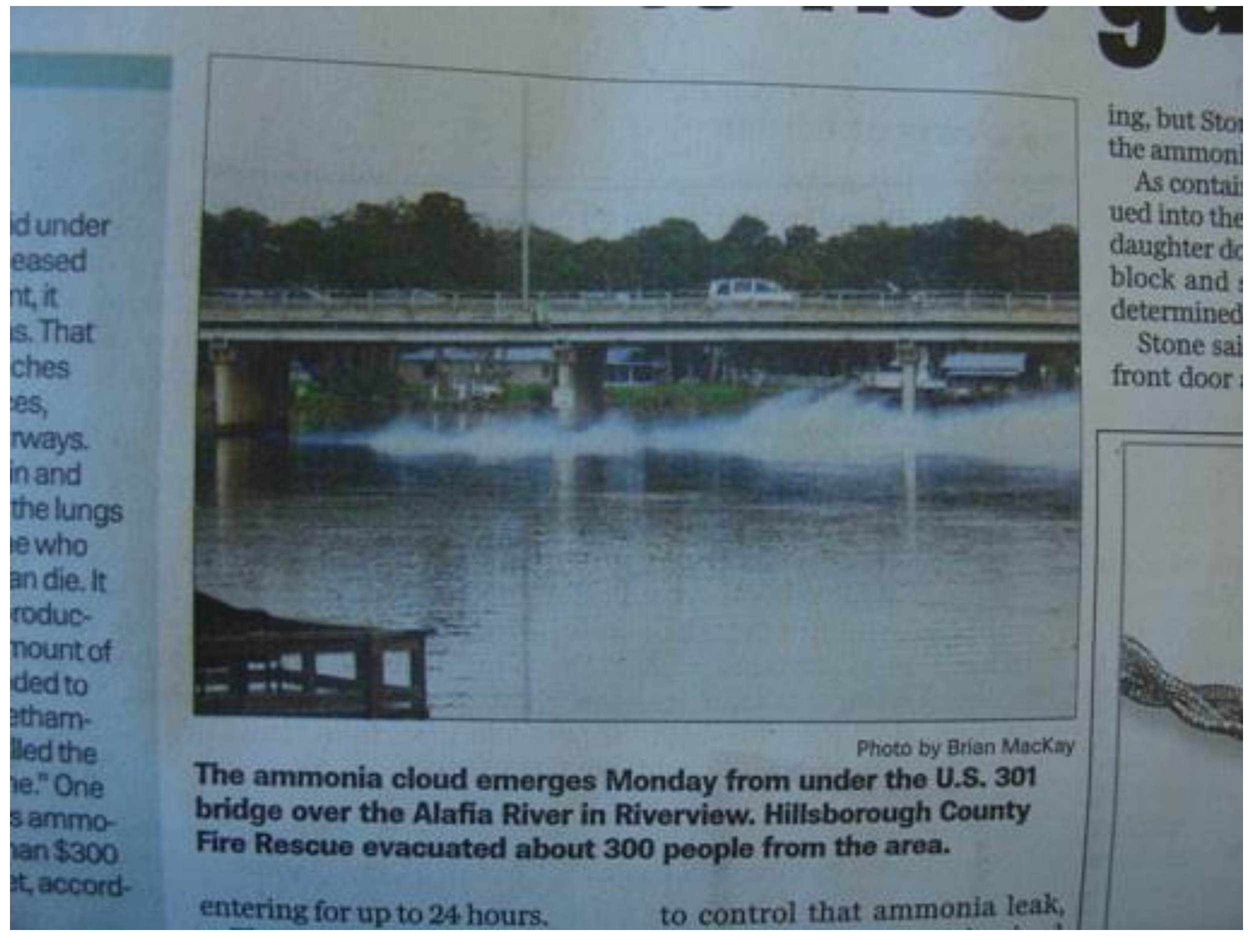
- 8-inch diameter Magellan pipeline ruptured and released 480 t of ammonia
- Visible vapour cloud 0.5 miles wide and 1.5 miles long
- Four families evacuated, no injuries
- Analysis showed pipeline rupture was caused by damage from digging equipment, either during construction or later agricultural activities



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

Tampa Bay, Florida (2007)

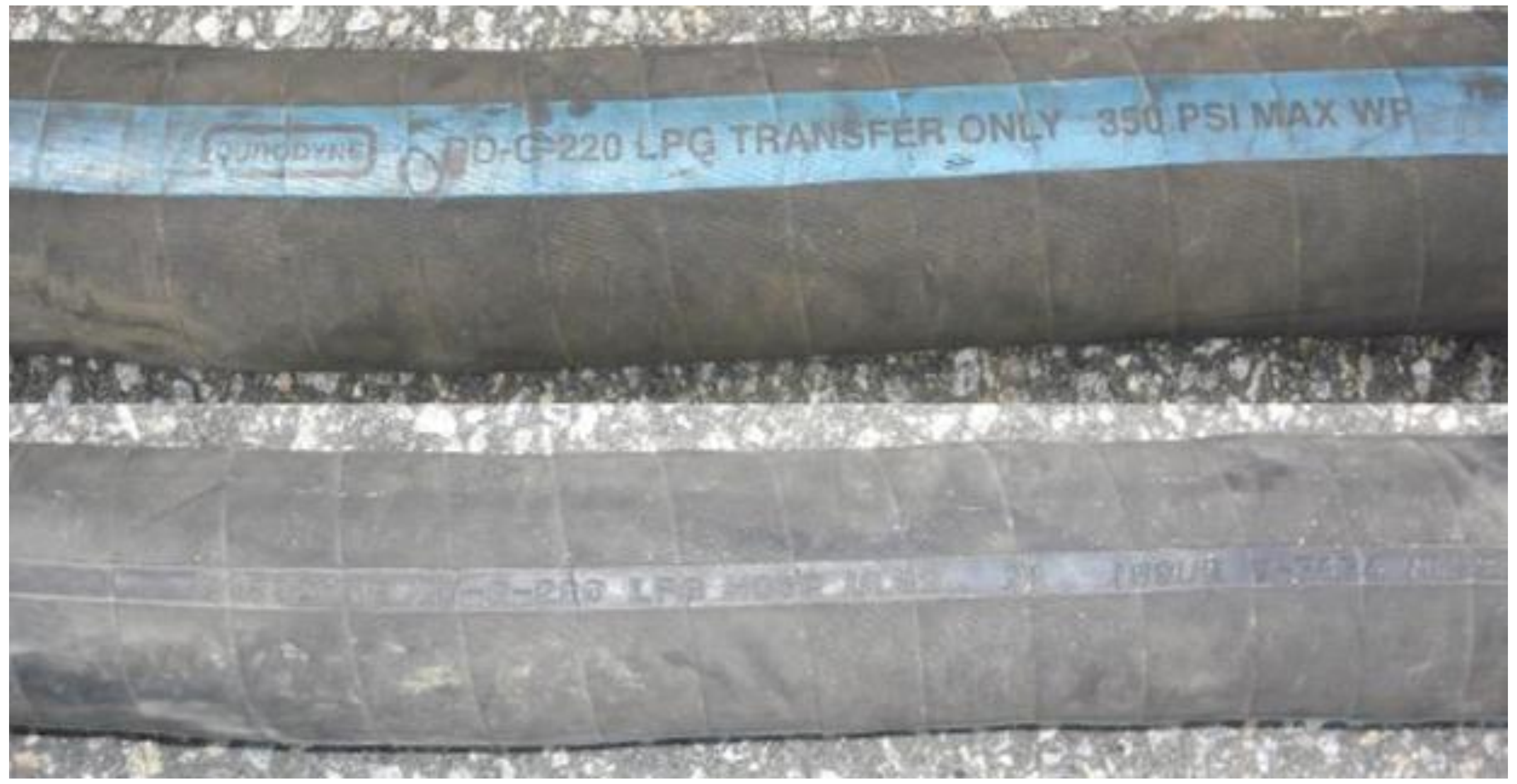
- Teenager took 2 days to drill through steel wall of 6-inch diameter ammonia pipeline using a cordless drill
- Suffered burns from jetting ammonia, but fell or jumped into river and survived
- Public evacuated from ¼ to ½ mile radius
- Fortunately, pipeline was operating at half usual pressure due to maintenance



https://incidentnews.noaa.gov/incident/7711#!

Swansea, South Carolina (2009)

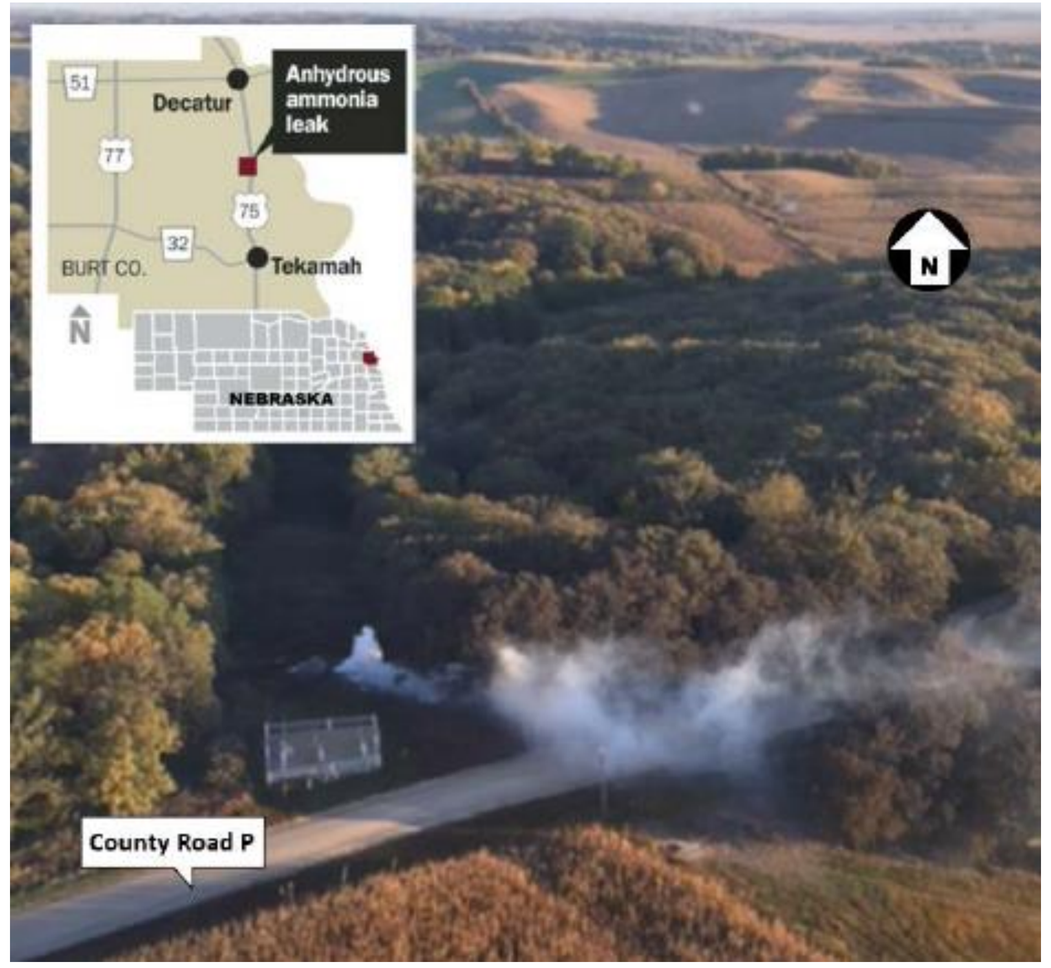
- Transfer hose ruptured between cargo tank truck and storage tank, releasing 3.1 t of ammonia
- Visible cloud drifted from parking lot of the facility across nearby highway
- 14 people suffered minor injuries, 7 people hospitalized, 1 death
- Investigation found that transfer hose was not compatible with ammonia service

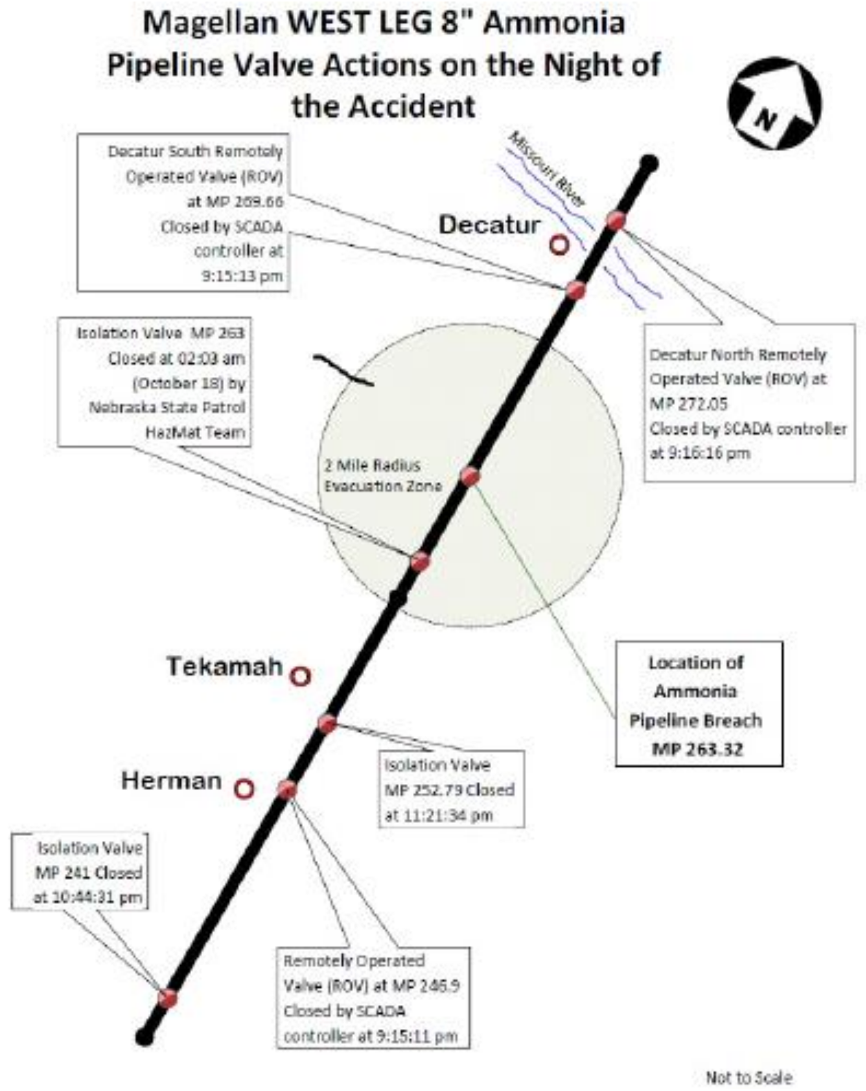


https://www.ntsb.gov/investigations/AccidentReports/Reports/HZM1201S.pdf

Tekamah, Nebraska (2016)

