Lloyd's Register

Working together
for a safer world

Hydrogen and Ammonia Infrastructure

Safety and Risk Information and Guidance

Report for:
Ocean Hyway Cluster

Arena Ocean Hyway Cluster

Summary

Document history

Revision	Date	Description/changes	Changes made by
v00	7.5.2020	First version	Olav Roald Hansen

Executive summary

This report discusses risk aspects related to infrastructure (production, transport, storage and bunkering) for zero emission fuels hydrogen and (anhydrous) ammonia related to use as a maritime fuel. Compressed and liquid hydrogen and refrigerated or pressurized liquid ammonia are considered in this study. In introduction, a brief overview of current production volumes and use of hydrogen and ammonia is given. Today 95% of hydrogen is produced from fossil fuels, more than half is used for ammonia production, and almost 90% of the ammonia is used to produce fertilizers. The current drivers for zero emission fuels are discussed, including sustainability, public health and comfort, while challenges include cost, storage density, availability, safety and technological maturity. An approximate evaluation of a range of zero and low emission fuels on these parameters is performed, all fuels have significant challenges related either to emissions, cost/availability or storage density. The introduction section also includes an overview of different types of production facilities (central, regional, local), types of transportation, storage and bunkering facilities that may be expected for ammonia and hydrogen.

Hazards and risks related to hydrogen and ammonia are discussed and compared to methane/LNG in Chapter 2. LNG was introduced as a fuel for the maritime industry over the past two decades. An overview of relevant historical accidents for the different fuels is given; for hydrogen and methane this is primarily explosion accidents, while for ammonia toxic exposure of people is the main concern. There is a potential for major accidents for all three fuels, for instance for transport accidents in tunnels. The recent increase in use of hydrogen in the society has led to several smaller explosion accidents damaging buildings, breaking windows, and at worst, claiming lives. Ammonia incidents seldom lead to loss of life, but people would often seek medical help after an incident. Only one person seems to have lost his life in an ammonia accident in Norway past 20-30 years. The use of natural gas is more widespread globally, quite a few accidents happened, for instance where natural gas is used for heating of homes. The introduction of LNG as maritime fuel has led to few incidents and barely any accidents. Recent incidents with compressed natural gas tank explosions in buses should be studied, to learn how to prevent similar or worse incidents with gaseous fuels in future.

The properties of hydrogen, ammonia and natural gas are compared, first related to storage properties and release characteristics. For most properties, hydrogen is very different from other gases. One particular challenge is that the liquid hydrogen storage temperature is well below the freezing point of air. This is demanding for materials and tank insulation, and risks are introduced related to potential for oxygen enriched air in gas or liquid phase. Other aspects include initial dense gas behaviour of LH2-releases with barely no pool formation. For the same pressure and hole size the combustion energy in a methane and a hydrogen release are comparable, both as gas and as liquid. The flammable plume from the hydrogen release is however much larger. Only ammonia is buoyant after evaporating from a pool, while hydrogen is the most buoyant among the gases at ambient

temperature. Ammonia released as pressurized liquid will form a denser than air, very cold, mist cloud. Other aspects to consider are potential BLEVE risk and permeation for hydrogen, and hydraulic shocks for ammonia.

The flammability and explosion properties for hydrogen are extreme compared to natural gas. A release of hydrogen into a confined or semiconfined room will more likely form a reactive gas cloud, ignite, burn fast, generate high pressures, and detonate. Traditional mitigation methods like room ventilation, explosion panels, water deluge and inert gases will normally not work for a reactive hydrogen mixture. A completely different mitigation philosophy may be required with main focus on prevention of flammable atmospheres. Large releases outdoors may also detonate and must be prevented. Ammonia, on the other hand, is not so flammable and more difficult to explode.

Both for hydrogen and natural gas, there have been an extensive experimental activity in recent decades to understand the explosion behaviour. Some of these experiments are discussed in the report. As ammonia is much less reactive than methane, and at the same time toxic, the main focus of ammonia experiments has been to study toxic hazard distances from pressurized, flashing releases.

Vulnerability of people and structures are also discussed in the report. The main risk of hydrogen is normally related to explosions. For LNG, flash-fire risk may be significant, while toxicity is the main concern for ammonia. Probit functions for blast, heat load and toxicity are described.

In Chapter 3 the permitting processes for a facility handling toxic or flammable gases are described. Due to various EU directives, such processes have many similarities across Europe. Regulations for the operation of a hazardous substances site related to production, transportation, storage and bunkering, are discussed.

Risk assessment methodology and approaches are presented in Chapter 4. Each step of a risk assessment is described and handling of uncertainties are discussed. Different risk assessment approaches, including probabilistic approach, maximum credible event and worst-case assessments are discussed, including advantages and disadvantages. Major differences between typical approaches in the USA and Europe regarding risk assessments are illustrated.

In the Chapter 5 some consequence assessment examples are performed for releases of refrigerated ammonia, pressurized ambient ammonia, liquid hydrogen, compressed hydrogen and LNG. Large, medium and small releases were simulated for a small storage facility in moderate winds.

The conclusion from this assessment is that the compressed hydrogen facility and the refrigerated ammonia facility seem to be the safer solutions. For these facilities, it might be feasible to bunker with limited interference in operations. Even for the more severe leak scenarios, the consequences were manageable. For the LNG and LH2 scenarios, the most severe events gave non-tolerable consequences, with fatality risk 200m or more away, with some fatality risk beyond the fence for the medium release scenarios. It is foreseen that bunkering for LH2 and LNG will require somewhat larger safety distances, and a potential need to move the bunkering site away from the operations. For larger vessels ship-to-ship bunkering on the outside the vessel could be an acceptable option.

For the pressurized ammonia scenarios more severe consequences were predicted. It is expected that pressurized ammonia will require a separate, well protected, bunkering location. Due to the severe consequences predicted, even for the medium release rate, it is proposed to aim for using refrigerated ammonia rather than pressurized ammonia during transport, storage and bunkering processes. Conclusions from this assessment are in line with conclusion from two previous ammonia safety studies, considering the use of ammonia as fuel for cars.

Glossary/abbreviations

AEGL	Acute Exposure Guideline Levels (for airborne chemicals) – EPA
ALARP	As Low As Reasonably Practicable
Ammonia (NH₃)	Widely used and transported chemical rich on hydrogen, carbon-free as fuel. More than half of hydrogen produced globally is used for ammonia, almost 90% of ammonia is used for fertilizer production. Green ammonia can be produced with hydrogen from electrolysis.
Biofuels	Bio-diesel, bio-ethanol, bio-methanol, bio-gas, LBG etc. produced using crops, wood or organic waste as feedstock. Exhaust and local pollution are as for fossil fuels, net carbon emissions considered lower and can even be negative.
BLEVE	Boiling liquid expanding vapour explosion
Blue H₂	Hydrogen produced by steam methane reforming (SMR) with CCS
BP	Boiling point
CCS	Carbon capture and sequestration
CFD	Computational Fluid Dynamics, tools include FLACS, FLUENT, CFX, KFX, FDS
Compressed H₂	Compressed hydrogen normally stored at pressures 200-500 bar (up to 1000 bar), can be produced by steam methane reforming (SMR) or electrolysis.
Cryogenic	Low temperature, cryogenic gases liquefy at temperatures at or below -150°C
CSB	US Chemical Safety Board – investigating process safety accidents in the USA
DDT	Deflagration to detonation transition
Deflagration	Turbulence-driven flame subsonic relative to air ahead (10-1200 m/s)
Detonation	Supersonic flame driven by shockwaves igniting unburnt fuel (1500-2000 m/s)
DSB	Norwegian Directorate for Civil Protection (regulator for onshore process safety)
E-fuels	Electrofuels (E-diesel, E-LNG etc.) produced from CO_2, water vapour and hydrogen from electrolysis. Exhaust and local pollution as for fossil fuels (but no sulphur), net carbon emissions close to zero if renewable energy is used to produce the fuels.
EPA	US Environmental Protection Agency
FAR	Fatal accident rate for workers – fatalities per 100 million work hours
FLACS	Leading CFD consequence model to predict gas dispersion and explosion (www.gexcon.com)
GHG	Green-house gas
Green H₂	Hydrogen produced by electrolysis from renewable energy sources

