THE ENERGY TRANSITION IS IN FULL SWING

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Alongside existing energy carriers that will continue to be used for the foreseeable future, the emergence of new energy carriers is becoming increasingly evident. One of the most significant carriers expected to develop in the near future is anhydrous ammonia. This introduces new safety challenges, particularly regarding emergency response to ammonia-related incidents. Further research on this subject is required. A logical starting point is to reflect on lessons learned from past experiences. This article presents several of those lessons.

BACKGROUND

Managing **emerging risks associated with the energy transition** has been a critical issue for several years. In particular, current emergency response strategies for ammonia-related incidents have demonstrated a **need for improvement.** Drawing on its extensive experience in training both industrial and municipal fire services, H2K has observed significant variation in opinions regarding which methods and techniques are most effective. Society increasingly expects emergency response teams to be well-prepared and also be capable of mitigating these new risks. Establishing a shared understanding of the safest and most effective practices should be the first step toward achieving this goal. H2K is not alone in this observation.

The Netherlands Institute for Public Safety (NIPV) and other stakeholders have also concluded that **knowledge and insights into mitigating the effects of ammonia incidents remain insufficiently developed**. H2K and NIPV are collaborating on a project to assess the current state of knowledge of repressive action after ammonia releases. Recently, the NIPV conducted a study of past incidents to identify lessons learned from previous fire service interventions.

DESIGN OF THE NIPV STUDY

The study consisted of **three components**. First, a literature review was conducted on ammonia incidents. Next, several databases were examined to determine the specific approaches taken by fire services. Finally, interviews were held with experts collect to practical knowledge.

The full report: ***"Responding to Ammonia Incidents: Lessons Learned"***, authored by M. Spoelstra and J. Reinders, *"Lessen uit de bestrijding van ammoniakincidenten"* (November 5, 2025) (Dutch), is available at http://www.nipv.nl, including all references.

This article shares the **key lessons** identified by NIPV, which we believe have broader relevance for anyone involved in emergency response and ammonia incident management.

RESPONDING TO AMMONIA INCIDENTS: LESSONS LEARNED (NIPV)

03

NIPV Nederlands Instituut Publieke Veiligheid

ALTHOUGH DETAILED INFORMATION IS OFTEN LACKING, LITERATURE AND DATABASES STILL PROVIDE VALUABLE CONTEXT. THEY REVEAL WHERE AMMONIA INCIDENTS TYPICALLY OCCUR AND WHAT THE MOST COMMON FAILURE CAUSES ARE. THIS INFORMATION CAN HELP FIRE SERVICES MAKE INFORMED DECISIONS ABOUT THEIR TACTICAL RESPONSE DURING AN INCIDENT. THIS ARTICLE DESCRIBES THE OPERATIONAL DEPLOYMENT OF FIRE SERVICES DURING AMMONIA INCIDENTS, INCORPORATING AVAILABLE INFORMATION ON OTHER ASPECTS OF THESE INCIDENTS TO SUPPORT THE ANALYSIS.

GENERAL LESSONS LEARNED (NIPV)

Most ammonia incidents occur in refrigeration systems within the food industry.

Currently, ammonia is primarily used in sectors where products or processes require cooling.
Most ammonia refrigeration systems are found in the food industry, so it is not surprising that most ammonia-related incidents occur there. A quick Google search using the keywords **"AMMONIA LEAK"** in the Netherlands mainly shows incidents at meat and vegetable processing plants, cold storage facilities, and dairy companies.

The U.S. Department of Health and Human Services examined 1,153 ammonia incidents between 1999 and 2008. Of these, 52% occurred in the food and textile industries, 17% in agriculture, and 4% during transport (Anderson, 2015).

Ammonia incidents in the food industry usually involve less than 500 kg of ammonia.

The amount of ammonia released during incidents with refrigeration system is generally limited. Nearly half of these incidents involved less than 100 kg, and 75% involved less than 500 kg. However, releases exceeding 1,000 kg (1 ton) are possible in refrigeration systems. In other sectors, the quantities can be significantly higher. Installations such as pipelines, tank trucks, rail tank cars, and chemical industry systems, contain much larger amounts of ammonia. In some cases, releases can exceed 100 tons. The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI) compiled data on the scale of ammonia leaks and typical leak points with corresponding quantities (Table 1.1) (BARPI, 1995). These data date from 1995; more recent sources were not found.