- 8-inch diameter Magellan pipeline ruptured and released 260 t of ammonia
- 49 people evacuated, 1 death
- Several previous leaks in West leg of Magellan pipeline needed repairs: one in 1984, five between 1988 and 1990, three between 1993 and 1994
- Cause of 2016 incident: corrosion fatigue cracking of pipeline steel
- In 2019, Magellan announced they would decommission the 1,100-mile pipeline





https://www.ntsb.gov/investigations/AccidentReports/Reports/PAB2001.pdf

Beach Park, Illinois (2019)

- 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

Teutopolis, Illinois (2023)

- Road traffic accident involving ammonia road tanker colliding with parked trailer
- Six-inch hole punched in tanker, which released 18 t of ammonia
- 500 people within 1 mile radius evacuated
- 5 people killed, 5 further people airlifted to hospital

https://apnews.com/article/teutopolis-effingham-illinois-truck-accident-chemical-spill-4e86653cb60515022dea05c45046329d

https://www.cbsnews.com/chicago/news/deadly-tanker-crash-chemical-spill-cause-illinois/?intcid=CNR-02-0623

Chennai, India (2023)

- Release from 8-inch diameter flexible high-density-polyethylene ammonia pipeline running underwater from fertilizer plant at Ennore port, near Chennai
- During pipeline pre-cooling process, pressure drop recorded in pipeline and gas bubbles observed 2 feet from shore
- Release occurred at night and cloud passed through nearby fishing village
- 52 people hospitalised

Residents from Periyakuppam fishing hamlet staging demonstration in front of Coramandel International Limited, Ennore on December 27, 2023 | Photo Credit: B. Jothi Ramalingam

https://www.thehindu.com/news/cities/chennai/many-hospitalised-as-ammonia-gas-leaks-out-at-an-industrial-unit-in-tamil-nadus-ennore/article67678852.ece

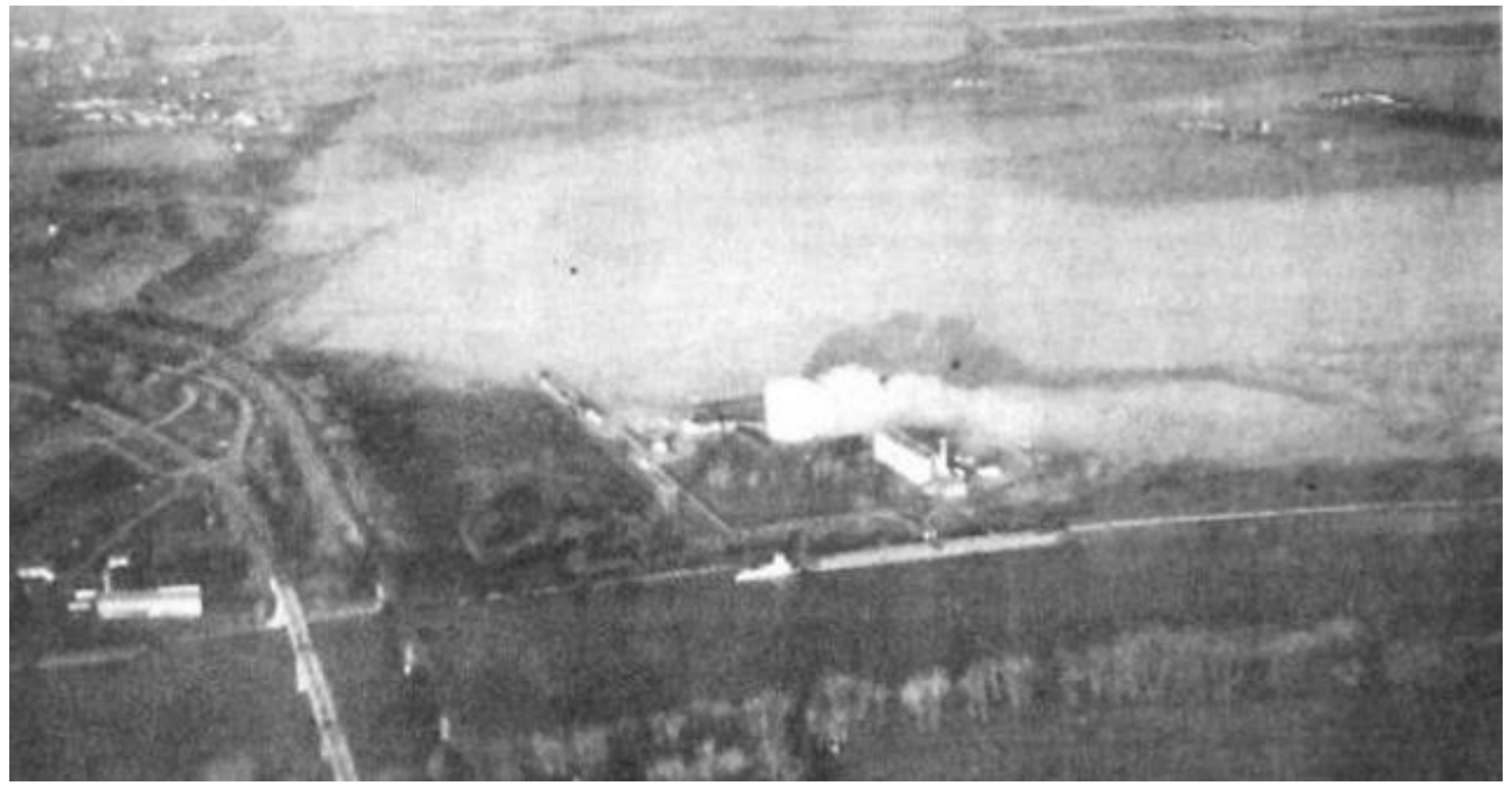
Incidents with temperature-liquefied ammonia

Pressures usually close to atmospheric pressure

Temperatures around -33°C

Blair, Nebraska (1970)

- 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 hospitalized



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

Jonova, Lithuania (1989)

- Release of 7,000 t of ammonia from 10,000 t refrigerated storage tank
- Cause: 14 t of warm ammonia at 10°C transferred into tank
- Warm ammonia liquid increased vaporization rate, vapour built up and over-pressurized the vessel, causing tank to violently burst (a “thermal overload”)
- Tank moved sideways from its base, smashed through the concrete wall, landing 40 m away
- Pool of ammonia ignited. Fire affected nearby ammonium nitrate store
- Ammonia facility was 5 km from town of Jonova with 40,000 inhabitants
- Cloud of ammonia and nitrous fumes spread 35 km downwind
- 32,000 people evacuated, 57 injured, 7 deaths

See Lees Loss Prevention, ISBN: 978-0-12-397189-0 and “Long-range transport of ammonia released in a major chemical accident at Ionava, Lithuania”
http://dx.doi.org/10.1007/978-1-4615-3720-5_59

https://www.aiche.org/resources/publications/cep/2024/february/rollover-possible-ammonia-storage-tank

Rostock, Germany (2005)

- During commissioning of tank into service after repairs, violent reaction caused failure of tank and release of 100 t of ammonia
- Aqueous ammonia had been added into base of tank
- Ammonia was sprayed into top of tank to initiate cooling process
- Thin layer of oil on pool surface in tank prevented mixing of ammonia droplets
- Opening of drain valve broke oil layer, causing ammonia and aqueous ammonia to mix
- Ammonia is water reactive and this mixing caused sudden pressure increase
- Relief valves not sized for rapid pressure rise, causing rupture of tank
- Two people injured, one later died

Source: K. Bakli, W. Versteele and B. Swensen (2006) *Safe ammonia storage*, Ammonia Technical manual, p117-124

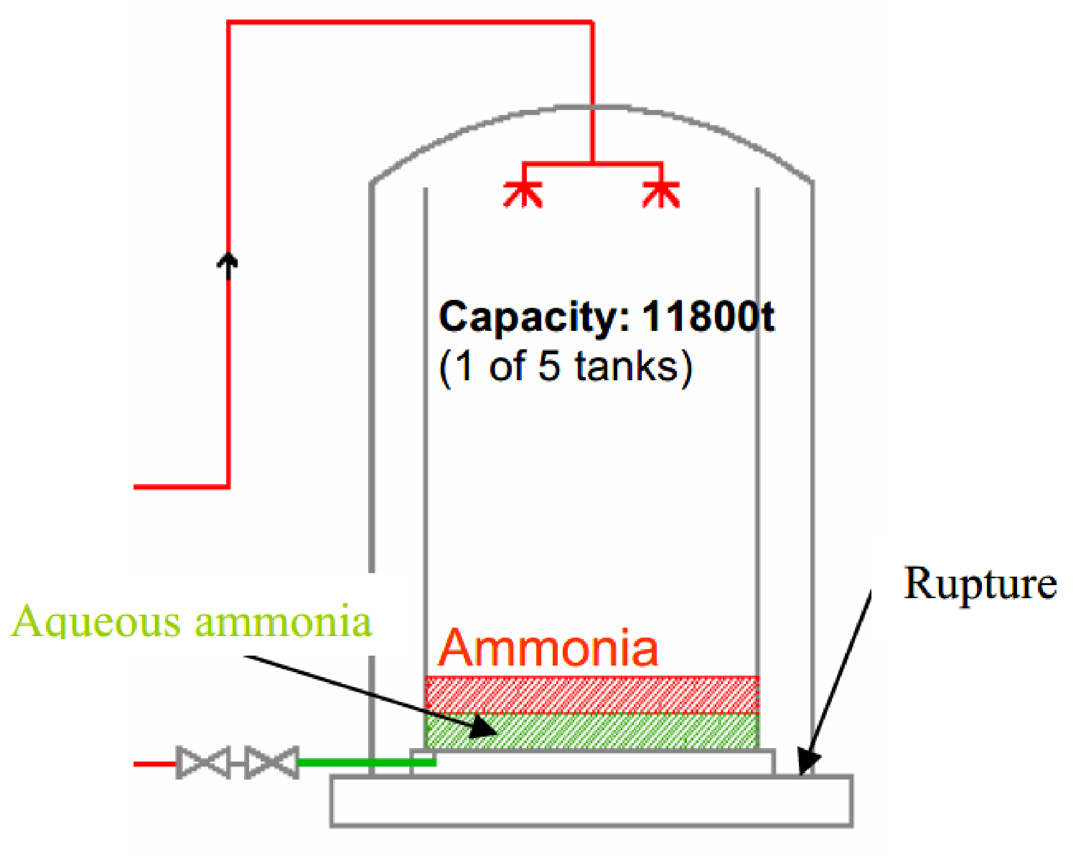


Figure 3 Schematic drawing of the Yara Rostock tank

Figure 4 Yara Rostock tank after the accident.

Pardis, Iran (2011)

- Vapour release from 20,000 t refrigerated storage tank
- Cause: transfer of liquid ammonia at high temperature (-12°C) and high flow-rate into the storage tank (human error)
- Warm ammonia liquid increased vaporization rate and over-pressurized the vessel, causing tank shell to rupture
- Ammonia vapour was released: 10-50 ppm concentrations up to 1 km downwind (ammonia is detectable by smell at ~17 ppm)
- Water sprayed onto tank to reduce vapour emissions, no injuries reported

https://ureaknowhow.com/wp-content/uploads/2015/04/2015-Orooji-Pardis-Lessons-learned-from-decommissioning-of-a-liqud-ammonia-storage-tank.pdf

Chittagong, Bangladesh (2016)

- Release of 325 t of ammonia from 500 t refrigerated storage tank
- Cause: over-pressurization by operational error or mechanical integrity failure
- Ammonia vapour cloud spread over several kilometres, 250 people fell sick, 52 of them hospitalized

https://www.safteng.net/index.php/free-section/safety-info-posts/chemical-process-safety-psmrmp/4506-catastrophic-failure-of-500-ton-anhydrous-ammonia-tank-2016

https://medcraveonline.com/IPCSE/IPCSE-01-00003.pdf

Kwinana, Western Australia (2018)

- Ammonia released during ship-to-shore transfer operation
- Coupler disconnected, releasing approximately 1 t of ammonia
- Cause: valve operated in incorrect sequence, valve position was not visible to operator, high hot gas purging rate caused hammering and valve disengaged
- No injuries

Patel, N (2021) *Ammonia Release During Ammonia Import Activity,* 65th Safety in Ammonia Plants & Related Facilities Symposium

https://www.dmp.wa.gov.au/Dangerous-Goods/DGS_SIR_0119.pdf

Review of USA incidents

Review paper

State Programs to Reduce Uncontrolled Ammonia Releases and Associated Injury Using the Hazardous Substances Emergency Events Surveillance System

http://dx.doi.org/10.1097/JOM.0b013e318197368e

TABLE 2
Distribution of Selected Characteristics of People Injured, Injury Severity, and Type of Injury Associated With Anhydrous Ammonia Incidents, HSEES 2002–2005

Variable	Number (% of Total, *n* = 907)
Victim category	
Employee	353 (38.9)
General public	341 (37.6)
Responder*	212 (23.4)
Student	1 (<1)
Severity of injury	
Nonhospital	264 (29.1)
Hospital-released	554 (61.1)
Hospital-admitted	63 (7.0)
Died	6 (<1)
Not stated	20 (2.2)
Injury type†	
Respiratory irritation	651 (71.8)
Eye irritation	215 (23.7)
Gastrointestinal problem	118 (13.0)
Headache	163 (18.0)
Burns	82 (9.0)
Skin irritation	79 (8.7)
Dizziness/central nervous system	41 (4.5)
Trauma	27 (3.0)
Shortness of breath	23 (2.5)

*Responder includes firefighters, police, and medical personnel.
†Persons could have more than one injury type.

TABLE 1
Distribution of Selected Characteristics of Anhydrous Ammonia Incidents, HSEES 2002–2005

Variable	Number (% of Total, *n* = 2428)	Number With Injury (% of Total With Injury, *n* = 368)
Event type		
Fixed facility	2086 (85.9)	307 (83.4)
Transportation	342 (14.1)	61 (16.6)
Top 5 industries		
Manufacturing (NAICS 32)*	592 (24.4)	13 (3.5)
Manufacturing (NAICS 31)†	413 (17.0)	60 (16.3)
Private households	271 (11.2)	103 (28.0)
Agriculture	240 (9.9)	39 (10.6)
Wholesale trade	223 (9.2)	32 (9.2)
Not an industry	135 (5.6)	40 (10.9)
Contributing factor		
Equipment failure	1205 (49.6)	83 (22.6)
Human error	346 (14.3)	118 (32.1)
Illicit drug production related	566 (23.3)	139 (37.8)
Intentional or illegal act: non-illicit drug production related	200 (8.2)	16 (4.4)
Bad weather	65 (2.7)	3 (0.8)
Other	11 (0.4)	4 (1.1)
Not stated	35 (1.4)	5 (1.4)

*US Census Bureau North American Industry Classification System—Revisions for 2002 (NAICS); NAICS 32 includes wood, paper, printing, petroleum & coal, chemical, plastic & rubber, and non-metallic mineral manufacturing.
†NAICS 31 includes food, beverage, tobacco, textile, apparel, and leather & allied products manufacturing.