Grey H_2	Hydrogen produced by steam methane reforming (SMR) without carbon sequestration (CCS)
HHV	Higher heating value, maximum energy from combustion
HSE/HSL	The UK Health and Safety Executive / Laboratories (regulator)
IDLH	Immediately Dangerous to Life and Health (US NIOSH) –exposure of toxic gas/mist
Inergen	Gas mixture used for fire quenching/inerting (52% N_2, 40% Ar and 8% CO_2)
LFL	Lower flammability limit in air of a gas
LH2	Liquid hydrogen stored at or near boiling point of 20.4 K
LNG	Liquefied natural gas (primarily methane) stored at or near boiling point of 111 K, fossil fuel with lower carbon emissions and very low sulphur, NOx and PM pollution.
LOHC	Liquid organic hydrogen carriers, e.g. toluene or similar aromatic hydrocarbons that can be used to carry and release hydrogen (~6% by mass). Residual liquid must be sent back to factory to reinsert hydrogen.
MCE	Maximum credible event, leak/explosion/fire
Methanol	Low flashpoint fossil fuel normally produced from SMR. Low carbon emissions and very low local pollution.
MGO, IFO, HFO	Conventional fuels like marine gasoil, intermediate fuel oil and heavy fuel oil are produced by distillation of crude oil (MGO, IFO) and the residual of the process (HFO). Significant carbon footprint and local pollution. Low sulphur versions include LSMGO, VLSFO and ULSFO.
NFPA	National Fire Protection Association – Leading US standardization organization
NIOSH	US National Institute for Occupational Safety and Health
NORSOK	Norwegian organization developing standards for offshore oil and gas production
PSV	Platform support vessel
RIVM	Dutch National Institute for Public Health and the Environment
RPT	Rapid phase transition
SMR	Steam methane reforming – method to produce hydrogen from fossil fuels
SOFC	Solid oxide fuel cell
STP	Standard temperature and pressure 0°C and 1.01325 bar
ton	In this report 1 ton = 1 metric ton = 1000 kg (not 1 short ton = 2000 lb = 907 kg)
UFL	Upper Flammability Limit in air

Table of contents

1   Introduction

This report is written for Ocean HyWay Cluster (OHC) by Lloyd's Register Consulting – Energy AS (LR). Due to the increased focus of zero emission fuels for shipping, e.g. hydrogen and liquids carrying hydrogen, there is a need to properly understand safety and risk aspects of the new fuels introduced related to operation of vessels but also related to the necessary infrastructure for production, transportation, storage and bunkering of these fuels.

The currently most popular zero emissions vessels in Norway are battery electric vessels, primarily local fjord crossing car ferries. Pure battery electric vessels will have a range limitation and be less practical for more power demanding operations with longer range or unpredictable routes. Most zero emission fuel vessel projects aim to store hydrogen either as compressed or liquid hydrogen. There are also initiatives working with LOHC, methanol and ammonia as fuel or source of hydrogen.

The main objective of this report is to be a guidance for OHC-members to safety and risk aspects related to necessary infrastructure for **compressed hydrogen**, **liquid hydrogen** and **ammonia**. The report gives an overview of possible hazards, describes the permitting processes in Norway (most aspects will also be relevant elsewhere in Europe), and describe necessary safety studies to fulfil authority requirements. Where possible, some guidance related to expected safety distances required around facilities and operations is also given.

Figure 1-1   Hydrogen and ammonia molecules, hydrogen is the first and lightest molecule among the elements. Its properties are very different from those of other gases, this must be properly understood for efficient and safe design. Hydrogen is mostly used for ammonia production, and ammonia for fertilizer production. Due to its hydrogen bonds and high heat of vaporization, ammonia is a popular heat transfer fluid in the refrigeration industry.

1.1   Hydrogen based fuels – overview

The main drivers for the ambition of emission free transportation include:

Sustainability means meeting the needs of the present without compromising the ability of future generations to meet their needs.

One traditional element in sustainability and finding alternatives to oil, had to do with predictions that the world would soon run out of oil, and that resources should be saved to future generations. Due to improved exploration technologies, new discoveries and the development of onshore hydraulic fracturing methods the production has never been higher than early 2020, more than 60 years after "peak oil" theories were first proposed.

Taking care of the environment is probably the most important pillar of sustainability. The main sustainability driver in recent years is the concern that CO_2-emissions from fossil fuels may lead to escalating global warming, to limit this, politicians around the world are discussing and committing their countries to emission cuts of greenhouse gases (GHG), primarily related to CO_2. The aim to reduce carbon footprint, or become carbon neutral in human activity, is currently a main driver for introducing

zero emission fuels. The International Maritime Organisation (IMO) has set targets to pursue a 70% reduction of emission intensity and a 50% overall emission reduction within shipping by 2050.

Green hydrogen (as fuel or carried by LOHC) and green ammonia, from which hydrogen is produced by electrolysis from renewable energy sources, can be considered to have zero carbon emission and fulfil the most ambitious environmental sustainability goals. E-fuels and biofuels will emit carbon but may be considered carbon-neutral or even negative in some cases due to the production methods. To the extent costs of these fuels become excessive compared to fossil alternatives, this will be negative regarding economic sustainability.

Fossil fuels are not considered environmentally sustainable being non-renewable and having significant carbon emissions.

Public health considerations and wish to minimize local pollution is another driver. Historically pollution from fuels have led to major health problems, one example is the lead additives to petrol which led to strongly increased lead blood levels in the population and negative health effects. SO_2, NO_x and particulate matters (PM) related to maritime activities also represent a serious health risk, studies around major ports have revealed orders of magnitude higher cancer risk from air pollution. Stricter SO_2 emission limits (0.1%) from maritime fuels were introduced in ECAs (emission control areas) in Europe and North America in 2015 and globally (0.5%) in 2020. Despite cleaner fuel requirements, local emissions are likely to impact public health in harbours and narrow fjords with lots of traffic, see illustrative photos in Figure 1-2.

Hydrogen and ammonia vessels using fuel cells will not give local pollution, if instead used in internal combustion engines there may be some NOx emissions. Fossil fuels, as well as e-fuels and biofuels will have local emissions, methanol and LNG give significantly less local emission than MGO and fuel oils.

Comfort improvement for passengers and crew is another element that can justify the introduction of zero emission fuels, both with regard to reducing smoke/emissions and potential for reducing noise and vibrations for fuel cell concepts due to electric propulsion.

Hydrogen and ammonia vessels using fuel cells may emit less noise than vessels with internal combustion engine. For some vessels and wind conditions odours from exhaust may be experienced, this may be an issue with ammonia given minor releases or engine slip.

Figure 1-2   Emissions of NOx, SO_2 and particulate matters (PMs) can represent a significant public health issue in exposed areas like port of Bergen (left, bt.no/H.M. Johannesen) and the Geirangerfjord (right, smp.no). With the stricter ECA-requirements recently introduced and port electrification initiatives, this problem should be reduced in the future.

There are currently several challenges and disadvantages of zero emission fuels, including:

Cost – Hydrogen and hydrogen derived fuels are generally more costly to produce and handle than current fossil fuels, more costly from renewables (green hydrogen) than from hydrocarbon steam reforming (grey hydrogen, or blue with CCS). How much the operational cost will increase with a hydrogen-based system will depend on oil price, electricity price, fuel efficiency and local conditions.

Storage density (weight/volume) – The volume energy density of hydrogen and hydrogen carriers is generally low, roughly half compared to methane and a factor four below conventional fuels like diesel, see Figure 1-4. Ammonia, containing 17% hydrogen by weight, has a higher volumetric energy density

than pure hydrogen, but a low gravimetric density. Due to the low temperature or very high pressures at which hydrogen is stored, the tanks and systems will add significantly to volume demands and weight, e.g. an LH2 tank system may be almost 10 times heavier than the fuel stored. Thus, both for LH2 and ammonia the storage energy density by weight and volume would be significantly lower than for conventional fuels.

Availability – The hydrogen supply chain and infrastructure are currently not well developed. LH2 is not available at all in Northern Europe. For any project planning to consume significant quantities of hydrogen, the production of hydrogen must be part of the planning. Only 4% of the hydrogen produced globally is from electrolysis, of the order 95% is from steam reforming of fossil fuels. The majority of hydrogen produced globally (53%) goes to ammonia production. Ammonia is to a greater extent a traded commodity. 175 million tons were produced globally, almost 90% of this is used for fertilizer production. Green ammonia, produced from renewable hydrogen, is not currently available, initiatives to produce green ammonia have been announced, e.g. in Norway at Yara Porsgrunn, see Figure 1-3.

Safety – Hydrogen is a very reactive and flammable gas normally stored either as LH2 at extremely low temperatures (20.4K) or as compressed gas at pressures up to 1000 bar. The general lack of experience with hydrogen safety both in the public, but also among many technology providers, is a significant challenge.