Table 1.1 Typical Leak Sizes and Sources (BARPI, 1995)

INCIDENT SIZE	REFRIGERATION SYSTEMS	OTHER INSTALLATIONS
< 100 kg	Minor leaks at seals or valves	
100 – 500 kg	Leakage through valve, rupture of small pipe, 1–2 mm hole at evaporator outlet	
1 – 3 tons	Emissions through safety valves in large systems, rupture of medium-sized pipe, valve opening	Similar to refrigeration systems and cracked pipes, defects in safety devices, prolonged leakage
> 3 tons	Equipment cracks, rupture in large pipe, domino effect	
5 – 15 tons		Burst hoses, pipe leakage due to opening of safety devices (valve, vent) Upright or Pendent
20 – 100 tons		Road or rail transport (collision, derailment, tank emptying during unloading)
> 100 tons		Rupture in large-capacity tank or break in pipeline (200 – 600 tons)

The main causes of ammonia release are equipment failure and human error.

Ammonia releases are largely caused by technical malfunctions in equipment and incorrect human intervention actions. Anderson reports percentages of 46% for equipment failure and 25% for human error (Anderson, 2015). Vannini cites figures for chemical industry incidents of 60% for mechanical failure and 38% for human error (Vannini & Paltrinieri, 2021), while Shikder reports percentages of 70% and 12% respectively for ammonia transport incidents in the United States (Shikder et al., 2024).

A fire and/or explosion involving ammonia is rare.

Pattabathula examined 290 failing systems in chemical plants that produce, crack, store, or transport ammonia (Pattabathula et al., 2011). *"Failing systems"* refers to incidents as well as deviations identified during inspection or operation. Of all these deviations and incidents, 63 involved components that could contain ammonia. None resulted in an ammonia fire. Four explosions occurred, three due to physical failure of containment and one due to explosive ignition of an ammonia-air mixture.

Shikder investigated the occurrence of ammonia fires and explosions during transport by road, water, and rail in the United States. Of 2,154 incidents between 1971 and 2021, 570 occurred on roads. Only four involved fire and/or explosion; none occurred in other transport modes (Shikder et al., 2024).

Gregson reviewed 139 ammonia incidents in England between 1992 and 1998. None involved fire or explosion (Gregson, 2000).

Ojha notes that ammonia explosions are rare because the lower explosive limit of ammonia is relatively high (16 vol.%) and its flammability range is narrow (16–25 vol.%). Additionally, ammonia's auto-ignition temperature (650 °C) is much higher than that of many hydrocarbons, making ignition difficult. Reaching a concentration outdoors of 16 vol.% is highly unlikely (Ojha & Dhiman, 2010).

Most people injured by ammonia are workers.

Individuals close to an ammonia incident are most likely to be injured through contact with liquid or gaseous ammonia. These are usually personnel. Anderson reports that 62% of ammonia incidents involved injured personnel (Anderson, 2015). BARPI confirms this pattern but does not provide percentages (BARPI, 1995). Both sources also note that bystanders and emergency responders have been injured during ammonia incidents.

Ammonia incidents result in proportionally more injuries than incidents involving other hazardous substances.

Kaye (2005) analyzed incidents recorded by 15 U.S. states in the HSEES database between 1996 and 2001, covering 39,766 hazardous substance incidents (Kaye et al., 2005). Nearly 8% of these incidents involved injuries and/or fatalities (3,133 incidents). During that period, the database contained 2,451 ammonia-related incidents, and more than 13% of those involved injuries and/or fatalities (324 incidents).

The number of fatalities in ammonia incidents is often lower than predicted by modeling.

Hanna investigated why fewer deaths occur in chlorine and ammonia incidents than predicted by dispersion models (Hanna et al., 2022). Contributing factors include:

- The assumption that the gas cloud spreads over flat terrain without encountering obstacles.
- Dispersion models insufficiently account for dry deposition.
- Models do not consider that people seek safety by moving away from the source or sheltering indoors.

LESSONS LEARNED REGARDING FIRE SERVICE RESPONSE (NIPV)

The most common tactical measures during ammonia incidents are stopping the ammonia flow, sheltering, evacuation, and the use of water curtains.

Literature on ammonia incident databases (Kaye et al., 2005; Shikder et al., 2024) provides little detailed information on fire service deployment, even in referenced sources. Measures are generally described only in broad terms. Melnikova is one of the few authors to detail protective actions, which focus on public health rather than technical intervention. These include sheltering, evacuation, decontamination of bystanders and residents, providing health advice, and conducting health assessments (Melnikova et al., 2015). Such measures are not unique to ammonia and are also applied in incidents involving other hazardous substances.

To gain better insight into how fire services have responded operationally to ammonia incidents, incident descriptions in reports and databases were reviewed. This included an overview of ammonia incidents compiled by the Health and Safety Executive (HSE) (Gant et al., 2024) and additional descriptions of major incidents identified through desk research.

