Review of ammonia incidents and update on ongoing research activities on ammonia safety

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FABIG Technical Meeting on "Harnessing history: safe design and operation of future energy systems", London, UK, 23-24 October 2024

Outline

- Ammonia incidents
- Learning from the ammonia refrigeration industry
- Emergency response
- Ongoing ammonia safety research

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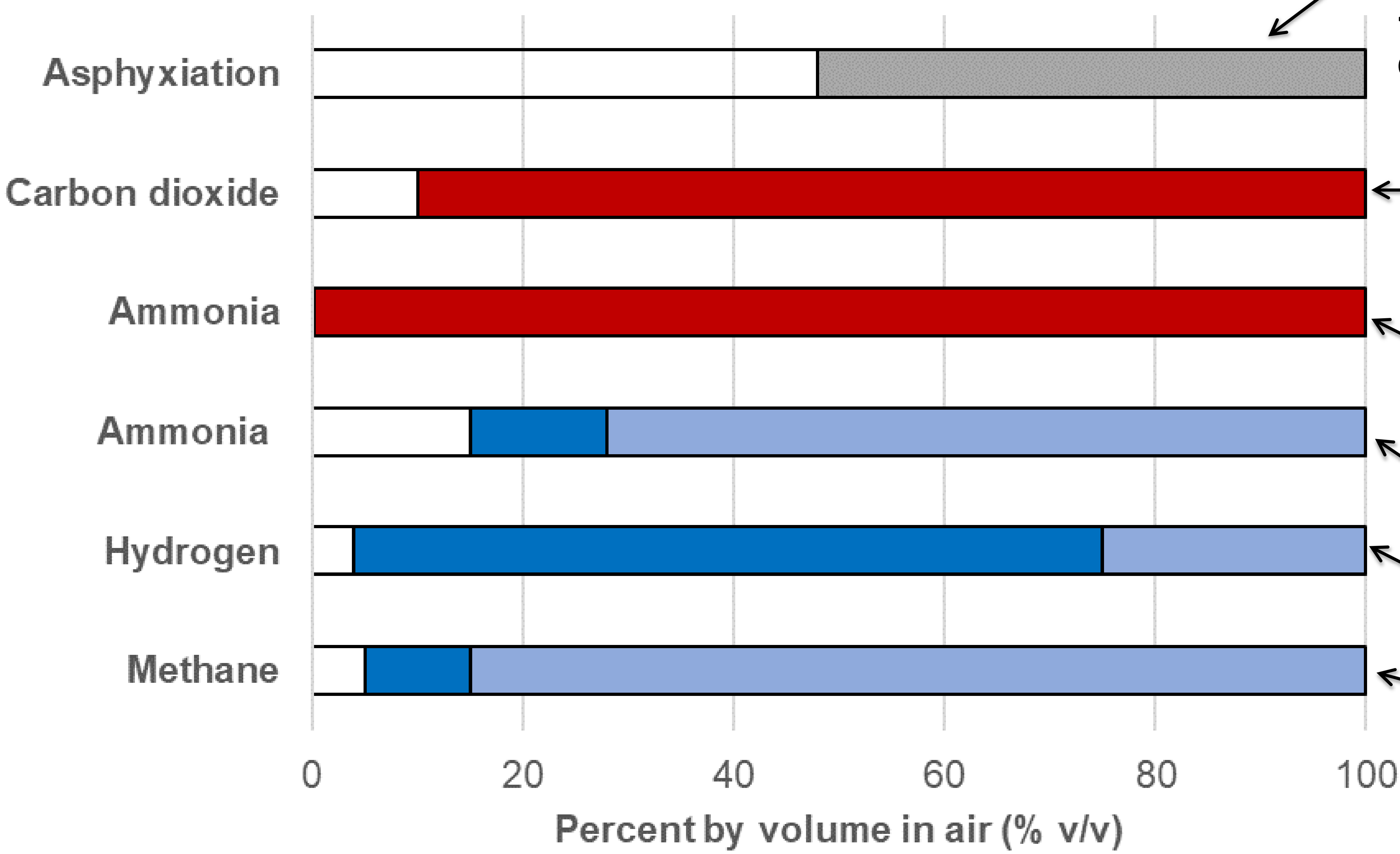
Comparison of ammonia hazard thresholds



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

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

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

Ammonia flammable range 15 – 28% v/v

Hydrogen flammable range 4 – 75% v/v

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

Too dilute to burn

Flammable

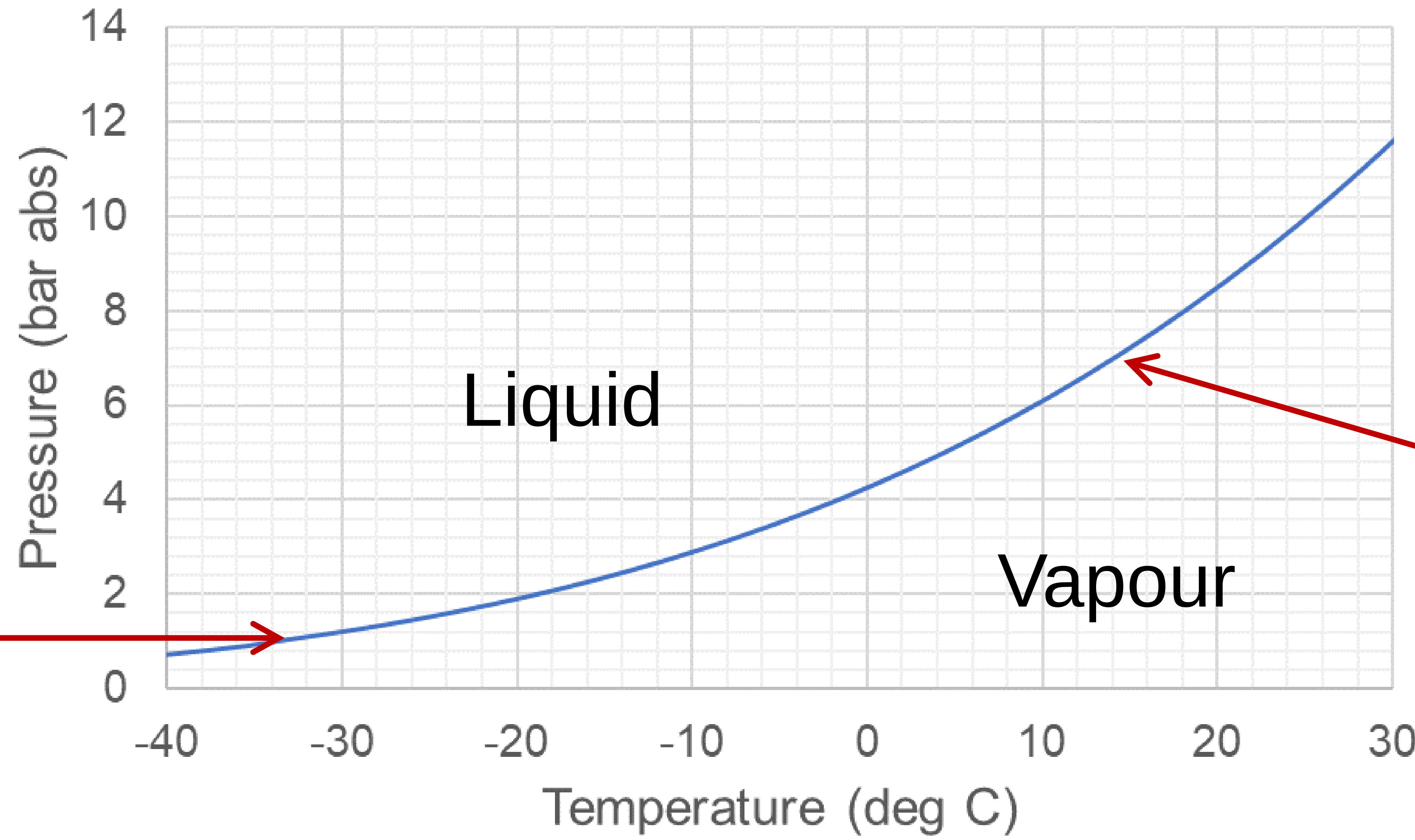
Too rich to burn (but could ignite if diluted)

Toxic (AEGL-3) or equivalent life-threatening health effects or death

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

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

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

Ammonia incidents

- Focus on immediate rather than underlying causes of incidents
  - e.g., leaks, corrosion, not safety management system or corporate culture

- Grouping of incidents in following slides:
  1. Pressure-liquefied ammonia incidents (usually at ambient temperature)
  2. Refrigerated ammonia incidents (usually close to ambient pressure)

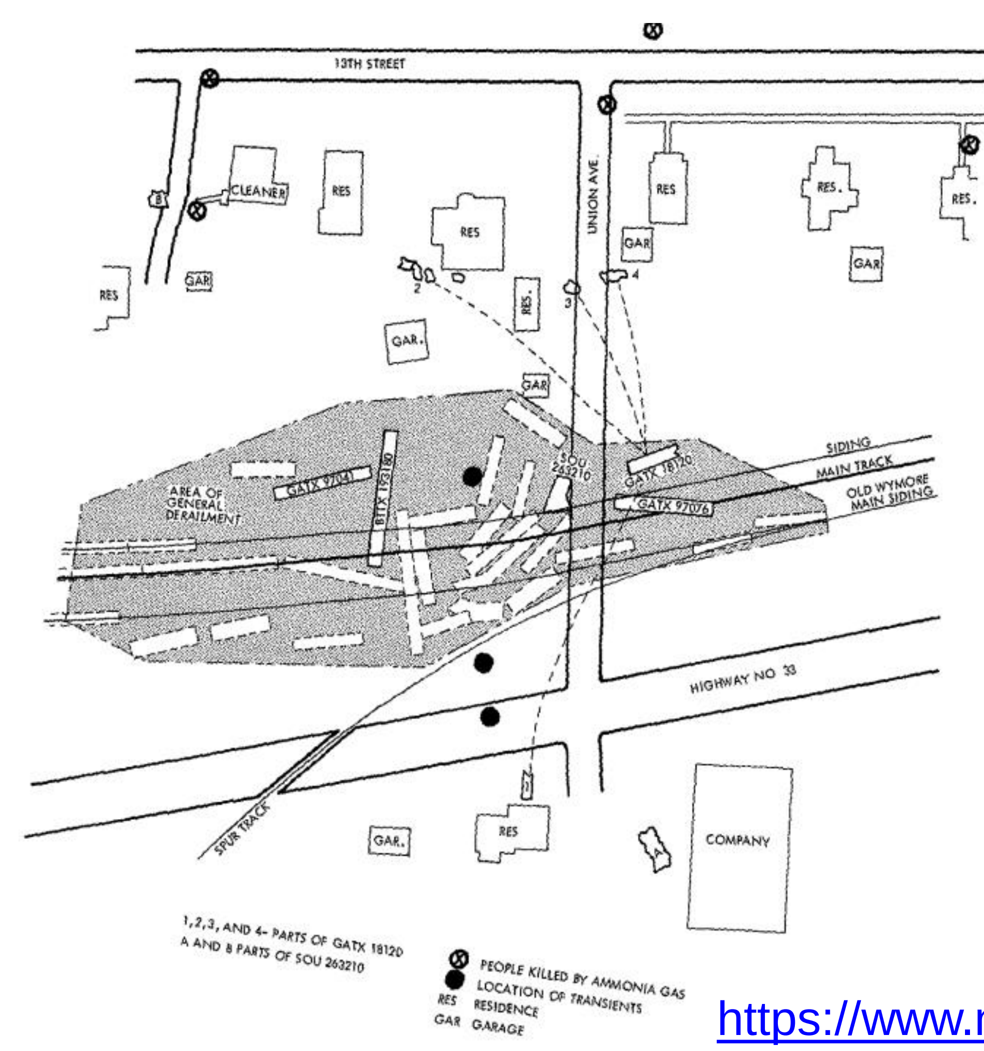
- Further examples taken from compendiums of incidents