Technology maturity – The cost of hydrogen infrastructure and systems is currently significant, and the maturity mixed. Much of this is expected to improve with increasing demand and technology development, still, innovative projects must expect to spend significant efforts to overcome unforeseen challenges on topics which would be trivial for conventional fuels. Challenges for ammonia are that current ammonia SOFC fuel cells are very large, while its low reactivity gives challenges to combustion engines, one way to solve this may be to inject some hydrogen.

In Table 1.1 an indicative ranking of the above properties for a selection of conventional fuels, hydrogen, hydrogen carriers and ammonia are shown. As each project will be different, technology choice will vary and many parameters will fluctuate depending on oil and electricity prices, taxes, incentives and policies, the parameter ratings can vary significantly from project to project.

Figure 1-3   Yara ammonia plant at Herøya in Porsgrunn, Norway, is among the larger ammonia plants in the world (photo Ernst Vikne/Wikipedia). They have announced plans to start production of green ammonia.

To conclude, despite a number of challenges there is a strong political dedication in the society to develop zero-emission technologies with significant R&D funding and stimuli provided from authorities. For the hydrogen technologies to become commercially viable and implemented in large-scale, there may be a need for a more extensive taxing of pollution, and, to ban pollution or emissions in specific areas. To facilitate the transition to increased use of zero-emission fuels it may also be recommended

that the authorities actively contribute to the development of important infrastructure, e.g. a supply chain of LH2 or green ammonia, to limit the investment risk for the front-runners.
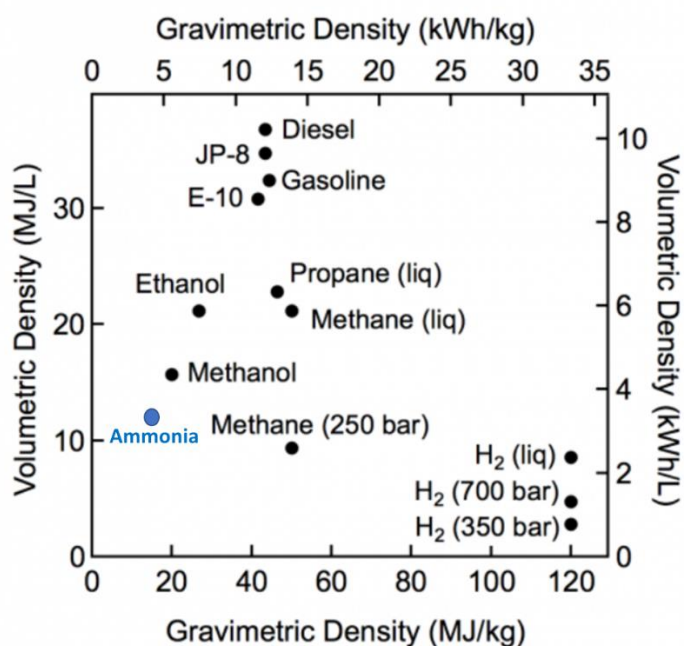
Figure 1-4   Net fuel density for various fuels (Source DOE energy.gov), ammonia has been added to the original plot. Weight and volume of tanks and systems will add to this.

Table 1.1 – Fuel properties overview and indicative rating (Good, Fair, Poor)

Fuel	Sustain-ability	Local emission	Comfort	Cost	Storage density	Avail-ability	Safety	Matu-rity
MGO	Poor	Poor	Fair	Good	Good	Good	Good	Good
HFO	Poor	Poor	Fair	Good	Good	Good	Good	Good
Biodiesel	Good	Poor	Fair	Poor	Good	Fair	Good	Good
e-fuels (F)	Poor	Fair	Fair	Fair	Good	Poor	Good	Good
e-fuels (R)	Good	Fair	Fair	Poor	Good	Poor	Good	Good
Methanol (B)	Good	Good	Good	Fair	Fair	Poor	Good	Fair
Methanol (F)	Poor	Good	Good	Good	Fair	Fair	Good	Fair
LNG	Fair	Good	Fair	Good	Fair	Fair	Good	Good
LBG	Good	Good	Fair	Fair	Fair	Poor	Good	Good
GH2	Good	Good	Good	Poor	Poor	Fair	Fair	Fair
LH2	Good	Good	Good	Poor	Poor	Poor	Fair	Poor
NH3 (F)	Poor	Good	Fair	Fair	Poor	Good	Fair	Fair
NH3 (R)	Good	Good	Fair	Poor	Poor	Poor	Fair	Fair
LOHC	Good	Good	Good	Poor	Poor	Poor	Fair	Poor

(R) – produced from renewable energy, (B) – from biomass/waste, (F) produced from fossil sources

1.2   Infrastructure requirements and considerations

For a vessel operating on hydrogen or ammonia the following infrastructure may be required for production, distribution, storage and bunkering.

Production facilities:

- Local production facilities for compressed hydrogen with electrolysers, compressors and high-pressure storage may be established at or near the home base or along the vessel route, dimensioned for one or more vessels for one or more routes. Electrolyser units would normally be inside containers. Typical production may be up to 1 ton per day, with local storage for direct bunkering onto vessels, see Figure 1-5.

- Regional production facilities may be built for compressed hydrogen with electrolysers, compressors and high-pressure storage from renewables, e.g. solar or wind, with short transport distances to vessel bunkering locations for one or more vessels on one or more routes. Typical production may be a 1-10 tons per day with road transport for transfer to vessel, bunkering storage or swap-containers. Facilities could also be located near offshore wind parks with hydrogen stored for peak-shaving and load distribution of renewable energy providing power to oil platforms and possibly bunkering possibilities for hydrogen driven PSVs.

- Central large-scale production facilities for compressed hydrogen with electrolysers or SMR (with or without CCS), compressors and storage for wide distribution nationally to different end users and industries. These facilities will be industrial-scale with a production of 10s of tons per day, see Figure 1-5.

- Central large-scale production facilities for liquid hydrogen (LH2), hydrogen production methods will be same as for industrial-scale compressed hydrogen plants but with liquefaction loops instead of compression and liquid storage and shipment by road tanker, ship, train or through swap-tanks. Typical production could be 30-60 tons per day.

- Central large-scale production facilities for liquid ammonia, production methods will be same as for industrial-scale compressed hydrogen plants (green ammonia will require that hydrogen is produced by electrolysers using renewable power), thereafter hydrogen is combined with nitrogen at high pressure through the Haber-Bosch process. Ammonia will be shipped by road tanker, ship or train, normally pressurized (saturation pressure is 10 bara at 25°C), but alternatively refrigerated (-33.4°C at atmospheric pressure).

- Small scale, local or regional production facilities for ammonia may also appear, with electrolysers for hydrogen production combined with small-scale Haber-Bosch units. As more than 80% of the effort/energy goes into producing hydrogen, such a facility could be competitive to centralized large-scale production if particularly low power price (e.g. from stranded renewable energy) can be utilized.
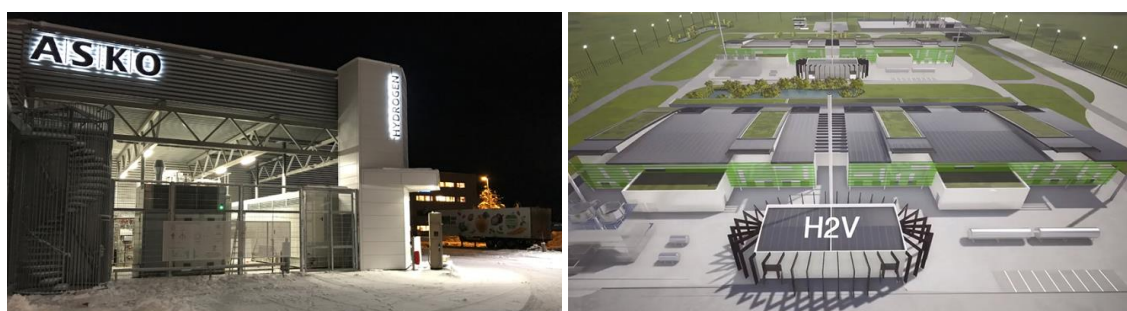

Figure 1-5   Examples of green hydrogen production at various scale, ASKO in Trondheim (left) with local hydrogen production partly from solar energy (capacity 300 kg/day), and planned H2V-facility near Le Havre, France, (right) to be opened 2022/23 (planned production 77 ton/day).

Distribution/transportation of fuel:

- With local production next to bunkering site there would normally be no need for transportation.

- For compressed gas and ammonia transport by pipeline from regional production sites could be an option but may not be likely.

