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AND PLACES

HSE

Recent research activities on ammonia at HSE Science Division

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28th Annual George Mason University Conference on Atmospheric Transport and Dispersion Modeling

21-23 May 2024, Fairfax, Virginia, USA

Contents

- Effect of temperature and humidity on dispersion of ammonia
- Review of ammonia incidents
- CFD modelling for the SH2IFT ammonia exercise
- Ongoing European research activities on ammonia dispersion
  - ARISE
  - SafeAm

Temperature and Humidity Effects

- Excerpt from forthcoming presentation at AIChE meeting in Sept 2024

  https://www.aiche.org/conferences/annual-safety-ammonia-plants-and-related-facilities-symposium/2024

Analyzing Ammonia Dispersion Under Varying Atmospheric Conditions Using DRIFT

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

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

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

Gemma Tickle
GT Science & Software

Temperature and Humidity Effects

- DRIFT model simulations of
  - Long-duration release, typical of a hole in a vessel (based on Desert Tortoise)
  - Instantaneous release from catastrophic vessel failure

Release scenario	Long-duration	Instantaneous
Orifice diameter	81 mm	-
Release temperature	21.5 °C	-33.3 °C
Release pressure	10 bar g	Atmospheric
Liquid fraction	1	0.0, 0.1,…, 0.3
Release rate	80 kg/s	-
Release duration	Continuous	-
Inventory	-	20 tonnes

Instantaneous cloud is initially stationary at ground level with an aspect ratio of one (i.e., height = width). Continuous release is horizontal from height of 0.79 m.

Temperature and Humidity Effects

- Modelled atmospheric conditions

Parameter	**Value**
Temperature (°C)	0, 3, …, 30
Relative humidity (%)	0, 10, …, 80
Wind speed	2 m/s at height of 2 m
Roughness length	3 mm
Pasquill stability class	D
Friction velocity (m/s)	0.442 m/s

No heat transfer from the ground

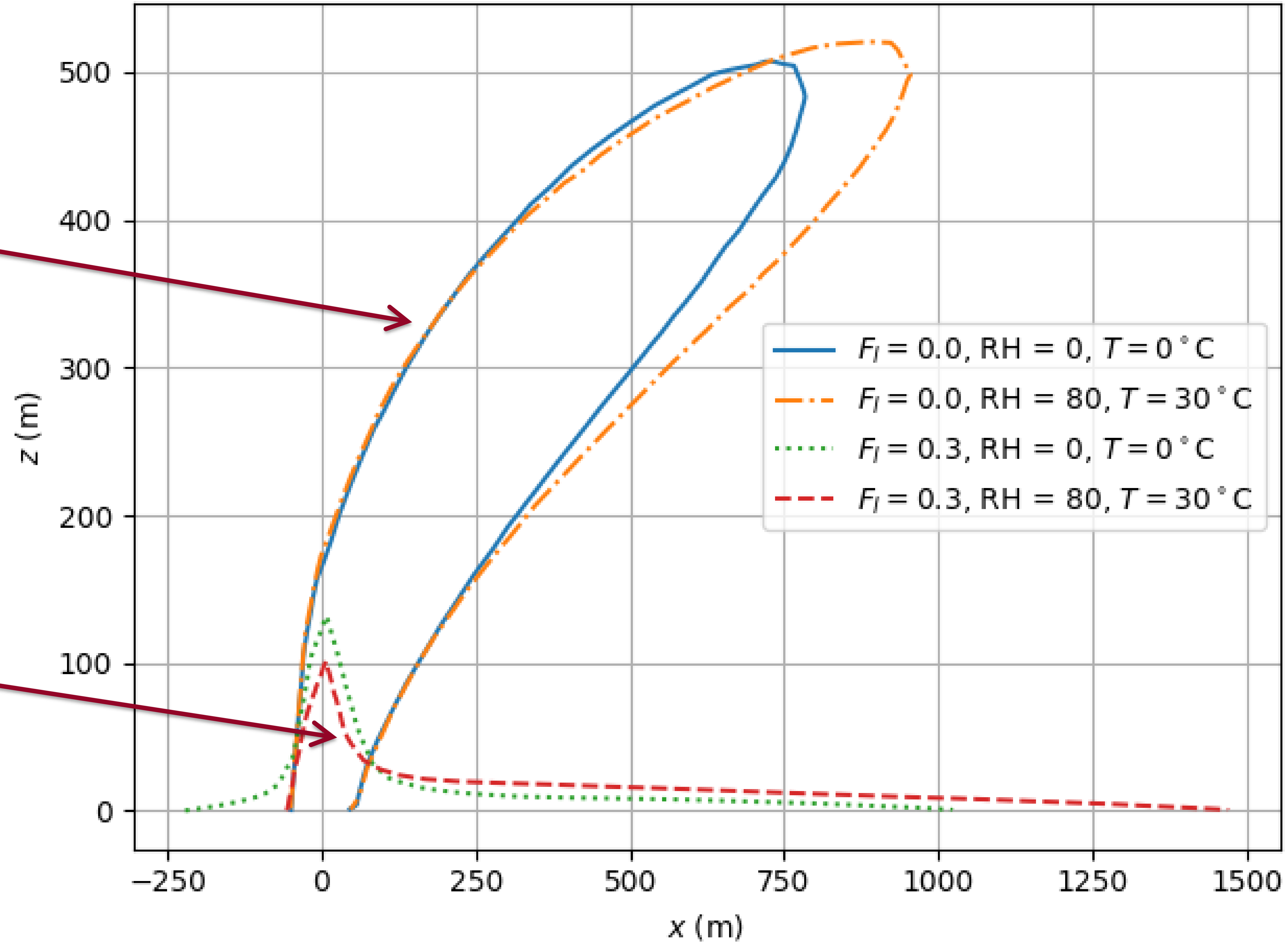
Surface roughness is taken from Desert Tortoise (open water or mud flats)

Temperature and Humidity Effects

- Liquid fraction has a significant effect on behaviour of instantaneous releases

Buoyant vapour-only releases

Dense clouds with initial liquid fraction of 0.3

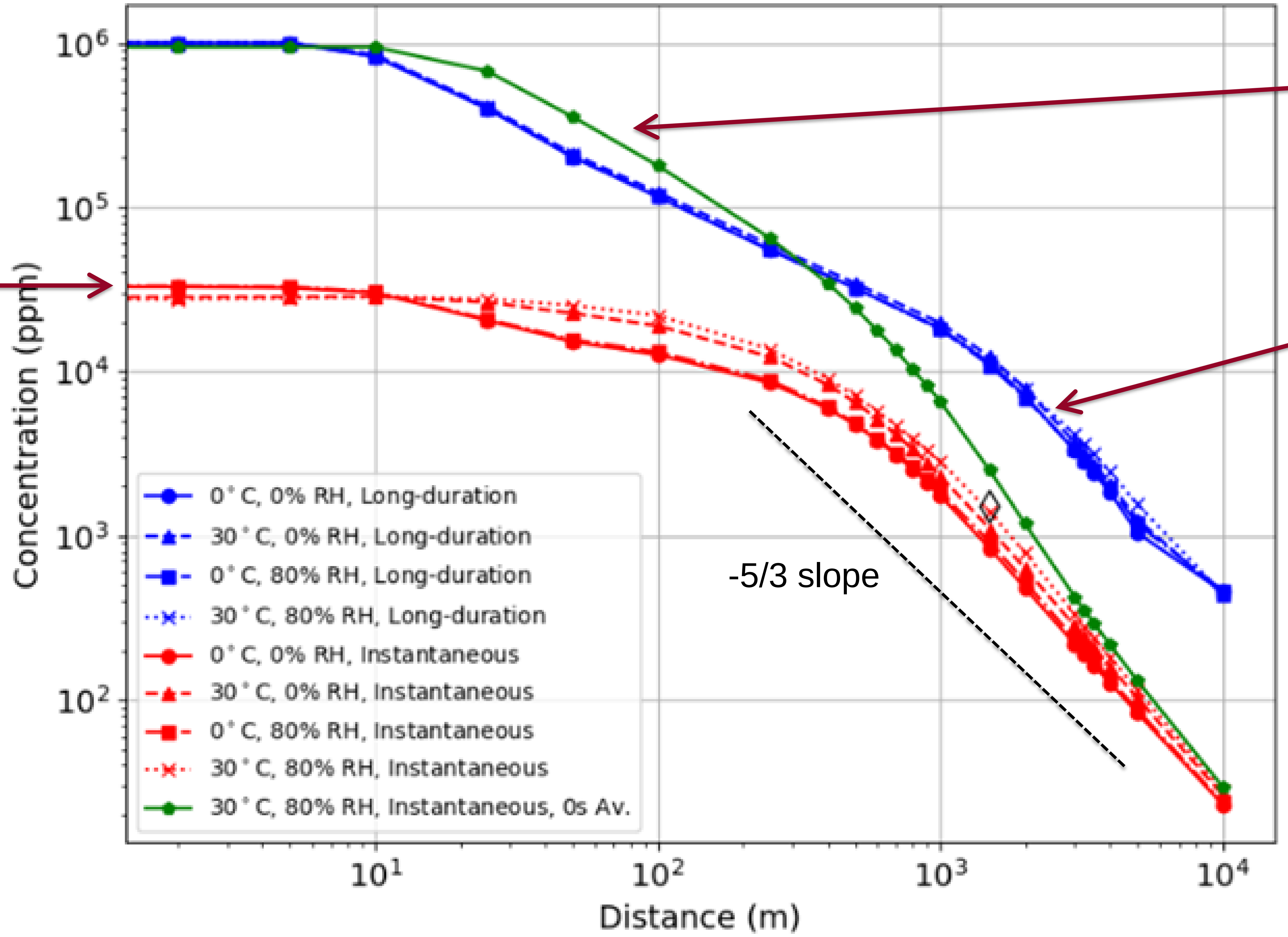


Contours of AEGL-3 (10 minute exposure) ammonia concentration of 2,700 ppm

Temperature and Humidity Effects

- Effects of changing temperature and humidity are modest
- Time-averaged concentrations over 10 minutes are higher for continuous releases

Lower concentrations of instantaneous releases in red are due to time-averaging the short duration release over 10 minutes.
This was done to assess toxic effects, i.e., distance to AEGL-3 (10-minutes exposure) of 2,700 ppm



Instantaneous release with no time-averaging in green

Continuous releases with 10-minute time-averaging in blue

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Ammonia incidents

- **Pressure-liquefied ammonia** (close to ambient temperature, pressure > 7 bar)
  - Potchefstroom, South Africa (1973) vessel failed due to brittle fracture
  - Houston, Texas (1976) road tanker collision
  - Houston, Texas (1983) refrigeration leak and vapour cloud explosion
  - Dakar, Senegal (1992) vessel over-pressurized
  - Minot, South Dakota (2002) railcar accident
  - Kingman, Kansas (2004) pipeline rupture from dent/gouge
  - Tampa Bay, Florida (2007) pipeline leak due to third-party activity
  - Swansea, South Carolina (2009) transfer hose failure
  - Tekamah, Nebraska (2016) pipeline rupture due to fatigue cracking
  - Beach Park, Illinois (2019) agricultural nurse tank coupling failed in transit
  - Teutopolis, Illinois (2023) road tanker collision
  - Chennai, India (2023) underwater pipeline failure

Ammonia incidents

- **Temperature-liquefied ammonia** (close to ambient pressure, temperature approx. -33°C)
  - Blair, Nebraska (1970) tank overfilled
  - Jonova, Lithuania (1989) tank over-pressurized following addition of warm ammonia
  - Rostock, Germany (2005) tank over-pressurized due to addition of ammonia during commissioning
  - Pardis, Iran (2011) tank over-pressurized following addition of warm ammonia
  - Chittagong, Bangladesh (2016) tank over-pressurized due to operational error or mechanical failure
  - Kwinana, Western Australia (2018) ship transfer connection failed

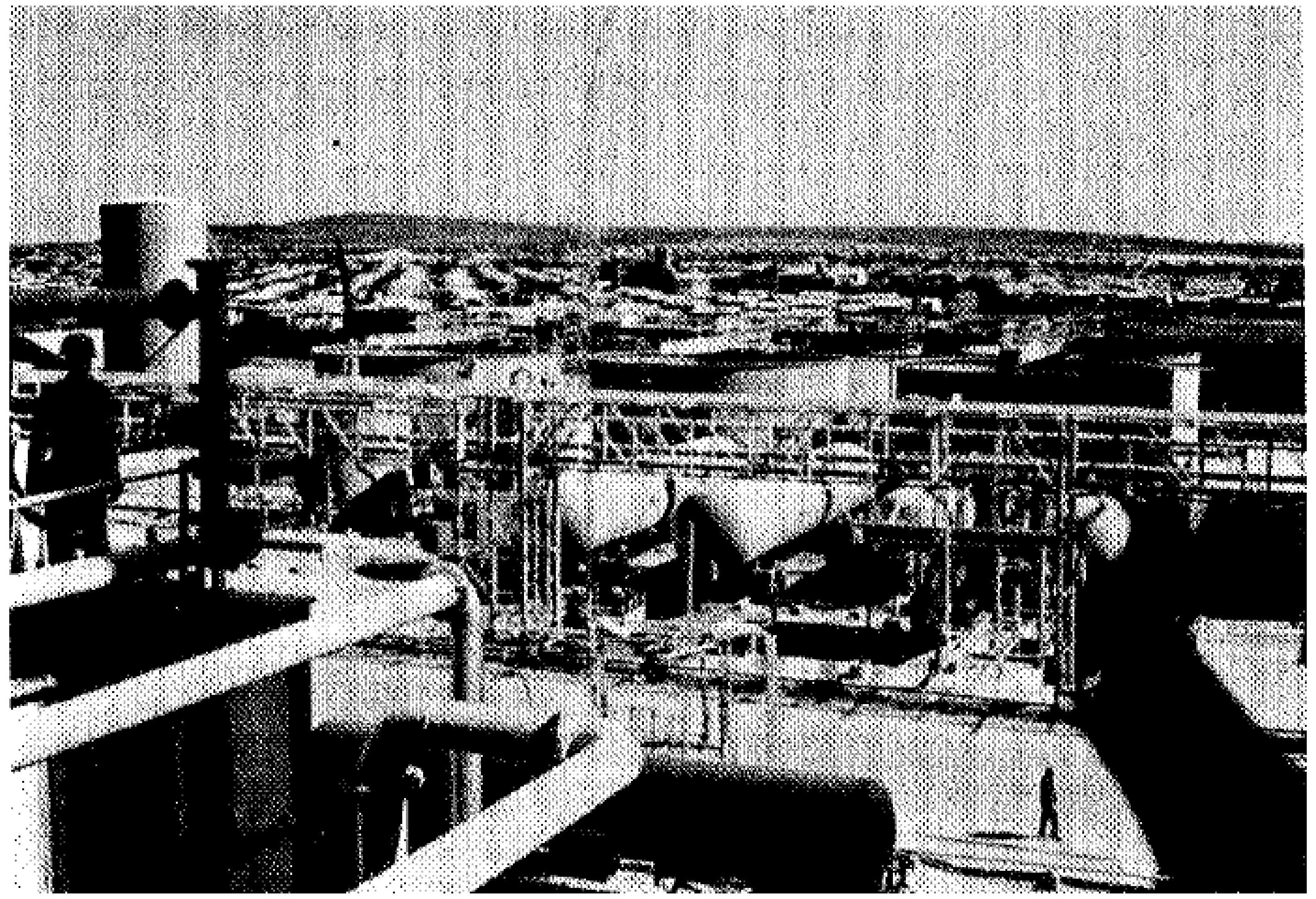
- In all cases, it seems that some ammonia aerosol was generated in these incidents due to either a pressurized release or a fountain of liquid – likely to produce dense-gas behaviour
  - Not simply a quiescent pool of cryogenic liquid, producing a buoyant ammonia vapour cloud
- Conclusion: it is useful to understand behaviour of sprays of cryogenic liquid ammonia