- Data from 2002-2005 for 17 USA states (large fraction from Iowa & Wisconsin)
- Sites: food manufacturing, agriculture, and production of illicit methamphetamine
- 2,428 incidents, 907 people injured, 6 deaths (roughly 300 injured and 2 deaths per year)
- "*Ammonia is the most commonly released hazardous chemical in work-related incidents and is the leading cause of blindness resulting from industrial accidents*"
- 90% of accidents caused by equipment failure or human error

Review of UK incidents

REVIEW OF AMMONIA INCIDENTS 1992 - 1998

by E M Gregson

This note presents the results of a review of ammonia incidents reported to HSE over the period 1992-1998. It also provides details of the main sources of guidance on the storage, handling and use of ammonia.

The information for the review was extracted from the MARCODE database (1992-1995) and from the FOCUS investigation database (1996-1998). All the incidents on MARCODE have been reported to HSE under RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) and have been investigated by HSE inspectors.

139 incidents were identified where ammonia gas had been released. Many of them resulted in injury caused by exposure to the gas or being splashed with liquid ammonia or a concentrated aqueous solution. There were no explosions involving ammonia gas or fatalities over the seven year period of the review. The details are summarised in the table. The incidents are categorised in terms of the process involved:

https://www.safteng.net/index.php/free-section/safety-info-posts/chemical-process-safety-psmrmp/1774-uks-hse-review-of-ammonia-incidents-1992-1998
Report kindly provided by Bryan Haywood on request

Summary of Ammonia Incidents 1992 - 1998

	YEAR	1992	1993	1994	1995	1996	1997	1998	Total
ACTIVITY									
Refrigeration		21	6	10	11	8	13	4	73
Process		6	3	7	6	2	5	1	30
Transport		3	3	3	2	0	1	1	13
Miscellaneous		2	6	6	4	3	2	0	23
TOTAL		32	18	26	23	13	21	6	139

- Majority of incidents associated with refrigeration equipment (size of releases: up to 3 tonnes)
- Incidents often occurred during maintenance and commissioning, mainly due to failure to isolate effectively
- Other incidents caused by plant failure (possibly due to lack of preventative maintenance), e.g., corroded pipework, failure of seals and valves, blockages
- Releases from chemical process and transport were typically due to corrosion, failure of valves and failure of process-monitoring equipment

PROTECTING PEOPLE AND PLACES

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Contents

Emergency Response

- At ammonia facilities: detection, alarms, emergency shutdown, toxic refuge, PPE, respiratory protection, drench showers, eye-washes, fire extinguishers
- Tarping of small pressure-liquefied jet releases to condense ammonia droplets and reduce size of airborne cloud
- Use of water sprays/curtains to tackle airborne releases
- Do not spray water on pool of refrigerated liquid ammonia: it enhances evaporation rate and produces larger vapour cloud
- Need to consider contaminated water runoff and effect on environment
- Ammonia solutions in water are corrosive: can burn skin

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

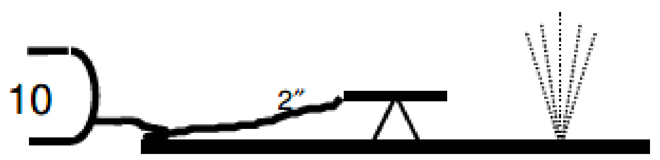
https://www.youtube.com/watch?v=1yBWdHg4_V0

Emergency Response

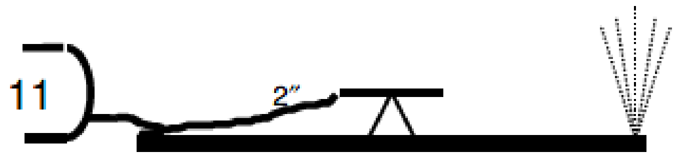
- French institute INERIS conducted series of ammonia release experiments at CEA test site near Bordeaux in 1996-1997
- Tests on water spray mitigation showed it had no significant benefit in reducing airborne ammonia concentrations

photo 1: horizontal release impacting a wall

photo 3: Typical ammonia plume



Release identical to release No. 4. A water curtain located 25 m from the release point was started up during the test.



Release identical to release No. 4. A water curtain located 60 m from the release point was started up during the test.

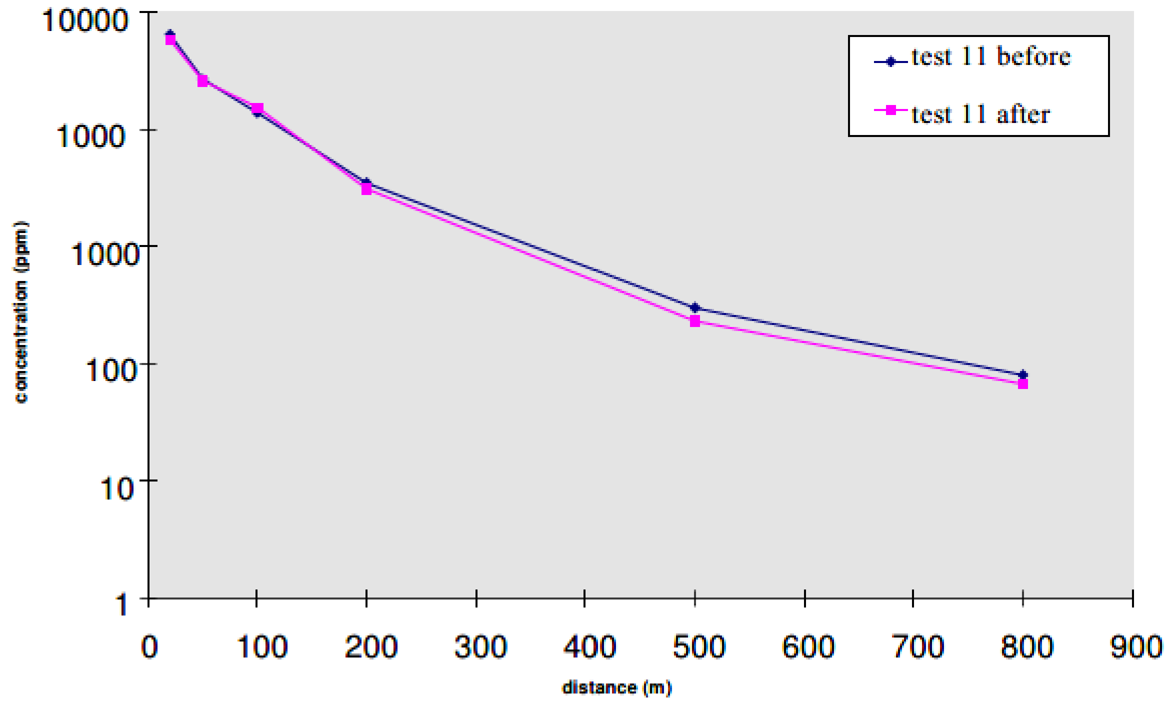


figure 29: Progression of ammonia concentrations leeward from release 11 before and after starting up the peacock tails

6.2.5 Influence of water curtain produced using peacock tail hoses

During this test campaign, two releases used peacock tail hoses installed on the release path. For these two tests, referenced 10 and 11, two 70 mm diameter peacock tail hoses were located 25 m and 60 m from the release point, respectively, as described in chapter 4. The purpose of these two tests was to try to evaluate the influence of the presence of a water curtain on atmospheric dispersion.

On analysing the results, it has emerged that significant fluctuations in the atmospheric conditions were recorded during the tests, particularly the wind direction, which did not remain constant. In this way, during the tests, the ammonia plume sometimes passed by the water curtain.

In addition, under our release conditions during test 10, the ammonia jet passed through the water curtain located at 20 cm, rendering this type of curtain practically ineffective. At times, the jet was pointing towards the peacock tail in which the water was output at its highest velocity. Under these conditions, mechanical mixing of the plume could be observed as the jet was deviated from its path. However, during this test, the cloud generally passed between the two peacock tails, meaning that the concentration at the centre of the plume was not affected very much.

In this way, in this test campaign, the presence of a water curtain produced with peacock tail hoses did not significantly decrease the concentrations before and after the water curtain. This may be explained by the fact that an ammonia jet can pass through a water curtain if the momentum is sufficient, and by changing weather conditions during the tests. A release of the same type as those used in these test campaigns, but with a much lower momentum when passing through the water curtain may result in lower concentration values in the environment. This point is worth studying in more detail.

https://ineris.hal.science/ineris-00972478/document

https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/ammonia.pdf

PHMSA Emergency Response Guidebook

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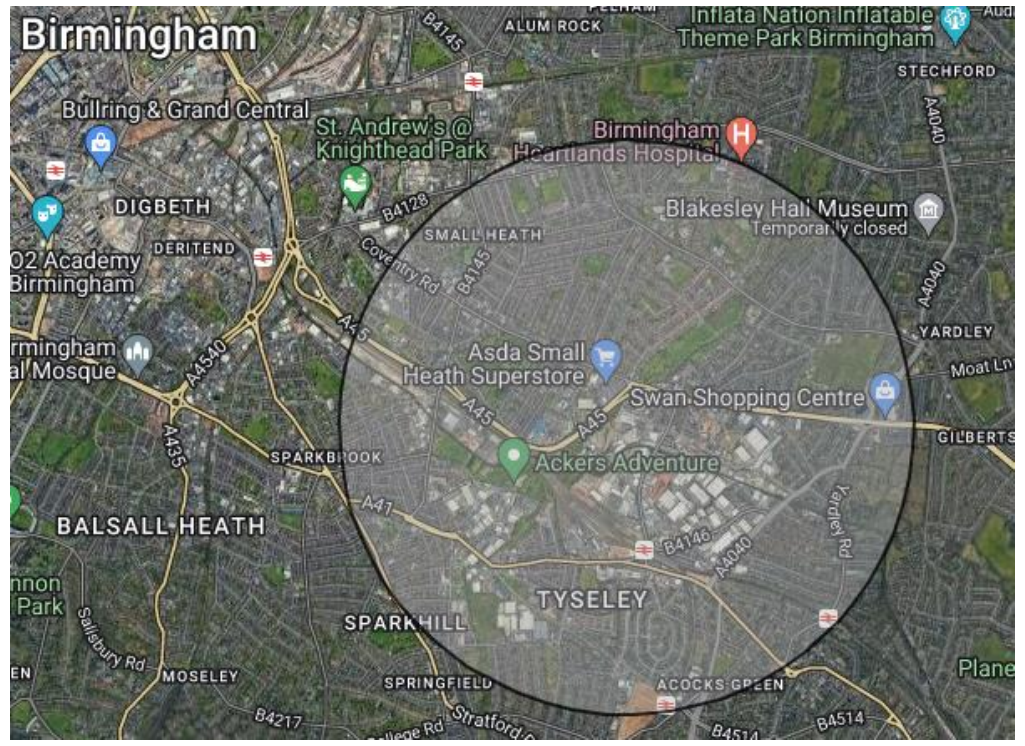
- Used by all North American and some UK first responders

TABLE 3 - INITIAL ISOLATION AND PROTECTIVE ACTION DISTANCES FOR LARGE SPILLS FOR DIFFERENT QUANTITIES OF SIX COMMON TIH (PIH in the US) GASES

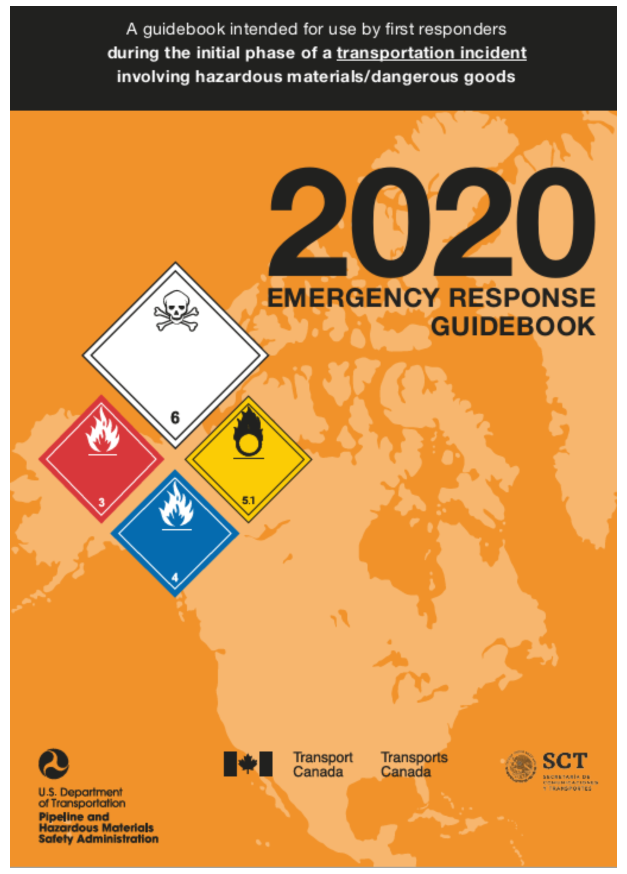
	First ISOLATE in all Directions		Then PROTECT persons Downwind during											
			DAY						NIGHT					
			Low wind (< 6 mph = < 10 km/h)		Moderate wind (6-12 mph = 10 - 20 km/h)		High wind (> 12 mph = > 20 km/h)		Low wind (< 6 mph = < 10 km/h)		Moderate wind (6-12 mph = 10 - 20 km/h)		High wind (> 12 mph = > 20 km/h)	
TRANSPORT CONTAINER	Meters	(Feet)	km	(Miles)	km	(Miles)	km	(Miles)	km	(Miles)	km	(Miles)	km	(Miles)
	UN1005 Ammonia, anhydrous: Large Spills													
Rail tank car	300	(1000)	1.9	(1.2)	1.5	(0.9)	1.1	(0.6)	4.5	(2.8)	2.5	(1.5)	1.4	(0.9)
Highway tank truck or trailer	150	(500)	0.9	(0.6)	0.5	(0.3)	0.4	(0.3)	2.0	(1.3)	0.8	(0.5)	0.6	(0.4)
Agricultural nurse tank	60	(200)	0.5	(0.3)	0.3	(0.2)	0.3	(0.2)	1.4	(0.9)	0.3	(0.2)	0.3	(0.2)
Multiple small cylinders	30	(100)	0.3	(0.2)	0.2	(0.1)	0.1	(0.1)	0.7	(0.5)	0.3	(0.2)	0.2	(0.1)