- For compressed hydrogen road transport from regional or centralized production facilities may be the most likely. Iso-containers filled with high pressure tanks can carry up to 500 kg (6m container) or 1,000 kg (12m container), which will also be the typical capacity for smaller or larger trucks. Both swapping of tanks/container and bunkering to local storage may be seen.

- Liquid hydrogen will most likely be transported by road tankers from centralized production facilities. Such road tankers can carry around 4,000 kg of hydrogen and would either be bunkering the vessels directly on arrival or transfer the LH2 to local storage tanks.

- Ammonia, either refrigerated or pressurized, would most likely be transported by road tanker from regional or centralized production plants, the typical maximum truckload of ammonia is 25,000 kg.

- Railway transportation could be an alternative to truck transportation for ammonia, for instance to ports with main railway connection like Bergen, towns and cities from Oslo to Stavanger and between Trondheim and Bodø. This could also be an option for hydrogen.

- Shipment by sea could be an alternative to road tanker transportation for ammonia, liquid hydrogen and compressed hydrogen, in particular when larger quantities are to be shipped from a central production facility to locations along the coast without railway connection and with poor road infrastructure.

Figure 1-6   Transportation of hydrogen and ammonia in Norway can be expected done primarily by liquid road tankers or compressed gas trucks or by ship, photos: Air Products (left), Hexagon (middle) and Wilhelmsen (right).

Storage facilities:

- For flexibility and redundancy against production or delivery problems, it is often practical to have fuel storage for a few days' consumption at the bunkering site. For ammonia, whether stored as refrigerated liquid or pressurized, this is assumed to be a preferred solution. Bunkering directly from tanker may also be an option.

- For liquid hydrogen bunkering sites. it will probably vary whether a storage facility will be planned or not. Bunkering for cryogenic fuels like LNG (and planned bunkering operations for LH2) are sometimes done directly from road tanker to vessel due to the significant thermal leakage to the cryogenic gas during the extra transfer operation, and possibly additional risk.

- For vessels operating using compressed hydrogen with regional/central production, it is assumed that swap-solutions or storage onshore (and possibly also on a bunker vessel) will be the preference, thus that standard transport units will be stored and replaced at the bunkering site. For vessels with local production of compressed hydrogen local storage tanks, considered as part of the production facility, will be likely.
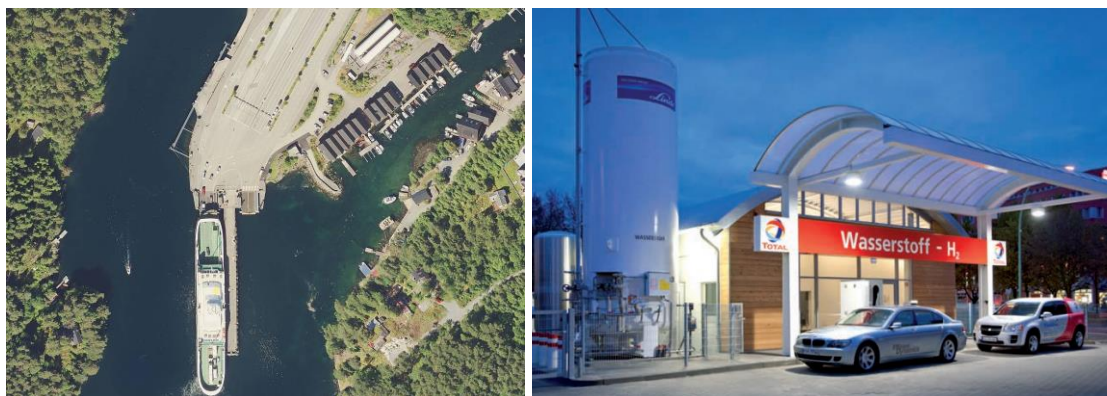
Figure 1-7   LNG storage at Halhjem ferryport (left –kart.gulesider.no) and vertical LH2 storage tank at refuelling station in Berlin, Germany (right – TOTAL/Pierre Adenis).

Bunkering site:

- Due to the lower energy density for hydrogen and ammonia compared to conventional fuels, a higher bunkering frequency may be required than for conventional fuels. The preferred solution would be to be able to bunker at the quay without any significant interference with normal operations of the vessel or adjacent vessels. For compressed hydrogen, delivered from standardized truck dispensers with built-in safety systems from the car industry seems realistic. The same could apply to bunkering by tank swap. These solutions are expected applicable primarily for smaller vessels.

- For fuels requiring larger safety distances it could also be feasible to bunker at quay if the bunkering operation is performed outside periods of operation (e.g. at night) provided it is possible to evacuate/secure the necessary area and establish a safety zone. For larger vessels it may also be possible to continue loading or other operations in parts of the vessel while bunkering operation takes place at the opposite end of the vessel, provided a large enough safety distance to people and operations at the vessel or quay can be ensured. Bunkering vessels operating on the outside of larger vessels could be an option, see Figure 1-8.

- For most operations it should be expected that the bunkering would take place at a controlled area with a sufficient safety distance to passengers or simultaneous operations, this could be central bunkering facilities serving various customers (e.g. in larger harbours), or dedicated facilities for one particular operation in more rural areas.

Figure 1-8   Bunkering operations from tanker vessel to Hurtigruten (left – photo: Gasnor/Marit Hommedal) and from road tanker to tug boat (right – photo: Gasnor)

2 Hazards and risks related to hydrogen and ammonia

In this chapter the properties of hydrogen and ammonia are discussed and compared to methane/LNG as a known reference fuel. As an introduction a brief overview of relevant accidents related to the fuels discussed is given. Thereafter, overview of properties related to storage, release and dispersion, as well as fire and explosion hazards is presented and discussed. Experiments performed to understand relevant hazards are discussed before giving an overview of vulnerability of humans and structures to fire, explosion and toxic exposure.

2.1 Relevant accidents

Hydrogen, ammonia and natural gas have all been widely used in the society in the past, how they were used however differed significantly.

Until recently the handling of significant quantities of hydrogen was primarily by major industrial users within the oil and gas, chemical and space industries. Over the past couple of decades, the handling of hydrogen among small businesses and soon consumers, has increased related to low emission technologies. Hydrogen is introduced for use in cars, buses, marine vessels, trains and heavy-duty vehicles. It is also in the process of being introduced for heating in homes in the UK.

Ammonia is one of the most widely used chemicals with nearly 200 million metric tons produced every year, approximately 80% is used for fertilizers and other agricultural use, 18% in industrial processes, and 1-2% is used for refrigeration systems. While most ammonia is produced and used at large industrial plants, the use among the public has been wider than for hydrogen, e.g. in thousands of larger refrigeration systems (freezers, coolers and ice-skating facilities), air-conditioning systems and within farming.

The use of methane (natural gas) is more extensive, it is widely handled within the hydrocarbon industries, upstream and downstream, and used for power, heating and feedstock for the chemical industry. The use is widely distributed since natural gas is used for domestic heating in numerous countries. Since 2000 LNG has been used as a maritime fuel, and more recently natural gas use has become widespread as fuel for buses and other vehicles.

The purpose of this description of accidents is to give some understanding of potential hazards and risks related to the use of the different gases. The purpose is not to scare, but to give some insight in hazard potential and accident scenarios to be prevented.

2.1.1 Hydrogen

The most famous accidents with hydrogen are probably the Hindenburg Disaster 1937. An airship crossing the Atlantic Ocean with 97 persons on board, filled with 15-20 tons of hydrogen, caught fire approaching the destination in New Jersey killing 36 people. Within the nuclear industry there have been major accidents in which explosions in hydrogen generated from meltdown represented steps in the chain of events, this was well documented in the recorded videos of building explosions during the Fukushima accident in 2011. The 1986 Challenger space shuttle disaster killing all 7 astronauts, also led to the release and a fireball involving liquid oxygen and hydrogen from the failing fuel tanks. The relevance of these accidents to hydrogen infrastructure is however limited, see illustrations in Figure 2-1.

Due to the high reactivity of hydrogen combined with the strong buoyancy, the process industry has learnt to handle hydrogen outdoors when possible. As a consequence, the amount of hydrogen involved in explosion incidents has mostly been limited, and injuries and fatalities resulting from incidents are kept low. The Tesoro refinery near Seattle, WA, USA, had a hydrogen explosion accident in 2010 where high temperature hydrogen attack (hydrogen atoms combining with the carbon in carbon steel forming methane inside the steel) led to the burst of a heat exchanger during a start-up procedure, claiming the lives of all 7 workers involved [CSB, 2014].