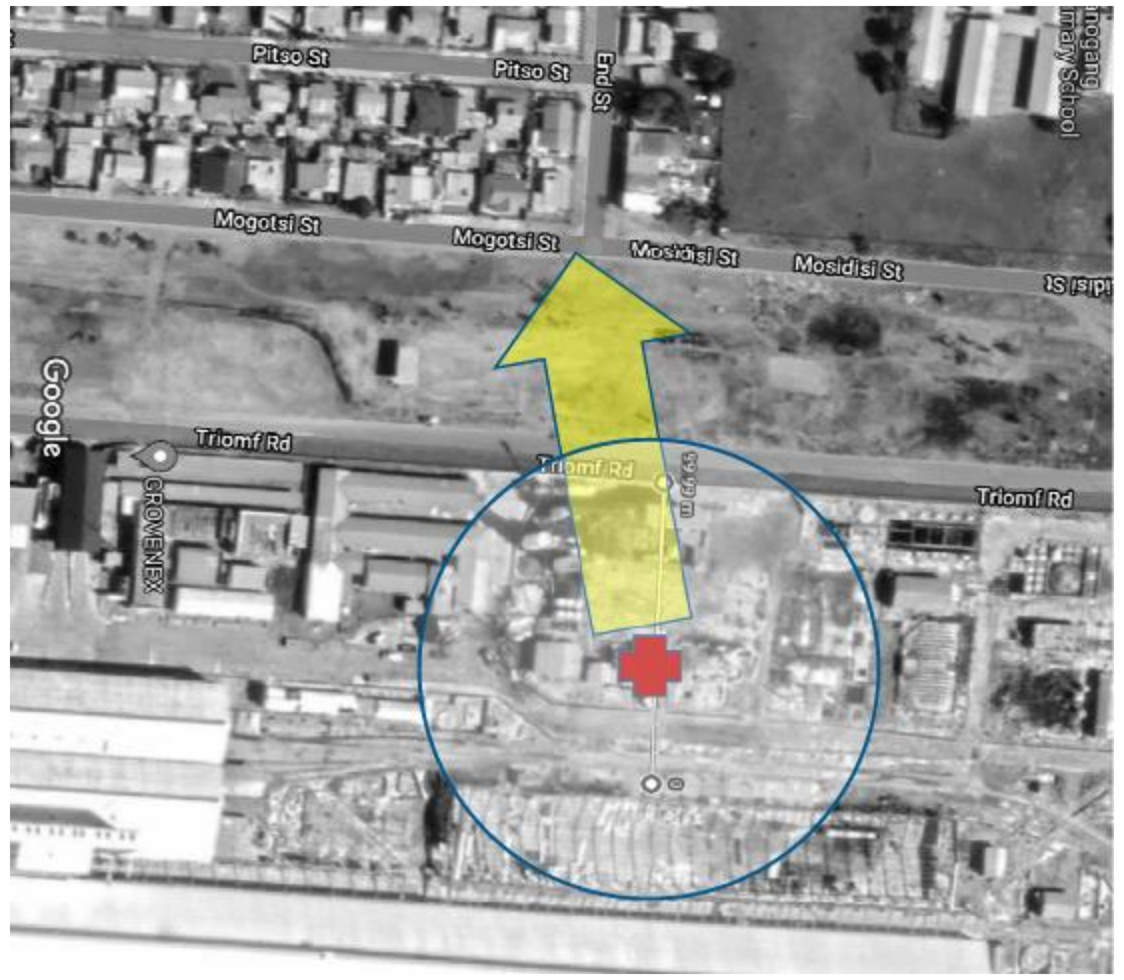
Incidents with pressure-liquefied ammonia

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

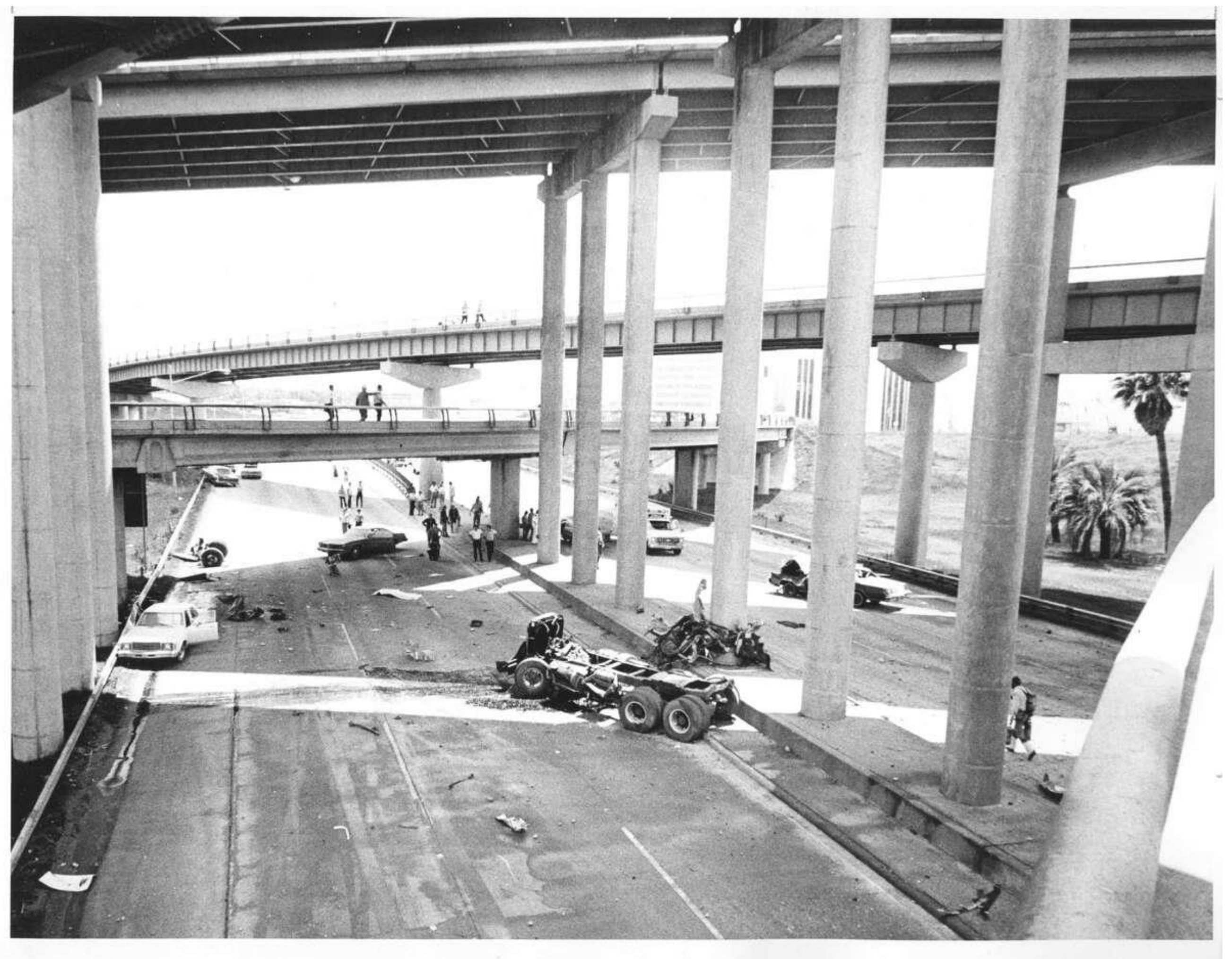




Lonsdale, H. Ammonia tank failure-South Africa, Ammonia Plant Safety 17: 126-131, 1975, and analysis by Doug Sommerville for US Department of Homeland Security

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 7 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 16 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

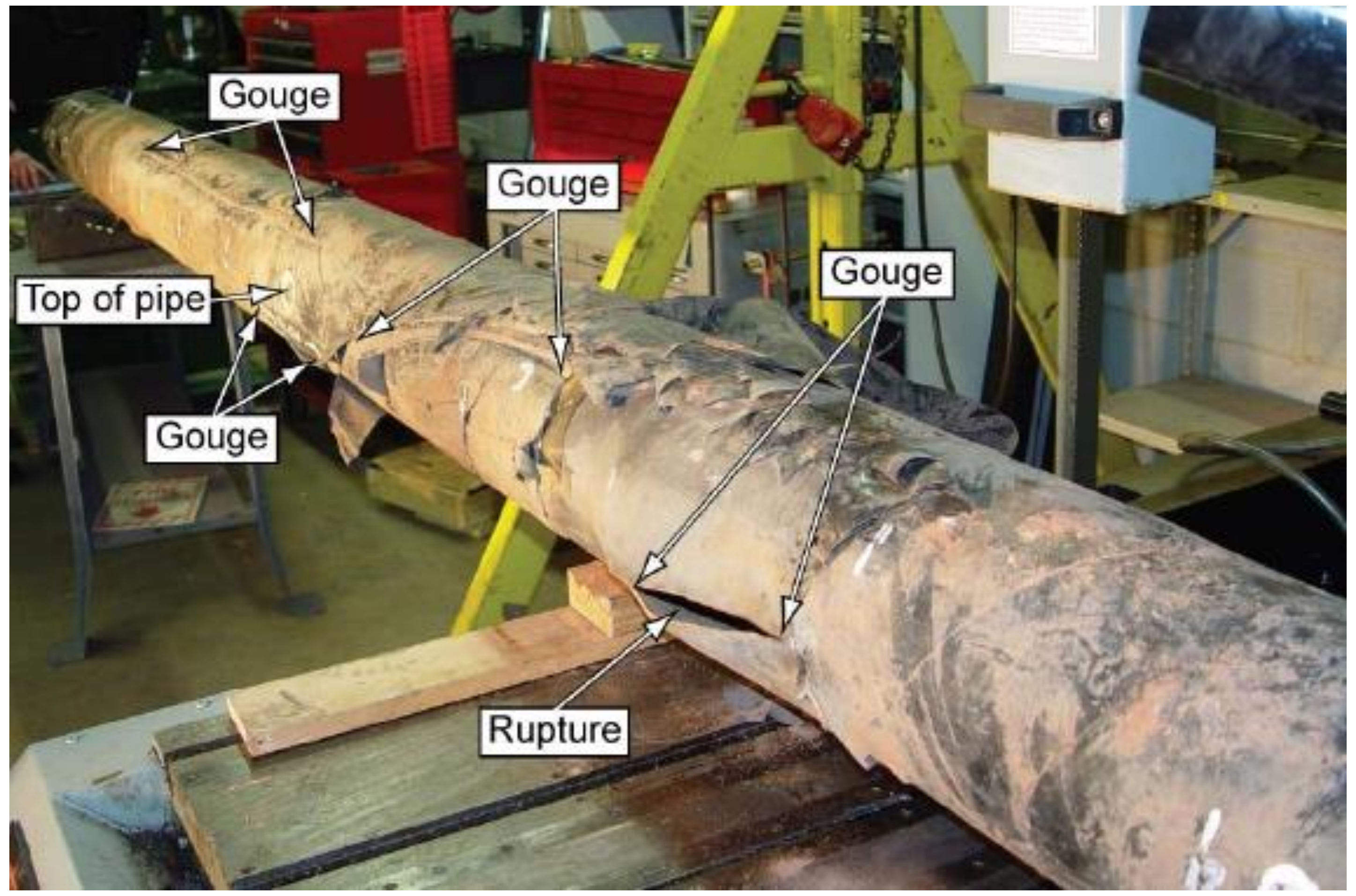
Minot, North Dakota (2002)

- 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

Kingman, Kansas (2004)

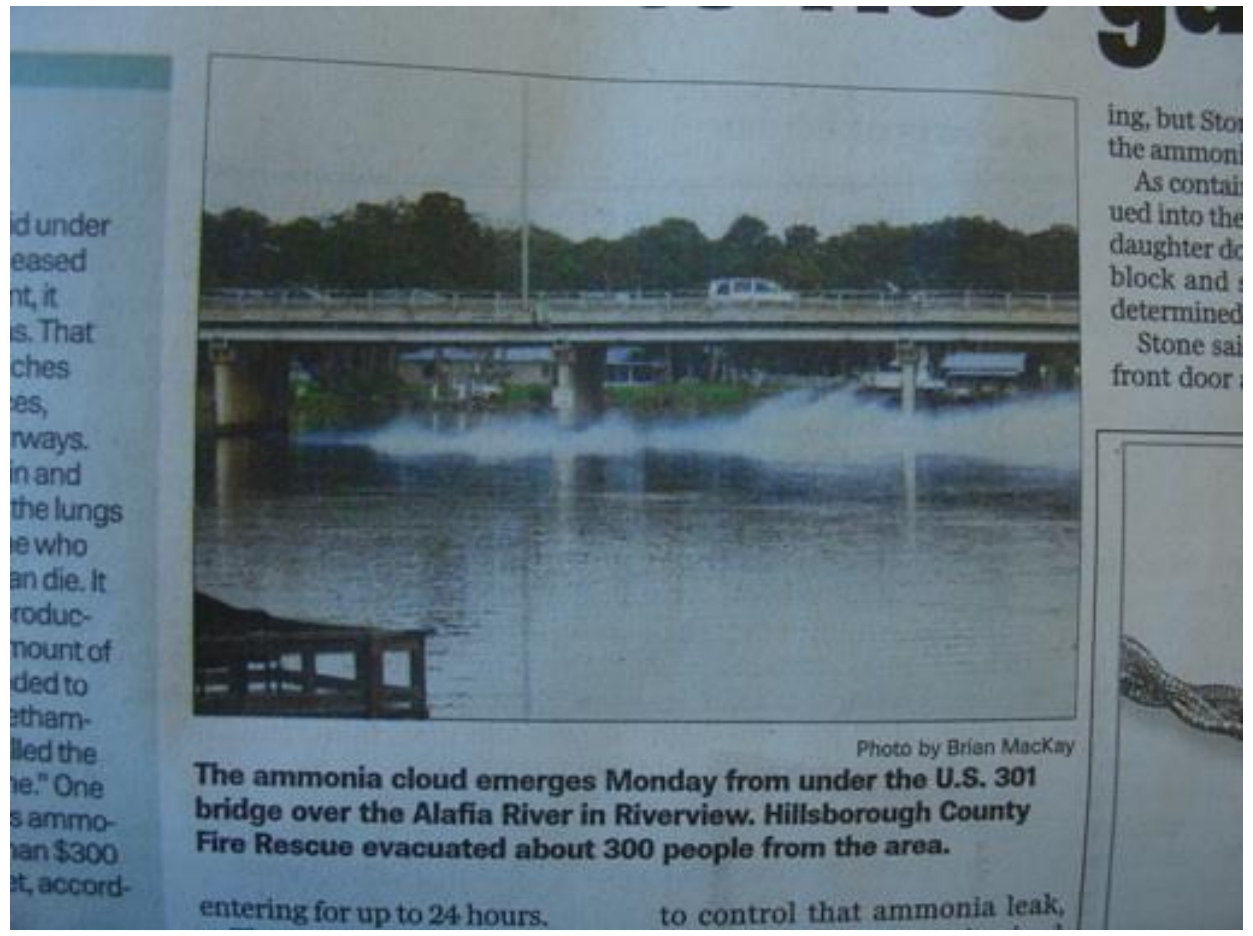
- 8-inch diameter Magellan pipeline ruptured and released 480 t of ammonia
- Visible vapour cloud 0.5 miles wide and 1.5 miles long
- Four families evacuated, no injuries
- Analysis showed pipeline rupture was caused by damage from digging equipment, either during construction or later agricultural activities



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

Tampa Bay, Florida (2007)