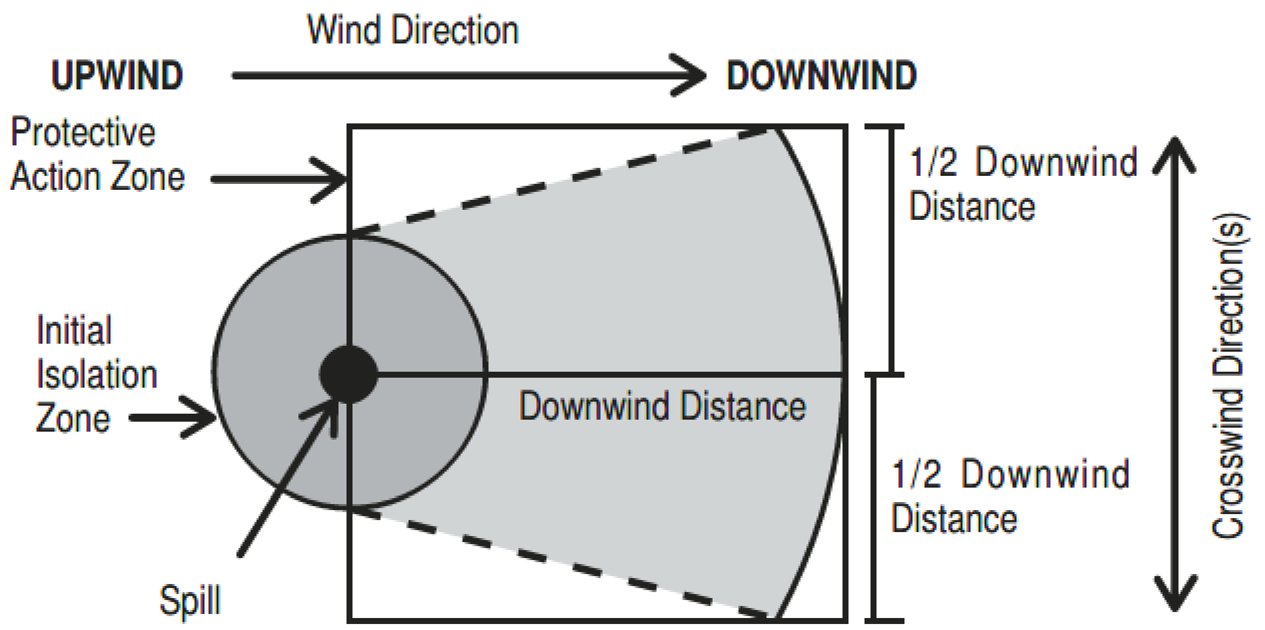


Example above: 2 km protective action radius (shelter in place or evacuate) for potential road-tanker incident at night in calm conditions

In comparison (below), petrol road tanker on fire has 800 m protective action radius

New 2024 edition published soon. Also available as app on mobile phones https://www.phmsa.dot.gov/training/hazmat/erg/emergency-response-guidebook-erg





https://www.mapdevelopers.com/draw-circle-tool.php © Google Maps

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Contents

Ammonia Storage Tank Designs

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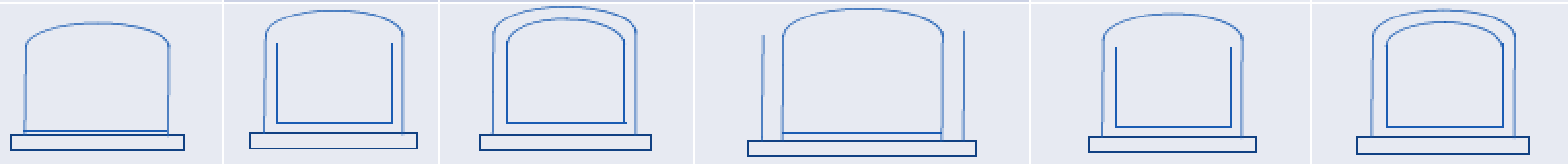
- Several different designs: single, double and full containment

Source: Meher & Cooperman (CB&I) *Ammonia storage safety and configurations*, AIChE Safety in Ammonia Plants & Related Facilities Symposium, Munich, Germany, August 20-24, 2023

23 Safety in Ammonia Plants & Related Facilities Symposium

Storage Containment Types

CB&I

CONTAINMENT TYPE	Single Containment			Double Containment	Full Containment	
	Single Wall	Double Wall: Open top Primary Container	Double Wall: Double Wall-Double Roof		Open Top Primary Container	Double Wall-Double Roof
Pictorial Illustration						
Primary Container (Inner tank)	Liquid Tight Vapor Tight	Liquid Tight	Liquid Tight Vapor Tight	Liquid Tight Vapor Tight	Liquid Tight	Liquid Tight Vapor Tight
Secondary Container (Outer Tank)	N/A	Vapor Tight	Purge Gas Container	Liquid Tight	Liquid Tight Vapor Tight	Liquid Tight Vapor Tight
Outside of Inner Tank Exposed to Product at Operation	No	Yes	No	No	Yes	No

To avoid stress corrosion cracking:
- 0.1 – 0.2% water in ammonia
- Nitrogen inerting of vapour space

Low temp. steel for cryogenic service
Monitor crack growth

Need to consider:

- Settlement of foundations, frost heave, insulation, heating, seismic protection
- Either: side penetrations with in-tank valves, automatic activation in case of pipe failure
- Or: top connections with in-tank pumps, to avoid side penetrations
- Inerting system, temperature/pressure control, boil-off gas system, emergency flare

R. Challa (2023) *Safety considerations for Ammonia storage tanks*, API Storage Tank Conference & Expo, Denver Colorado
A. Wright (2022) *Cryogenic storage of anhydrous ammonia*, IChemE Hazards 22 Symposium
See also: K. Bakli, W. Versteele and B. Swensen (2006) *Safe ammonia storage*, Ammonia Technical manual, p117-124

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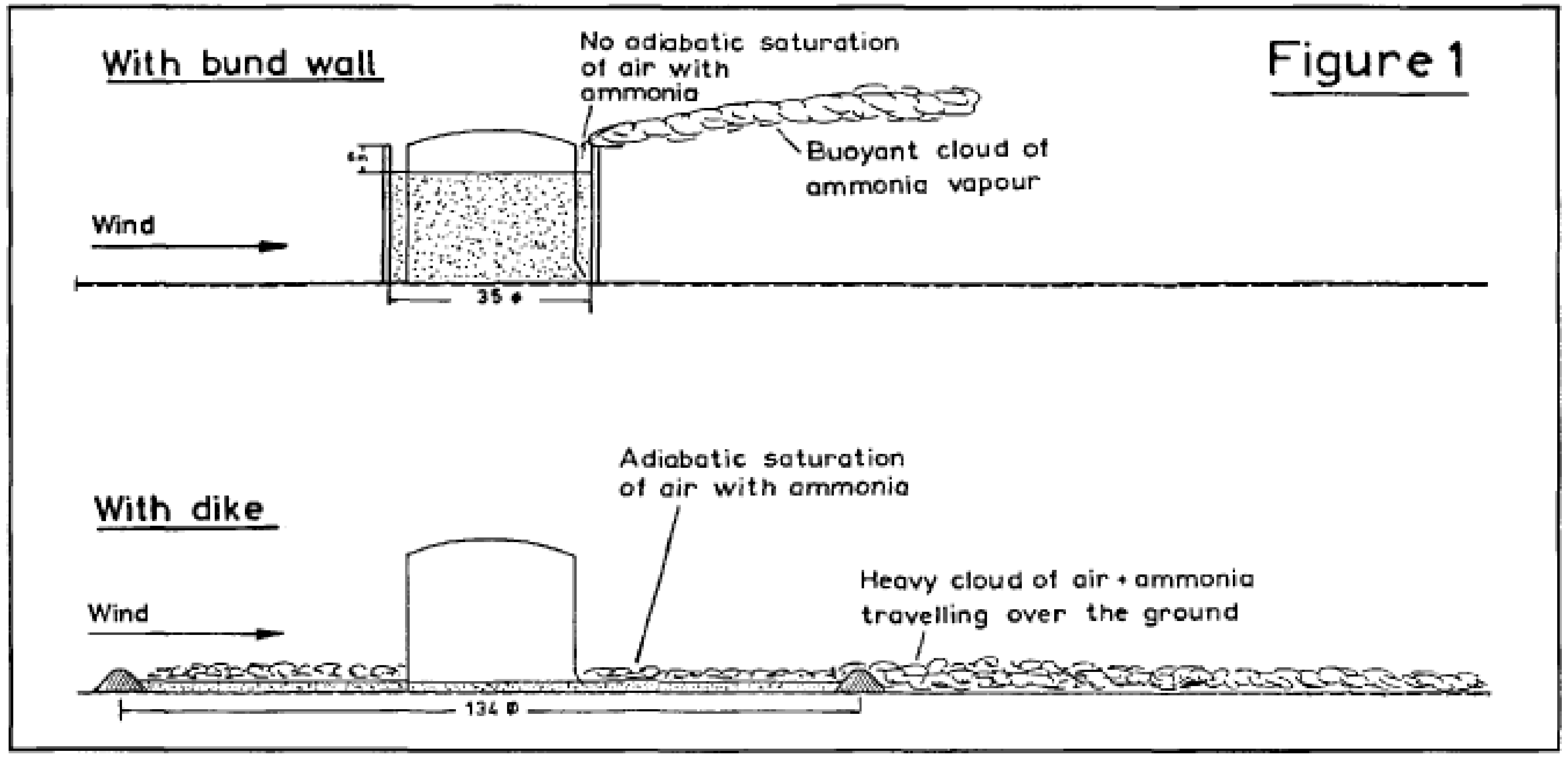
Ammonia Bulk Storage Tank Designs

Comments on "Hazard Analysis and Safety Consideration in Refrigerated Ammonia Storage Tanks" by Falah Al-Abdulally, Saad Al-Shuwaib and B. L. Gupta

Jan M. Blanken

DSM Fertilizers, Process Engineering Department, Ymuiden Site, P.O. Box 463, 1970 Al Ymuiden, The Netherlands

Plant/Operations Progress (Vol. 6, No. 4) **October, 1987**



- Recommended tank-in-cup design to reduce low-level ammonia cloud in case of spill