Based on the consulted databases and collected information, details were obtained on dozens of ammonia incidents regarding the fire service's operational response.

The results are summarized in Table 1.2, followed by the lessons derived from these findings.

Table 1.2: Emergency response to ammonia incidents

LOCATION	DESCRIPTION	SOURCE
1969, Crete, Nebraska	Firefighters conducted house-to-house searches to ensure full evacuation. Gas masks were required and masks had to be available for evacuees.	(NTSB, 1972)
1976, Houston, Texas	The fire department used fog spray to disperse ammonia from the ground and to rinse cars containing ammonia vapors.	(NTSB, 1976)
1977, Pensacola, Florida	Firefighters, wearing respiratory protection, searched for shipping papers on the derailed train. Based on these papers, they verified the contents and locations of ammonia tank cars. The fire department ordered evacuation within a one-kilometer radius and requested assistance from Air Products experts. Escaping ammonia vapor was controlled by spraying the leak openings with a fine water mist, reducing the vapor cloud by about 30%. Water was then carefully pumped into the tank to dilute the ammonia until the next morning, when the ammonia was reduced to a 30% solution and emissions ceased.	(NTSB, 1977)
1981, Cartwright, Louisiana	Attempts to dig a trench to drain ammonia were unsuccessful because the ground was frozen due to ammonia evaporation. The pipeline operator reduced the impact area by burning ammonia with propane in two pits. The spread of the ammonia cloud was monitored from the ground and air.	(NTSB, 1982)
1989, Jenava, Lithuania	The incident created an ammonia cloud 35 km long. Water curtains were placed along the entire route. The army was called in to assist. Measures were taken to prevent contamination of the Neris River.	(BARPI, 1989) (Stewart, 2024)
1990, Montelimar, France	Firefighters measured ammonia levels. Homes and a supermarket were evacuated.	(BARPI, 1995)
1990, Dieue-sur-Meuse, France	Firefighters closed valves on a pipeline that were inaccessible due to ammonia vapors. Personnel were evacuated.	(BARPI, 1995)
1990, Verdun, France	Firefighters mixed the ammonia cloud using fans and water curtains to locate the source and close the supply valve.	(BARPI, 2002), #2182
1990, Parthenay, France	Firefighters sealed the leak wearing protective suits.	(BARPI, 2002), #2489
1992, Aix-les-Bains, France	Firefighters used multiple water jets to disperse a diethylamine (DMA) cloud, a substance that smells like ammonia. A specialized team in gas suits inspected the damaged rail tank cars and took measurements.	(BARPI, 2025), #3468
1992, Le Moustoir, France	Firefighters cooled gas and sealed the leak.	(BARPI, 2002), #4027
1992, Meyrin, Switzerland	Ammonia was captured in a water mist and discharged with wastewater. Residents were instructed to close windows.	(BARPI, 2002), #3561
1994, Dax, France	Firefighters deployed a water curtain and spread sawdust (acidic, resinous) to absorb and neutralize ammonia.	(BARPI, 2002), #5292
1994, Reims, France	Firefighters diluted ammonia in a tank before discharging it into the wastewater system.	(BARPI, 1995)
1994, Nanterre, France	Firefighters took six hours to seal the leak due to poor visibility and lack of planning.	(BARPI, 2002), #5438
1994, Penne-d'Agenais, France	Firefighters sealed the leak in gas suits, diluted ammonia with water, and performed measurements.	(BARPI, 2002), #2249
1997, Cuiseaux, France	Firefighters were called one hour after the ammonia leak and checked if everyone had evacuated the slaughterhouse. About 20 firefighters used water curtains to disperse the ammonia cloud.	(BARPI, 2025), #10165
1998, Toulouse, France	The company was alerted after numerous complaints from the public. Firefighters conducted measurements.	(BARPI, 2025), #12671
2002, Minot, South Dakota	A command post was set up about 3 km away at a fire station. The shelter and command post had to be relocated due to wind changes. Firefighters instructed people to stay indoors and provided guidance via media. Sirens were activated.	(NTSB, 2004)
2003, Saint Chély d'Apcher, France	Personnel placed a drip tray under the leak and sprayed water on it until firefighters arrived. Firefighters conducted reconnaissance in gas suits. After the incident, firefighters visited nearby residents to inform them that the situation was safe.	(BARPI, 2025), #25699
2004, Lannemezan, France	The industrial fire brigade knocked down the ammonia cloud using water curtains. The water was collected in a basin.	(BARPI, 2025), #28416
2005, Nemours, France	Firefighters, wearing protective clothing, diluted ammonia vapors with water curtains at the ruptured tank and resting area to shield them. The water was collected in a 300 m^3 basin and discharged when the pH reached 8–9.	(BARPI, 2025), #29687
2006, Argentan, France	Firefighters assisted with the extraction of ammonia and ventilated the area.	(BARPI, 2025), #32347
2007, Laneuveville-devant-Nancy, France	Ammonia evaporation from water occurred. Firefighters were alerted after hundreds of residents called with complaints. Measurements were taken.	(BARPI, 2025), #34027