Pressure-liquefied ammonia incidents

- Crete, Nebraska (1969) ammonia railcar release due to derailment and collision
- Potchefstroom, South Africa (1973) vessel failed due to brittle fracture
- McPherson, Kansas (1973) pipeline leak due to over-pressurization
- Houston, Texas (1976) road tanker crashed through bridge barrier and ruptured
- Landskrona, Sweden (1976) hose failed during ship-to-shore transfer
- Cedarville, Ohio (1977) hose failed during road tanker transfer
- Houston, Texas (1983) ammonia refrigeration leak and vapour cloud explosion
- Dixie Cold Storage, Shreveport, Louisiana (1984) ammonia refrigeration leak and explosion
- Dakar, Senegal (1992) ammonia vessel ruptured due to over-pressurized
- Minot, South Dakota (2002) ammonia railcar accident
- Kingman, Kansas (2004) pipeline rupture from previous dent/gouge damage
- Tampa Bay, Florida (2007) pipeline leak due to third-party activity
- Swansea, South Carolina (2009) transfer hose failure due to incompatible material
- 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

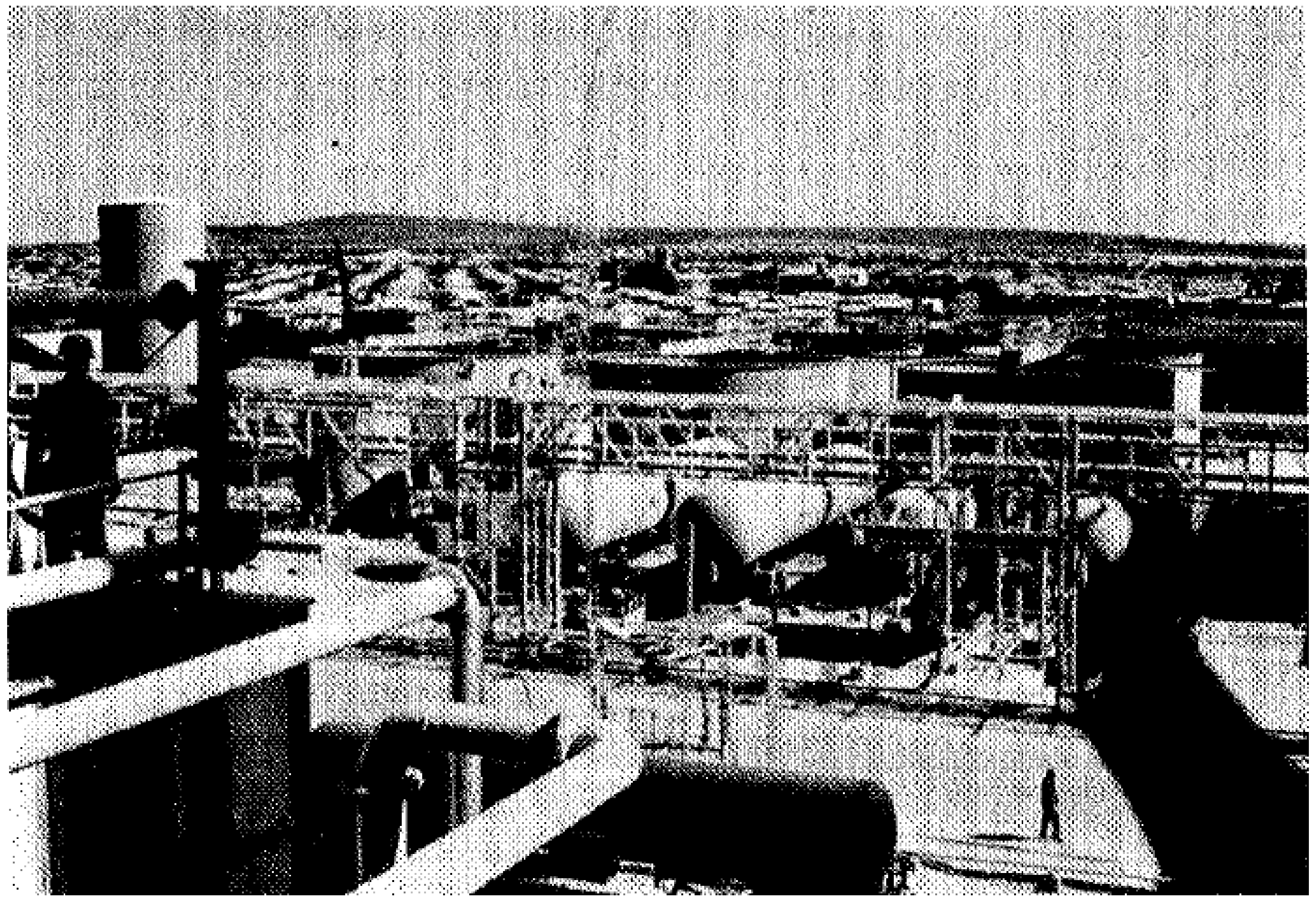
Crete, Nebraska (1969)

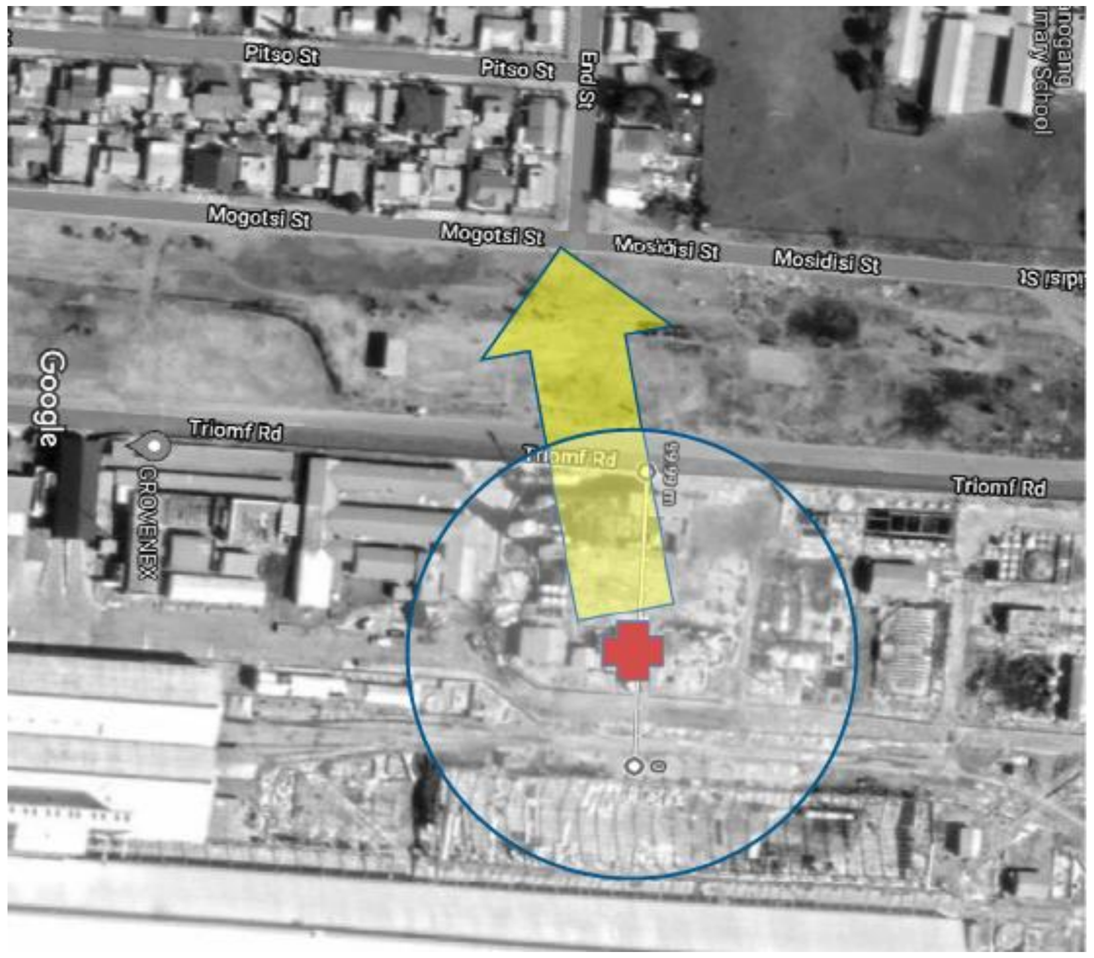
- Derailed railcars struck standing ammonia railcars
- 29,200 gallons (111 m^3) of liquid ammonia released
- Gas cloud blanketed the area, winds were calm with inversion
- 3 people killed in collision, 6 killed and 53 injured from exposure to ammonia cloud
- NSTB investigation attributed causes to surface deficiencies of track and fracture of railcar, which was affected by low ambient temperatures and brittle failure of the steel



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

McPherson, Kansas (1973)

- Since start of ammonia pipeline operation in 1968, 3 major leaks
- Third leak occurred at distance of 300 ft from pump station
- Ice storm caused power outage and pipeline shutdown
- Power restored and pumps activated but electrically-operated block valve failed to open, resulting in increased line pressure
- Pipeline failed at point of prior construction damage
- 5-10 mph winds blew dense cloud across highway at ground level
- Two vehicles drove into cloud, one stopped and driver escaped, the other crashed into ditch and driver escaped: two people hospitalised
- Sheriff evacuated nearest dwellings, 1 mile away