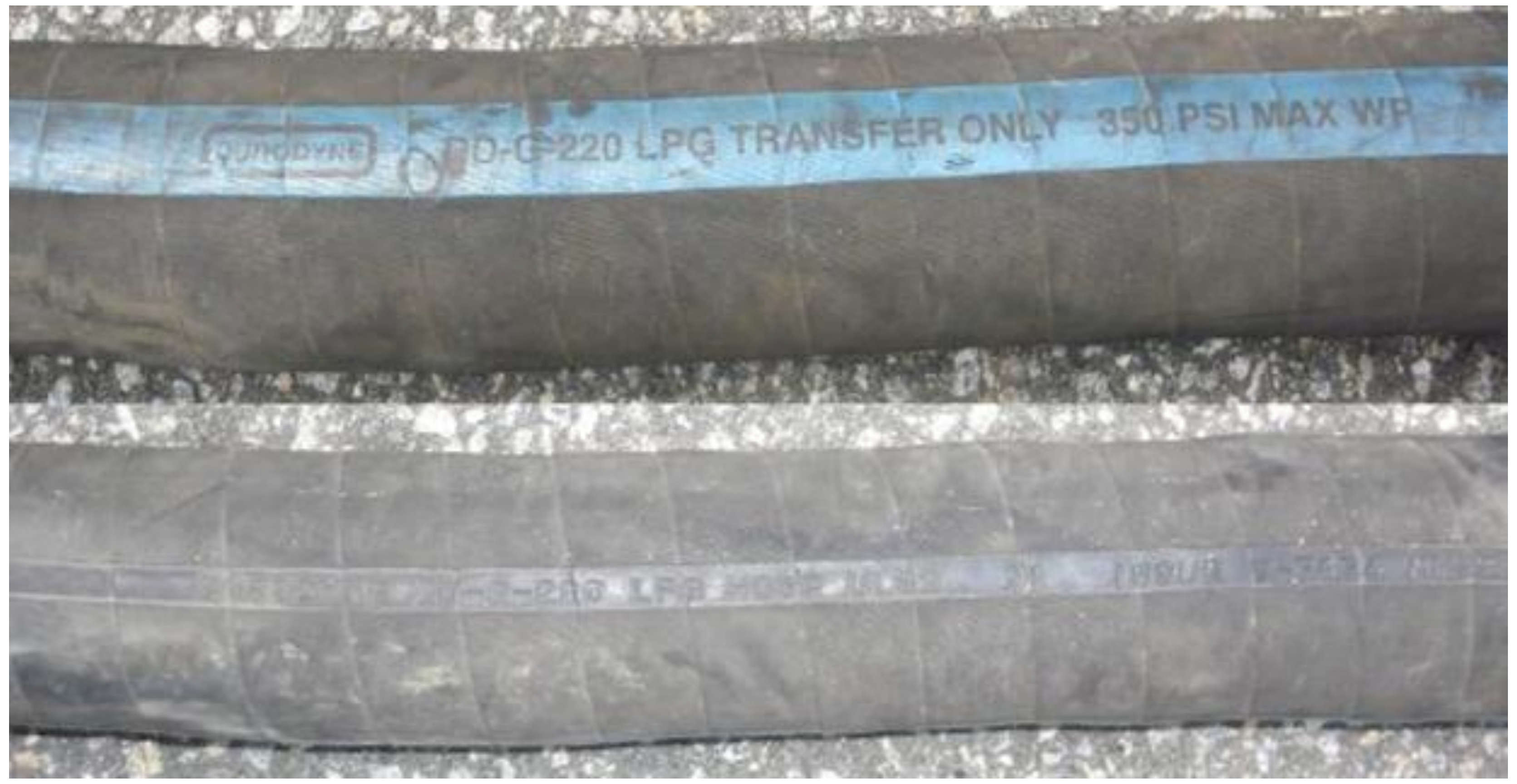
- Teenager took 2 days to drill through steel wall of 6-inch diameter ammonia pipeline using a cordless drill
- Suffered burns from jetting ammonia, but fell or jumped into river and survived
- Public evacuated from ¼ to ½ mile radius
- Fortunately, pipeline was operating at half usual pressure due to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



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

Swansea, South Carolina (2009)

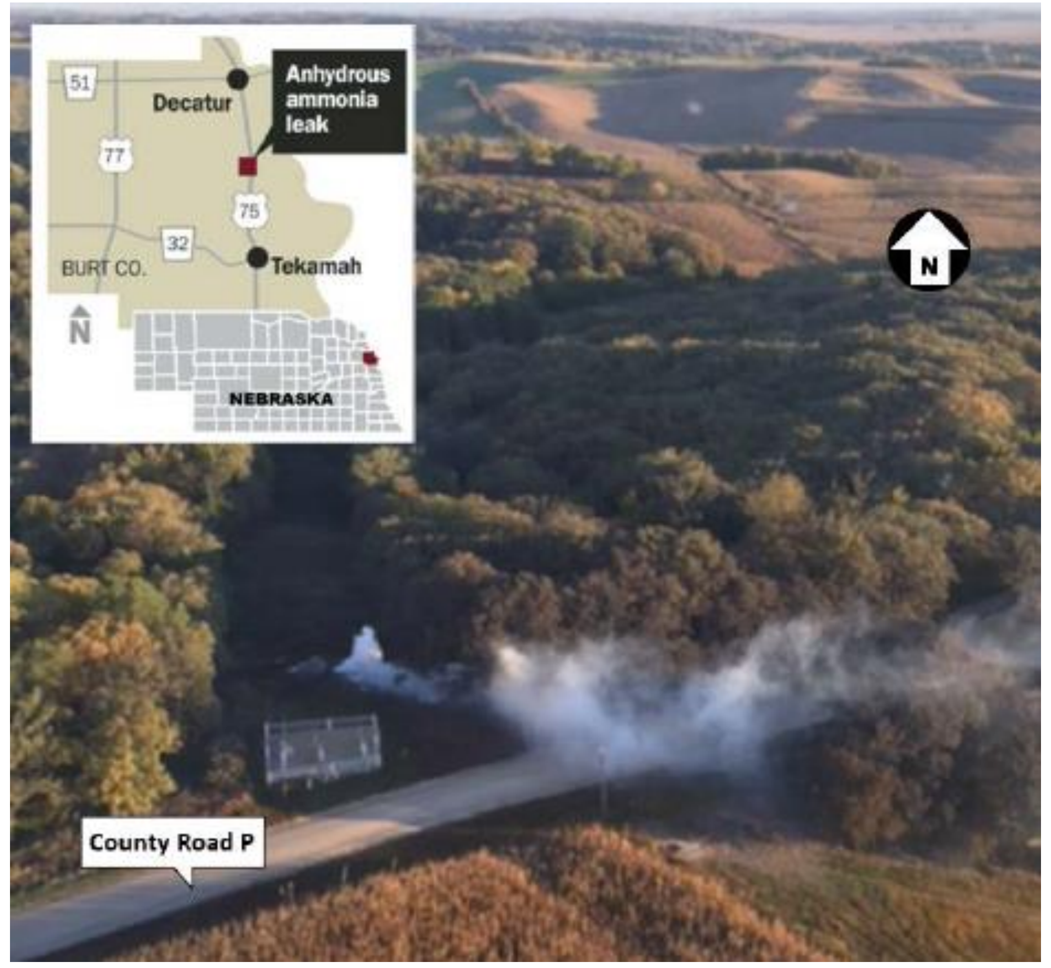
- Transfer hose ruptured between cargo tank truck and storage tank, releasing 3.1 t of ammonia
- Visible cloud drifted from parking lot of the facility across nearby highway
- 14 people suffered minor injuries, 7 people hospitalized, 1 death
- Investigation found that transfer hose was not compatible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

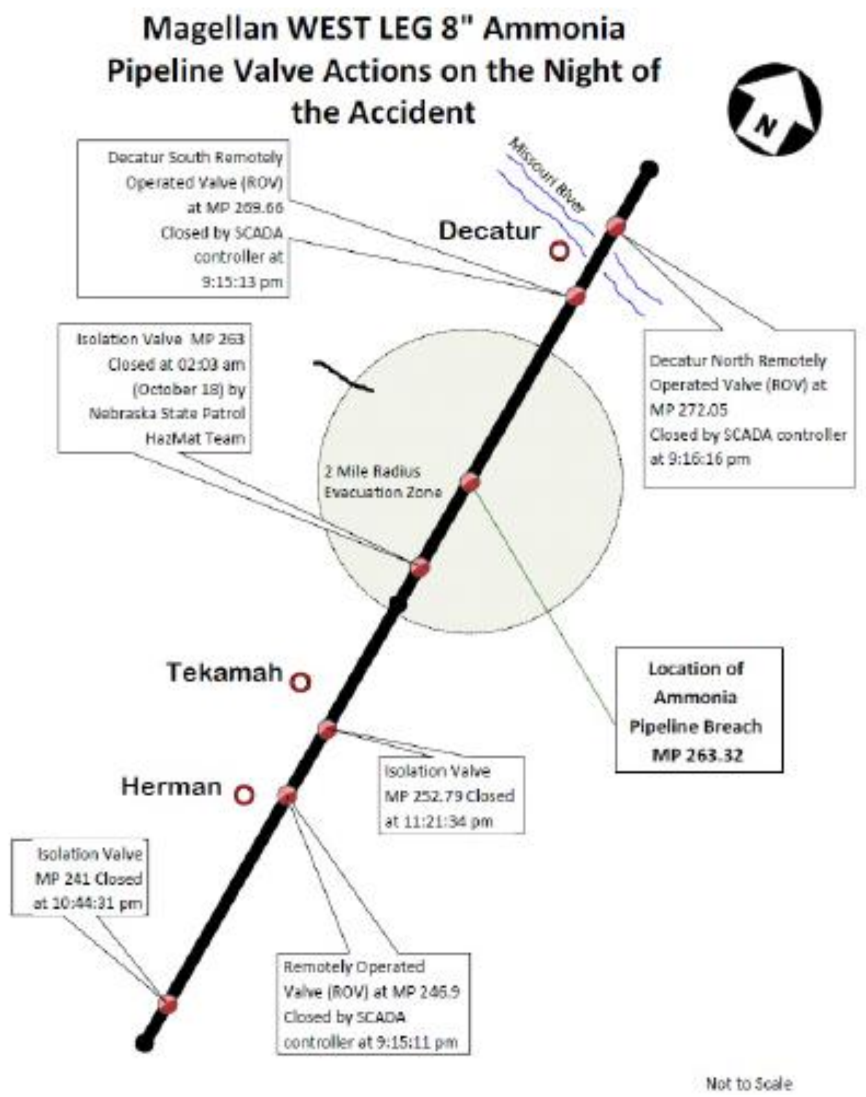


https://www.ntsb.gov/investigations/AccidentReports/Reports/HZM1201S.pdf

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

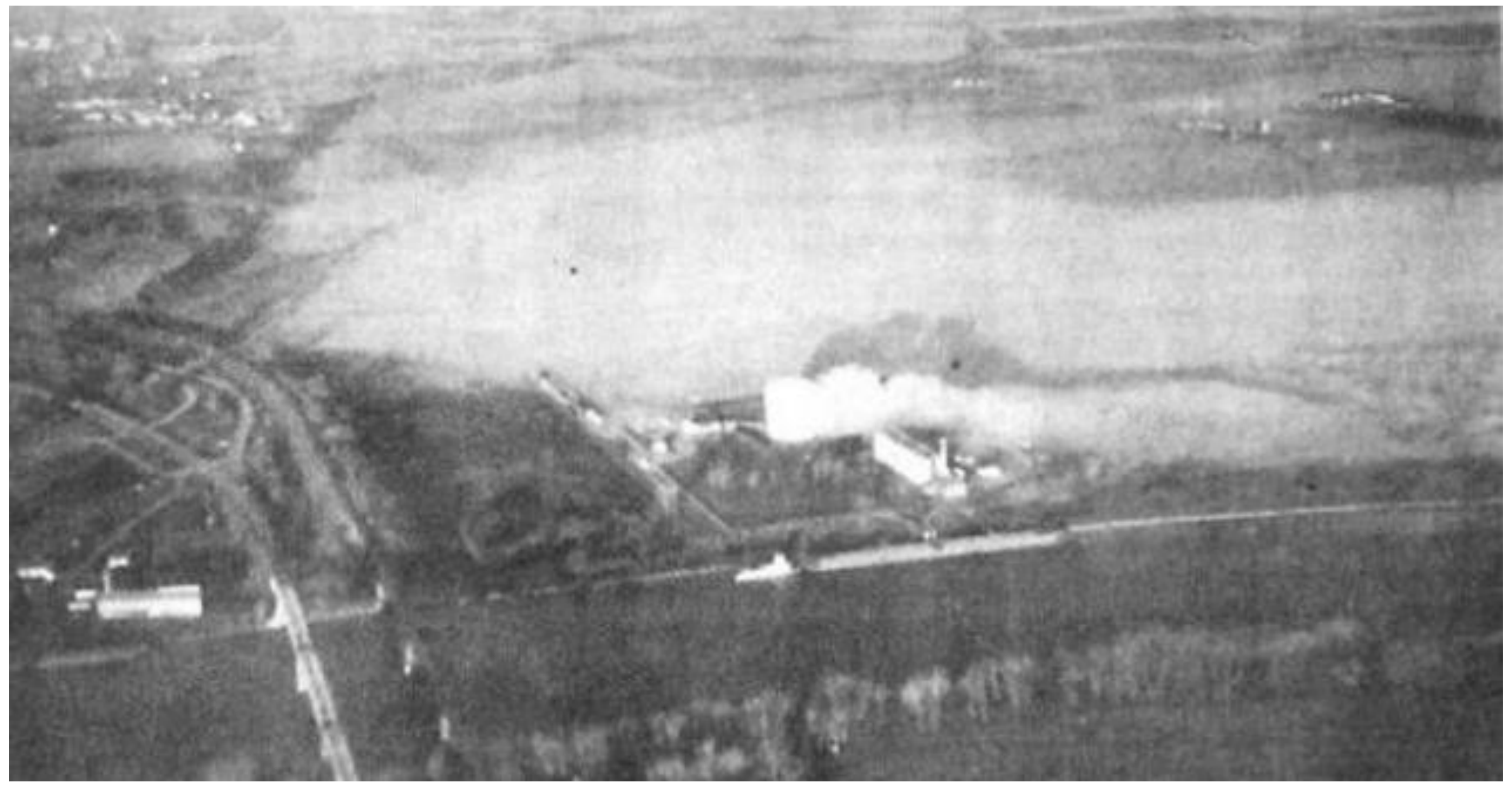
Incidents with temperature-liquefied ammonia

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

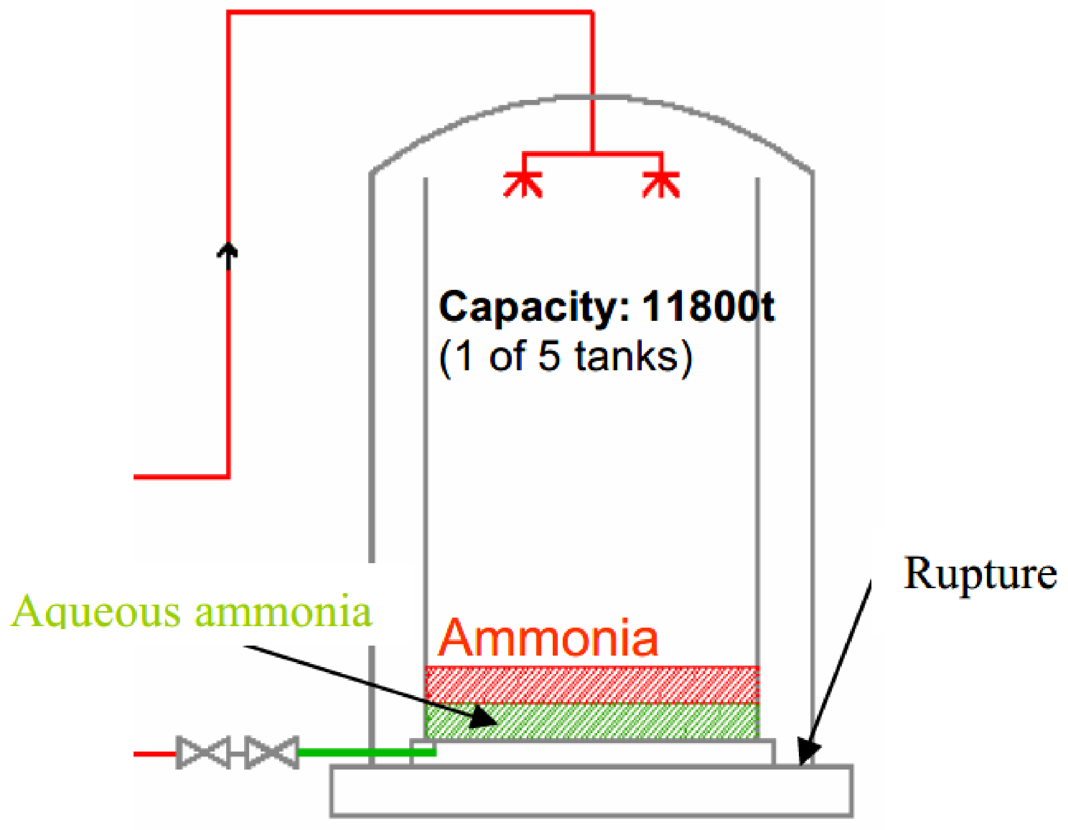


Figure 3 Schematic drawing of the Yara Rostock tank


Figure 4 Yara Rostock tank after the accident.