Figure 2-1 **Spectacular accidents Hindenburg, Fukushima and Challenge, in which the combustion of hydrogen was part of the chain of events, neither are considered particularly relevant for risks to hydrogen infrastructure.**

Cold climate with snow and ice part of the year can make it necessary to process hydrogen indoors, this can give potential for more severe explosion events in case of a major leak. In 1985 a strong hydrogen explosion took place at the NI ammonia plant of Norsk Hydro (now Yara) at Herøya, Norway, damaging a larger plant building beyond repair and leading to severe window shattering within 400m radius. This resulted in fatalities of two employees. With the large amounts of hydrogen continuously produced and handled at this facility other significant explosions have taken place over the years, for instance two explosions in pipelines (1986 and 1997). All three explosions may have involved deflagration-to-detonation transition (DDT), see [Bjerketvedt, 2014].

The recent drive for more sustainable energy carriers has led to a more distributed small-scale use of hydrogen in the society. A number of smaller businesses are developing hydrogen infrastructure elements like storage tanks, electrolysers, fuel cells and refuelling infrastructure. System integrators or manufacturers are applying these to develop small scale hydrogen production or operations of vehicles/vessels fuelled by hydrogen. An increasing number of accidents has been seen among such businesses in recent years. Causes may vary, lack of experience handling hydrogen (or compressed flammable gas in general) and a misconception by many green entrepreneurs that hydrogen is safer than other fuels may explain some incidents, see e.g. https://hydrogeneurope.eu/hydrogen-safety where it is claimed that hydrogen is safer than other fuels, the very high reactivity of hydrogen is not mentioned at all. In June 2019, Norway saw a significant explosion at an Uno-X Hydrogen refuelling station at Kjørbo in Sandvika (https://nelhydrogen.com/status-and-qa-regarding-the-kjorbo-incident/). A major release from a 950 bar tank containing less than 3 kg hydrogen ignited after 2-3 seconds resulting in a strong outdoor explosion. An attempt to model possible release and explosion scenarios using computational fluid dynamics (CFD) indicates that an unconfined detonation of around 0.5 kg hydrogen would be likely, and required, to explain observed effects [Hansen, 2019]. There have been quite a few explosions involving facilities handling hydrogen recently, e.g. in Gangneung, South-Korea (May 23, 2019), Santa Clara, California (June 2, 2019) and Long View, North Carolina (April 7, 2020). Effects are mostly local, usually with none or at worst 1-2 fatalities. Photos of Herøya, Kjørbo, Santa Clara and Gangneung explosions are shown in Figure 2-2.

Incidents with LH2-delivery trucks have also been reported in the USA, see examples in Figure 2-3. Given the limited number of smaller enterprises handling hydrogen it can be suspected that the incident frequency within this industry is somewhat high.

More hydrogen incidents can be found in the US DoE Lessons learned (http://h2tools.org/lessons) and the European Union HIAD database (https://odin.jrc.ec.europa.eu/giada/). Please be aware that these databases are far from complete, some of the incidents mentioned above are not found in these databases, while other known accidents can be hard to find when searching.

Figure 2-2   Upper left picture shows building damage from 1985 explosion at Herøya, while upper right picture shows the Kjørbo hydrogen refuelling station shortly after the 2019 explosion. Lower left picture shows burnt trucks in 2019 explosion in Santa Clara, CA, while lower right picture shows tanks exploding in 2019 in Gangneung, South Korea.

Figure 2-3   Examples of leaks and fires related to transportation of hydrogen, upper plots show compressed gas incidents from in Los Angeles, California, 2018 (left) and Rochester; New York, 2010 (right) while lower plots show incidents with fires in LH2 trailers in Ohio, 2015 (left) and El Cajon, California, 2018 (right).

2.1.2 Ammonia

Due to the low flammability of ammonia compared to hydrocarbon fuels and chemicals the ammonia accident statistics does not include fire and combustion events of ammonia. Severe explosion and fire events at facilities handling ammonia are usually either related to hydrogen (11 ignited hydrogen events

are listed in the HIAD database) being a main component when producing ammonia, or ammonium nitrate fertilizer produced from ammonia. Ammonium nitrate can be turned into a solid explosive when mixed with fuel oil or certain other components, as seen in major explosions in Oppau (1921), Texas City (1947), and more recently in Toulouse (2001) and Texas West (2013). While these ammonia production incidents may have relevance for the infrastructure, these are discussed as part of the hydrogen accidents, the fertilizer accidents have less relevance. The ammonia incidents considered are therefore all related to releases of ammonia and its toxic and corrosive effects.

In Norway no fatal accidents involving ammonia release have taken place in recent years. In 2002 an overfilled tank exploded on a farm in Larvik during a heat wave killing a worker in the next room and 137 cattle. Ammonia leak incidents are relatively frequent, the typical outcome is injuries and discomfort, with exposed people seeking medical treatment.

An annual fatality rate of 2 per billion people from ammonia accidents has been claimed [Anderson, 2017], which is very low relative to the extensive use of ammonia in the society. A US Government fact sheet (http://www.allgov.com/news?news=849995) indicated that more than 10,000 facilities in the USA stored 4.5 tons ammonia or more, in the period from 1996 to 2011 these had 939 accidents with a total of 19 fatalities and 1651 injuries, supporting the low fatality rate estimate as not all these accidents involved ammonia releases. Due to the strong smell of ammonia, which becomes unbearable at concentrations well below fatal concentrations, fatalities will mostly be seen when people are exposed to very high concentrations (next to a major release) or trapped without the ability to escape the toxic gas plume.

Examples of major accidents include the 1976 ammonia transport truck falling from a Houston highway ramp into a busy road leaving 7 fatalities and 200 people injured, see Figure 2-4. An even higher death toll of 129 is reported from an overfilled ammonia truck exploding in Senegal in 1992, showing the major accident potential when catastrophically releasing large quantities of ammonia.

Figure 2-4   May 11, 1976, an ammonia truck with near 20 tons of ammonia crashed and fell from an elevated highway ramp in Houston, Texas, releasing its entire ammonia inventory within moments (Photos: Houston Chronicle)

2.1.3   Methane and natural gas

From the oil and gas industry, and before that, from coal mines, the society has become well aware of the risks of methane and natural gas. The Courrieres coal mine explosion in France 1906 claimed 1099 lives, while the 1942 Benxihu explosion in China took more than 1500 lives. Norway had a coal mine accident with the 1962 Kings Bay explosion claiming 21 lives. While accidents can be strongly reduced with proper safety measures (ventilation, detection, sealing off abandoned areas, coal dust handling) major accidents continue to happen. After the 2006 Sago mine explosion in West-Virginia killing 12 miners, US NIOSH concluded that a methane detonation had taken place [Zipf et al., 2007]. Despite renewed focus to understand and prevent such accidents an even worse explosion in the Upper Big Branch Mine took place in the same region in 2010, killing 29 miners.

In Norway the oil exploration has made us well aware of risks of natural gas, 5 lives were lost on oil rigs in the 1970s, another in 1985 with the West-Vanguard accident. The UK Piper Alpha explosion, which escalated into a fire inferno claiming 167 lives, further increased the focus on gas safety in the oil and gas business. Despite around 500 of gas leaks larger than 0.1 kg/s reported since 1992 on the Norwegian Continental Shelf, no ignited hydrocarbon leaks have been reported since 1992 [PTIL, 2019].

Natural gas is widely used for heating and cooking around the world, and accidents happen regularly in homes due to leaks. The deadliest explosion of this category may be the New London, Texas, school explosion in 1937, claiming the lives of 294 school children and teachers. In Figure 2-5 pictures after some accidents are shown from the USA and the UK, in some cases there is only rubble left of homes. In Merrimack Valley in Massachusetts (2018) the Columbia Gas Company by mistake increased the pressure in the low-pressure gas piping from 35 mbar to 5 bar leading to leaks into numerous houses among which 40 exploded/burned, leading to one fatality. In 1968 at Ronan Point, London, UK, a 22-storey apartment building partially collapsed after a gas explosion in 18th floor killing 4 residents.