Ammonia Pipeline Maintenance and Repair

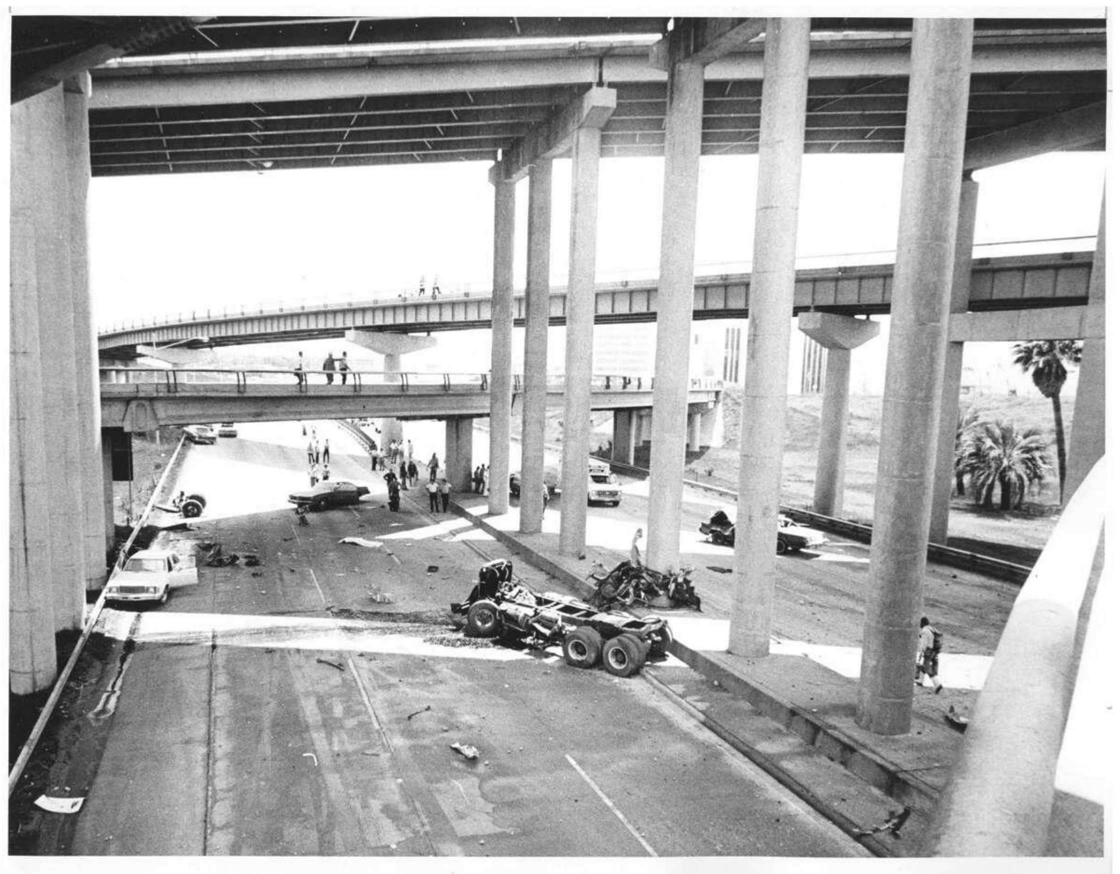
A case history of how one company with a 939-mile line maintains operations and the procedure it followed when a major leak problem occurred.

D.E. Luddeke
Mapco, Inc.
Tulsa, Okla.

https://appsparadeep.iffco.coop/CD_LIBRARY/technical/aiche%20papers%201956-2013/1974/Aiche-17-017.pdf

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

Landskrona, Sweden (1976)

- The René 16 Belgian ship tanker was unloading ammonia in the port of Landskrona
- Ammonia was pumped through a rubber hose into an onshore vessel
- After a few hours, the hose suddenly ruptured and a large white cloud of ammonia engulfed the vessel
- Firemen used water sprays to knock down the cloud and closed the valve aboard the ship and stop the flow of ammonia after 50 minutes
- About 180 tonnes of ammonia escaped
- The cloud drifted towards a shipyard nearby
- Five crew members were found on board, two of whom had to be hospitalized
- After 1 hour, the ammonia cloud had been dispersed and two crew members were found dead on the quay side
- No crew member was standing near the quick-closing valve, which was remotely controlled from two places on the ship. If the valve had been closed immediately, only a small quantity of ammonia would have leaked
- The hose used was intended for propane and butane, and not ammonia

https://midsis.rempec.org/en/incidents/1976-rene-16

(Unclear if this was pressurized or semi-refrigerated ammonia: reports refer to “pressurized” ammonia)

Cedarville, Ohio (1977)

- Hose ruptured during transfer from tanker into a farm tank
- The trucking company transported both ammonia and LPG. Different hoses were used for the two substances, but they were similar in appearance. On this occasion, the LPG hose was erroneously used to transfer ammonia, which ruptured
- The ammonia vapour cloud initially trapped the driver, who was rescued and taken to a nearby hospital, and local fire department summoned
- The fire department sprayed water onto the ammonia, the vapour cloud dissipated
- State officials were notified that no ammonia had reached nearby water bodies
- It later transpired that around 16 m^3 of ammonia were spilled, nearly the entire truckload, and this had reached a nearby stream, Massie Creek, causing a fish kill
- Bales of straw and peat moss were installed to dam the stream
- 7.9 m^3 of hydrochloric acid (HCl) was poured into the ammonia-affected area to neutralise the pH, causing some localised boiling and toxic fumes
- Dikes around the spill would have prevented the ammonia solution from reaching the water course – which could have been pumped into trucks for disposal

https://midsis.rempec.org/en/incidents/1977-storage-tank

https://rib.msb.se/bib/Search/Download?url=media/22395.pdf

Borden's Ice Cream, 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

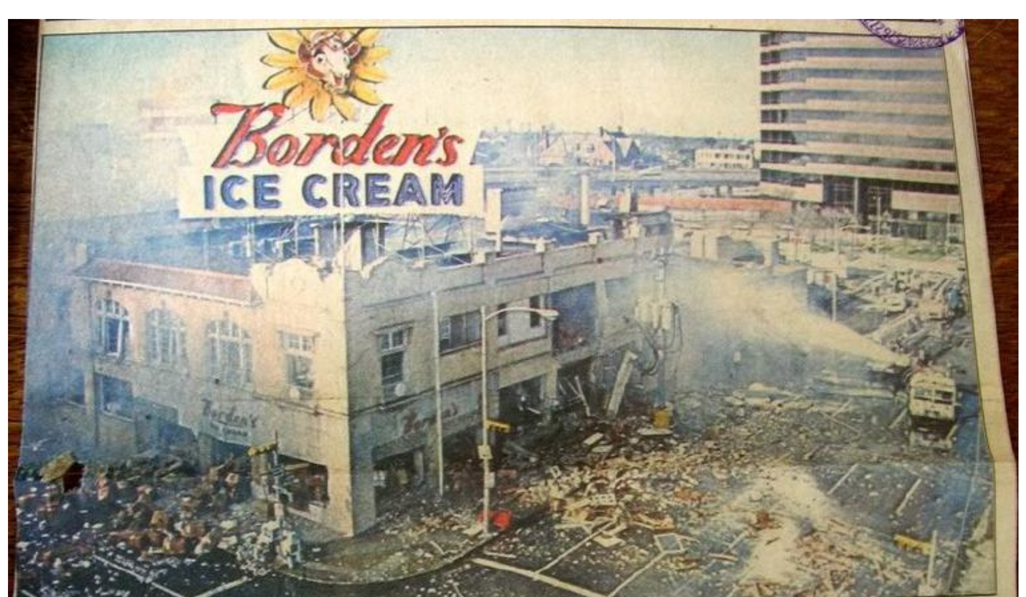


Photo by John Steiger

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 [illegible] 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.

Dixie Cold Storage, Shreveport, Louisiana (1984)

- Leaking valve in refrigeration plant caused accumulation of ammonia vapour within cold store building
- Fire department erroneously informed that the leak had been isolated
- Water sprays and fans used by fire department to help disperse the cloud
- Two firefighters entered the building to repair the valve wearing fully encapsulated chemical suits, without full appreciation of the fire risks
- Ammonia cloud ignited, explosion damaged roof and walls, firefighter's protective suits ignited, severe fire from nearby combustibles
- One firefighter died, one survived (Pat Johnson) who later set up the Ammonia Safety and Training Institute (ASTI) with Gary Smith
- Issues with design of refrigeration plant and maintenance methods
- Seminal incident for ammonia refrigeration industry and emergency responders

https://www.safteng.net/images/cold-storage-shreveport-nfpa-investigation.pdf
https://doi.org/10.1002/prsb.720050107
https://ammonia-safety.com/

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

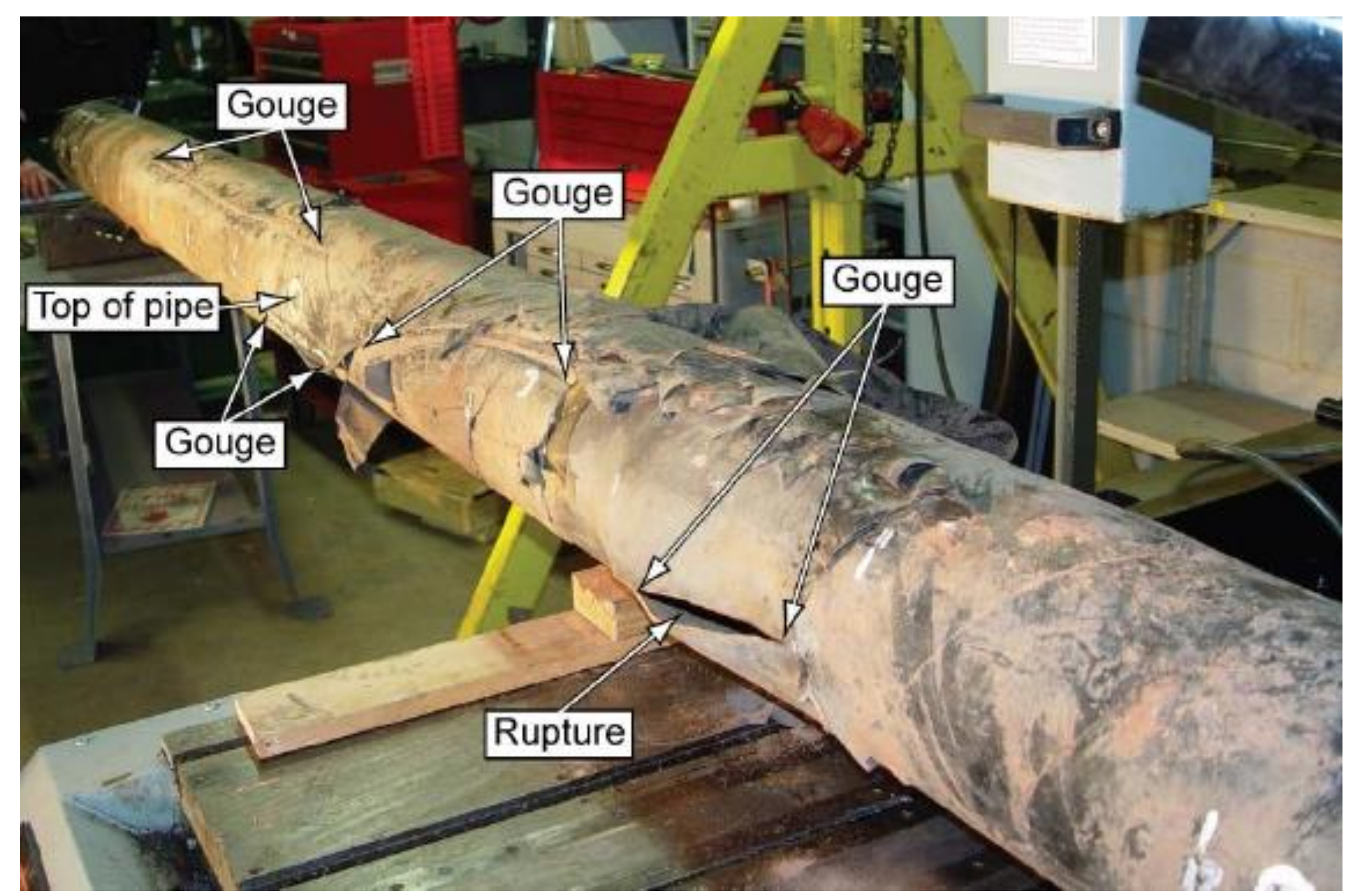
Minot, North Dakota (2002)