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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

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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

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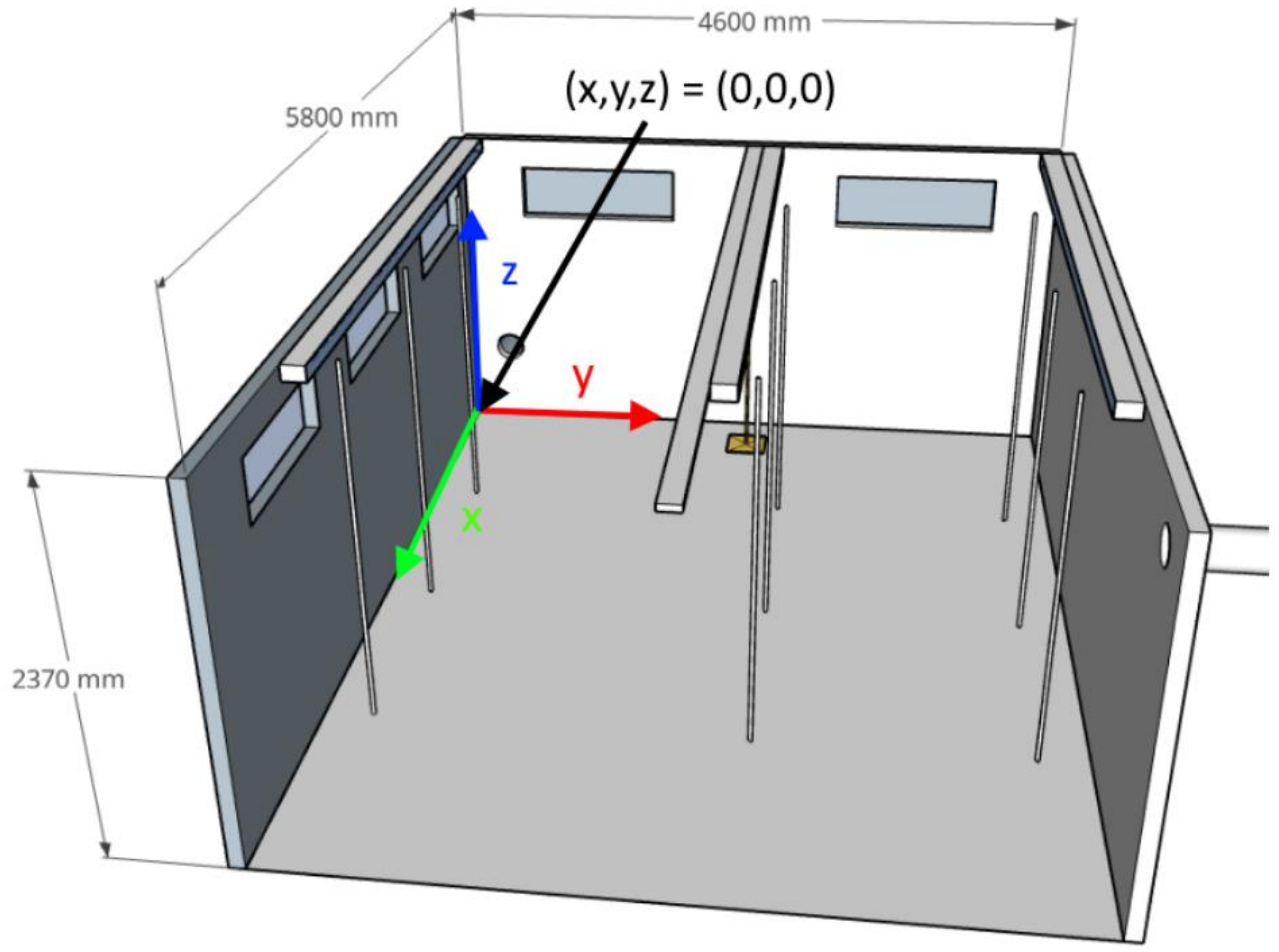
SH_2IFT-2

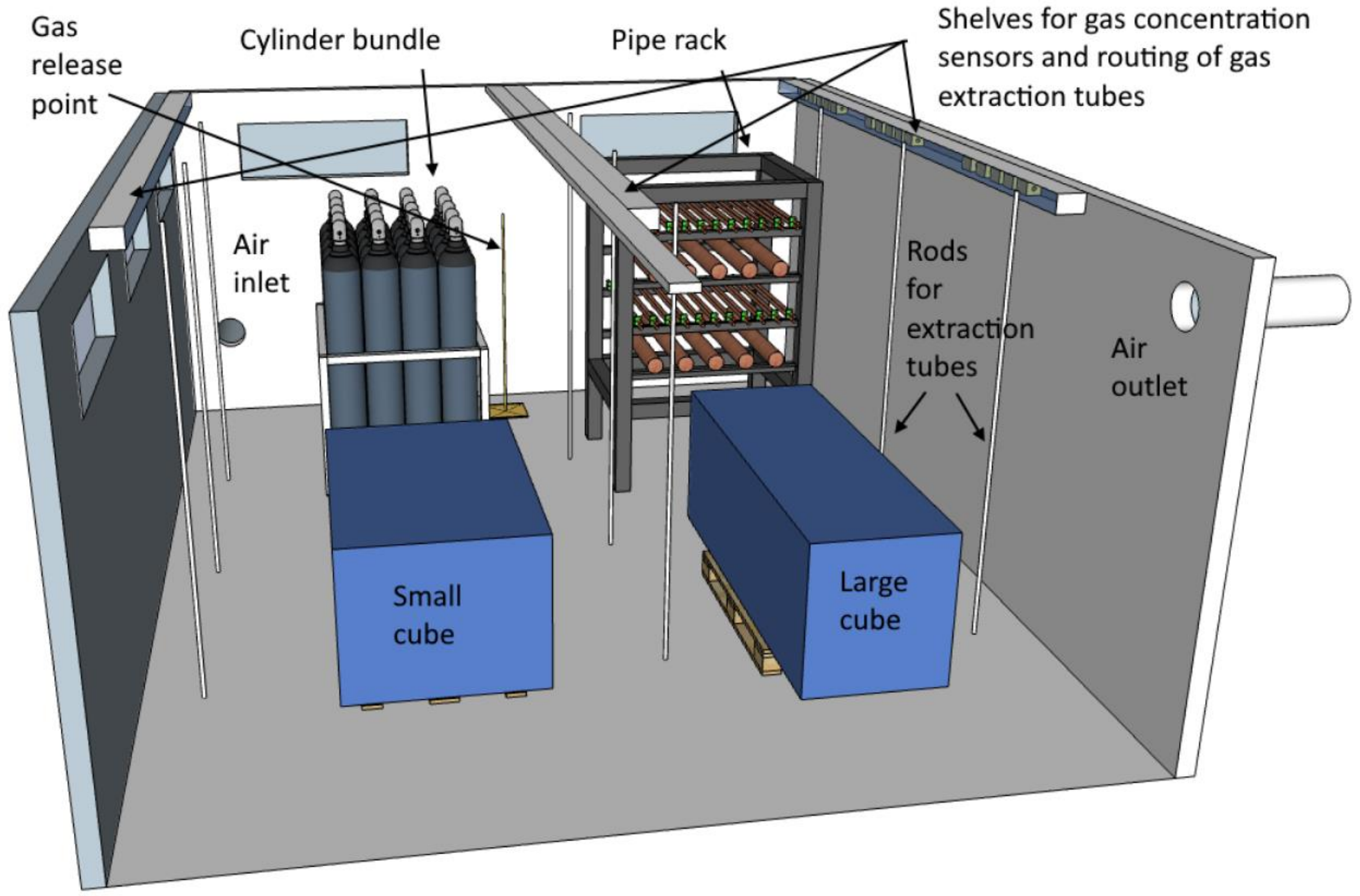
- Safe hydrogen fuel handling and use for efficient implementation 2 SH2IFT II
- Project funded by Research Council of Norway and industry sponsors, 2021 – 2025
- Aim: study explosive and toxic atmospheres of hydrogen and ammonia, respectively, in ventilated enclosed spaces (includes dispersion, fire and explosion tests and modelling)
- Partners: SINTEF, RISE Fire Research, Gexcon, Universities of Southeast Norway, NTNU, Stavanger, Bergen, Demokritos and Karlsruhe Institute of Technology
- Two blind modelling exercises announced in late 2023 on dispersion of hydrogen and ammonia in a confined geometry with active ventilation, with or without congestion
  - Hydrogen results deadline 4 March 2024
  - Ammonia results deadline 11 March 2024
- https://sh2ift-2.com/blind-prediction-study
- Exercises coordinated by Trygve Skjold (University of Bergen) Trygve.Skjold@uib.no
- HSE participated in providing results for the ammonia study using the CFD model Fluent

SH_2IFT-2

- Ammonia gas bottle supply, ventilated room

Description	Nr.	Gas type	Gas flow [g/s]	Ventilation flow [l/s]	Nozzel diameter [mm]	Release direction	Runtime [mins]	Congestion	Release type
Scenario 1	**1**	NH3	2.6	525	18	+Z	5	empty	jet
Repeat #1	2	NH3	2.6	525	18	+Z	5	empty	jet
Scenario 2	**3**	NH3	2.6	525	18	+Z	5	congested	jet
Repeat #1	4	NH3	2.6	525	18	+Z	5	congested	jet
Scenario 3	**5**	NH3	2.6	263	18	+Z	5	congested	jet
Repeat #1	6	NH3	2.6	263	18	+Z	5	congested	jet
Scenario 4	**7**	NH3	2.6	263	18	+X	5	congested	jet
Repeat #1	8	NH3	2.6	263	18	+X	5	congested	jet

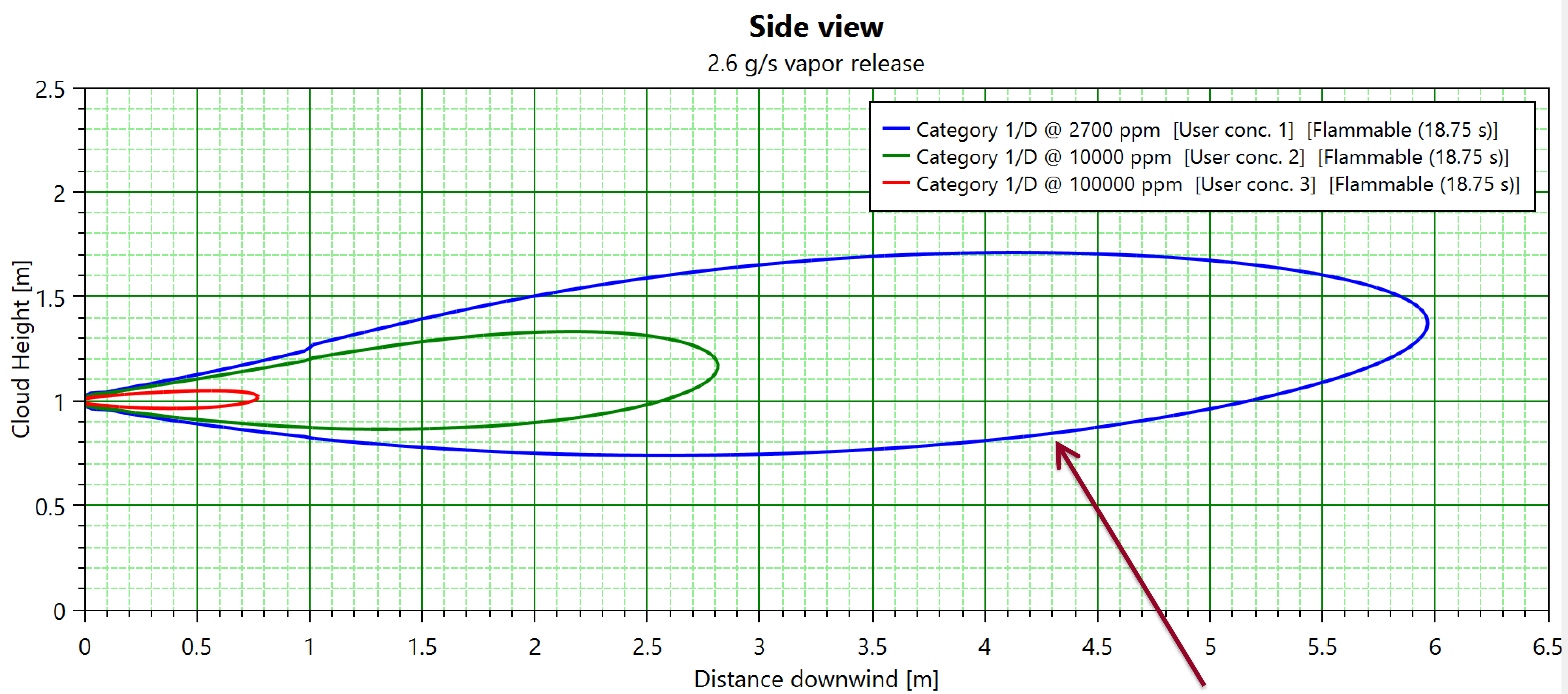




SH_2IFT-2

- Quick scoping calculations using Phast to understand unconfined plume size
  - Modelled with user-defined source as horizontal ammonia release 2.6 g/s at 0°C
  - Release velocity is 13 m/s through 18 mm (0.7 inch) diameter orifice
  - Low wind speed of 1 m/s (coflowing) with release height of 1 m

Audit Number	214
Equipment	Pressure vessel
Material	AMMONIA
Material to track	AMMONIA
Offset from Centerline	0 m
Program	Phast 8.9
Scenario	2.6 g/s vapor release
Spacing parameter for the grid in the x dimension	0.01
View Time	299.999 s
Weather	Category 1/D
Workspace	SH2IFT ammonia free jet

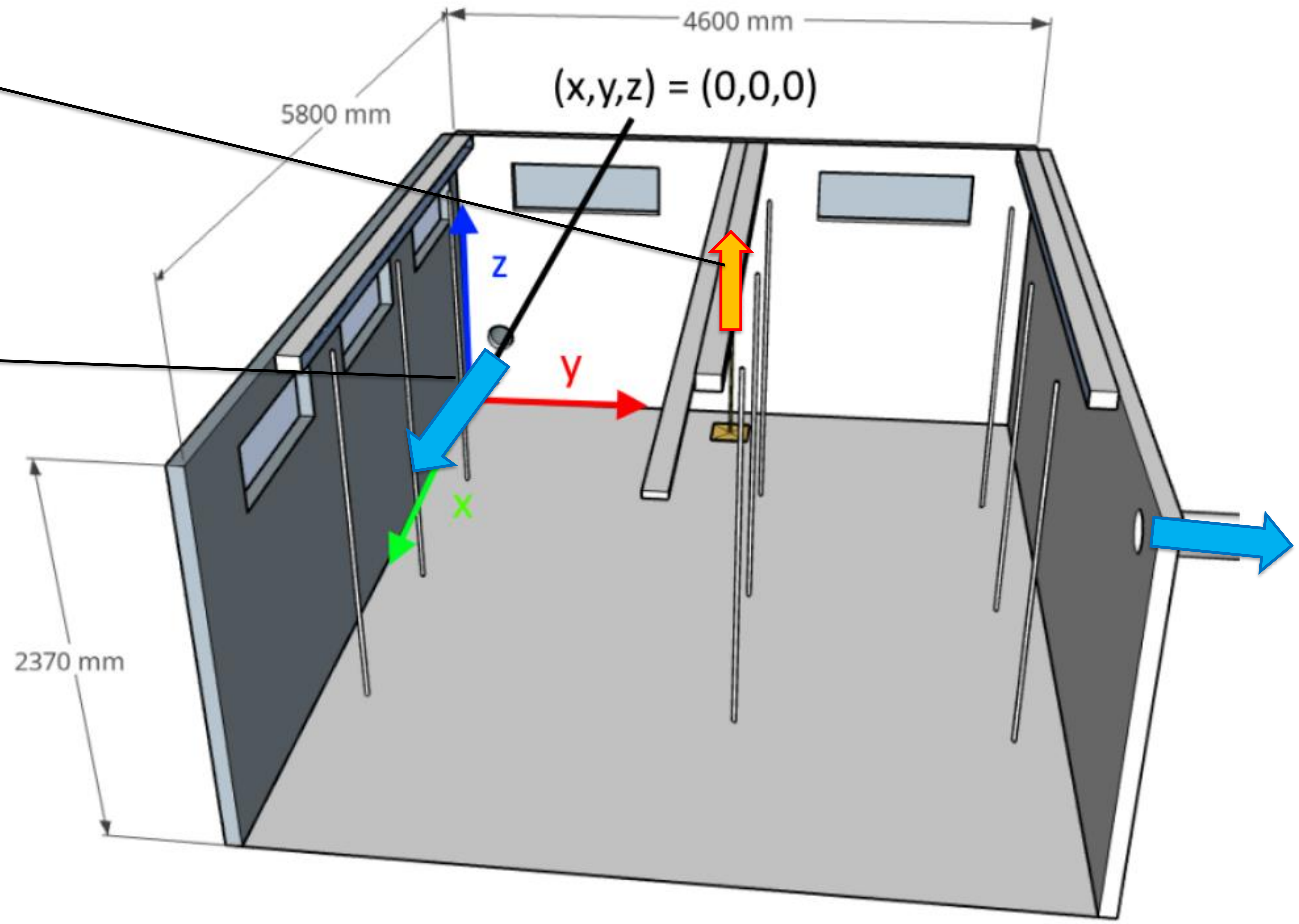


AEGL-3 (10 minute exposure) concentration of 2,700 ppm

SH_2IFT-2

Ammonia source	2.6 g/s
Density at 0°C	0.77 kg/m^3
Velocity	13.2 m/s
Volumetric flow rate	0.003 m^3/s