Figure 2-5   House explosions from Pennsylvania 2017 (Lancaster Online, upper left), from 1999 in Scotland (BBC, upper right), from Massachusetts 2018 (NTSB, lower left) and Ronan Point, England 1968 (Derek Voller, lower right)

In Norway the use of methane for heating is very limited and mostly among industrial users. The use of methane and natural gas has however been introduced within transportation since 2000. There can be a significant accident potential from LNG related to production (e.g. Skikda 2004, 27 fatalities), storage (e.g. Cleveland 1944, 128 fatalities when LNG tank failed) as well as transportation (e.g. 23 dead from gas pipeline explosion in Belgium 2003). The introduction of LNG as fuel for ships since 2000 has so far taken place with no serious accidents. By 2017 there were more than 100 vessels fuelled by LNG, more than half were Norwegian. Across Norway major cities have phased out most buses fuelled by diesel and are now operating 100s of buses on biogas (methane). A similar trend is seen in Sweden. From Sweden a couple of accidents have taken place in recent years which highlight a potential for serious accidents with such gas buses. In Gothenburg 2016 a small leak from a gas tank on the roof of a bus ignited inside a tunnel. Passengers became aware of the incident and warned the driver who drove out of the tunnel and evacuated passengers. Half an hour later a tank being heated by the jet fire exploded injuring first responders. An even more serious incident took place in Stockholm in March 2019. The driver of a bus not in route returning to the bus depot took a short cut through a tunnel. Unfortunately, the tunnel was too low for the bus, and the gas tanks hit the height restriction barrier ahead of the tunnel and ruptured. Within fractions of a second unburnt gas was expelled outwards and down into the bus, ignited and flames was seen burning through the empty passenger compartment of the bus, see Figure 2-6. If this had happened in a full bus with more than 100 passengers, the death toll would likely be high.
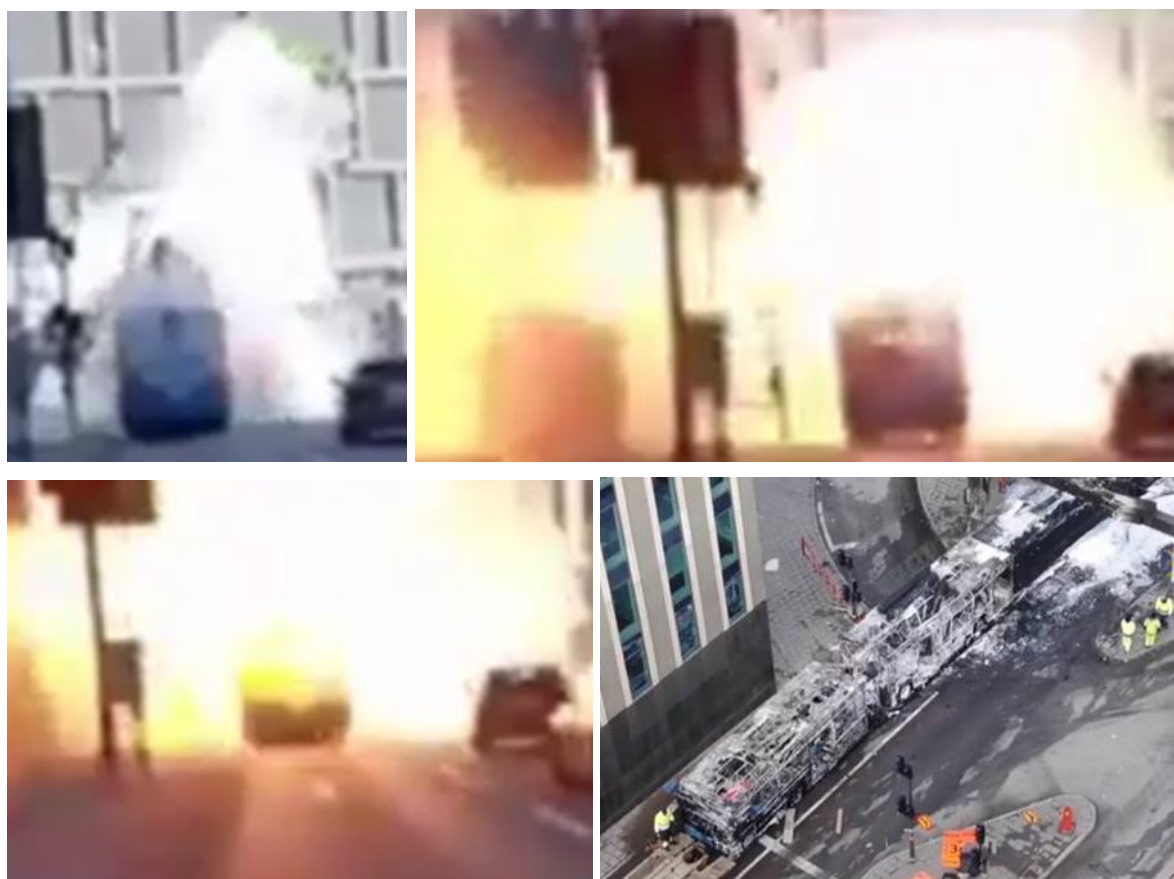

Figure 2-6   Stockholm gas bus explosion 2019 (Video frames from Expressen.se). Frames show 1) pressure tank rupture, 2) ignited gas explosion, 3) flashfire/explosion through bus compartment, and 4) completely burnt-out bus afterwards.

2.2   Properties relevant for storage, release and dispersion dynamics

When presenting properties of hydrogen and ammonia with comparison to methane these are split into two groups. Properties related to storage, leaks and dispersion phenomena are presented in Table 2.1 and discussed below, while properties related to flammability of the various gases are presented in Table 2.2 and discussed in the following section.

The boiling point of the three gases are very different. Hydrogen and methane (LNG) are both cryogenic gases.

For liquefied methane (LNG), infrastructure with distribution, storage and use e.g. in ships has been established. A main challenge is that the cryogenic liquid must be stored in properly insulated double tanks as any heat ingress will lead to boil-off of methane or increased pressure in the storage tank. If LNG is spilled, some gas will immediately evaporate/flash depending on temperature, leak rate and spill trajectory in air, for larger releases near ground level most of a spill may form a pool which will spread and boil until the ground/substrate has been cooled to the LNG boiling point. The evaporating gas is ~50% denser than ambient air. A denser than air gas release (e.g. LNG-vapour) will stick to the ground and dilute much slower than a buoyant gas (e.g. natural gas at ambient temperature), leading to significantly longer hazard distances. To limit the risk effort should be made to collect spilled LNG in dedicated bunding to minimize heat transfer and evaporation.

The boiling point of liquid hydrogen (LH2) is only 20.4 K (-253°C) which is 90 K below the boiling point of LNG. It is also lower than the boiling point and freezing point of the main components of air, nitrogen and oxygen. Implications of this is that LH2 cannot coexist with air, a spray of LH2 into air will immediately evaporate in contact with air, while air will condense and possibly freeze into solid oxygen and nitrogen. Only very significant releases at or close to ground will have the potential to form a pool, but this will be short-lived as heat from the ground will immediately evaporate the LH2. It can thus be expected that all LH2 being released will almost immediately evaporate, and there should be no need for LH2 collection systems other than some cryogenic spill protection at exposed locations. Significant deposits of frozen air can be expected, with risk for LH2-condensed oxygen detonations. The low boiling point makes it critical to insulate properly any storage tanks and piping handling cold hydrogen. Insulation must be either by vacuum or helium, if nitrogen is used it would condense or freeze. Uninsulated parts of the containment would lead to LH2 boiling or pressure increase inside the piping, and air condensation and icing outside the piping. Due to different boiling/freezing points for nitrogen and oxygen, zones with elevated oxygen content (and increased fire/explosion risk) may form e.g. below poorly insulated pipes carrying LH2 or cold hydrogen gas. The density of evaporated LH2-vapour is almost neutral in ambient air, however if evaporation is caused by heat transfer from ambient air the plume of cold air and evaporated hydrogen will be significantly denser than ambient air at high concentrations. When further diluted in air to lower concentrations, the density becomes neutral (dry air) or buoyant (with some air humidity), see [Hansen, 2020]. The fact that a significant LH2 release will show dense gas behaviour is not well known but must be taken into consideration when planning hydrogen infrastructure and system designs.

The density of LH2 is about 1/6th of liquid methane (LNG), this will influence the outflow velocity given a leak. For a leak from the same pressure and same hole size, leak velocity and volume rate of LH2 will be 2.45 times higher, while the mass leak rate will be 2.45 times lower compared to liquid methane (LNG). As discussed in the next section the combustion energy for these two releases are similar.

Typical storage pressures for both LNG and LH2 are below 10 barg. As critical temperatures are 191 K and 33 K for LNG and LH2, respectively, storage in liquid phase is not possible at room temperature.