- 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

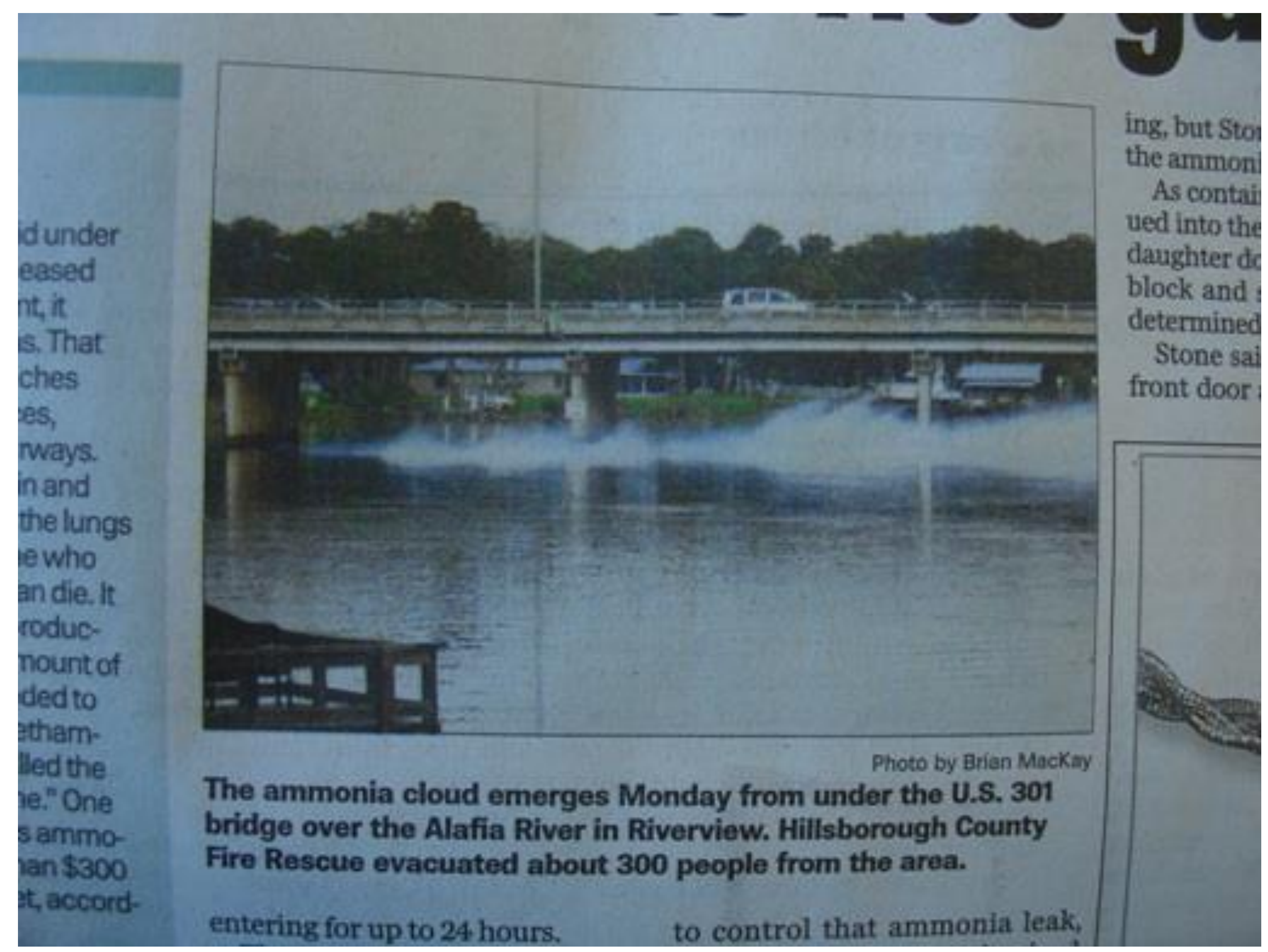


Photo by Brian MacKay

The ammonia cloud emerges Monday from under the U.S. 301 bridge over the Alafia River in Riverview. Hillsborough County Fire Rescue evacuated about 300 people from the area.

entering for up to 24 hours. to control that ammonia leak,

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

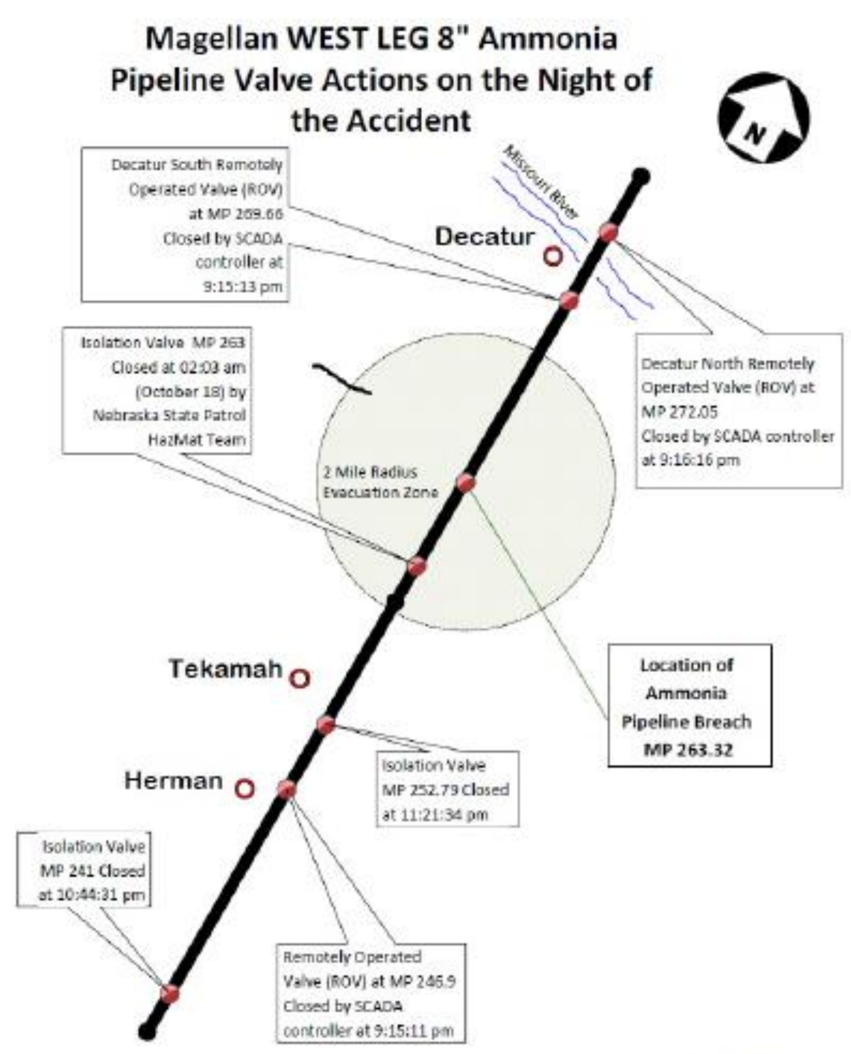
Swansea, South Carolina (2009)

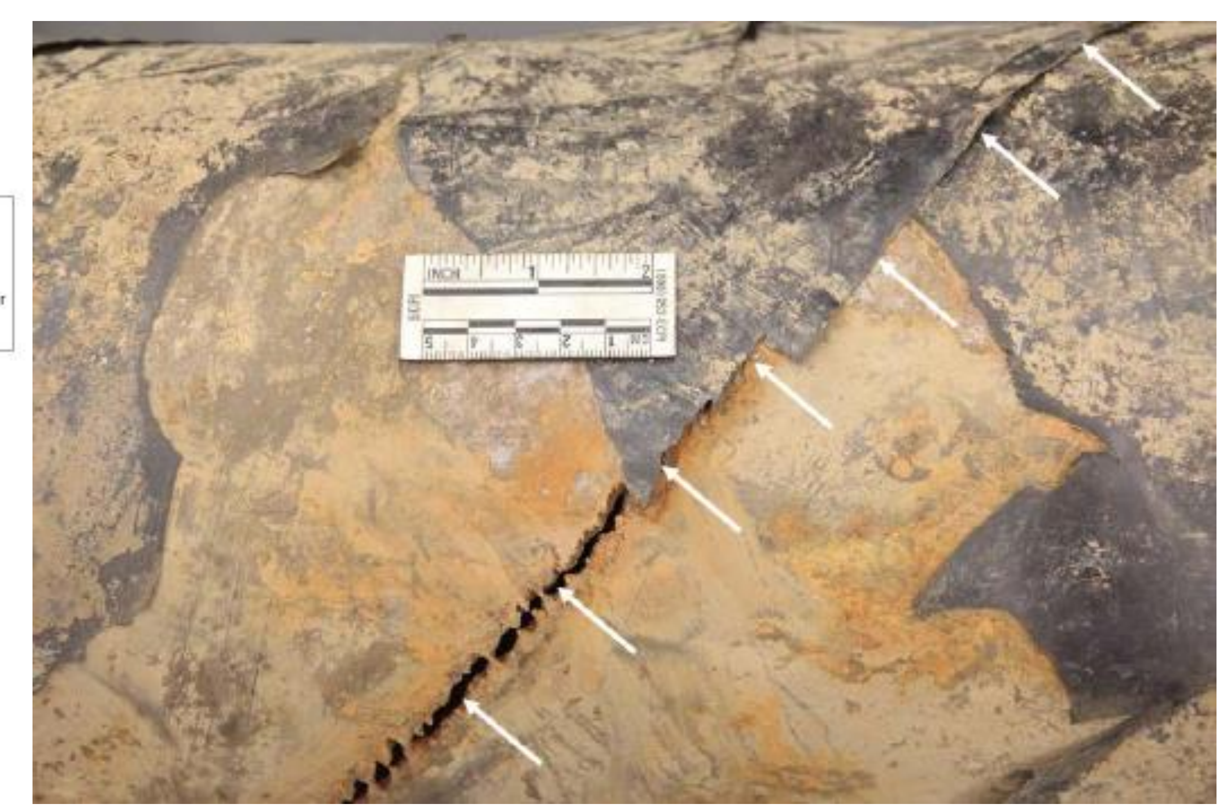
- Transfer hose ruptured between cargo tank truck and storage tank, releasing 3.1 t of ammonia
- Visible cloud drifted from parking lot of the facility across nearby highway
- 14 people suffered minor injuries, 7 people hospitalized, 1 death
- Investigation found that transfer hose was not compatible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