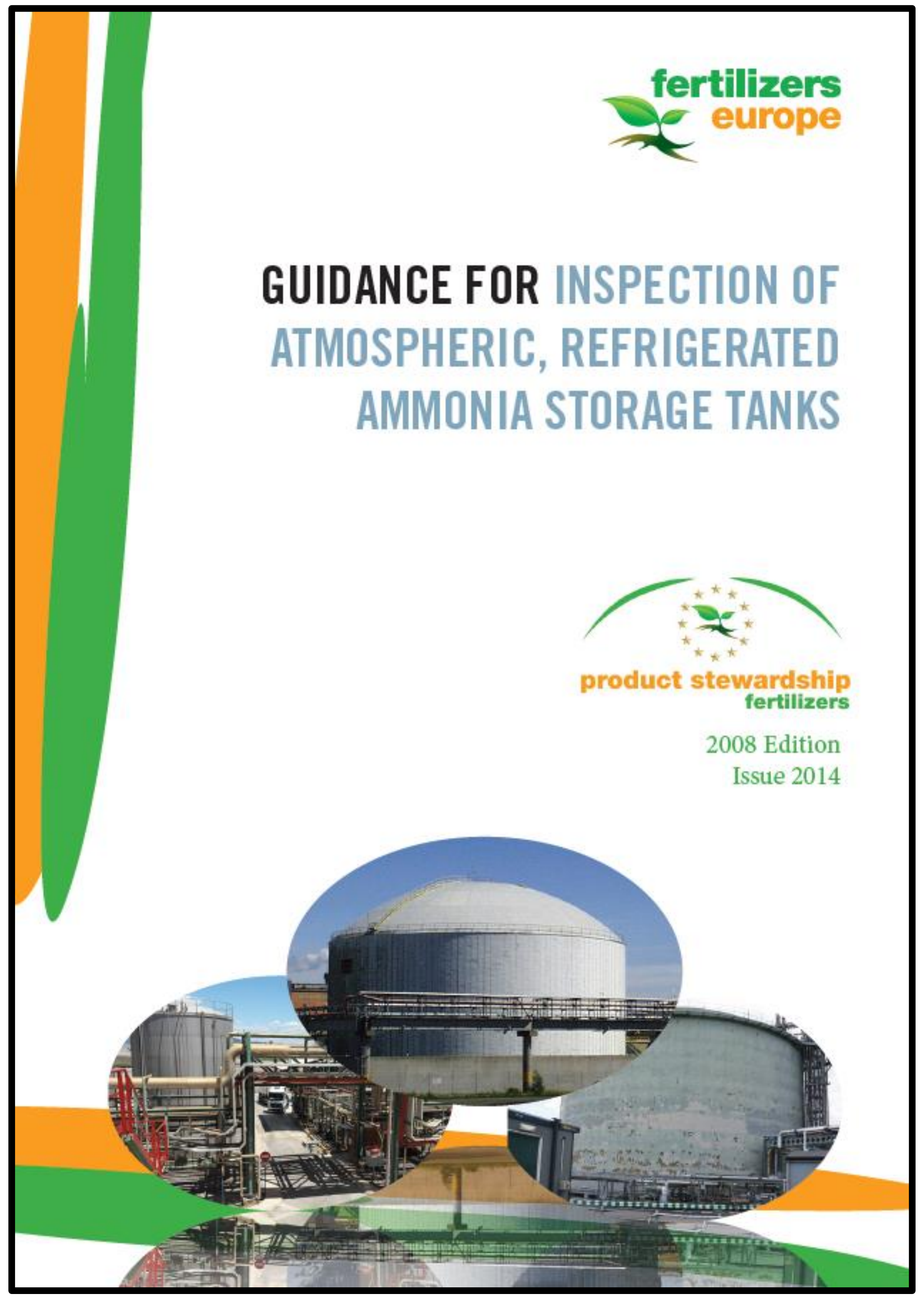
Standards and guidance

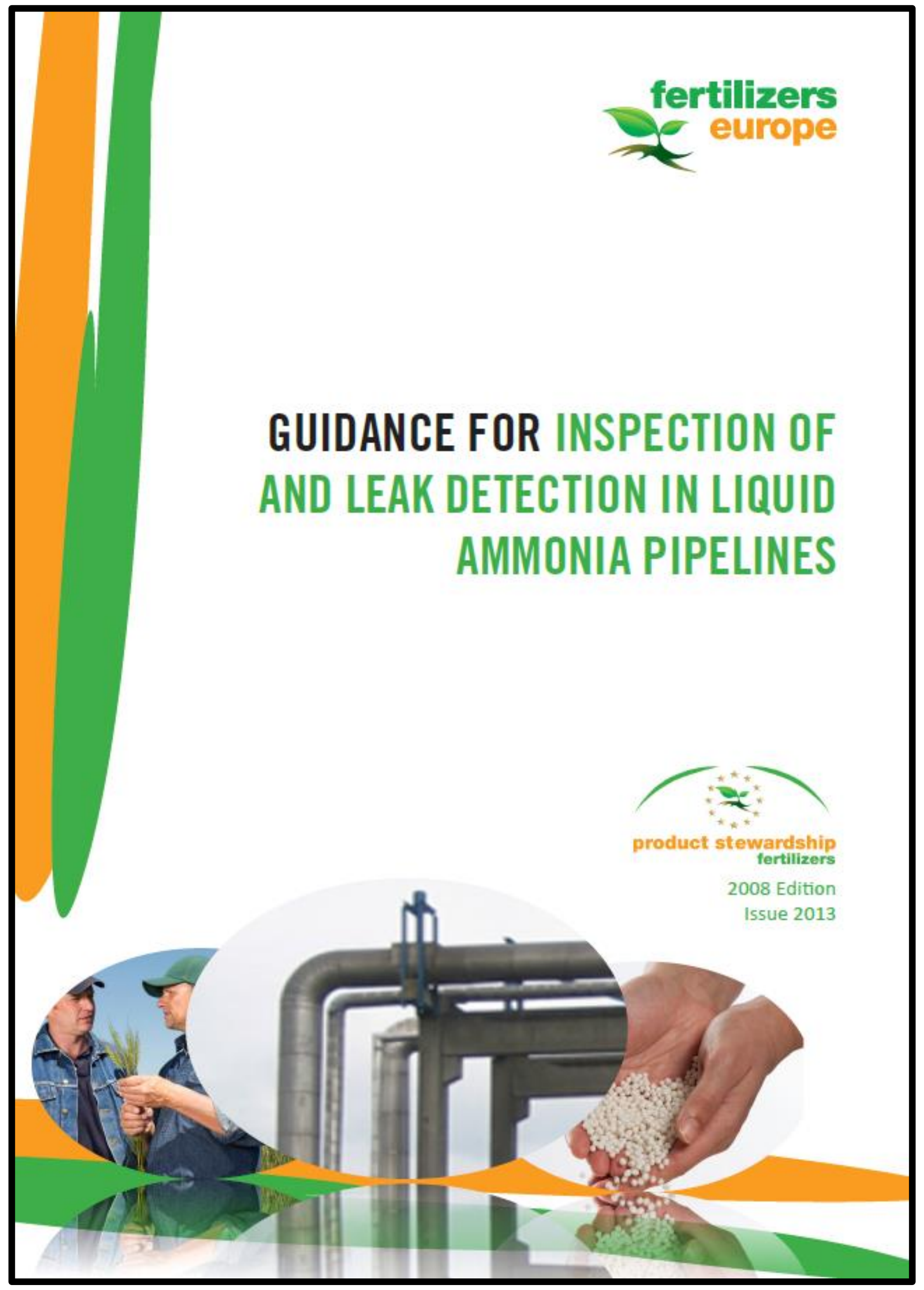
- Public Health England (2014) *Ammonia: health effects, incident management and toxicology*
  https://www.gov.uk/government/publications/ammonia-properties-incident-management-and-toxicology
- Compressed Gas Association CGA G-2.1-2023 *Requirements for the storage and handling of anhydrous ammonia*
- Health and Safety Executive HS(G)30 *Storage of anhydrous ammonia under pressure in the UK*, 1986
- Chemical Industries Association, *Guidance for the large-scale storage of fully refrigerated anhydrous ammonia in the UK*, 1997
- British Standard BS EN 14620 *Flat-bottomed, vertical, cylindrical storage tanks for low temperature service*
- Engineering Equipment and Materials Users Association (EEMUA) Publication 147 *Recommendations for refrigerated liquefied gas storage tanks*
- American Petroleum Institute API Standards 620, 625 and 2000: *Design, construction and venting of low-pressure storage tanks*
- American Society of Mechanical Engineers ASME B31.3 *Process piping*
- BSI Standard PD 8010 *Pipeline systems*
- USA Code of Federal Regulations
  - 6 CFR 27 Chemical Facility Anti-Terrorism Standards (CFATS)
  - 29 CFR 1910.119 Process safety management of highly hazardous material
  - 29 CFR 1910.111 (OSHA) Storage and handling of anhydrous ammonia
  - 33 CFR 105 Maritime security of facilities
  - 40 CFR 355 Emergency planning and notification
  - 49 CFR Parts 171-180 Transportation of hazardous materials

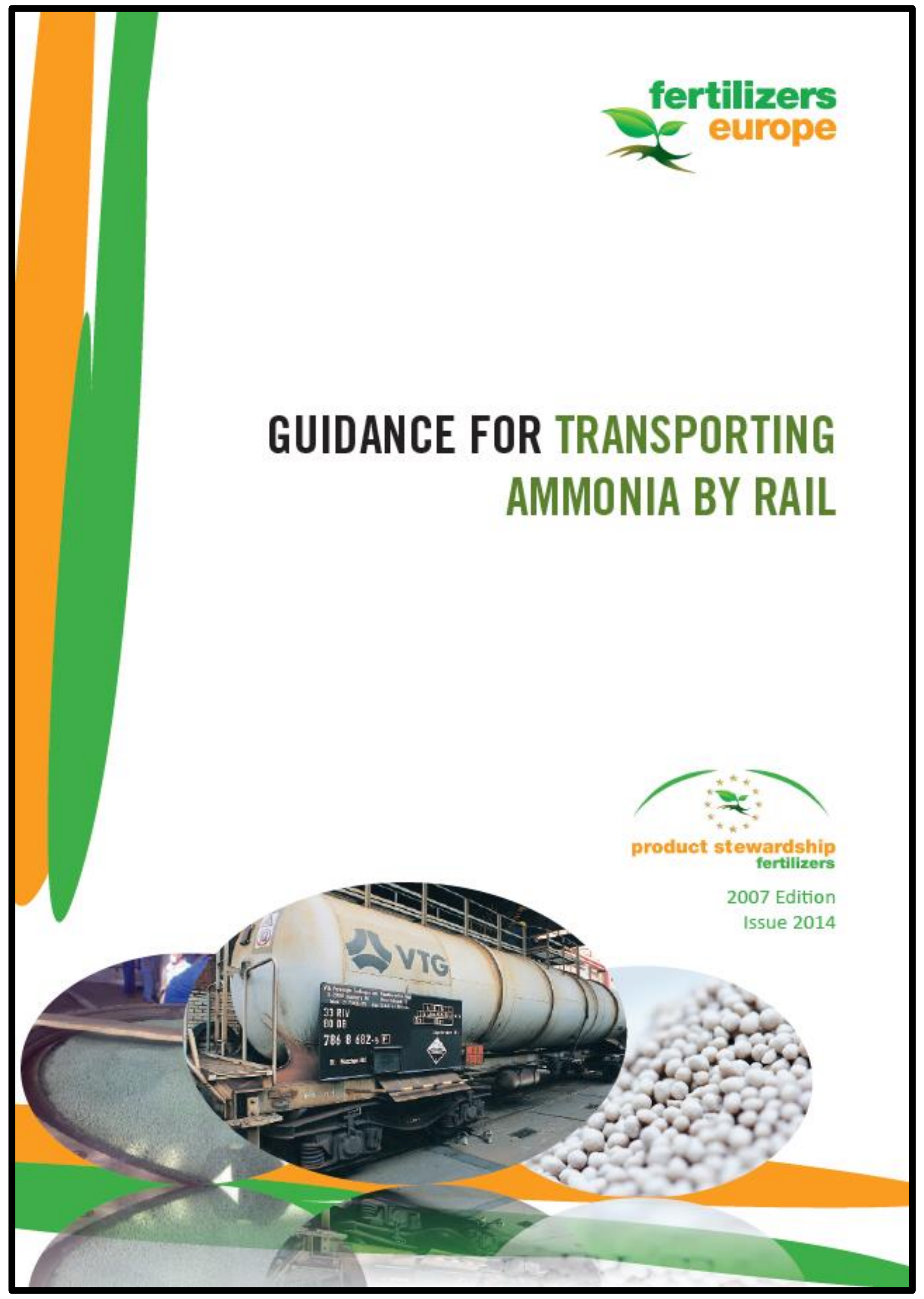
NB: this list is not exhaustive

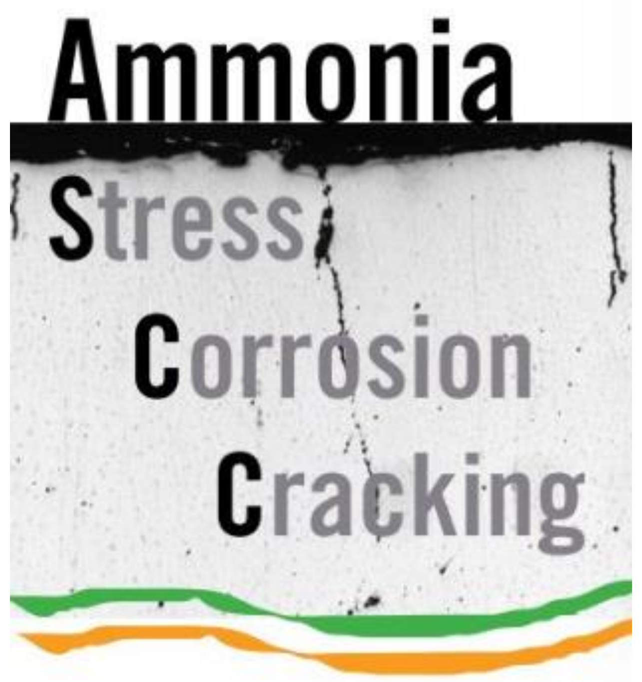
Guidance

- Fertilizers Europe publications https://www.fertilizerseurope.com/









25 May 2013
Stress Corrosion Cracking

24 April 2013
Safety assessment of ammonia tanks

Review of global regulations

SYMPOSIUM SERIES NO 161 HAZARDS 26

Review of Global Regulations for Anhydrous Ammonia Production, Use, and Storage

Mark Fecke, P.E., Principle Engineer, Exponent Inc., 4580 Weaver Parkway, Suite 100, Warrenville, IL, USA

Stephen Garner, Senior Engineer, Exponent Inc., 4580 Weaver Parkway, Suite 100, Warrenville, IL, USA

Brenton Cox, Senior Engineer, Exponent Inc., 4580 Weaver Parkway, Suite 100, Warrenville, IL, USA

In this article, several applications of ammonia are briefly summarized. Some of the major hazards associated with anhydrous ammonia are then highlighted through case studies of ammonia failures. Finally, a variety of regional ammonia safety standards are reviewed and compared including North America, the European Union, Asia, India, and Australia.

Table 3. EU Regulations and Guidance Documents Overview

Regulation and Guidance Document	Title
ATEX 94/9/EC	Equipment Directive - Equipment and protective systems intended for use in potentially explosive atmospheres
ATEX 99/92/EC	Workplace Directive - Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.
EN 378	Refrigerating systems and heat pumps. Safety and environmental requirements. Basic requirements, definitions, classification and selection criteria
EN 60079	Explosive atmospheres. Electrical installations inspection and maintenance
IEC 60335-2-40	Household and similar electrical appliances - Safety - Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers
PED 97/23/EC	The Pressure Equipment Directive

Table 2. U.S. Regulations and Guidance Documents Overview

Regulation and Guidance Document	Title
ANSI K61 / CGA 2.1 - 2014	American National Standard Safety Requirement for the Storage and Handling of Anhydrous Ammonia
ANSI/IIAR 2-2008	American National Standard for Equipment, Design and Installation of Closed-Circuit Ammonia Mechanical Refrigerating System
ANSI/IIAR 3-2012	American National Standard for Ammonia Refrigeration Valves
ANSI/IIAR 4-2015	Installation of Closed-Circuit Ammonia Refrigeration Systems
ANSI/IIAR 5-2013	Start-up and Commissioning of Closed-Circuit Ammonia Refrigeration Systems
ANSI/IIAR 7-2013	Developing Operating Procedures for Closed-Circuit Ammonia Mechanical Refrigerating Systems
ASHRAE 15-2013	Safety Standards for Refrigeration Systems
ASHRAE 34-2013	Designation and Safety Classification of Refrigerants
ASME Boiler and Pressure Vessel Code - Section VIII, Division 1	
ASME Boiler and Pressure Vessel Code - Section VIII, Division 2	
ISO 5771	Rubber hoses and hose assemblies for transferring anhydrous ammonia - Specification
OSHA - 29 CFR 1910.111	Storage and handling of anhydrous ammonia.
US-Dept. of Transportation 49 CFR Parts 171-180	Transportation of Hazardous Materials
US-EPA EPCRA	Emergency Community Right-to-know Act
US-EPA RMP	Risk Mgmt. Plan
US-EPA SNAP	Sig. New Alt. Policy
US-OSHA 29 CFR 1910.119	Process Safety Management of Highly Hazardous Chemicals Standard

https://www.icheme.org/media/11771/hazards-26-paper-34-review-of-global-regulations-for-anhydrous-ammonia-production-use-and-storage.pdf