The boiling point of ammonia is -33.4 °C. Ammonia is typically stored either refrigerated at room temperature or pressurized at ambient temperature. The vapour saturation pressure curves for LH2, liquid methane (LNG) and ammonia are shown in Figure 2-7 for the typical storage conditions. If an atmospheric pressure tank of refrigerated ammonia would start leaking, ammonia would pour out pushed by gravity (3m ammonia level would correspond to 0.2 bar overpressure), giving very moderate

leak rates and very limited evaporation until a pool is formed that would evaporate by heat transfer from the ground. A leak from a pressurized ammonia tank at ambient temperature, on the other hand, would at 20°C be pushed by a vapour pressure of 7.5 barg (6x higher leak rate than for refrigerated ammonia example). 8% of the liquid ammonia would immediately evaporate when leaving the tank, potentially generating fine mist particles when flashing, that would also evaporate when further diluted in air. The properties of the pool bunding/collection system will decide how large a difference there is in total evaporation rate between the leak in the refrigerated tank and the ambient temperature tank.

Table 2.1 – Storage & dispersion properties of hydrogen and ammonia compared to methane

Properties	Hydrogen	Ammonia	Methane
Boiling point	-253°C (20.4 K)	-33.2° C (240 K)	-162°C (111 K)
Liquid density (BP & 20°C)	70.8 & N/A kg/m^3	682 & 610 kg/m^3	423 & N/A kg/m^3
Molecular weight	2 g/mol	17 g/mol	16 g/mol
Density at STP (relative to air)	0.09 kg/m^3 (0.07)	0.76 kg/m^3 (0.59)	0.72 kg/m^3 (0.55)
Density gas at BP (relative to 20°C air)	1.20 kg/m^3 (1.01)	0.86 kg/m^3 (0.71)	1.75 kg/m^3 (1.46)
Compressed gas density	44 kg/m^3 (700 bar)	N/A	180 kg/m^3 (200 bar)
Speed of sound STP	1290 m/s	440 m/s	450 m/s
Critical point	33.2 K at 13 bar	406 K at 113 bar	191 K at 46 bar
Vapour pressure at 20°C	N/A	8.5 bar	N/A
Liquid to gas volume ratio (BP & 20°C)	60 & 840	790 & 970	240 & 600
Combustion energy (HHV)	142 MJ/kg	19 MJ/kg	56 MJ/kg
Heat of vaporization	446 kJ/kg	1375 kJ/kg	512 kJ/kg
Material strain	H_2 embrittlement cryogenic	Corrosive in water solutions	Cryogenic
Main hazards	Explosive Flammable Cryogenic	Toxic Flammable	Explosive Flammable Cryogenic
Other issues	Ortho-para conversion, solidification of air, permeation, BLEVE	Hydraulic shocks	Roll-over, BLEVE, RPT
Toxic combustion products	(Some NOx)	NH_3, (Some NOx)	CO_2, CO, soot, NO$_x$
Smell threshold	Odourless	5-50 ppm	Odourless

With molecular weight 2 g/mol hydrogen is the lightest element at ambient temperature with a relative density of 0.07 compared to air, for comparison ammonia and methane have relative densities 0.59 and 0.55. At their boiling points only ammonia vapour is lighter than ambient air (relative density 0.73). High concentration ammonia evaporating from a pool could therefore be expected to rise upwards, when further diluted, however, density differences may be of secondary importance relative to wind.

Compressed hydrogen is mostly stored at pressures from 200 bar to 500 bar but as high as 700 to 950 bar for automotive applications, while compressed methane is mostly stored at 200 bar. Due to a poor compressibility for hydrogen at high pressures (Z=1.45 at 700 bar) compared to methane (Z=0.8 at 200

bar) the volumetric combustion energy density of the 200 bar methane tank is 60% higher than for the 700 bar hydrogen tank.

A hydrogen release from a given pressure, temperature and hole size will have a flow velocity and volume release rate around 2.8 times higher than a methane release at the same pressure and temperature, while methane mass flow rate will be 2.8 times higher than the hydrogen mass flow rate. The combustion energy for the two releases would be comparable.

To understand the possible differences in evaporation, dispersion and hazard distances some simulation examples are included in Chapter 5.

The heat of vaporization per unit mass is comparable for methane and hydrogen, for the same heat transfer evaporating hydrogen the combustion energy of hydrogen is roughly 3 times higher. Combined with the lower temperature of LH2 this sets significantly stricter requirements for insulation of LH2 systems than for LNG to limit boil-off to an acceptable level. While boil-off for LNG should be limited due to greenhouse gas emissions, the reason to limit boil-off for LH2 is primarily to conserve the energy on the tank. Due to the low molecular weight any hydrogen released would leave the atmosphere and end up in space. Costly tank reliquification systems, or special valves or procedures to prevent gas emissions during bunkering operations must therefore be justified commercially, not for environmental reasons, as for LNG.

For ammonia the heat of vaporization is 10-20 times higher relative to its heat of combustion compared to hydrogen and methane. This is one reason ammonia has become the most popular heat transfer fluid for the refrigeration industry. Thus, the heat of vaporization corresponds to as much as 7.2% of the combustion energy. Ammonia boil-off or leaks during bunkering should be prevented, not due to green-house gas potential, but due to the strong odour at very low concentrations.

The different fuels can give various challenges to materials used for storage and handling. Tank and piping materials, as well as materials of critical objects nearby, should keep their strength both at very low storage temperatures but also be robust against potential flame impingement. LH2 and LNG are cryogenic gases, therefore thermal contraction and ductile to brittle behaviour of certain materials can be a challenge. Stainless steel maintains strength much better than carbon steel at low temperatures and could be used for tank and piping materials, while cryogenic spill protection (CSP) may be considered to protect leak exposed surroundings.

Another major challenge to materials is hydrogen embrittlement. Due to its small size, hydrogen atoms/molecules will permeate through materials of storage tanks and piping to a greater extent than other gases. For certain materials, including carbon steel, hydrogen may combine with carbon in the steel and form methane pockets potentially weakening the materials. Such mechanisms, e.g. high temperature hydrogen attack, was identified as cause of the Tesoro Refinery Explosion 2010. Again, low carbon austenitic stainless-steel qualities (e.g. 316L or 304L) are more robust than carbon steel. Attention must also be given to permeation of hydrogen from high pressure storage tanks or piping. If there is no ventilation of the surrounding volumes, hydrogen concentration can gradually build up to flammable concentrations.

Pure anhydrous ammonia is generally not corrosive to tank materials, however mixed with some water it becomes highly corrosive to a range of materials including zinc, copper and brass. Stainless steel and iron are reasonably robust, even with some humidity, within the normal operational temperature range of ammonia.
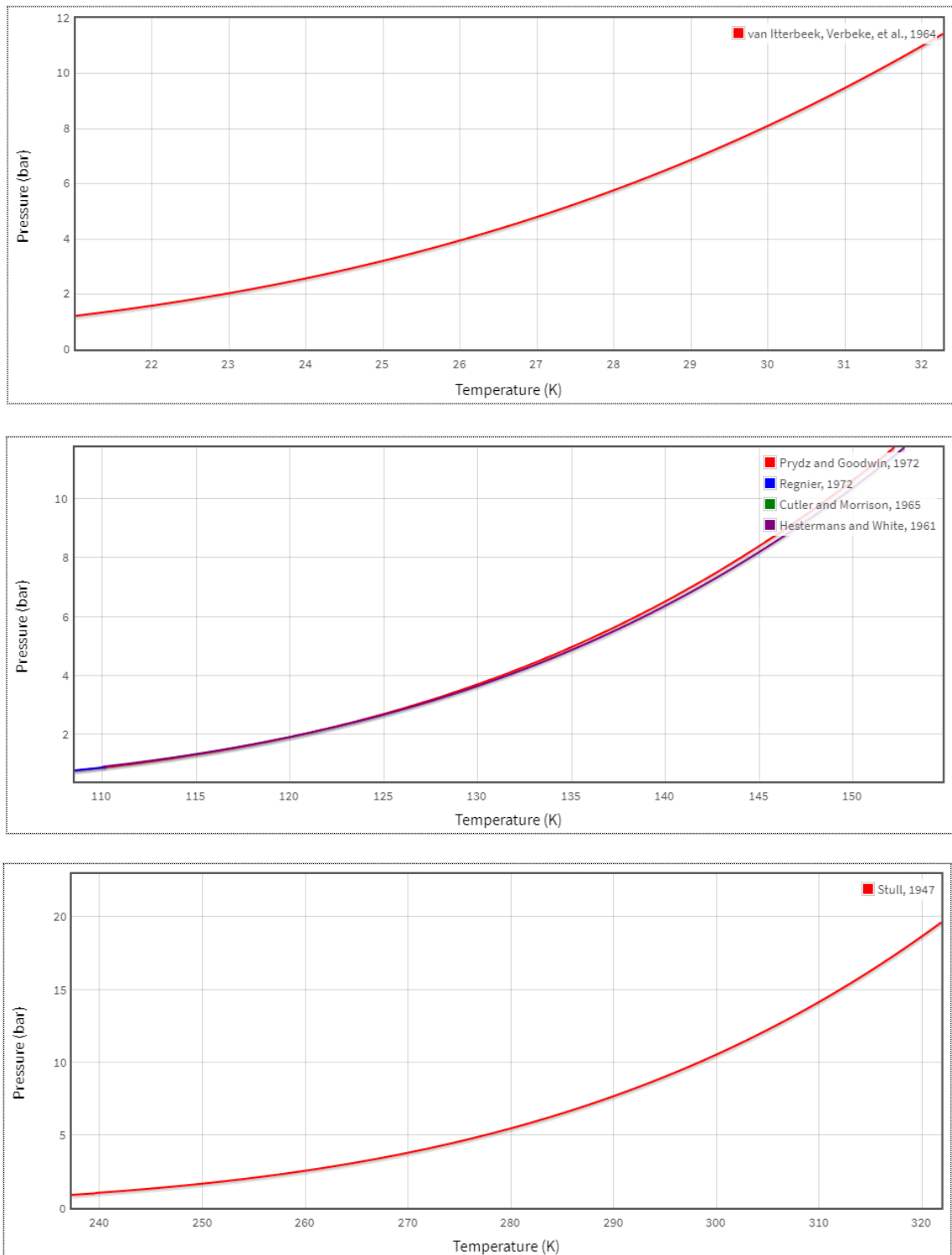
Figure 2-7   Vapour saturation curves for LH2 (upper), liquid methane (middle) and ammonia (lower) for typical storage conditions (www.nist.gov)