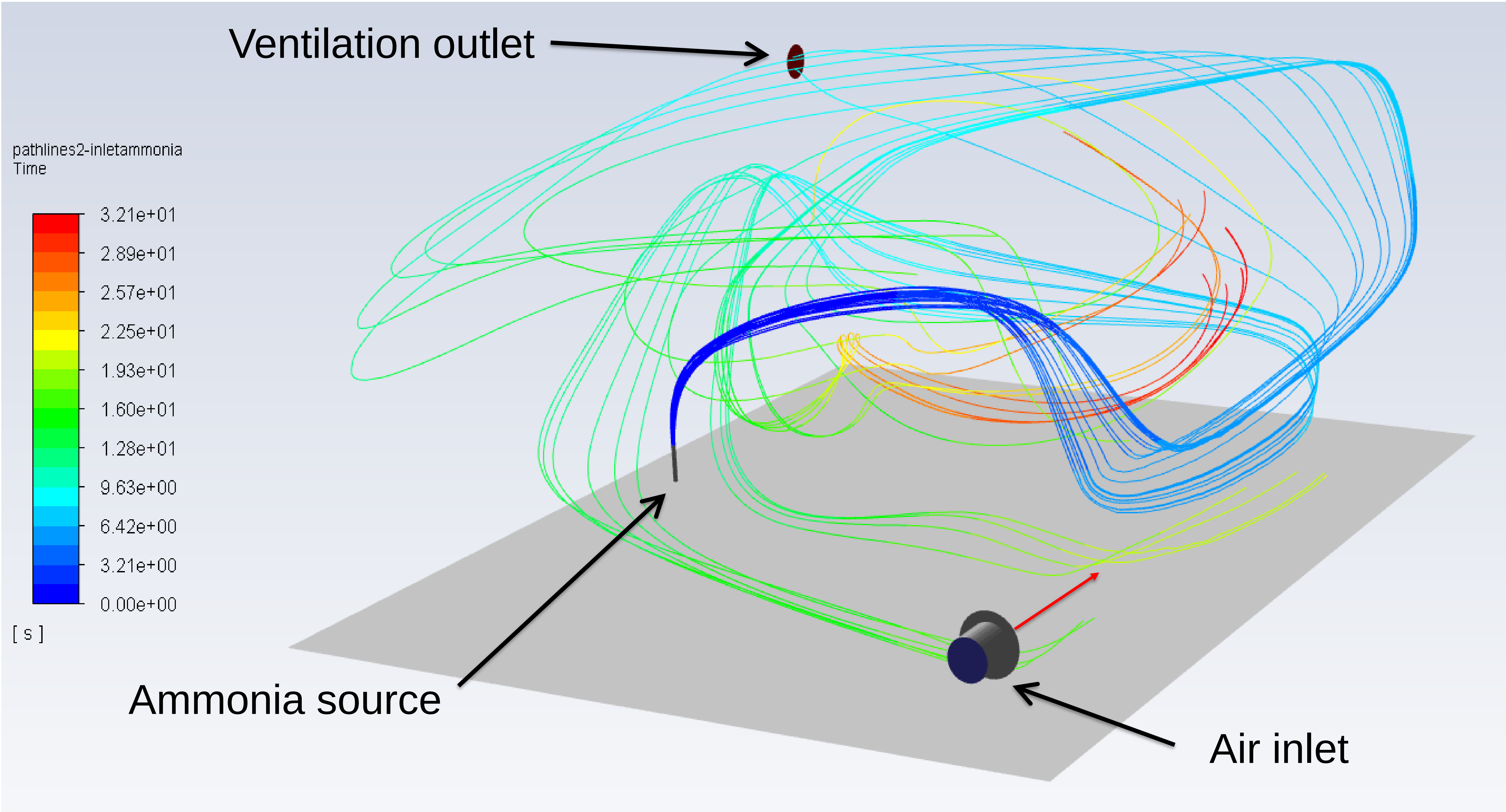
Ventilation rate	30 ach	15 ach
Volumetric flow rate	0.525 m^3/s	0.263 m^3/s
Velocity	14.5 m/s	7.2 m/s
Mass flow rate	679 g/s	339 g/s
Outlet concentration assuming full mixing	6,400 ppmv	12,700 ppmv



Flow rate of air is around 100 to 200 times that of ammonia

SH_2IFT-2

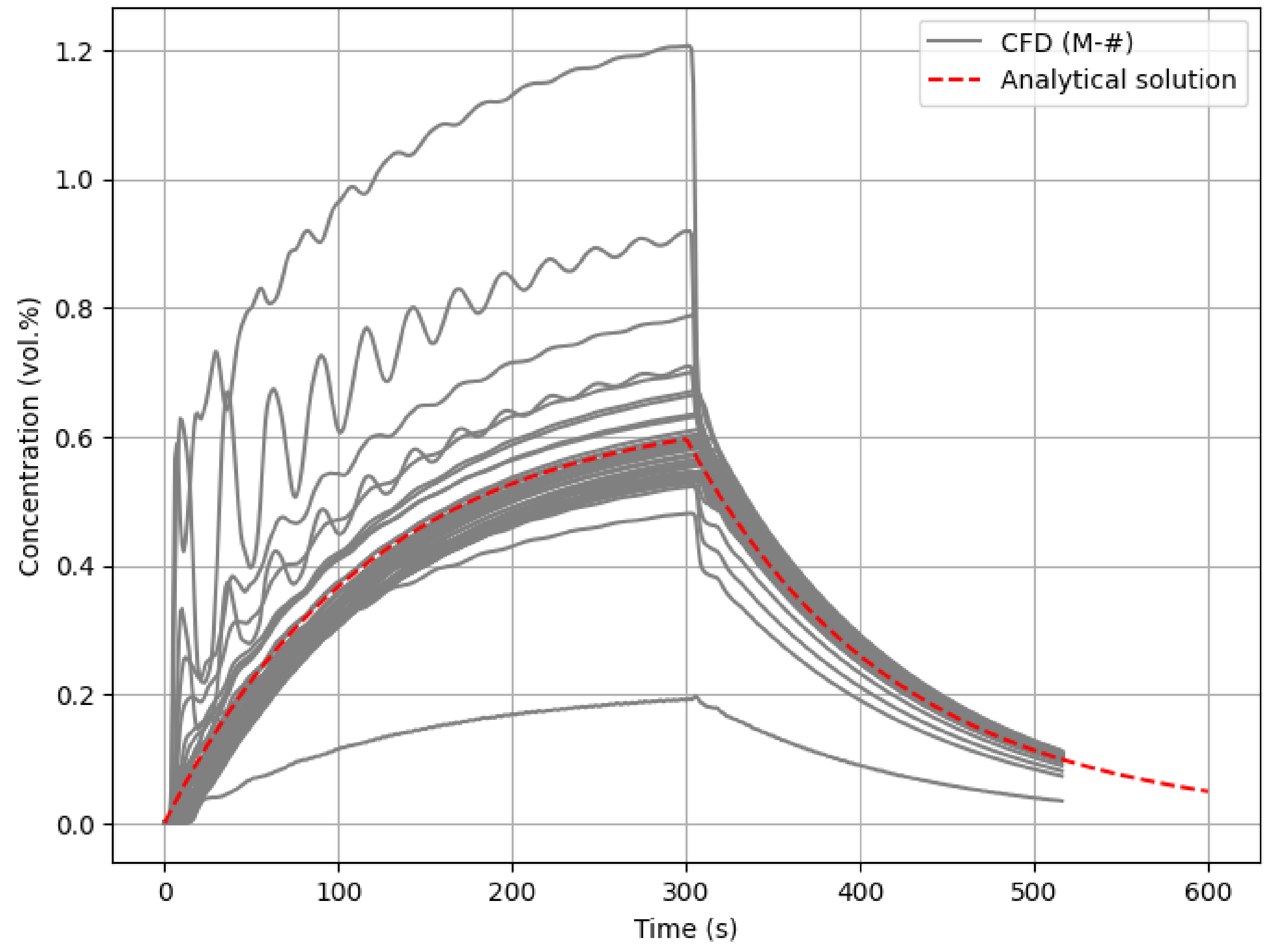
- Streamlines plotted from the ammonia source show a tracer's motion through the domain under the influence of the flow field
- Tracer travels upwards, then towards the air inlet, where it is carried along towards the back wall
- Large-scale swirling motions in the room



SH_2IFT-2

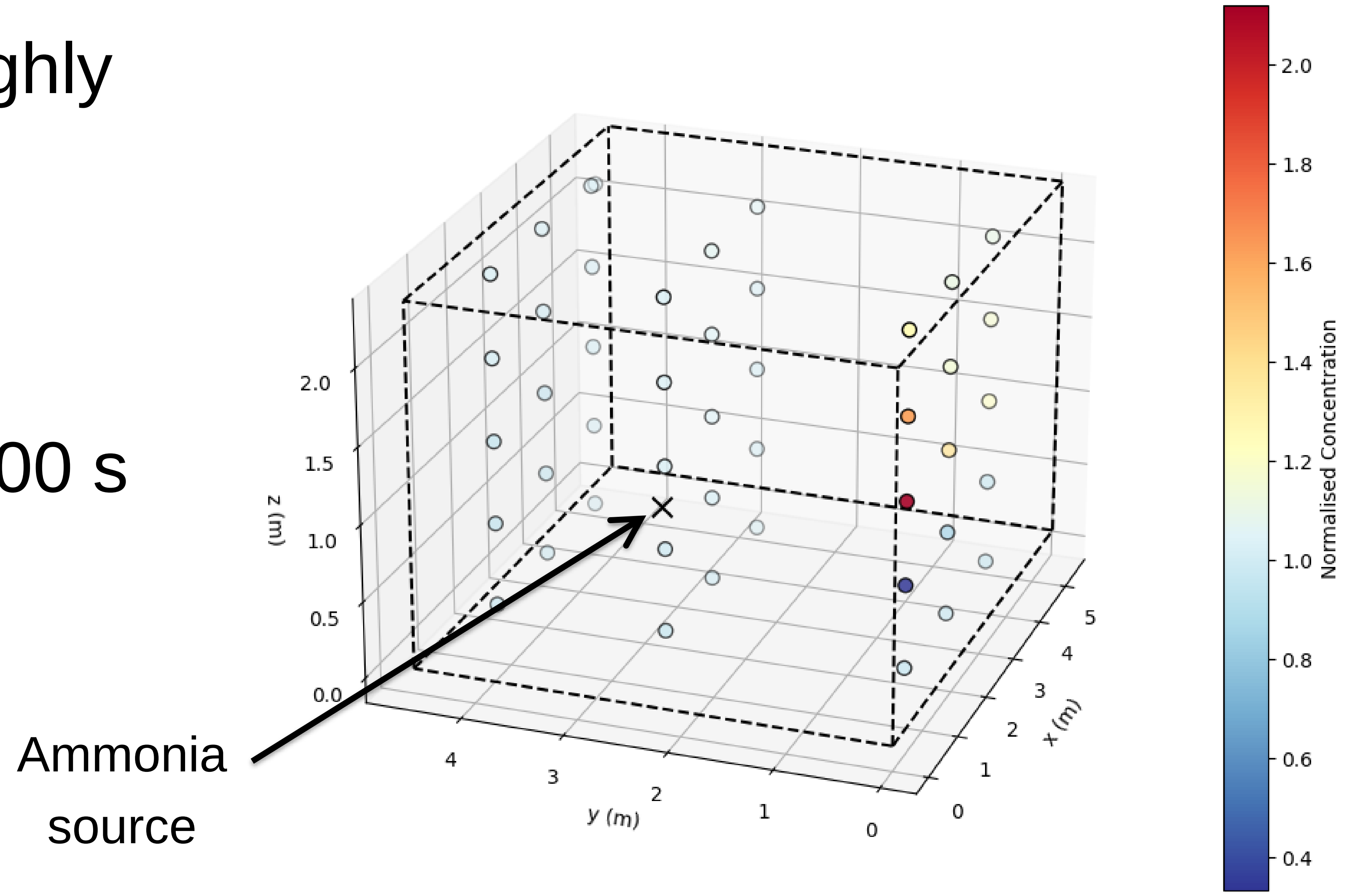
Top right:

- 46 sensors used to record concentration
- Build-up of concentration for the injection period (0 to 300 s) followed by decay
- Peak of 1.2 vol % (or 12,000 ppm) is reached, but room average is closer to 6,000 ppm
- Analytical solution is a fair representation of the general trend
- Predicted maximum concentration in the room is roughly double the room-averaged value



Bottom right:

- Plot of normalised concentrations at the sensors at 300 s (concentrations divided by the outlet concentration)



SH$_2$IFT-2

- Contours of ammonia concentration at 300 s at each sensor height (see table)
- Additional vertical plane shown through the first measurement rake
- Ammonia inlet protrudes 16 mm above the middle contour plane
- Ammonia plume is deflected by air flow towards the highlighted measurement points
- Maximum concentrations are predicted at M-19 and M-28, not at the highest sensors, despite the ammonia plume being buoyant