PGS 12: Ammoniak – Opslag en verlading

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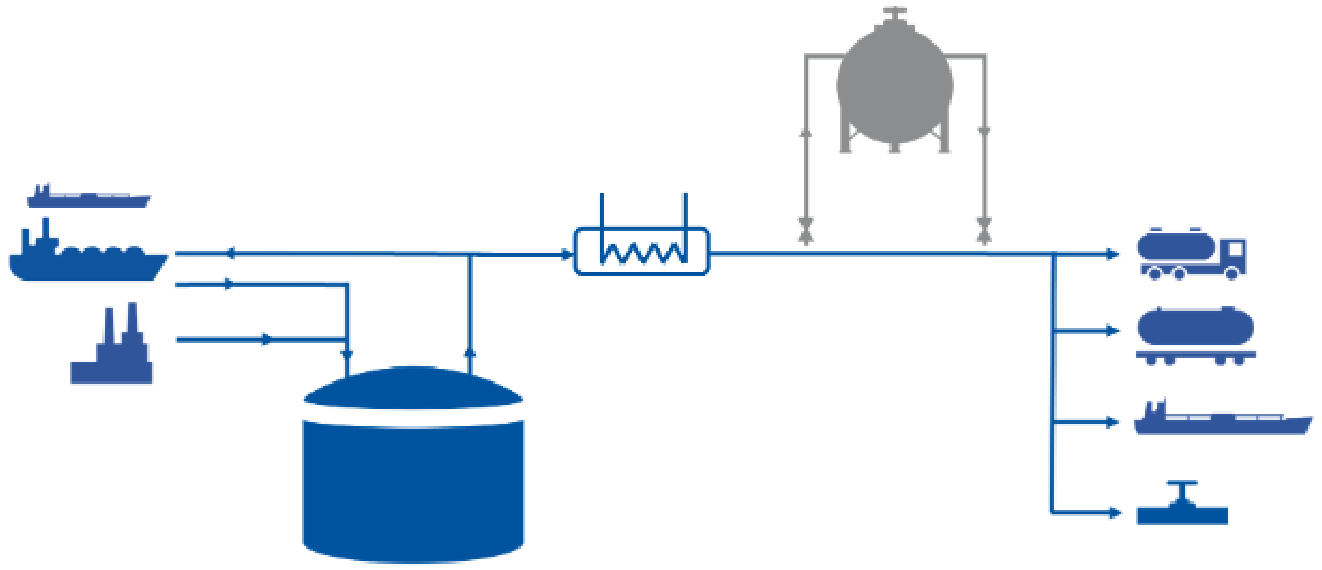
- Guideline for the safe storage and loading of ammonia in the Netherlands
- Topics covered: environmental and occupational safety, fire and disaster relief
- Developed by panel including Dutch government, industry and fire brigade
- In scope: both cryogenic and pressure-liquefied storage tanks, ancillary pipe connections, heat exchanger and pipelines within storage sites
- Out of scope: refrigeration, transport,(road, rail, ship, pipeline), ship-to-ship bunkering, environmental emissions of ammonia to soil, water and air
- Causes of tank failure: trapping, overpressure, overfilling, heating, lightning, hold down, internal/external corrosion, refrigeration, failure of fittings/connections, external load/impact, human error, unauthorised actions
- Consequences: release, dispersion, fire/explosion
- Requires full-containment cryogenic tank design with top connections and in-tank pumps



https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS12/Concept_interim_PGS_12_v0.2_april_2020%20met%20opmerking.pdf

New edition currently out for comment
https://publicatiereeksgevaarlijkestoffen.nl/publicaties/online/pgs-12/2023/0-1-fase-1-december-2023

COMAH Regulations

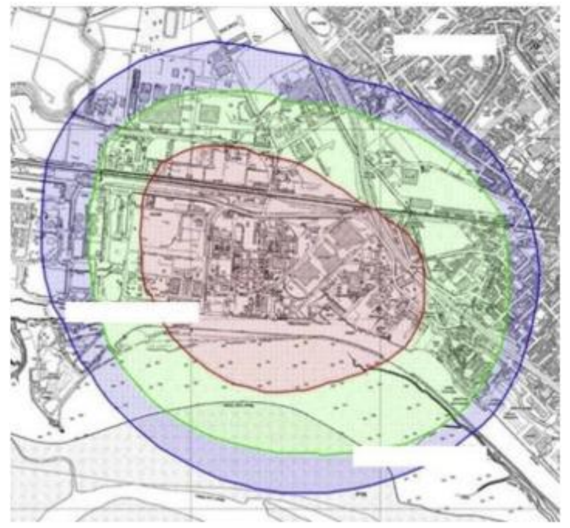
- Control of Major Accident Hazards (COMAH) Regulations 2015
- Implements the majority of the Seveso III Directive (2012/18/EU) in Great Britain
- Competent authority: HSE, Environment Agency (EA, SEPA, NRW), ONR
- All sites: reduce risks to As Low As Reasonably Practicable (ALARP)
- Adopt relevant good 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

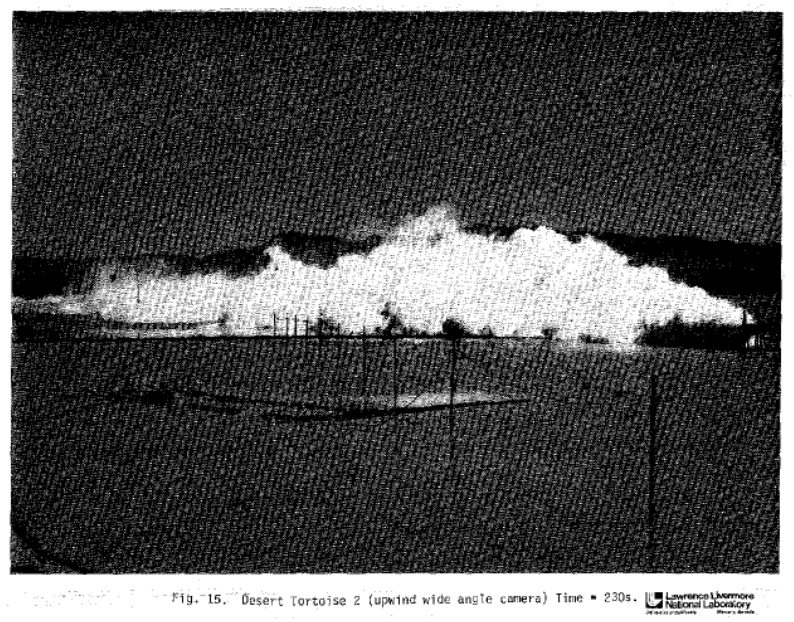
PROTECTING PEOPLE AND PLACES

Contents

Scientific Knowledge Gaps

- Dispersion behaviour of ammonia is complex
  - Clouds can be buoyant or dense, 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.

- Knowledge of dispersion behaviour 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
    - No 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

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Scientific Knowledge Gaps

- Other ammonia experiments
  - Mourmelon (Resplandy, 1969)
  - A.D.Little (Raj *et al*., 1974)
  - ICI (Reed, 1974)
  - Unie van Kunstmestfabrieken (Blanken, 1980)
  - 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 ttp://dx.doi.org/10.1002/prs.12454

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

- Hanna *et al*. (2021) and Batt (2021) reviewed the 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/

PROTECTING PEOPLE AND PLACES

Contents

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/

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

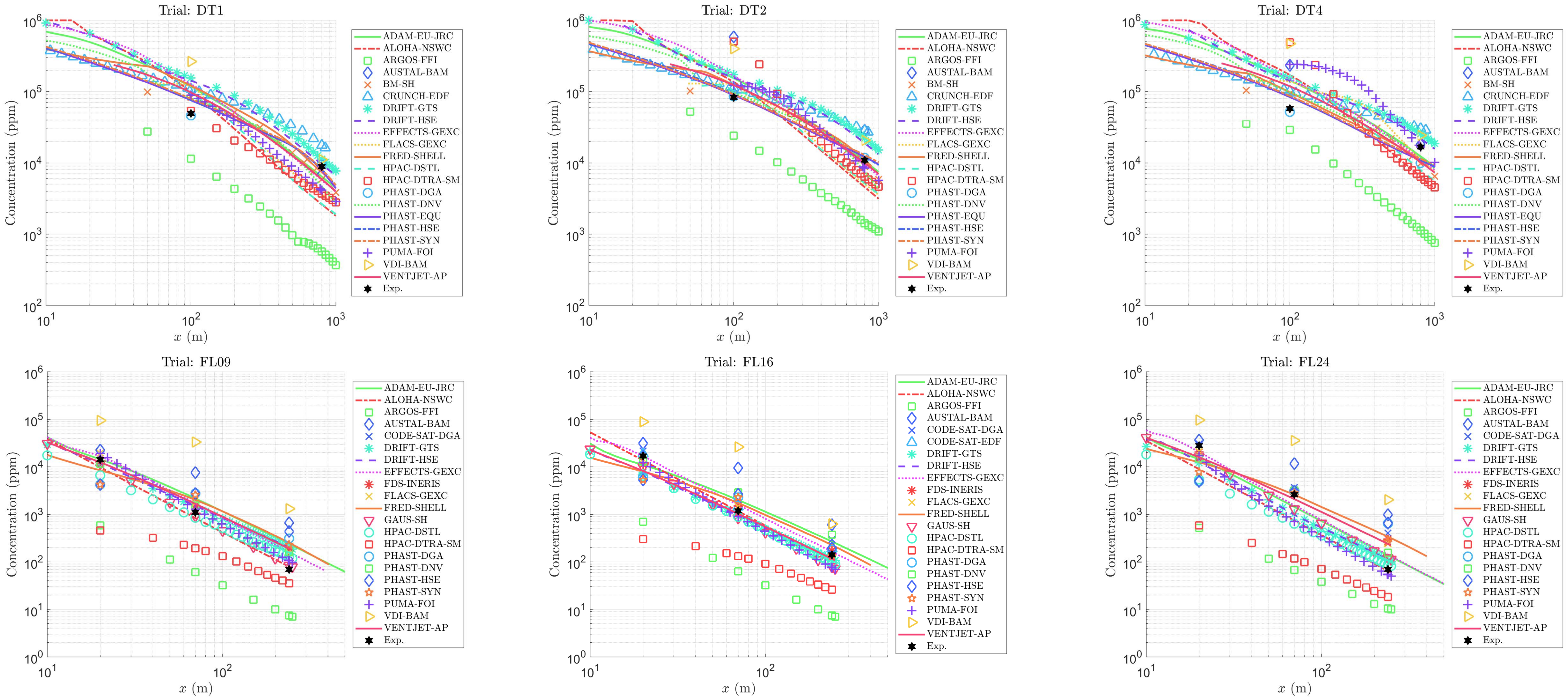
RESEARCH AND GUIDANCE FROM HSE

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		■			■	■	■	■	■	■

RESEARCH AND GUIDANCE FROM HSE

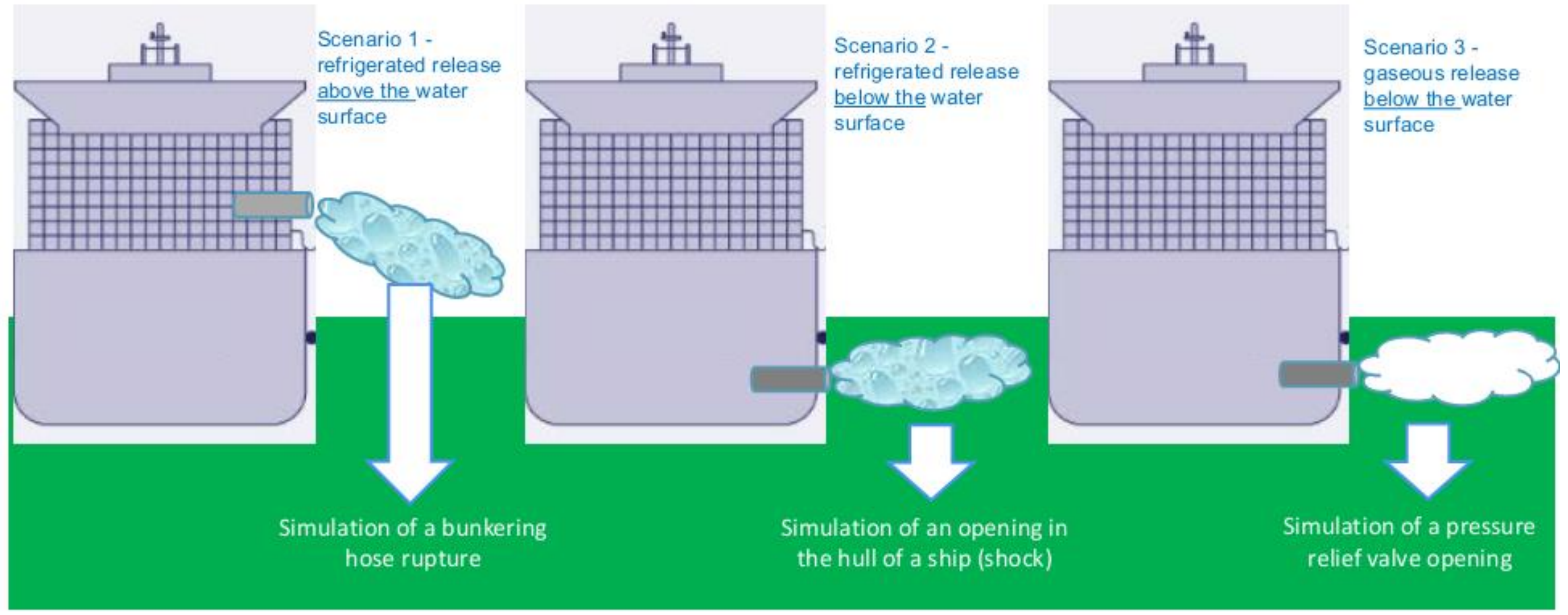
All Model Results



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



Contents

HSE planned research on CCUS safety

PROTECTING PEOPLE AND PLACES

- Development of CO_2 pipeline risk assessment model for application to land-use planning
  - Extension of existing HSE natural gas pipeline risk assessment model
  - Requires revised failure rates, fault trees, fracture, release rate and dispersion models
- Dispersion modelling to inform potential regulatory thresholds for CO_2
- Review safety aspects of CO_2 capture, transport (mainly pipeline and ship), and offshore sequestration
  - Scope includes reviewing ongoing UK CCUS project developments, potential major accident hazard scenarios, applicable standards, international lessons learned from CCUS operations
- Coordinate and collaborate with other organisations (UK and international) with aligned interests, e.g., through joint industry projects

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CCUS safety: Joint Industry Projects