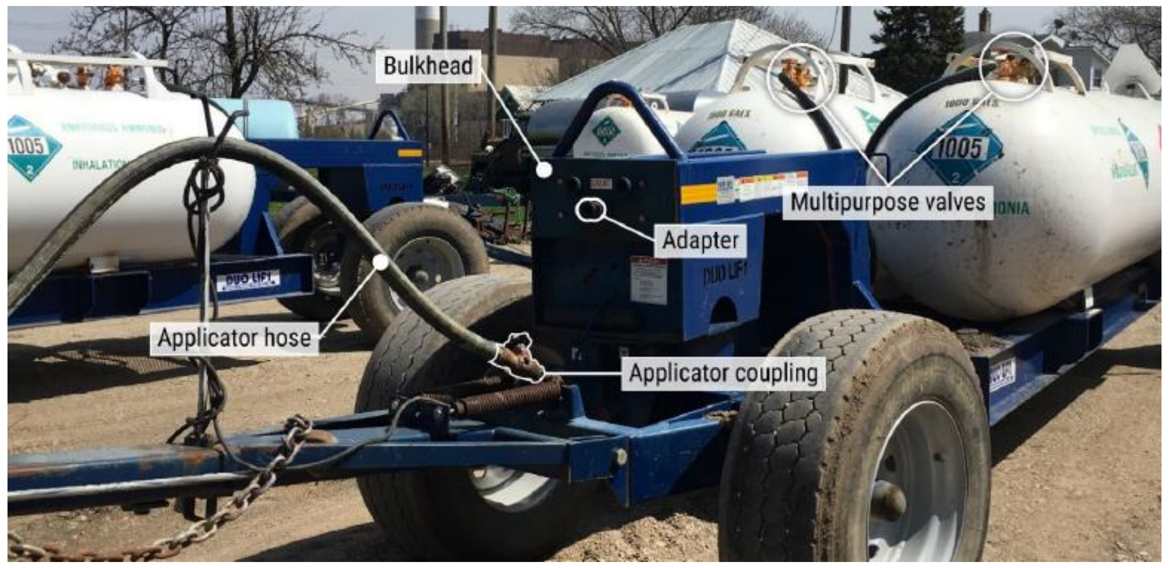




https://www.ntsb.gov/investigations/AccidentReports/Reports/PAB2001.pdf

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 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

Ammonia incidents

- Focus on immediate rather than underlying causes of incidents
  - e.g., leaks, corrosion, not safety management system or corporate culture
- Grouping of incidents in following slides:
  1. Pressure-liquefied ammonia incidents (usually at ambient temperature)
  2. Refrigerated ammonia incidents (usually close to ambient pressure)
- Further examples taken from compendiums of incidents

Refrigerated ammonia incidents

- Blair, Nebraska (1970) tank overfilled
- Jonova, Lithuania (1989) tank over-pressurized following addition of warm ammonia
- Rostock, Germany (2005) tank over-pressurized during commissioning following addition of ammonia
- 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

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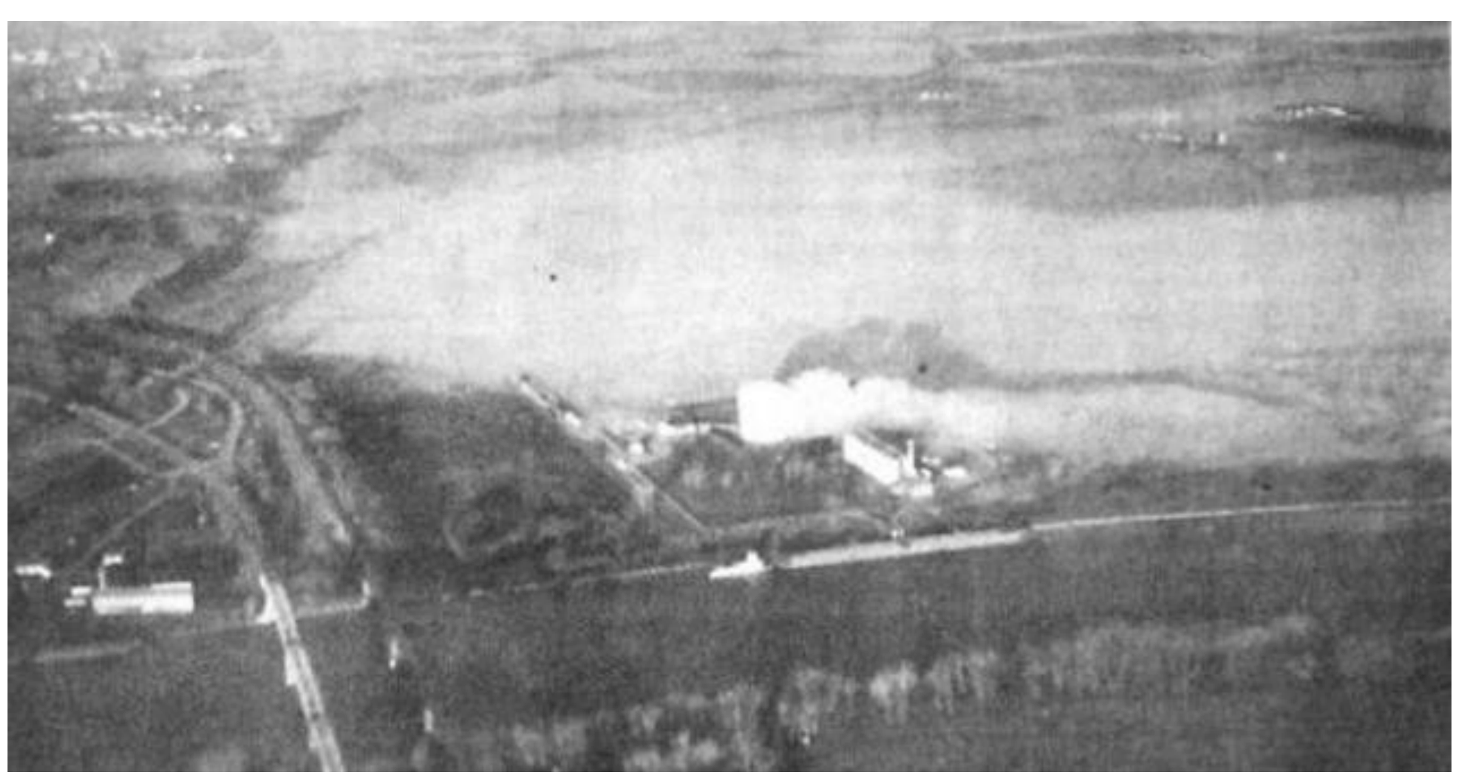
Observations:

- In all cases, it seems that some ammonia aerosol was generated 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
- Very few dispersion experiments to date have studied behaviour of refrigerated ammonia
- Useful to improve understanding of behaviour of sprays of refrigerated ammonia?

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, smashed through concrete containment wall
- Pool of ammonia ignited, probably due to broken natural gas line igniting
- Fire affected nearby ammonium nitrate store
- 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

https://www.icheme.org/media/26106/lpb295_pg02.pdf

https://www.lrt.lt/mediateka/irasas/2000260243/jonavos-azoto-avarija-bei-jos-pasekmes

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

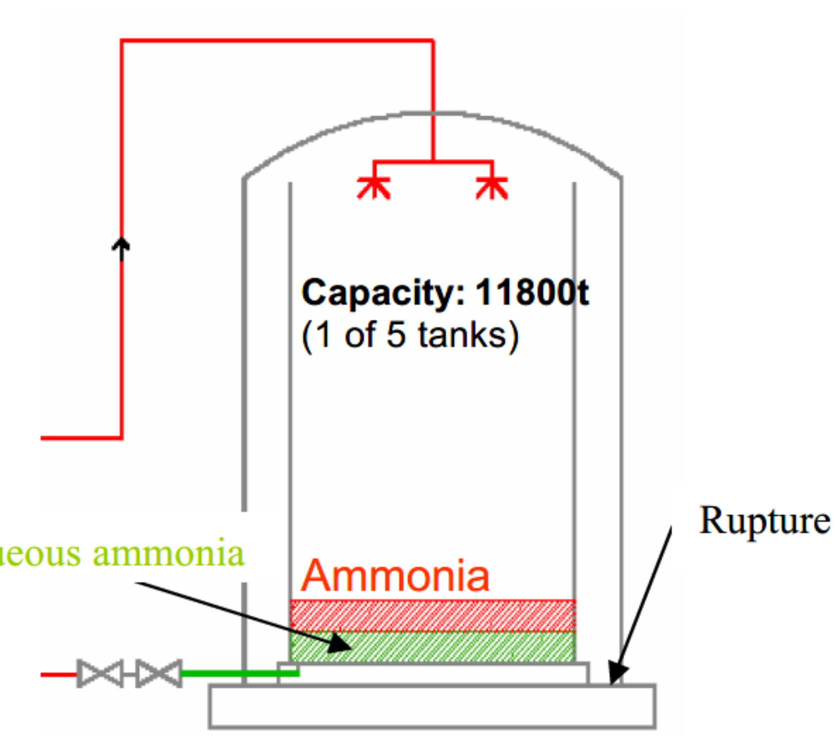


Figure 3 Schematic drawing of the Yara Rostock tank

Figure 4 Yara Rostock tank after the accident.

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

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 failure of mechanical integrity
- 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

Further information on ammonia incidents

1. Review of USA incidents 2002-2005 for 17 USA states
2. HSE review of UK ammonia incidents 1992 – 1998
3. “What went wrong” by Trevor Kletz and Paul Amyotte
4. AIChE Ammonia Safety Symposia: 50 years of shared experiences
5. HSE discovering safety programme
6. “Lessons learned from investigations of ammonia incidents” Moltu *et al*. (Equinor), 2024 AIChE Ammonia Safety Symposium https://www.aiche.org/conferences/annual-safety-ammonia-plants-and-related-facilities-symposium/2024

Review of USA ammonia incidents

- 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 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.

Review of UK ammonia incidents

- Majority of incidents associated with refrigeration equipment (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

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:

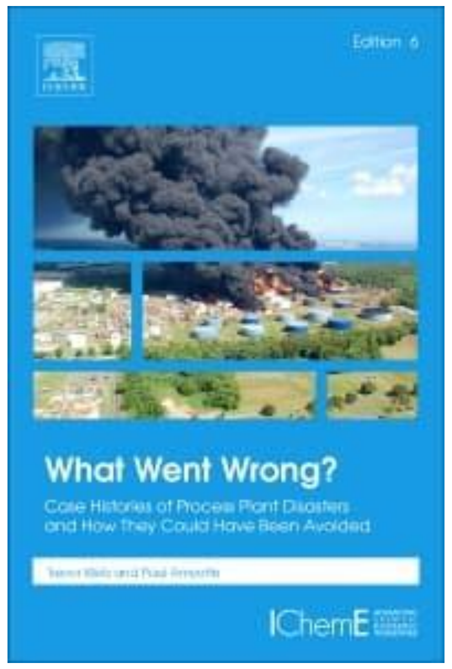
Summary of Ammonia Incidents 1992 - 1998

	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

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

Ammonia incidents from "What went wrong?"