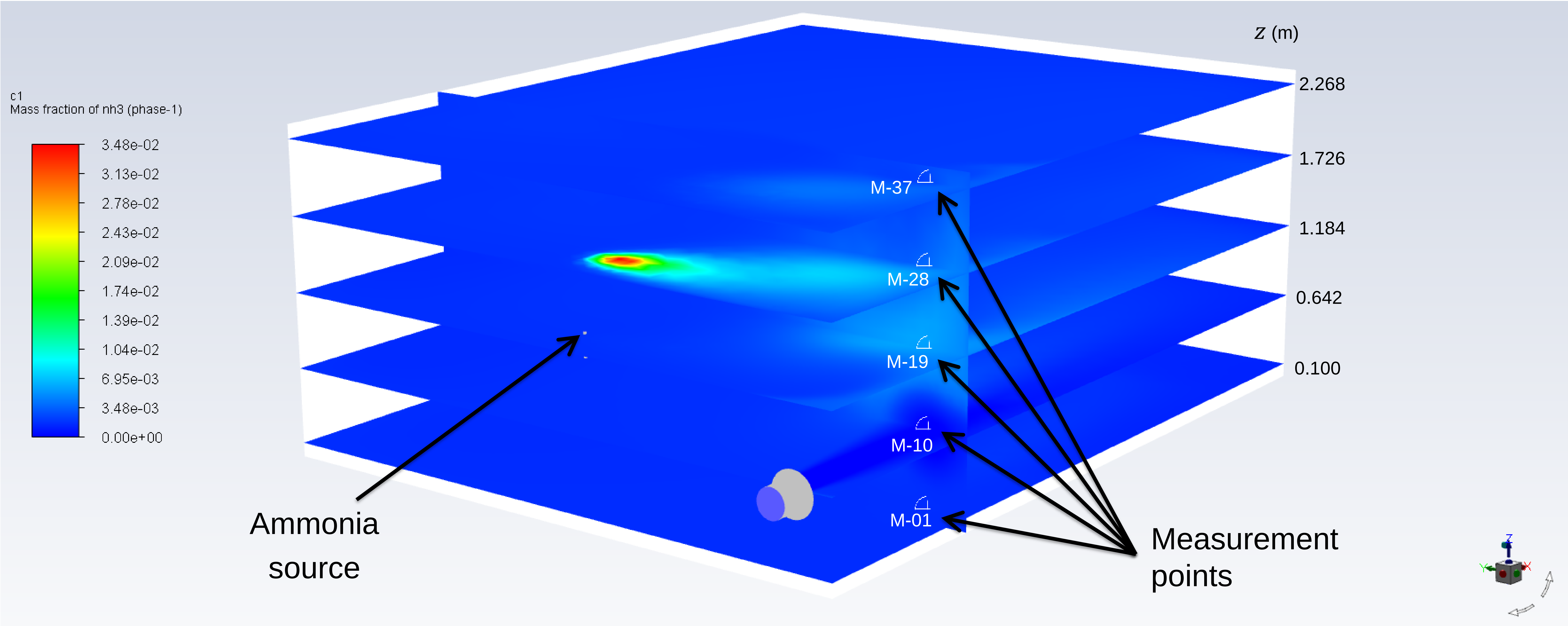
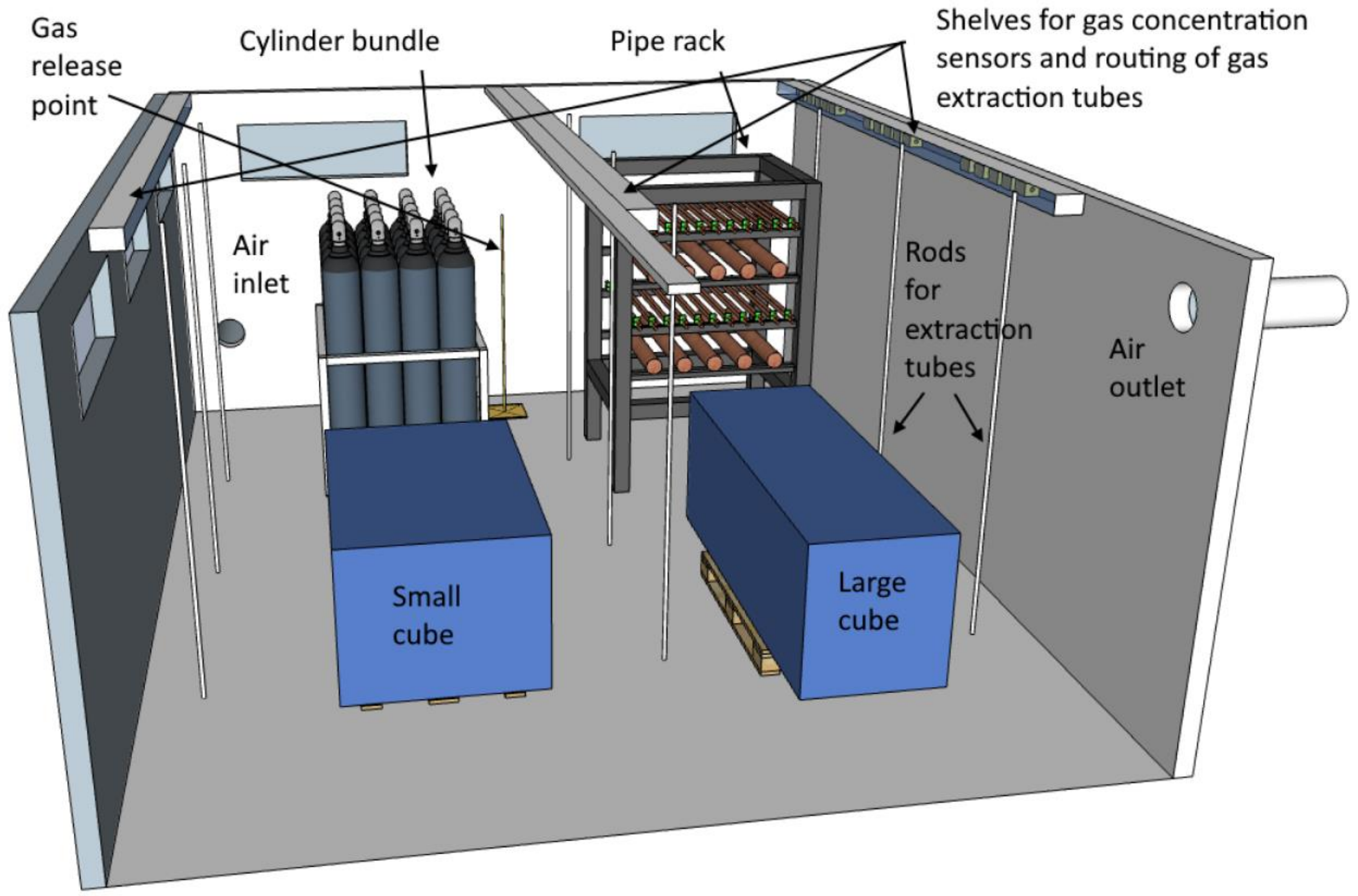


Table 1: Positions of the measuring points inside the enclosure.

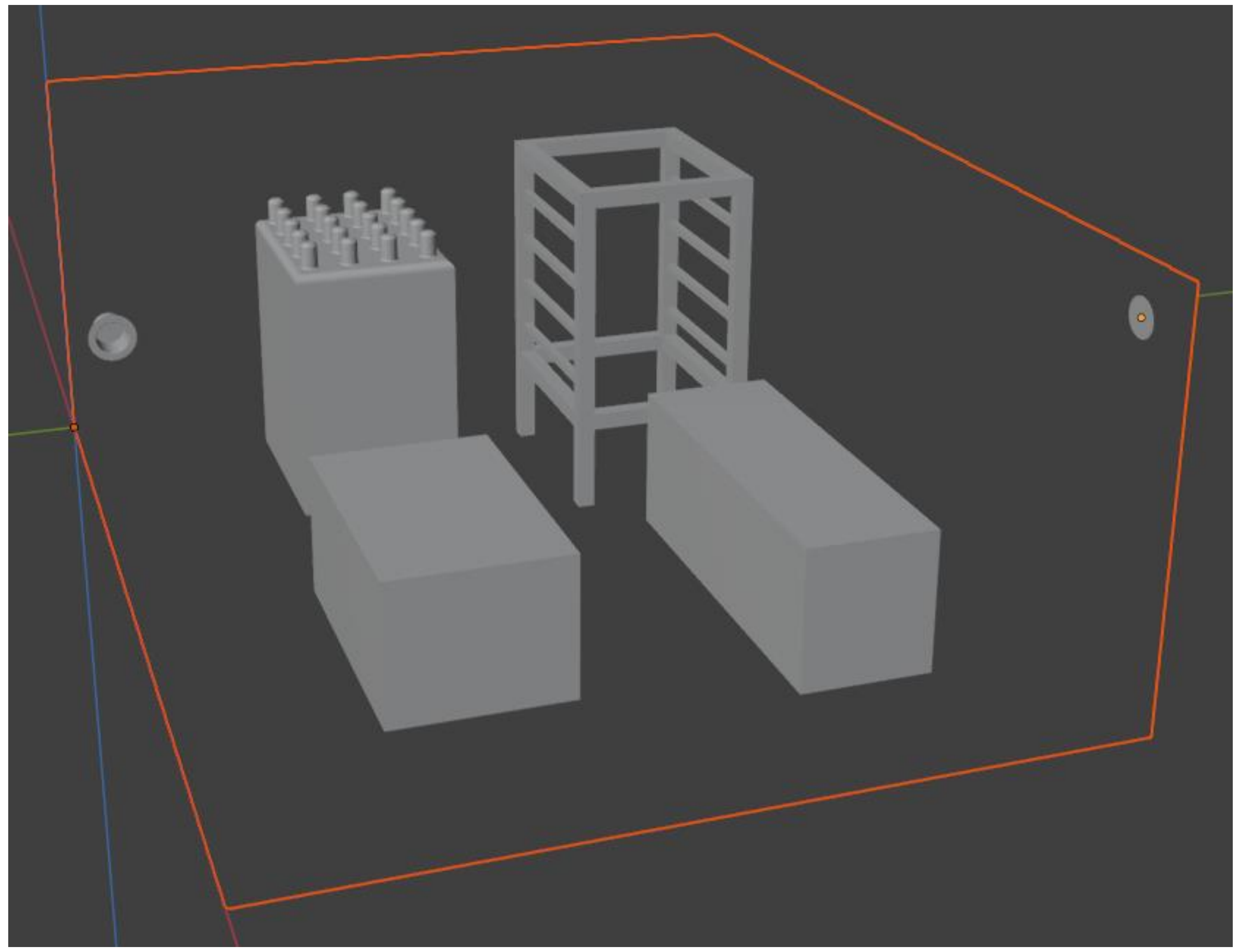
M#	x-coordinate	y-coordinate	z-coordinate
M-01	1.450	0.300	0.100
M-02	2.900	0.300	0.100
M-03	4.350	0.300	0.100
M-04	1.450	2.612	0.100
M-05	2.900	2.612	0.100
M-06	4.350	2.612	0.100
M-07	1.450	4.291	0.100
M-08	2.900	4.291	0.100
M-09	4.350	4.291	0.100
M-10	1.450	0.300	0.642
M-11	2.900	0.300	0.642
M-12	4.350	0.300	0.642
M-13	1.450	2.612	0.642
M-14	2.900	2.612	0.642
M-15	4.350	2.612	0.642
M-16	1.450	4.291	0.642
M-17	2.900	4.291	0.642
M-18	4.350	4.291	0.642
M-19	1.450	0.300	1.184
M-20	2.900	0.300	1.184
M-21	4.350	0.300	1.184
M-22	1.450	2.612	1.184
M-23	2.900	2.612	1.184
M-24	4.350	2.612	1.184
M-25	1.450	4.291	1.184
M-26	2.900	4.291	1.184
M-27	4.350	4.291	1.184
M-28	1.450	0.300	1.726
M-29	2.900	0.300	1.726
M-30	4.350	0.300	1.726
M-31	1.450	2.612	1.726
M-32	2.900	2.612	1.726
M-33	4.350	2.612	1.726
M-34	1.450	4.291	1.726
M-35	2.900	4.291	1.726
M-36	4.350	4.291	1.726
M-37	1.450	0.300	2.268
M-38	2.900	0.300	2.268
M-39	4.350	0.300	2.268
M-40	1.450	2.612	2.268
M-41	2.900	2.612	2.268
M-42	4.350	2.612	2.268
M-43	1.450	4.291	2.268
M-44	2.900	4.291	2.268
M-45	4.350	4.291	2.268
M-46	5.378	4.610	2.058

SH_2IFT-2

- Next/possible steps:
  - Consider the geometry with obstructions
  - Sensitivity analysis on ammonia temperature



Experimental geometry



Computational CAD (simplified)

PROTECTING PEOPLE AND PLACES

HSE

Contents

Ammonia as a future shipping fuel

Department for Transport | Clean Maritime Plan | maritime 2050 NAVIGATING THE FUTURE

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.

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

July 2019

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

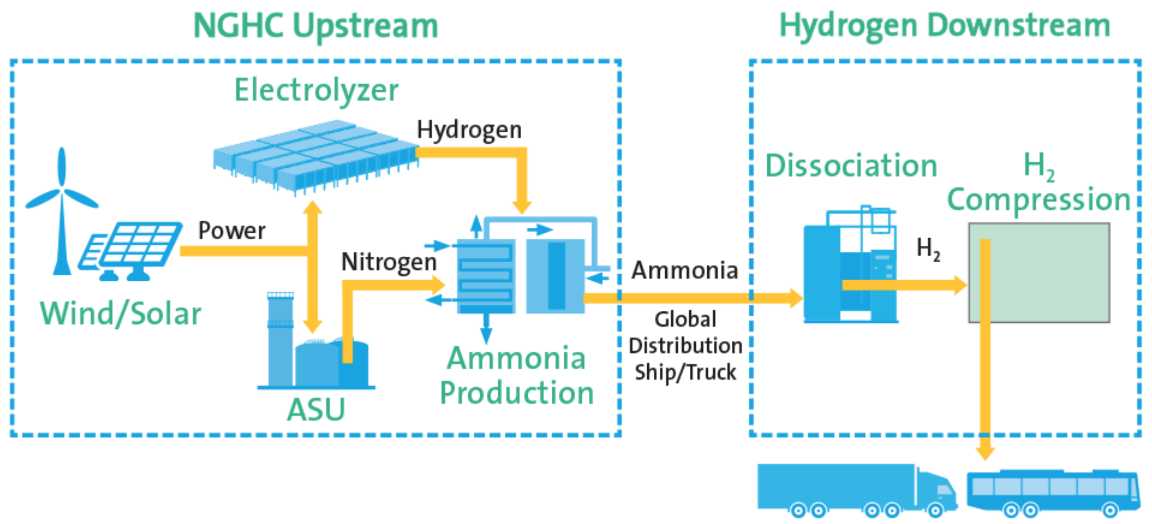
Green / blue ammonia production projects