Lead company	Name	Objectives	Website	Timeline
DNV	CO2SafePipe	To close knowledge gaps identified in the transportation of CO2 in pipelines covering CO2 in both gas phase and dense phase, including: 1. CO2 stream composition and its effect on corrosion and materials 2. the risk of running ductile fracture The project will update Recommended Practice DNV-RP-104	https://www.dnv.com/article/design-and-operation-of-co2-pipelines-co2safepipe-240345/	2023-2024
DNV	Materials in CCS Wells	1. Identifying the role of key environmental factors on damage modes in Corrosion Resistant Alloys (CRAs) based on preliminary thermodynamic calculations. 2. Characterizing the performance of CRAs and establishing environmental limits for localized corrosion and SCC in CCS storage wells. 3. Creating a framework to translate qualification test observations into long-term performance predictions in service.	https://www.dnv.com/article/materials-performance-in-ccs-wells/	2023-2025
DNV	Skylark	Study CO2 dispersion in complex terrain and CO2 venting, dispersion model validation and emergency response preparedness	https://www.dnv.com/article/skylark-pioneering-excellence-in-co2-pipeline-safety-250648/	2024-2026
DNV	CO-CO2 cracking in pipelines	1. Define limits on CO and oxidizers (O2, NO2) to prevent CO/CO2 cracking 2. Identify metallurgical limits (yield strength/hardness) to mitigate CO/CO2 cracking 3. Develop a qualification test methodology to screen line pipe steels and welds for susceptibility to CO/CO2 cracking.	https://www.dnv.com/article/establishing-guidelines-to-avoid-co-co2-cracking-in-co2-pipelines-251263/	?
DNV	CO2 CFD simulation software	Model development and validation of KFX including complex thermodynamics and heat transfer processes for release of liquid CO2, including: dry ice formation, deposition of dry ice on the ground and in complex geometries, sublimation of dry ice, condensation of moisture in the surrounding air	https://www.dnv.com/article/co2-cfd-simulation-software-232808/	-2024
Energy Institute	Offshore CO2 good practice	Good Practice Guide for working on offshore oil and gas structures repurposed for CO_2 streams, including consideration of what action to be taken in the event that an evacuation proves necessary	Andy Brown proposed to EI in 2024	2024-
Safetec	SAFEN	Develop risk models for hydrogen, ammonia and CCS Share knowledge for development of best practices for safe design of technologies	https://www.safetec.no/en/news/safen-jip-ready-to-meet-new-challenges	Phase 2 2024-
Sintef	Offshore Monitoring of Large-Scale Subsea Releases of CO2	The project will collect observations from four releases from 300 meters depth, each lasting approximately 30 minutes Aim is to create an open curated dataset for public utilization	contact: Paal.Skjetne@sintef.no	2024-2025
Sintef	CO2 EPOC	Characterization and prediction of the CO2 effect on polymeric materials within the CO2 transport chain (pipelines and ships) to avoid leakage and failure	https://www.sintef.no/en/projects/2020/co2-epoc/	2020-2025
TWI	MASCO2T II	Materials Assessment for Supercritical CO2 Transport 1.Generate corrosion data for candidate metallic materials in high pressure/supercritical CO2, with varying types and concentrations of impurities 2.Establish a thorough knowledge of the impact of a range of environmental factors (such as pressure, temperature, fluid composition etc.) on (i) the corrosion behaviour of candidate metallic materials including welds, and (ii) the effect of stress on the environmental performance of candidate metallic materials and welds.	https://www.twi-global.com/media-and-events/press-releases/2023/join-our-new-supercritical-co2-transport-project	2023-2026
TWI	Permeation of CO2 through thermosets	Combined Permeation of Pressurised CO2 and Impurities through Thermosets 1. To establish the barrier performance of thermoset materials to CO2 with associated impurities. 2. To establish if any transport of these impurity species causes ageing in the thermoset matrix.	https://www.twi-global.com/what-we-do/research-and-technology/research-programmes/joint-industry-projects#/	?
Wood	Industry Guidelines for Setting the CO2 Specification for CCS Chains	to define an industry accepted set of guidelines to set the CO2 specification for effective and economic CCSchains • The guidelines shall cover the full CCUS chain, considering different CO2 sources and transport options. • The JIP will collaborate with research and industry experts to provide a holistic understanding of the impact of impurities.	https://www.woodplc.com/insights/blogs/leading-the-way-with-carbon-capture-and-storage-ccs	2022-2024

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)

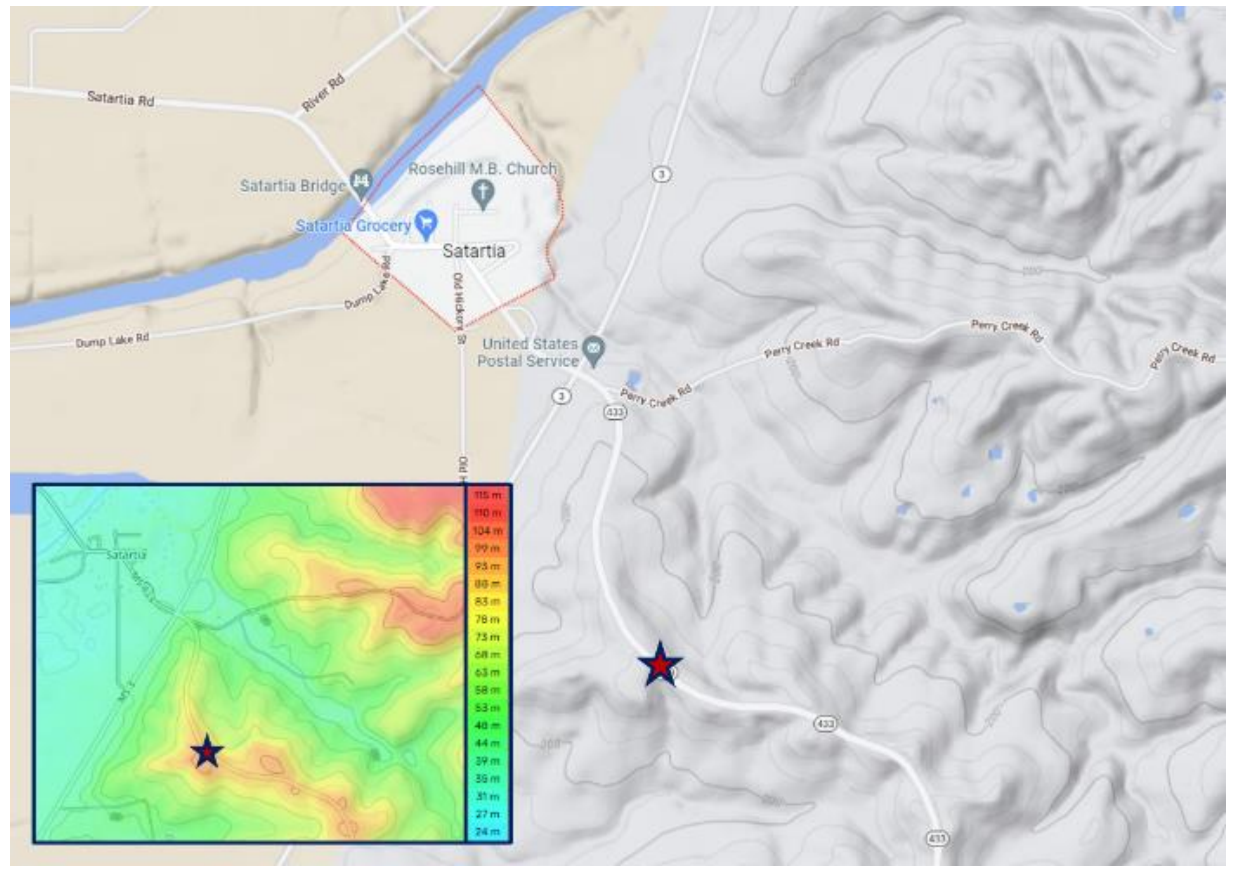
API Pipeline Conference, Salt Lake City, Utah, USA, 6-8 May 2024

PROTECTING PEOPLE AND PLACES HSE

Background: Satartia incident

- 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

Knowledge Gaps

1. Source characteristics from CO_2 pipeline craters

Moderate wind

Bent-over plume, no re-entrainment

Light wind

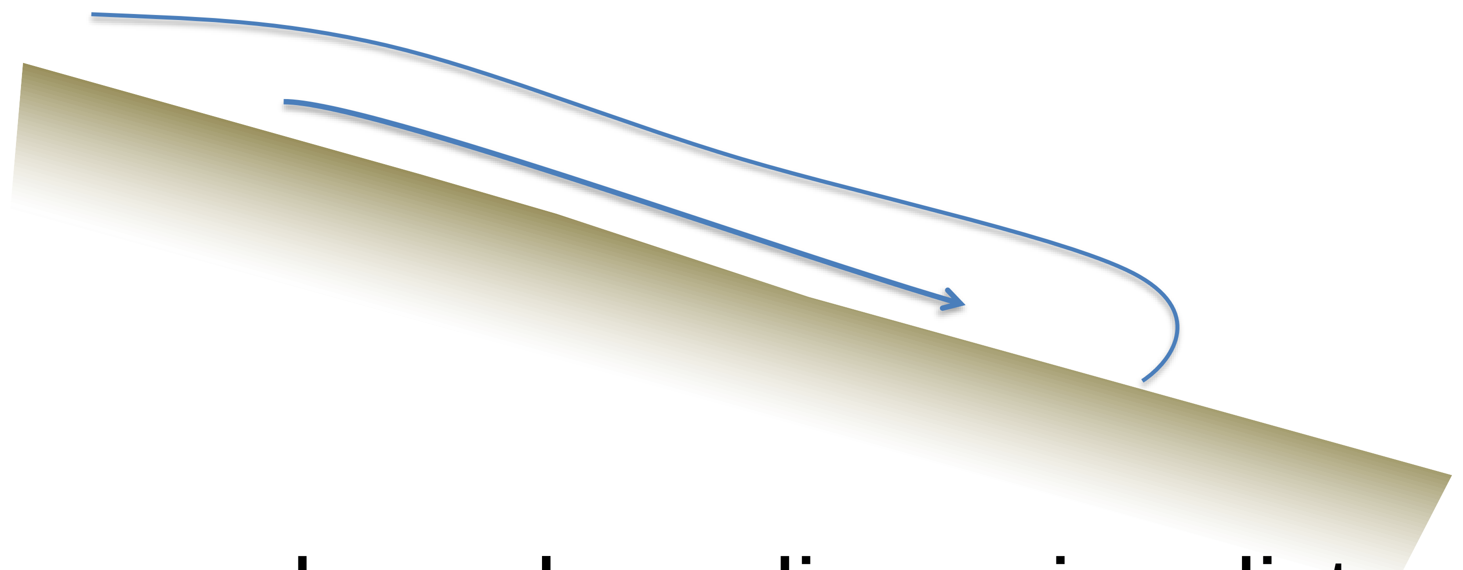
Plume falls onto crater, re-entrainment, blanket

- Questions:
  - Which set of conditions give rise to these two different sources (wind speed, release size etc.)?
  - What are the characteristics of the dispersion source term (composition, flow rate, temperature etc.)?
  - Experimental data is limited to just two COSHER tests (COOLTRANS data is currently unavailable)

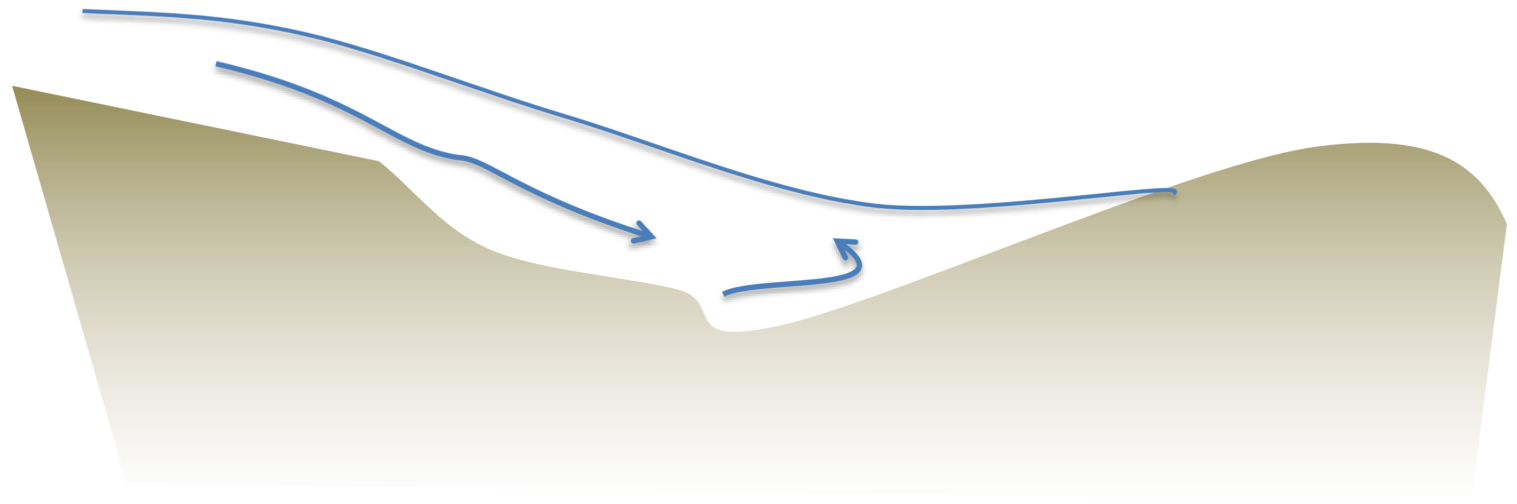
Source of images: Allason D., Armstrong K., Barnett J., Cleaver P. and Halford A. "Behaviour of releases of carbon dioxide from pipelines and vents", Paper IPC2014-33384, Proc. 10th International Pipeline Conference IPC2014, Calgary, Alberta, 29 September – 3 October 2014, © Copyright National Grid /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

Knowledge Gaps

2. Terrain effects on dense clouds



Larger downslope dispersion distances?



Channelling effects in complex terrain, vapour hold-up in valleys

- Questions:
  - How confident are we in dispersion model predictions for dense-gas dispersion in complex/sloping terrain?
  - Have the dispersion models been validated against reliable experimental data?
  - Do any dispersion models exist that produce results quickly, i.e., within a few seconds (or minute at most) for use in risk assessment and emergency planning/response?