Book by Kletz and Amyotte



https://shop.elsevier.com/books/what-went-wrong/kletz/978-0-12-810539-9

- Hydraulic shock in ammonia refrigeration system, 100 people exposed, 2010
  - https://www.csb.gov/csb-releases-safety-bulletin-on-anhydrous-ammonia-incident-near-mobile-alabama-safety-bulletin-notes-five-key-lessons-to-prevent-hydraulic-shock
- Production of explosive mercury-nitrogen compounds from mixing of ammonia with trace amounts of mercury in natural gas (e.g., in syngas plants)
  - https://ureaknowhow.com/wp-content/uploads/2022/08/1991-Wilhelm-The-Effect-of-Elemental-Mercury-on-Engineering-Materials-Used-in-Ammonia-Plants.pdf
- Explosive decomposition of ethylene oxide caused by trace amounts of ammonia in nitrogen gas used to inert an ethylene oxide tank
  - R. Grollier Baron (1992) Hazards caused by trace substances, 7th Int. Symp. Loss Prev. Safety Promotion Process Industries, Taormina, Italy 4-8 May 1992
- Rupture of heat exchanger that used ammonia as a coolant. Relief valve failed to open because isolation (block valves) left closed following maintenance. One killed and five injured.
  - https://www.csb.gov/goodyear-heat-exchanger-rupture

Ammonia incidents from “What went wrong?”

Book by Kletz and Amyotte

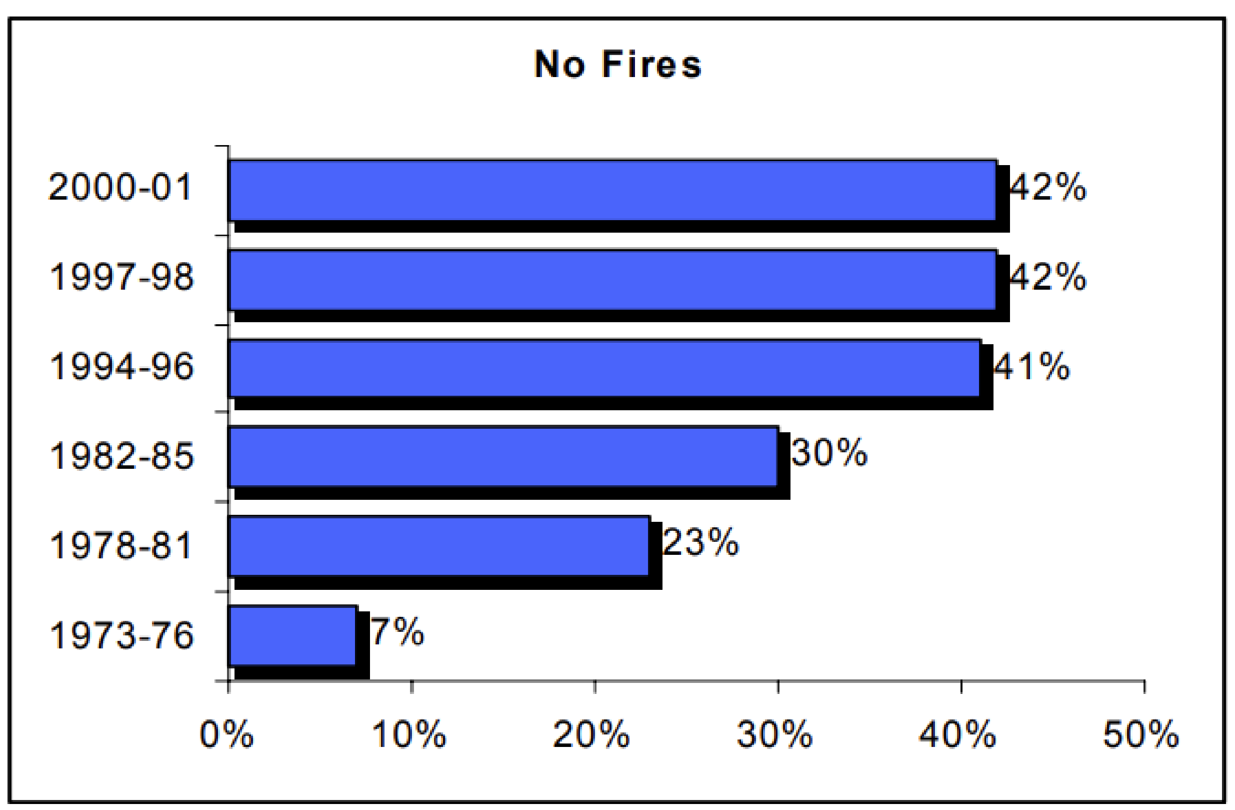
- Chapter on “Ammonia can explode”, examples:
  - 1968: Explosion in sausage factory killed 9. Gasoline truck fire heated ammonia vessels, which discharged contents, ammonia accumulated in confined space and ignited
  - 1976: Explosion in refrigeration plant during demolition in Hexham, UK
  - 1978: Fire from leaking ammonia valves in Llandarcy, Wales, 1978
  - 1978: Fire from ammonia pressure relief valve, ignited by nearby flare in Oklahoma, USA
  - 1983: Borden’s ice cream plant explosion, Houston, USA
  - 1993: Pipe rupture and explosion in nitric acid plant: rust passed through ammonia gas filter and catalysed oxidation of ammonia https://doi.org/10.1002/prs.680150207
  - 1991: Explosion caused by welding on ammonia tank, New Zealand, 1991
  - 2017: Ammonia leak and explosion at food manufacturing site in Chicago, Illinois, injured 2 people

AIChE Ammonia Safety Symposia

50 years of shared experiences, Pattabathula *et al*. (2011)

- 44-page long review of incidents reported at AIChE safety symposia over 50 years
- Includes breakdown of causes of fires, explosions, and equipment failures (290 incidents)
- Many incidents unrelated to ammonia, e.g., steam boilers rupturing

Figure 1 shows that ammonia plants reporting no fires have increased from 7% to 42% over the last 30 years and it has been held at 42% since 1998.



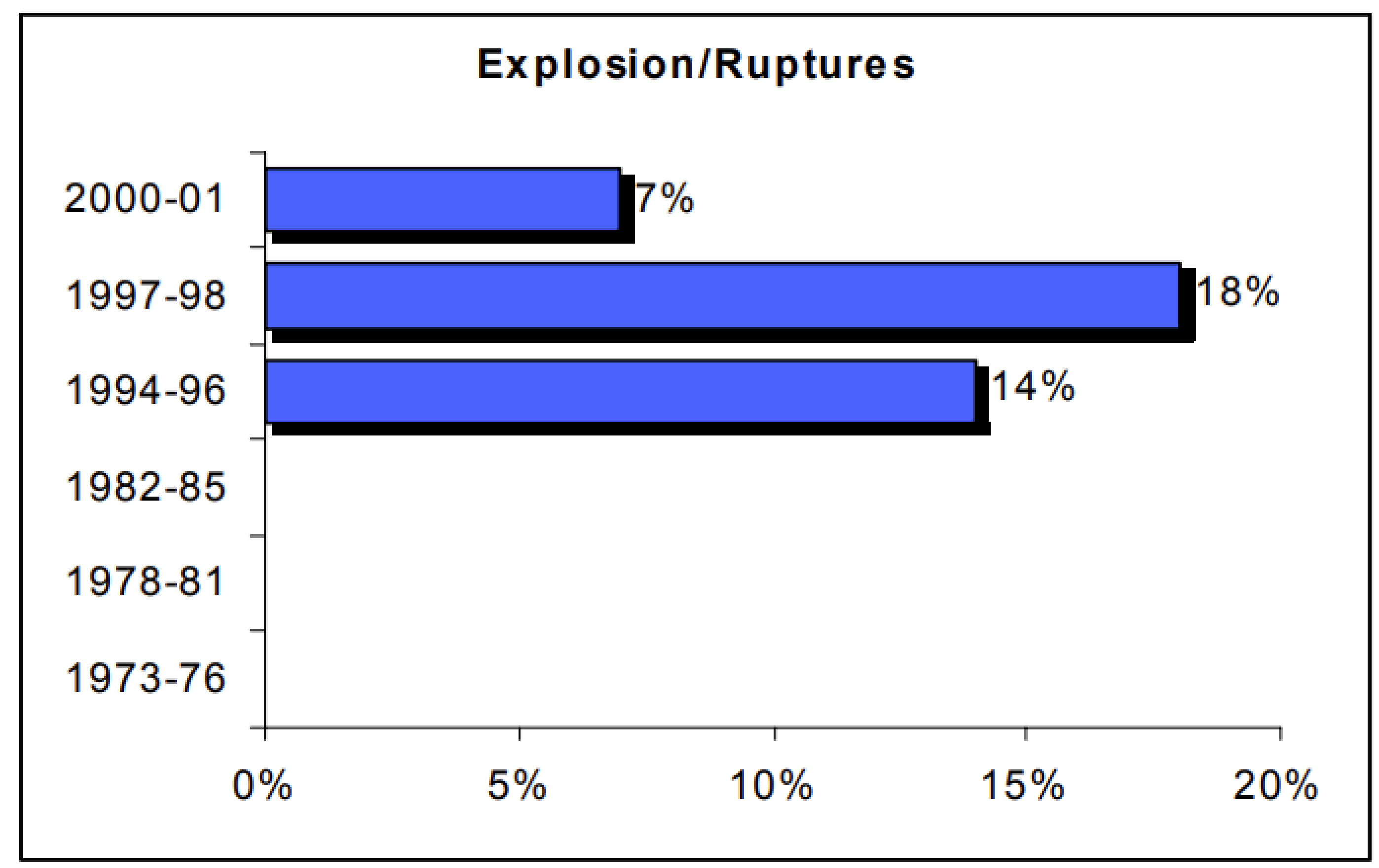


Figure 4. Ammonia plants reporting Explosion/Ruptures

https://ureaknowhow.com/pdflib/535_2011_04_Venkat_AICHE_50_Years_of_Shared_Experiences.pdf

(see also: https://appsparadeep.iffco.coop/CD_LIBRARY/technical/AIChE%20Papers%201956-2013)