2007, Bulgneville, France	Firefighters rescued a worker in heavy protective gear and shut off pipelines by closing several valves.	(BARPI, 2025), #34235
2009, Swansea, South Carolina	Firefighters formed search teams to locate and evacuate victims. Many residents had fled on their own. Air samples were taken.	(NTSB, 2012)
2016, Chittagong, Bangladesh	Firefighters attempted to limit and disperse the ammonia cloud using water curtains.	(Khan, 2016)
2016, Tekamah, Nebraska	A company employee provided technical support to firefighters and advised on the evacuation radius. He later assumed command.	(NTSB, 2020)
2017, Fernie, Canada	An operator instructed firefighters during the emergency call to open a safety valve and activate the emergency shutdown. Firefighters escorted the operator to the machine room and visually inspected the area.	(Technical Safety BC, 2017)
2019, Cuincy, France	Emergency services deployed a mechanical extractor to remove gases and a water curtain to neutralize the toxic cloud.	(BARPI, 2025), #54839
2022, Pirot, Serbia	Firefighters conducted measurements to determine strategy and rescued people from cars involved in collisions caused by the ammonia cloud.	(CIAT, 2023)
2023, Geleen, Netherlands	Firefighters used water curtains to prevent further spread.	(Verbiesen, 2023)
2023, Teutopolis, Illinois	Firefighters carried out rescues, performed decontamination, and specialized teams sealed the leak. A federal environmental response unit conducted measurements. Drones were used to monitor the situation and search for victims.	(NTSB, 2023)

Incident reports rarely address the fire service's response.

In many descriptions of ammonia incidents, there is no mention of emergency response in general or the fire service's actions. These incidents were therefore not included in Table 1.2. When incident descriptions do mention the fire service actions, the information is brief and general.

Water curtains are deployed for various reasons.

In many ammonia incidents, water curtains are used. Reasons for deploying water curtains include:

- Blocking the ammonia cloud
- Dispersing the ammonia cloud
- Diluting – mixing the ammonia cloud
- Knocking down – dissolving the ammonia cloud

In practice, these purposes often overlap and occur simultaneously. This explains why terms such as blocking, dispersing, diluting, and knocking down are used interchangeably in reports. Incident descriptions do not specify whether one or multiple water curtains were used.

Evacuation occurs more often than sheltering during ammonia incidents.

In the incidents described in Table 1.2, evacuation of affected individuals and/or nearby residents is mentioned more frequently than sheltering. This aligns with Anderson's finding that evacuation is more common than sheltering in ammonia and chlorine incidents (Anderson, 2015). A possible reason is that most incidents occur at fixed installations (Ruckart & Orr, 2015), and many companies prefer to clear the site rather than have employees shelter in place.

RESEARCH CONCLUSIONS (NIPV)

Based on literature on ammonia incidents, the following lessons can be drawn:

- Most ammonia incidents occur in refrigeration systems within the food industry.
- Ammonia incidents in the food industry usually involve less than 500 kg of ammonia. In other sectors, quantities can be significantly higher.
- The main causes of ammonia release are equipment failure and human error.
- Fires and/or explosions involving ammonia are rare.
- Most people injured in ammonia incidents are workers.
- Ammonia incidents result in proportionally more injuries than incidents involving other hazardous substances.
- The number of fatalities in ammonia incidents is often lower than predicted by modeling.

Based on descriptions of ammonia incidents, the following lessons about fire service response can be drawn:

- Incident reports rarely address the fire service's response.
- The most common tactical measures during ammonia incidents are stopping the ammonia supply, using water curtains, sheltering, and evacuation.
- Water curtains are deployed for various reasons (blocking, dispersing, diluting, knocking down).
- Evacuation occurs more often than sheltering during ammonia incidents.

FINAL REMARKS

The NIPV-study shows **a limited consistency in emergency response to ammonia incidents**, resulting in a wide variety of approaches. There is need for clear, evidence-based guidelines for ammonia incident response, including decision-making frameworks for i.e. offensive vs. defensive tactics.

Finally, learning lessons from past incidents is hindered by the absence of adequate and standardized reporting on emergency response actions as the NIPV-research pointed out. It is our collective responsibility to ensure proper documentation and sharing of lessons learned.

Only in this way can we shape a safe energy transition and define the role of incident response within it.

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