PROTECTING PEOPLE AND PLACES

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Knowledge Gaps

3. Are emergency responders sufficiently prepared to deal with possible incidents involving large CO_2 releases from CCS infrastructure?
   - Learning points from Satartia incident, e.g., vehicle engines stalling in CO_2-rich atmosphere: difficulties evacuating casualties (could electric vehicles be used?)
   - Similar approach could be adopted to the Jack Rabbit II chlorine dispersion experiments

     Work led by Andy Byrnes at Utah Valley University https://www.uvu.edu/es/jack-rabbit/

Knowledge Gaps

4. Limited experimental data available for CO_2 venting and blowdown to validate dispersion models used for site risk assessments and permitting studies
   - Dense-phase CO_2 venting at pipeline pig traps
   - Gas-phase CO_2 venting at capture plants
     - Process upset leading to high oxygen levels in CO_2 stream
     - Loss of dehydration leading to high water levels in CO_2 stream

5. Uncertainties in venting strategies and consequences of major loss of containment of CO_2 on offshore platforms (including evacuation scenarios)

6. Useful to have further data on performance of CO_2 valves
   - Pressure safety valves on refrigerated liquid CO_2 storage vessels (e.g., 18 bar, -30 ^{o}C)
   - Pressure safety valves on high-pressure compression (dense-phase CO_2)
   - Pipeline emergency shutdown valves (dense-phase CO_2)
   - Valves to isolate flow of off-spec CO_2 from capture plants (e.g., 20-30 bar, ambient temp)

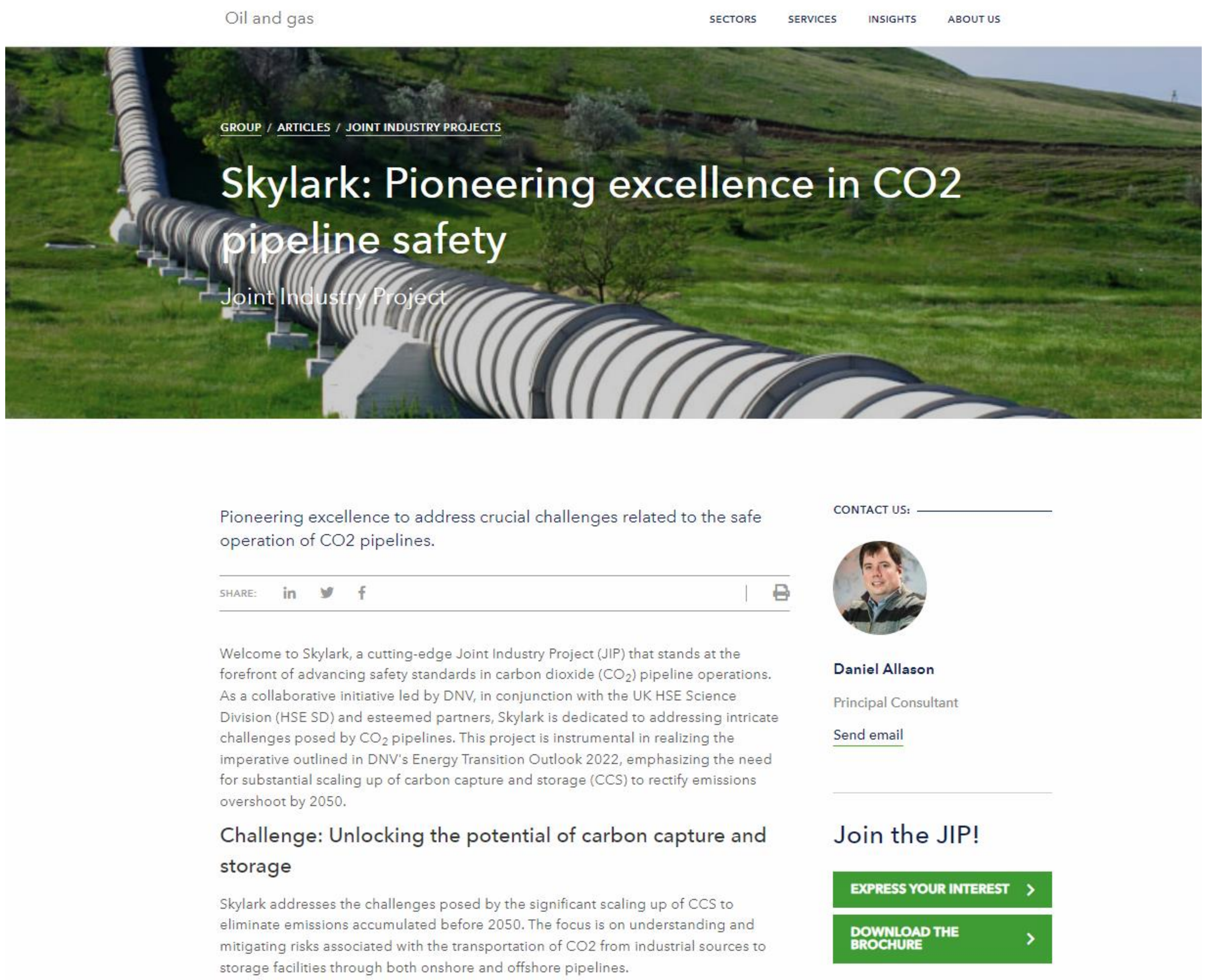
Proposed Skylark Joint Industry Project

- Work Package 0: Project Management – **DNV**
- Work Package 1: CO_2 pipeline craters and source terms – **DNV**
- Work Package 2: Wind-tunnel experiments – **University of Arkansas**
- Work Package 3: Simple terrain dispersion experiments – **DNV**
- Work Package 4: Complex terrain dispersion experiments – **DNV**
- Work Package 5: Model validation – **HSE**
- Work Package 6: Emergency response – **NCEC**
- Work Package 7: Venting – **DNV**

with support from the **Met Office**
in the DNV field trials

Skylark project website

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


Oil and gas

SECTORS SERVICES INSIGHTS ABOUT US

GROUP / ARTICLES / JOINT INDUSTRY PROJECTS

Skylark: Pioneering excellence in CO2 pipeline safety

Joint Industry Project

Pioneering excellence to address crucial challenges related to the safe operation of CO2 pipelines.

SHARE:

Welcome to Skylark, a cutting-edge Joint Industry Project (JIP) that stands at the forefront of advancing safety standards in carbon dioxide (CO_2) pipeline operations. As a collaborative initiative led by DNV, in conjunction with the UK HSE Science Division (HSE SD) and esteemed partners, Skylark is dedicated to addressing intricate challenges posed by CO_2 pipelines. This project is instrumental in realizing the imperative outlined in DNV's Energy Transition Outlook 2022, emphasizing the need for substantial scaling up of carbon capture and storage (CCS) to rectify emissions overshoot by 2050.

Challenge: Unlocking the potential of carbon capture and storage

Skylark addresses the challenges posed by the significant scaling up of CCS to eliminate emissions accumulated before 2050. The focus is on understanding and mitigating risks associated with the transportation of CO2 from industrial sources to storage facilities through both onshore and offshore pipelines.

CONTACT US:

Daniel Allason

Principal Consultant

Send email

Join the JIP!

EXPRESS YOUR INTEREST

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PROTECTING PEOPLE AND PLACES

HSE

HSE research planned on hydrogen safety

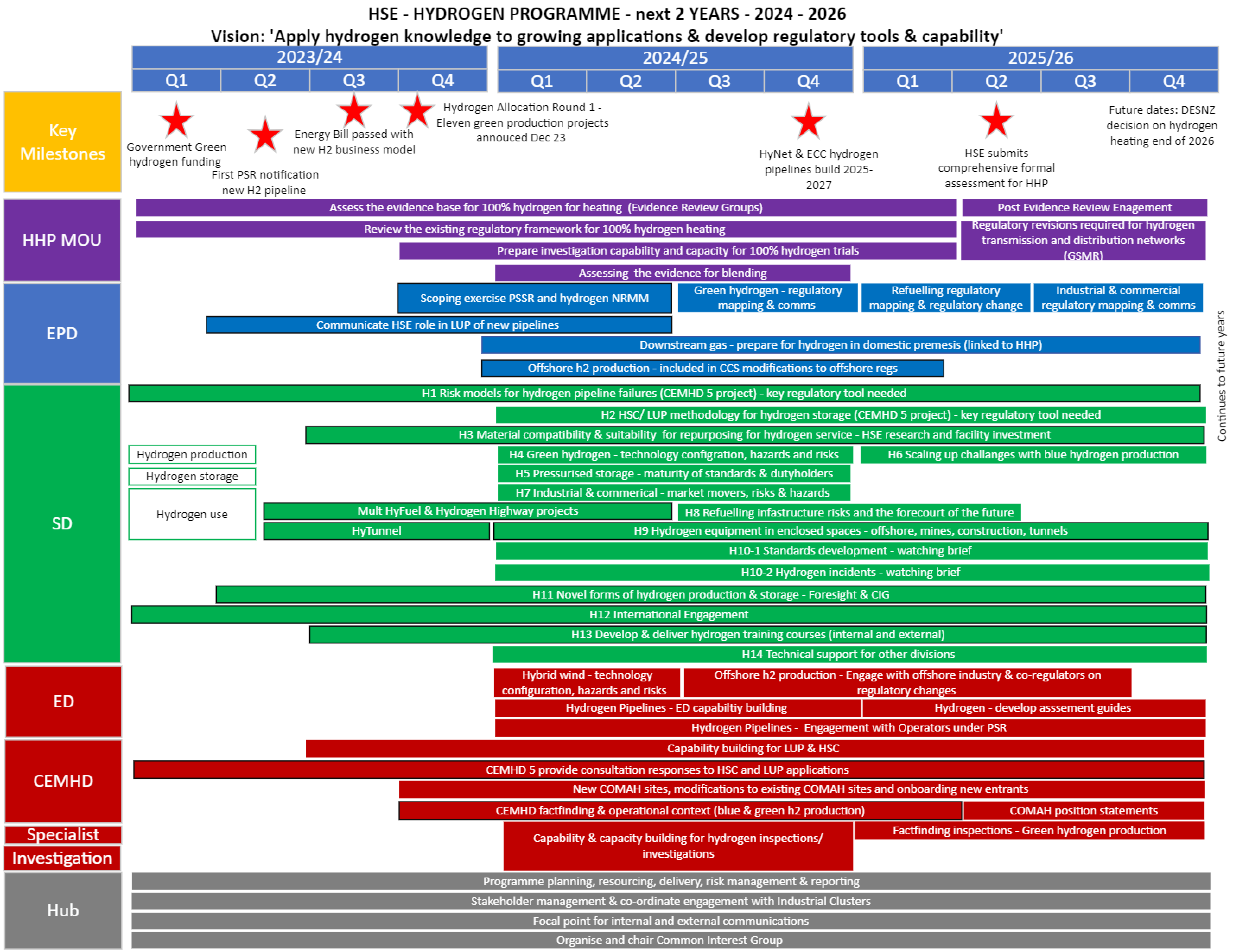
Hydrogen heating programme

Engagement and Policy Division

Science Division

Energy Division

Chemicals, Explosives and Microbiological Hazards Division



Risk models for hydrogen pipelines

- Objectives
  - Review HSE's pipeline risk assessment methodology to determine its suitability for hydrogen, and update it if needed, considering:
    - Failure rate model, including changes in material behaviour in the presence of hydrogen
    - Gas pipeline release rate model
    - Ignition model and event trees – are delayed ignitions credible for hydrogen pipelines?
    - Fire model for immediate ignition
    - Explosion model for delayed ignition (if needed)
- Motivation
  - Need to update pipeline risk assessment methodology for hydrogen pipelines, for application to provision of HSE's statutory land-use planning advice to local planning authorities
- Key milestones
  - Planning application for 125 km high pressure HyNet North West hydrogen pipeline expected in Spring 2024 https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/EN060006
- Relevant information
  - SAFEN Joint Industry Project https://www.safetec.no/en/news/safen-jip-ready-to-meet-new-challenges
  - FutureGrid https://www.nationalgas.com/insight-and-innovation/transmission-innovation/futuregrid
  - Energy Institute guidance https://publishing.energyinst.org/topics/hydrogen
  - IGEM standards development https://www.igem.org.uk/technical/buy-technical-standards/transmission-and-distribution.html

Hydrogen Storage

- Objectives
  - Review HSE’s risk assessment methodology for bulk storage of gaseous and liquid hydrogen
  - Widen validation of models, considering results from recent hydrogen experiments
  - Improve understanding of hydrogen incidents and review release scenarios and failure rates
- Motivation
  - Need to ensure HSE’s risk assessment methodology keeps pace with developing knowledge, for application to provision of HSE’s statutory land-use planning advice to local planning authorities
- Key milestones
  - Ongoing discussions with developers of GB hydrogen infrastructure
- Relevant information
  - SAFEN Joint Industry Project https://www.safetec.no/en/news/safen-jip-ready-to-meet-new-challenges
  - Energy Institute guidance https://publishing.energyinst.org/topics/hydrogen
  - SH2IFT experiments on liquid hydrogen BLEVEs https://sh2ift-2.com/
  - ELVHYS project https://elvhys.eu/

Material compatibility

- Objectives
  - Review new test data and recent literature on material compatibility and suitability for hydrogen service
  - Develop HSE testing facility for long-term exposure of materials in gaseous hydrogen up to 8 bar, including in-situ micro tensile testing and ex-situ impact and tensile testing (metals, polymers and elastomers)
  - Review and (if necessary) update fracture mechanics model for HSE's hydrogen pipeline risk assessment model
- Motivation
  - Advice to HSE inspectors and information to support guidance and incident investigation
  - Need to update pipeline risk assessment methodology for hydrogen, for statutory LUP advice
- Key milestones
  - HSE to provide policy options for future safety regulation of hydrogen for heating in September 2024, and final written advice to the Department for Energy Security and Net Zero in March 2025
- Relevant information
  - HSE Safe Net Zero 2024 event, 13 February https://www.hsl.gov.uk/health-and-safety-training-courses
  - SAFEN Joint Industry Project https://www.safetec.no/en/news/safen-jip-ready-to-meet-new-challenges
  - FutureGrid https://www.nationalgas.com/insight-and-innovation/transmission-innovation/futuregrid
  - Energy Institute guidance https://publishing.energyinst.org/topics/hydrogen
  - IGEM standards development https://www.igem.org.uk/technical/buy-technical-standards/transmission-and-distribution.html

Round Tensile Specimens

Flat Tensile Specimens

Risk assessment and area classification

- Objectives
  - Review hydrogen flammability and explosion limits (4% or 8% v/v? Downward flame propagation?)
  - Review appropriate hole sizes for hazardous area classification with hydrogen
  - Review “negligible extent” criteria for hydrogen, based on potential fire and explosion hazards
  - Review transition point at which hydrogen leaks affect the ventilation rate in enclosures
- Motivation
  - Advice to HSE inspectors on review of hazardous area classification at sites handling hydrogen
  - Information to support guidance (e.g., for vehicle refuelling stations) and incident investigation
- Key milestones
  - Ongoing discussions with developers of GB hydrogen infrastructure
- Relevant information
  - SAFEN Joint Industry Project https://www.safetec.no/en/news/safen-jip-ready-to-meet-new-challenges
  - Energy Institute guidance https://publishing.energyinst.org/topics/hydrogen
  - IGEM standards development https://www.igem.org.uk/technical/buy-technical-standards/transmission-and-distribution.html
  - ISO/TC197 Hydrogen technologies https://www.iso.org/committee/54560.html and IEC 60079
  - IEA Task 43 https://www.ieahydrogen.org/task/task-43-safety-and-rcs-of-large-scale-hydrogen-energy-applications/

Thank you

Any questions?

- Sincere thanks to Adam Bannister (HSE), Seshu Dharmavaram (Air Products) and Ron Meris (DTRA) for helpful feedback on an earlier version of these slides

- Contact: Simon.Gant@hse.gov.uk