HSE discovering safety: loss of containment insights

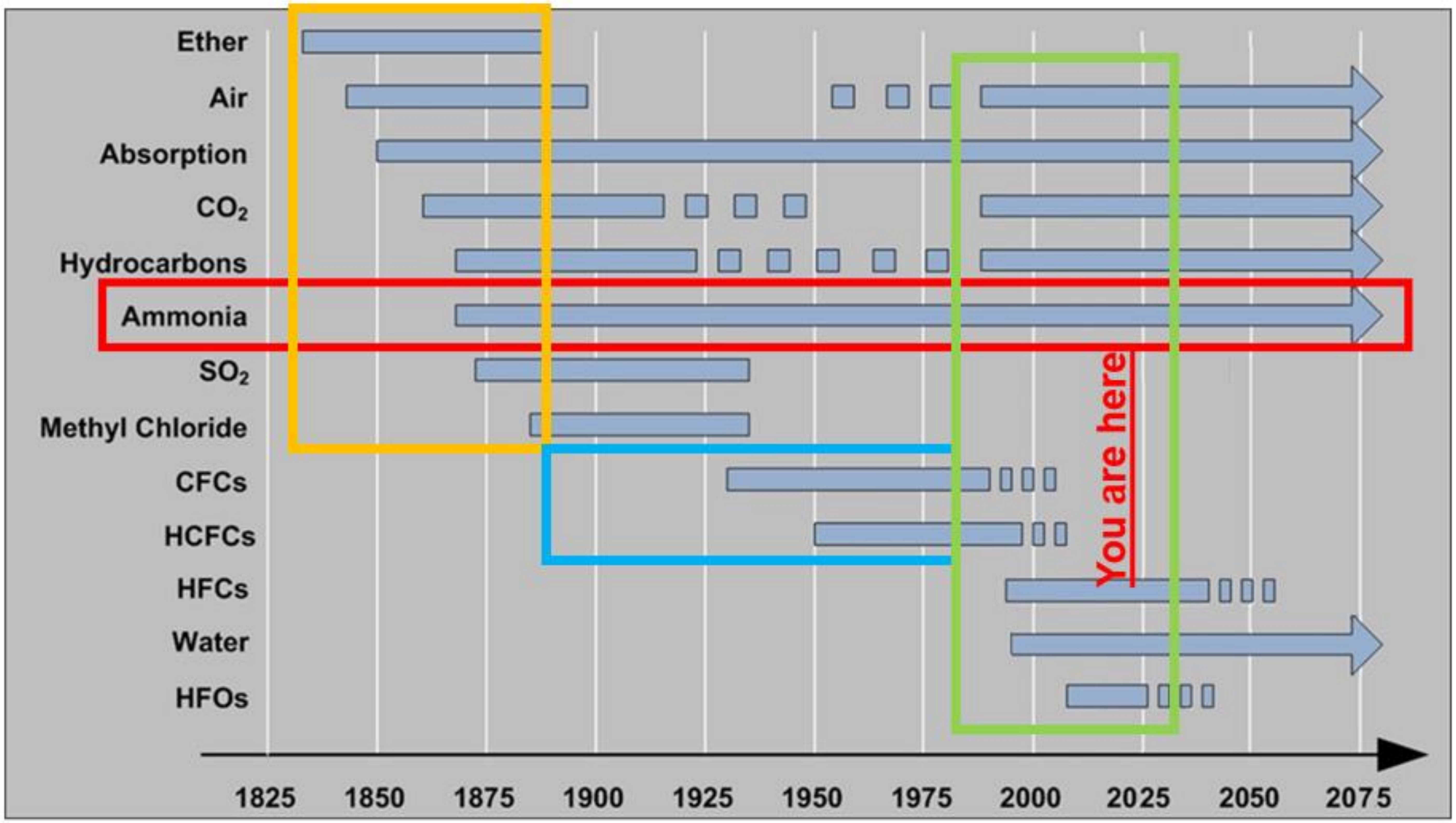
- Text mining and Natural Language Processing (NLP) of data in HSE regulatory databases, investigation reports etc.
- Work funded by Lloyd's Register Foundation includes input from regulatory experts and NLP experts at University of Manchester
- https://www.youtube.com/watch?v=WUqMFD_64_s
- https://www.youtube.com/watch?v=Z9MkLfuXglo
- Work ongoing…

https://www.discoveringsafety.com/

Outline

- Ammonia incidents
- Learning from the ammonia refrigeration industry
- Emergency response
- Ongoing ammonia safety research

Ammonia as a refrigerant



- **Why?**
  - Cheap
  - Available
  - Effective
  - Robust
  - Reliable
  - Efficient
  - Ozone friendly
  - Climate friendly
  - Safe
  - Easy

Ammonia as a refrigerant

- Primarily in industrial facilities and some building services applications

Water chillers for buildings (this one is a 4 minute walk from this venue, in a basement and is 0.1kg/kW, 94kg charge)

Large “central plant” – tens of tonnes

“low charge” –about 1kg/kW
unit size 100kW – 600kW

Ammonia as a refrigerant – market trends

- Strong desire to find ways to reduce ammonia charge in plant
  - For sound technical reasons,
  - For perceived cost and risk reduction benefits,
  - From a position of lack of knowledge/lack of experience
- Many attempts to produce “low charge systems” – some successes
- Others trying alternative technology such as CO_2 or even propane
  - Often in response to false reporting and spread of misinformation
- Some traditionalists digging their heels in, happy with what they’ve got

Modern warehouse application

- Volume 450,000m^3
- Store at -22°C
- Six cooling modules
  - 4 x 300kW (180kg charge)
  - 2 x 700kW (350kg charge)
- No flanges, threads etc inside the rooms
- Central plant would have required at least 20,000kg
  - lots of indoor leaks

Lessons from ammonia refrigeration – part 1

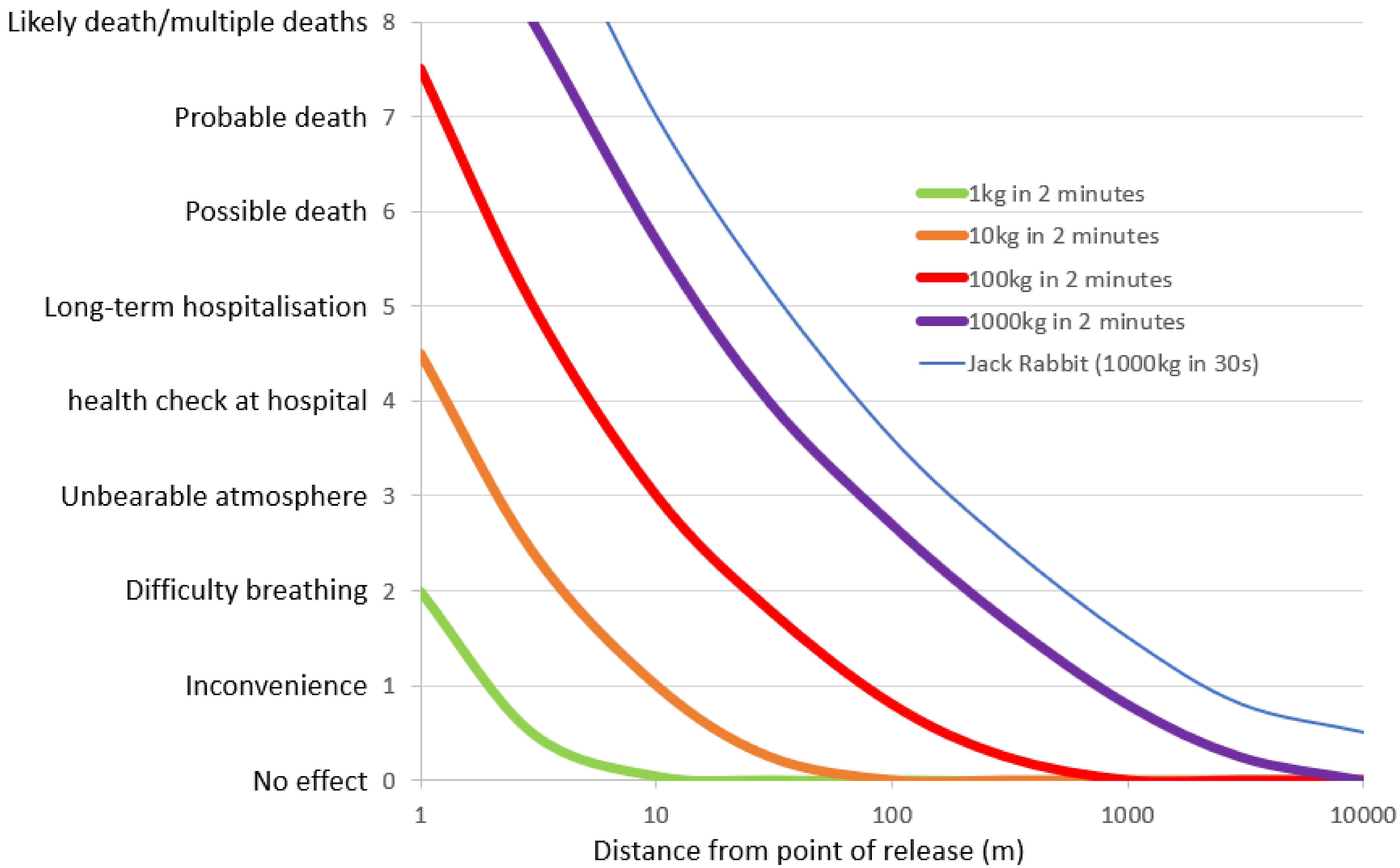
(things that apply to other ammonia applications)

- Material selection is key
  - for metals (steel, stainless steel, galvanised steel, aluminium)
  - for elastomers (if in doubt, Aflas or FFKM)
  - for epoxy resins and adhesives
  - Corrosion under insulation
- Use suitable PPE for maintenance activity
  - Canister respirator, powered respirator or escape hood (SCBA is <u>not</u> required)
  - Suitable coveralls, boots, gloves and goggles
  - Mandatory for all break-in activity (including removing seal caps from valves)
- Train for emergency and expect the unexpected
  - Personal detectors, fixed sensors, emergency ventilation, evacuation drill

Key safety considerations

- What quantity of ammonia can leak from the system?
  - How fast does it leak?
  - How long does the leak last?
  - Where does it leak?
- Who is affected by a release of refrigerant?
  - Specialist technicians equipped to work on the system
  - Employees working in the vicinity with no special knowledge
  - Neighbours
    - In other professional businesses
    - General public living nearby
    - General public driving past on a motorway
    - General public walking past on a footpath

A new quantitative risk analysis methodology



Notes:

1. Graphic is illustrative only, not based on measurements
2. Based on liquid release outdoors
3. Based on quantity actually released, not total system charge
4. Based on toxic effect on humans
5. Severity effects shown are expected worst cases in the absence of other factors
6. Other factors include:
    1. Victims constrained or unable to escape
    2. Lack of PPE
    3. Spray to the face
    4. Clothes saturated