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

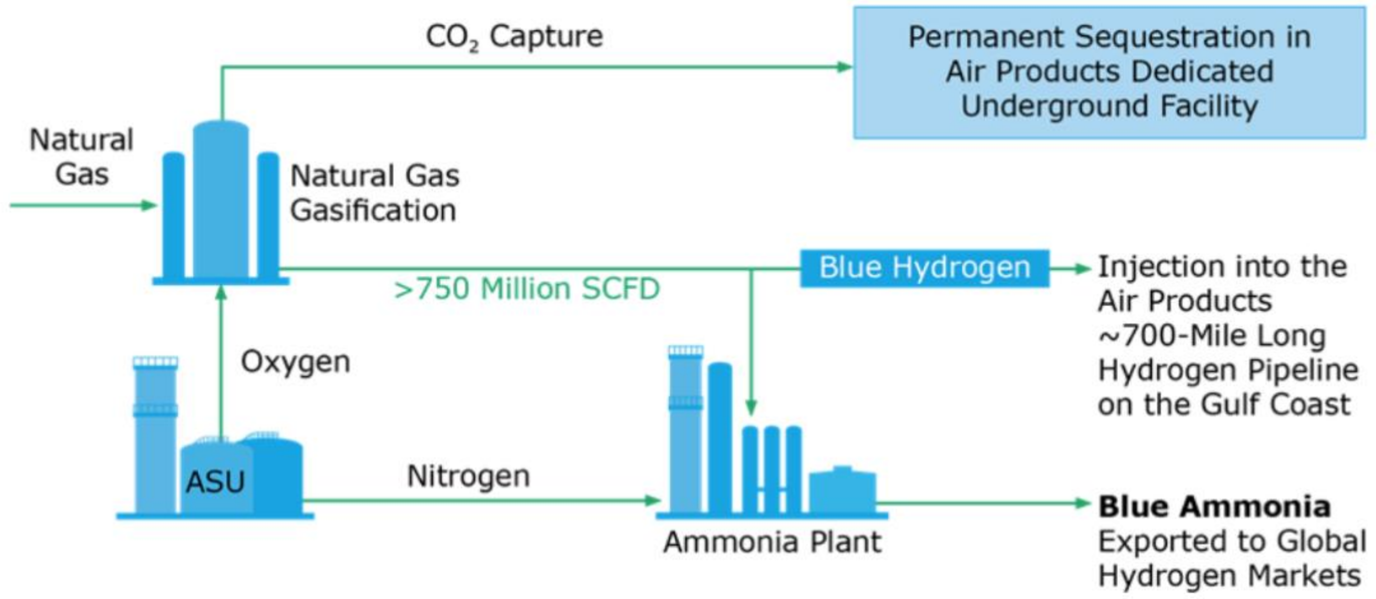


https://www.airproducts.com/news-center

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

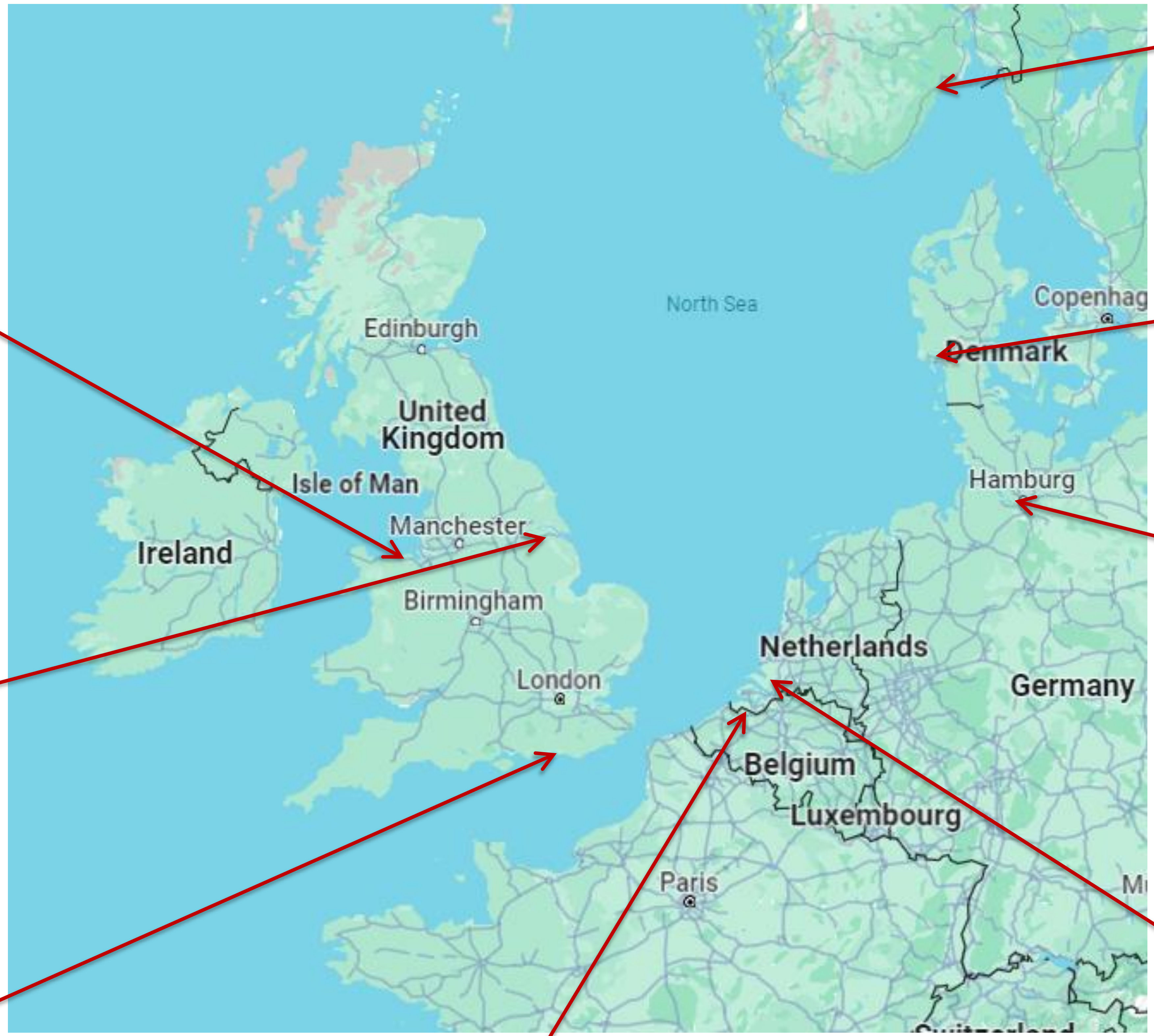
Barents Blue (Norway)

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 shipping terminals



© Google Maps

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/

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

Immingham
https://immighamget.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/

ARISE

ARISE
Ammonia Response In Sea Emergencies

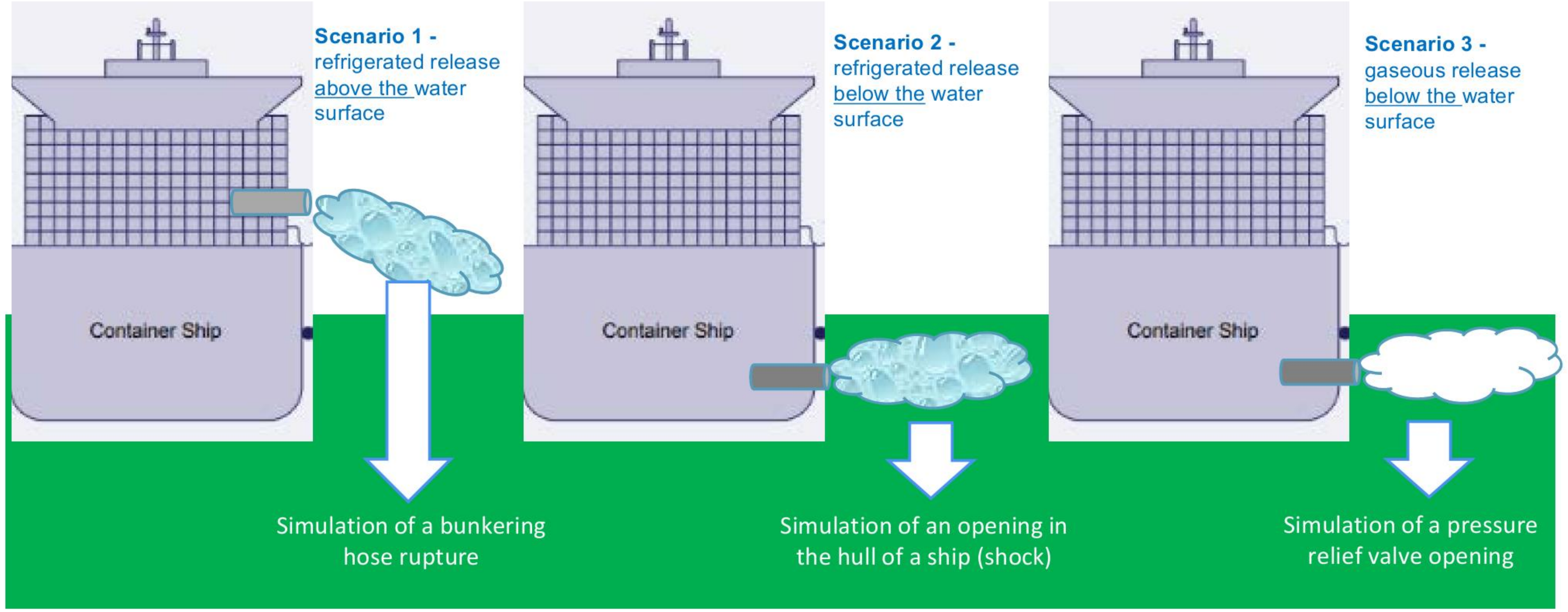
JOINT INDUSTRIAL PARTNERSHIP FOR CONTROLED AMMONIA RELEASES AT SEA

PROJECT PRESENTATION FOR SPONSORS

MAY 2ND, 2024 (10:00 – 13:00 CEST)

Cedre | INERIS | Yara Clean Ammonia | natural sciences .be | ONERA | HSE Health and Safety Executive | INERIS Développement | IMT Mines Alès | SINTEF

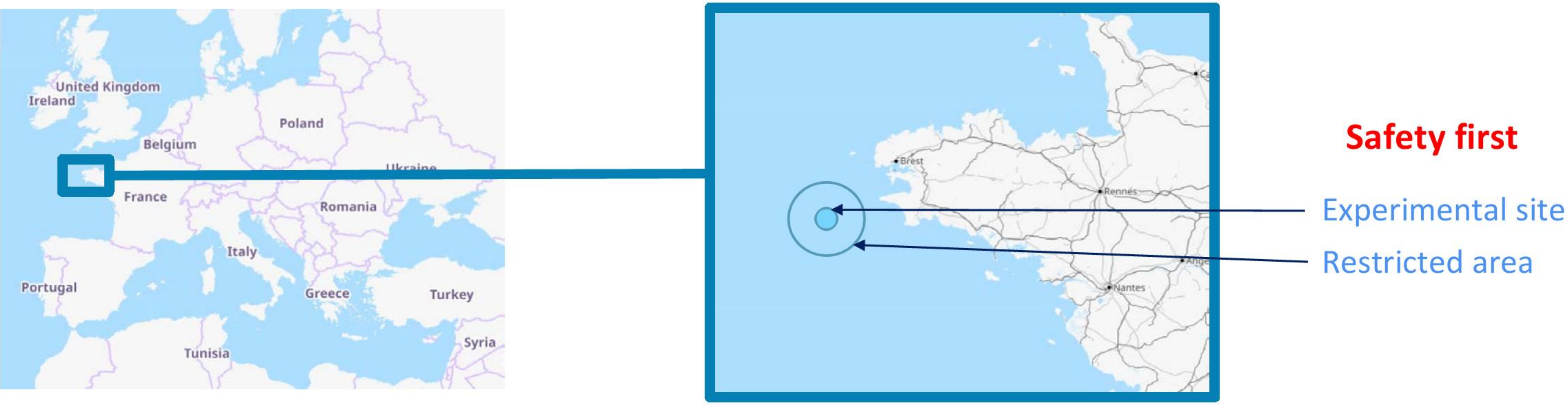
ARISE: Objectives



- **To acquire the needed dataset** to upgrade consequence modelling tools capability and reliability (both for air and water dispersion).
- To **test current and innovative detection and measurement technologies** in a sea environment (with involvement coast guards and governmental agencies).
- To identify potential response **techniques and strategies**.
- To enable accurate **environmental impact assessment** (impact on sea life and recovery time and recommendations for response).

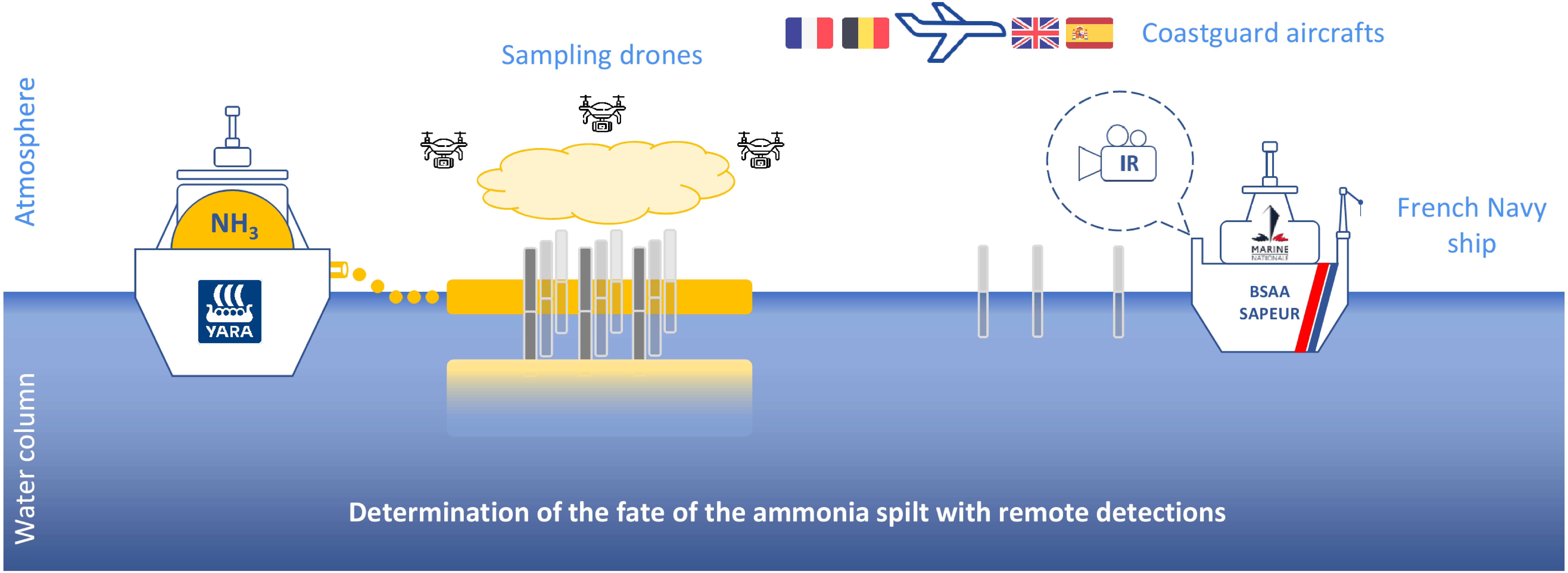
ARISE: Experiments

- Sea tests will be carried out 100 km from the coast in the Atlantic Ocean



- WP6a : sea pilot tests – **Sept 2024**
  - ✓ To test our instrumented buoys,
  - ✓ To simulate Scenario 3 (= pressure relief valve opening)
  - ✓ To test and validate the large-scale test protocol
- WP6b : large-scale tests – **June 2025**
  - ✓ To simulate Scenario 1 (bunkering hose rupture)
  - ✓ & Scenario 2 (opening of the hull)

ARISE: Experiments



ARISE: Experiments

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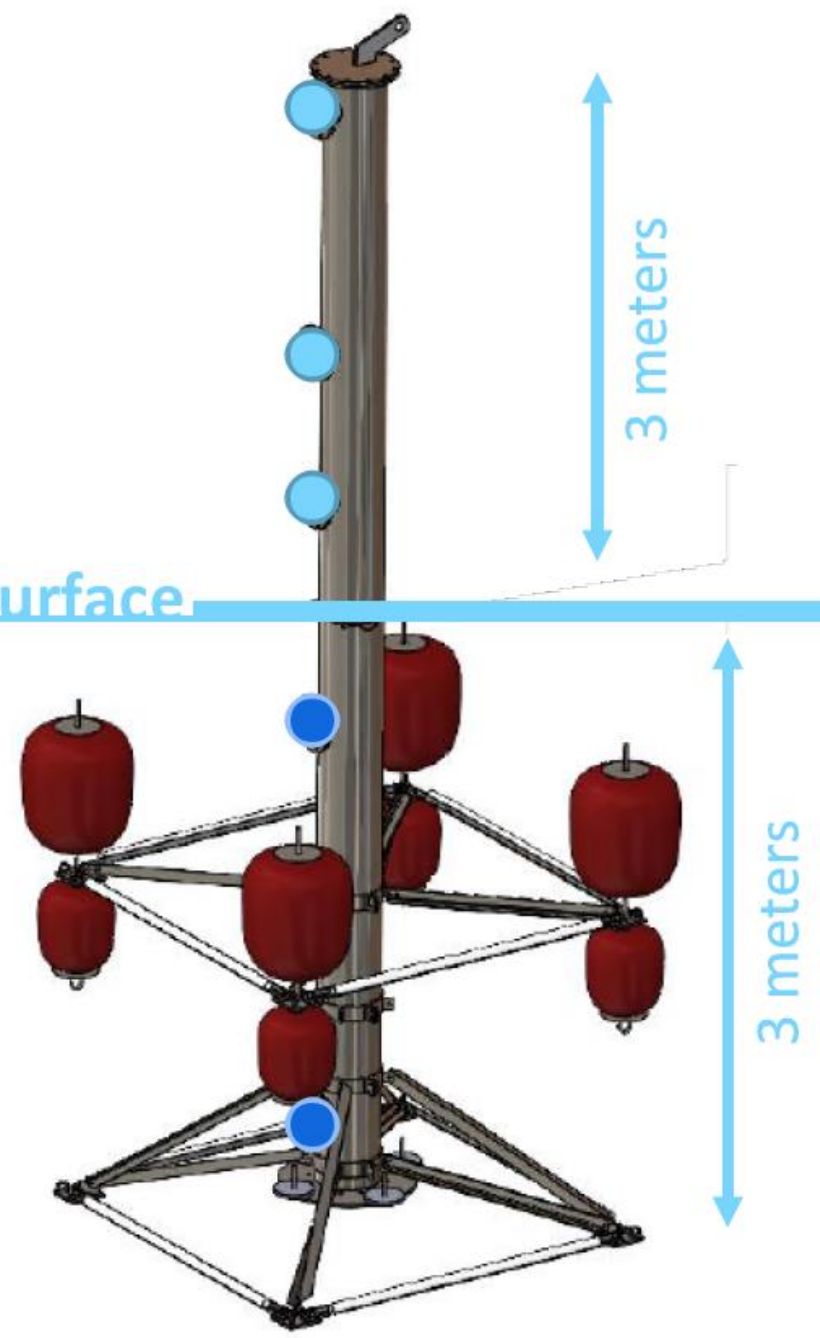
A network of 10 buoys equipped with state-of-the-art technology for the near field