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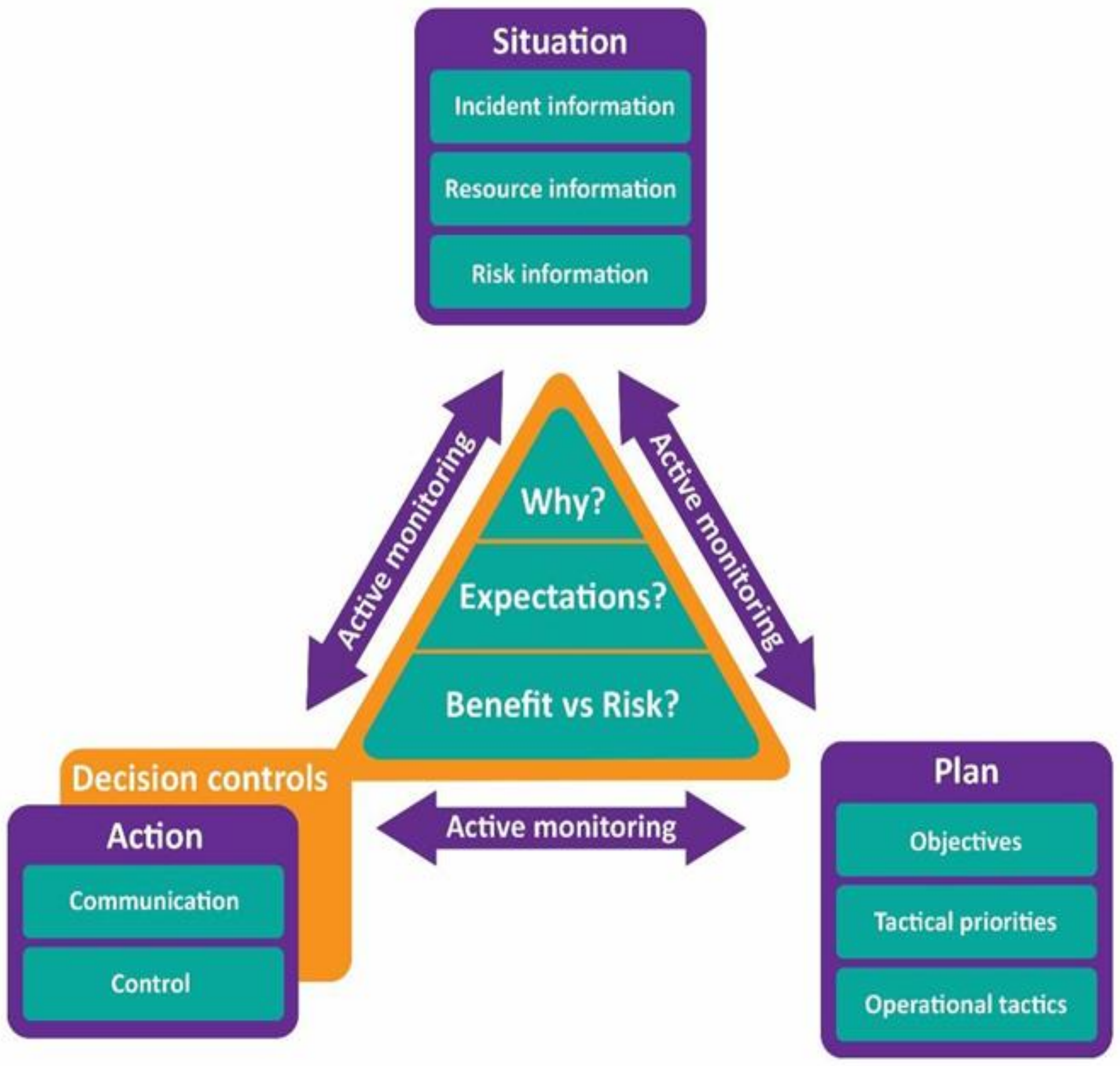
Emergency response to incidents involving ammonia

One of the most common hazmat incident types FRS attend.

- What would a response from the FRS look like?
- Resource intensive – especially when people are involved.
- Why?

Incident - ammonia leak within building

- Persons reported missing within building following racking collapse
- Residual amounts of ammonia present within affected area
- Premises used for food processing
- Temperature within the compartment was approximately -20 °C
- Saveable lives – risk versus benefit analysis.



PPE / RPE considerations for emergency response – the difference between maintenance and response PPE / RPE

The importance of proportionality in response.

Protection

Very Small Spills

- Breathing apparatus with fire kit, protective gloves and boots.

Small Spills

- Breathing apparatus with fire kit, protective gloves and boots.

Medium Spills

- Gas-tight chemical protective clothing in combination with breathing apparatus and fire kit should be worn. The fire kit is to provide additional thermal protection.
- Thermal resistant overgloves should be worn when liquefied gas is present.

Large Spills

- **APP CODE - A(c):** Gas-tight chemical protective clothing in combination with breathing apparatus, fire kit and thermal resistant overgloves should be worn. The fire kit and overgloves are to provide additional thermal protection against the hazards provided by liquefied gas with a boiling point below -20C.

Immediate Life Saving (Snatch) Rescue

- Where the risk assessment of the Incident Commander deems it necessary to perform a snatch rescue to alleviate an immediate threat to life an alternative level of personal protective equipment may be used. A minimum level of protection is afforded by breathing apparatus with full fire kit and standard firefighting or PVC gloves. Consider appropriate decontamination strategy (see Decontamination of Equipment section for advice regarding fire kit).

Window of opportunity – taking a risk to save saveable life. The challenges this gives to response teams.

What are the considerations of incident commanders when dealing with incidents involving ammonia, and how can business collaboration assist?

- Familiarisation with site / premises
- Knowledge and understanding of business processes
- Relationship with people form the organisation
- Responsible person from site meeting the FRS in a timely manner
- Provision of information

If you and your organisation can provide this, it increases the chance of survivability of any causalities.

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Jack Rabbit III

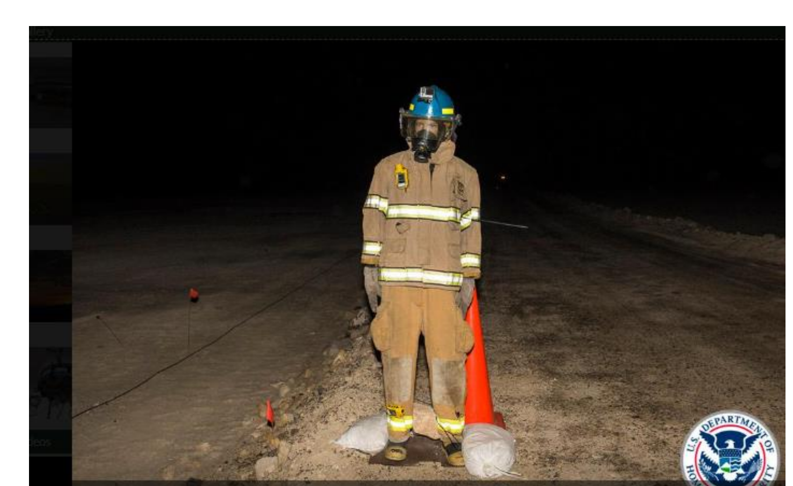
- Ammonia release experiments and modelling (2021-ongoing)
- Led by US Departments of Homeland Security and Defense
- Aims:
  - Conduct large-scale releases of ammonia
  - Validate dispersion models
  - Improve preparedness of emergency responders
- Indoor ammonia release trials at Battelle Institute in Ohio in 2024-2025
  - Presentation by Matt Rowley at GMU Conference http://camp.cos.gmu.edu/conference.html

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



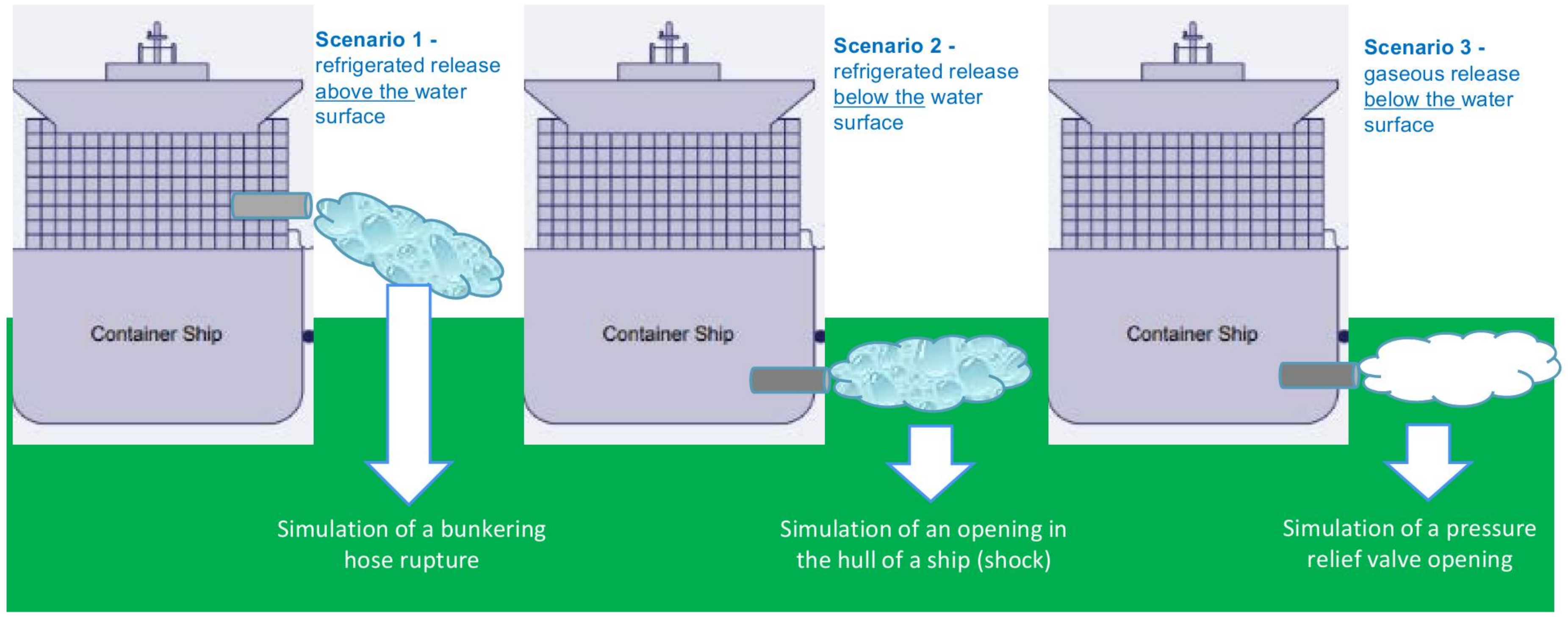






Images © DHS S&T CSAC and Utah Valley University https://www.uvu.edu/es/jack-rabbit/

ARISE



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Laurent.Ruhlmann@yara.com

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).

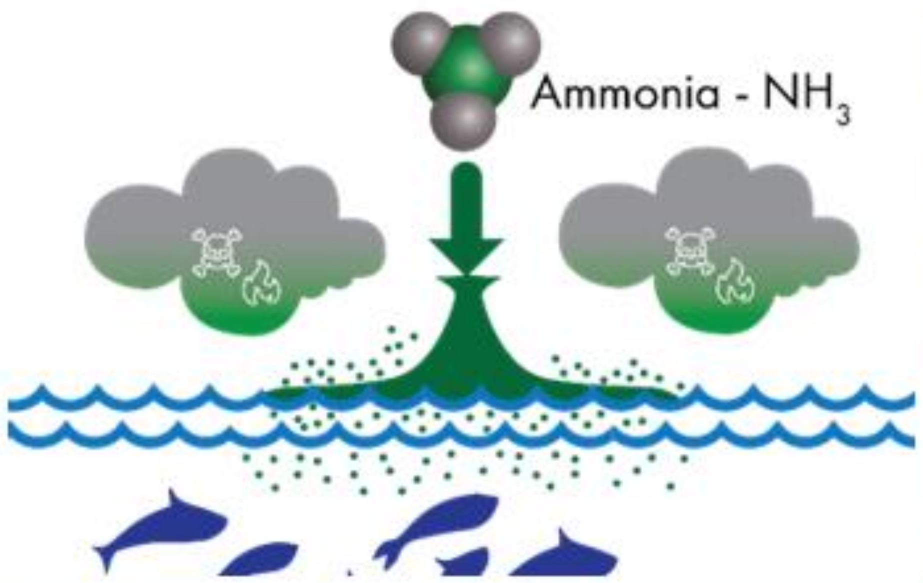
www.arise-partnership.org

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

SafeAm

Increased Safety of Ammonia Handling for Maritime Operations

SafeAm



Consortium of 21 partners led by SINTEF

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

BACKGROUND

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

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

APPROACH AND EXPECTED OUTCOMES

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

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

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

SH_2IFT-2

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

Thank you

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- Disclaimer: the contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy
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