3 measurement heights

Use of industrial technology to monitor the ammonia concentration

2 measurement depths

Use of oceanographic sensors to follow seawater parameters



Air detection

Electrochemical detection
(low concentration)

Catalytic detection
(high concentration)

Water detection

Sea water parameters monitoring:

- Conductivity
- Temperature
- Dissolved oxygen

Ammonia concentration via ultrasonic velocity measurement

ARISE: Experiments

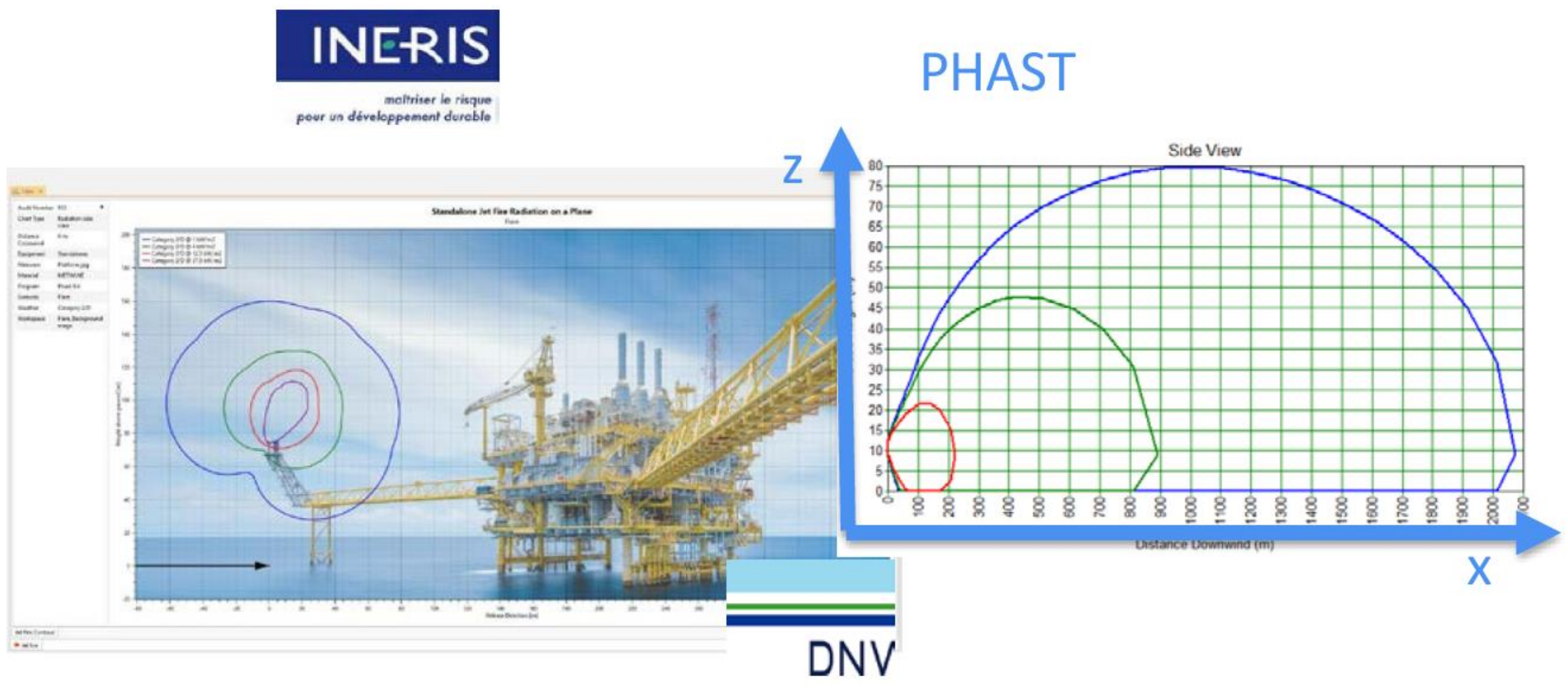
Sensors qualification

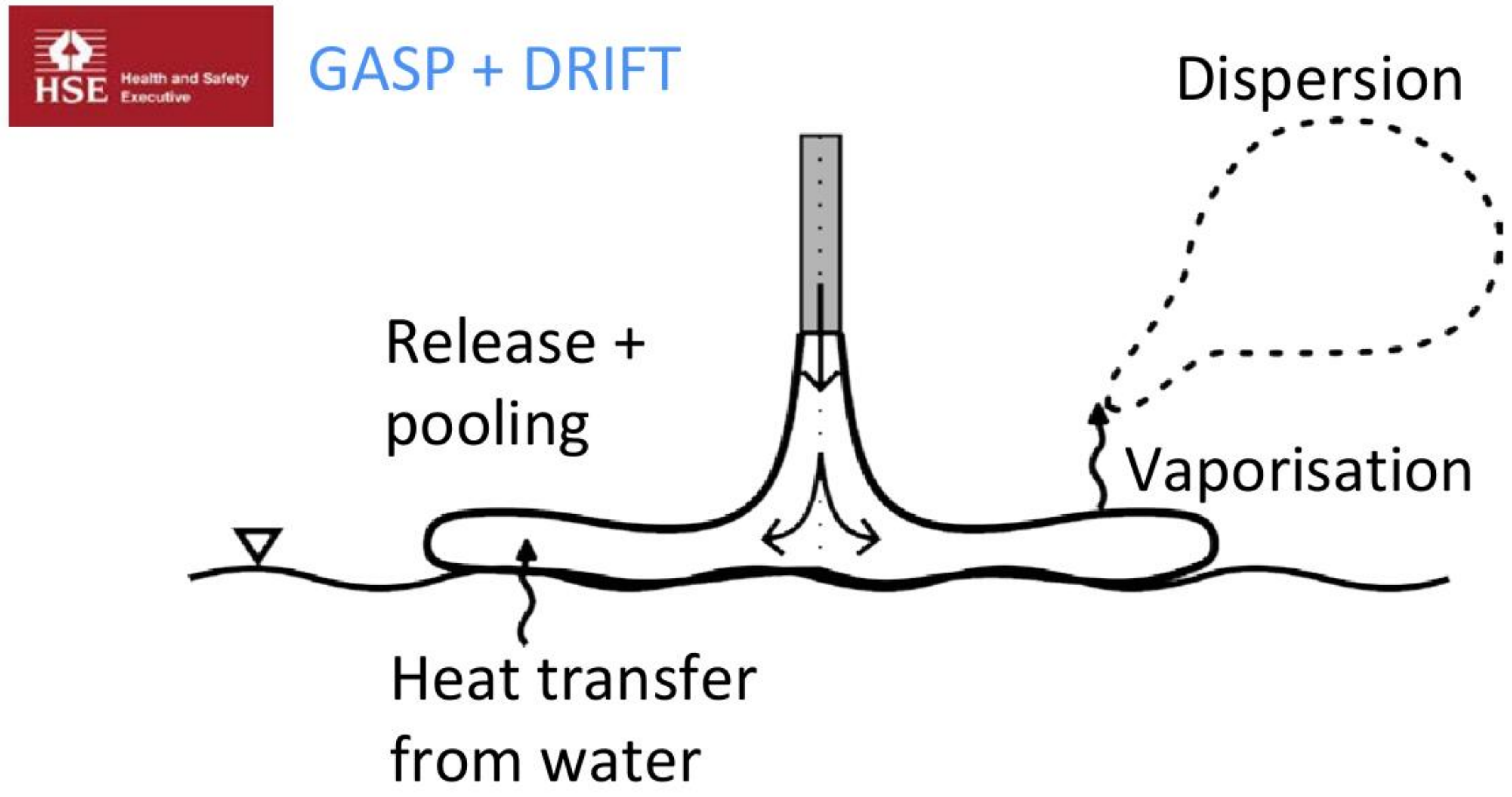
At Ineris for air detection sensors

At Cedre for water detection sensors

Small scale pilot tests

ARISE: Modelling





ARISE: Status

- Total cost €3.5m, sponsorship promised to date €2.1m
- Further sponsors sought
- Contacts: Olivier.Salvi@ineris-developpement.com and Laurent.Ruhlmann@yara.com

PLATINUM
- YARA Clean Ammonia (500 k€)
- EQUINOR (400 k€)
- Lloyd's Register (400 k€)

GOLD
- ITOCHU (200k€)
- ClassNK (200k€)
- Total Energies (200k€)

SILVER
- Hapag Lloyd (100k€)

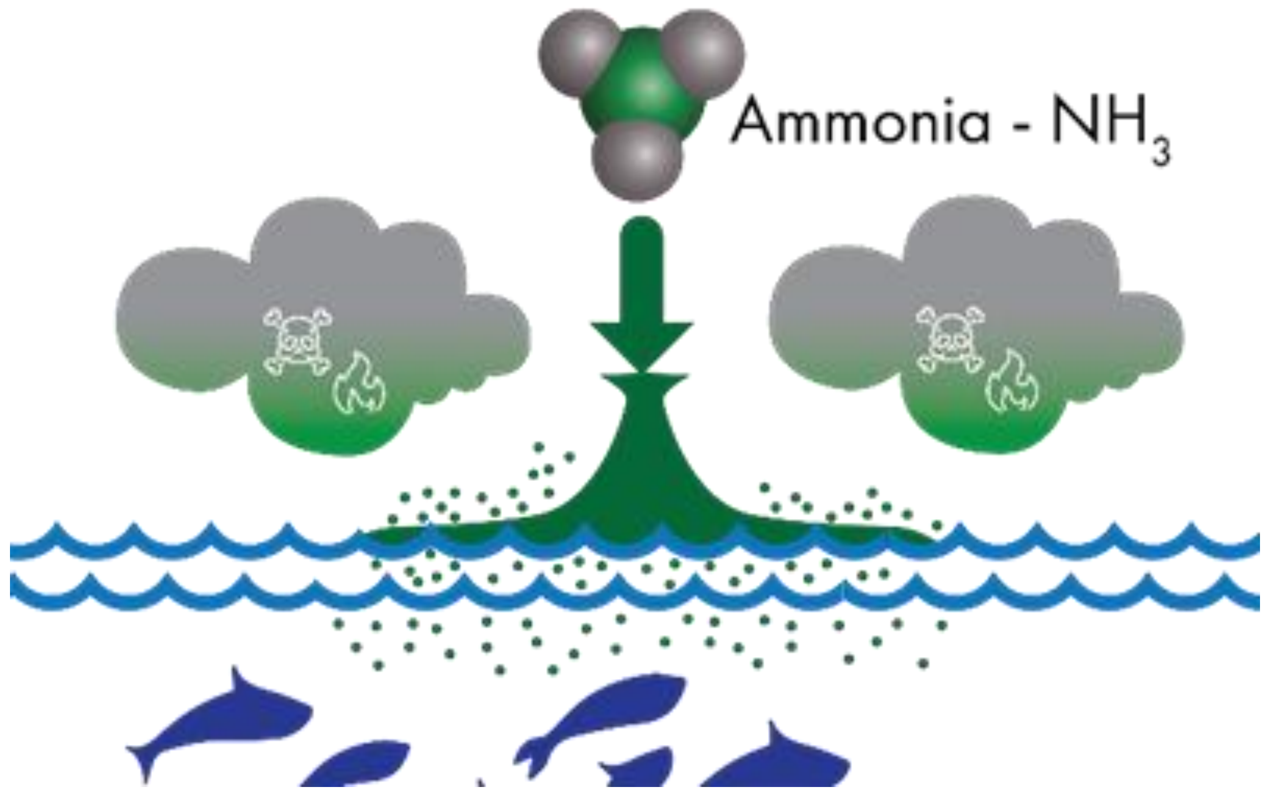
SUPPORTER
- Bureau Veritas (25k€)
- Gexcon (25k€)
- GCMD (25k€)
- Imodco (25 k€)
- MOL (25 k€)
- Navios (25 k€)

- ✓ May 3, 2024: Sponsorship Agreements to be sent to the Sponsors
- ✓ May 16, 2024: Deadline to receive the signed Sponsorship Agreements

- ✓ First payment (60%) due by May 31, 2024.
- ✓ Second payment (30%) in October 2024 after the completion of the pilot sea trial planned in September 2024
- ✓ Third payment (10%) in November 2025 after the completion of the guideline for risk assessment and consequence modeling (D5.5, due in October 2025)

SafeAm

Increased Safety of Ammonia Handling for Maritime Operations



Consortium of 21 partners led by SINTEF

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

BACKGROUND

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

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

APPROACH AND EXPECTED OUTCOMES

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

Total budget ca. 18 MNOK

For info: marta.bucelli@sintef.no (project manager)

Thank you

Any questions?

- Contacts: Rory.Hetherington@hse.gov.uk and Simon.Gant@hse.gov.uk
- The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy

Additional Material

PROTECTING PEOPLE AND PLACES

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Ammonia-powered ships

Yara "Eyde" container ship

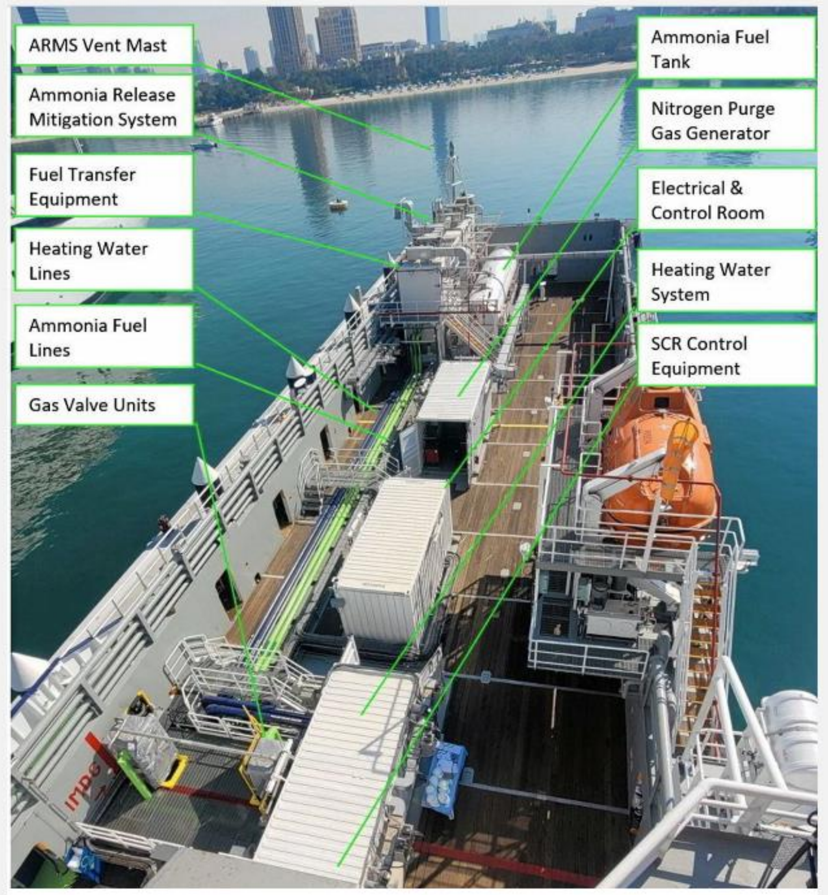
Due to start operating between Norway and Germany in 2026

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)

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

11

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/

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