Some other possible safety concerns include ortho to para conversion for LH2. Hydrogen exists with two different spins called ortho-hydrogen and para-hydrogen, with ortho-hydrogen having a higher energy level than the para-hydrogen. When hydrogen transfers from ortho to para-hydrogen the heat release is higher than the heat of vaporization, thus if this happens for LH2 it could lead to immediate boiling of a larger amount of LH2. Whether there is any risk related to rapid ortho to para conversion of significant volumes of hydrogen or whether this is a theoretical hazard is unclear. In any case, producers of LH2 will have production methods and routines to ensure that their product consists of para-hydrogen only.

For LNG there are roll-over challenges in which LNG of different compositions can develop layers where a colder, but lighter composition, filled onto the tank could make a dense layer at the bottom of the tank. When the mixture is gradually heated with time, the denser composition in the warmer top layer will be cooled due to surface evaporation and gradually become denser, and at some stage a roll-over can happen, see Figure 2-8. For liquid hydrogen, components of different specific density do not exist, however, there is a strong density gradient with temperature. For a storage tank LH2 near walls will be slowly heated while the surface layer will be cooled by evaporation. As these processes are slow and LH2 viscosity low, the density differences should lead to a continuously mixing so that major density differences will not develop. Similarly, if colder or warmer LH2 is filled onto a tank the temperature equalization should be rapid, and roll-over phenomena should not be a concern.
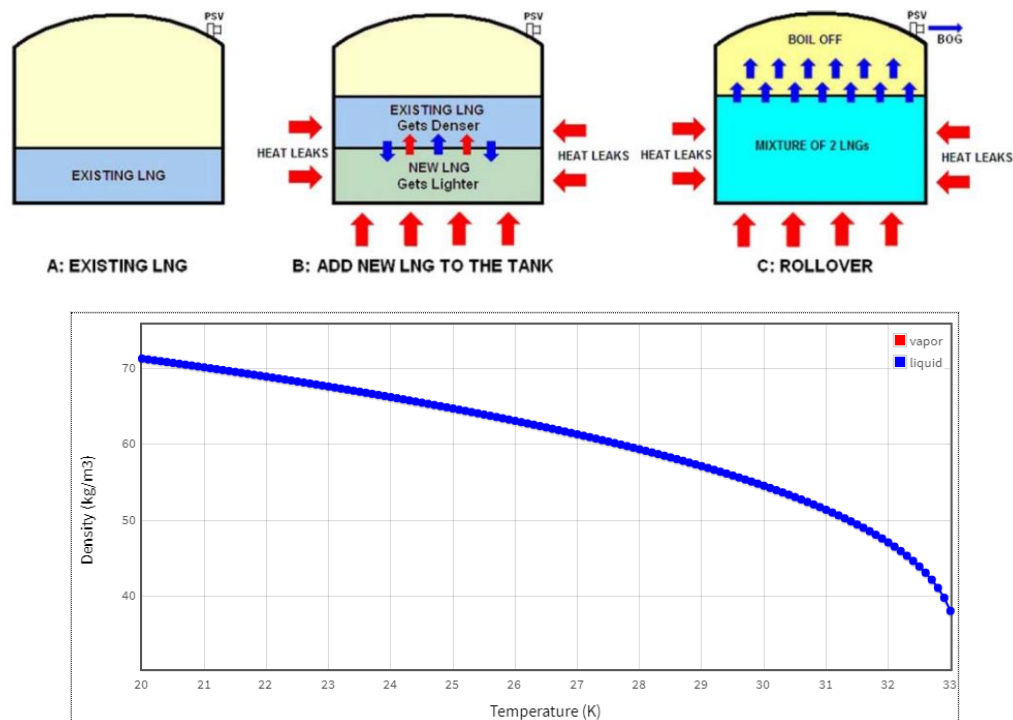

Figure 2-8   Illustration LNG roll-over (VTT-upper plot) and liquid hydrogen density with temperature (NIST-lower plot).

Rapid phase transition (RPT) is a well know concern with LNG. [Aursand and Hammer, 2018] described so-called early and delayed RPT mechanisms with LNG, early being LNG captured by water e.g. by breaking waves or direct injection into water, while delayed RPTs result after prolonged preferential methane/ethane boiling to form propane/butane rich LNG so that the difference between the boiling point of the rest-LNG and the water is reduced enough for the insulating film-boiling layer to collapse.

For LH2 there is no delayed RPT mechanism. Early RPT will require significant amounts of LH2 to be trapped inside water, and except for significant LH2 releases below water it is hard to see the mechanisms that will make releases of very light, fast evaporating LH2, to penetrate sufficiently into water to generate a significant RPT.

For ammonia RPT is not believed to be of major concern, due to the limited temperature difference between water and ammonia, the high solubility of ammonia in water, and the very high heat of vaporization of ammonia.

Due to its high heat of vaporization and strong expansion when boiling hydraulic shocks may be of particular concern for ammonia. An accident with 14 tons ammonia released in August 2010 in Louisiana, USA, was explained to have happened because cold liquid ammonia was injected into pipes in defrost mode filled with warm gaseous ammonia [CSB, 2015]. This led to fast condensation and

pressure drop breaking the pipes (see CSB video at https://www.youtube.com/watch?v=_icf-5uoZbc). This phenomenon should be considered e.g. when planning bunkering procedures.

There may be cryogenic hazards for personnel for releases of LNG and LH2. Contact with uninsulated equipment or piping carrying LH2 and LNG may give injuries. The plume of a flashing ammonia release can also expect temperatures down to -70°C. The hazards related to being cooled, trapped in cryogenic LH2 and LNG releases or a flashing ammonia plume will however be negligible compared to the flammability or toxic risks from these plumes. Toxicity hazards of ammonia will be covered in section 2.5.3.

The combustion products of hydrogen and ammonia are mostly water and nitrogen and non-toxic, at high temperatures some NOx may be generated, and ammonia combustion may give some slip. For comparison methane/natural gas combustion will in addition to NOx give 5-10% of CO_2, potential significant concentrations of CO, soot (and H_2S if natural gas contains sulphur).

2.3   Properties related to flammability

When handling low flash-point fuels, flammability and explosion risk are usually a major concern. In Table 2.2 relevant flammability properties of hydrogen and ammonia gas are compared to the reference fuel methane (LNG).

Compared to methane gas, hydrogen has a 6-7 times wider flammable range, with up to 6-7 times higher burning velocity (explosion pressures are often proportional to the square of the burning velocity, i.e. $P \sim Bv^2$). Hydrogen also has 15-20 times lower minimum ignition energy than methane.

For releases into a closed or semi-enclosed volume, the explosion risk (= Σ frequency x consequence) for an incident including a) release, b) explosive cloud formation, c) ignition and d) explosion, could be several orders of magnitude higher for hydrogen leaks than for a similar system with methane, see e.g. [Hansen, 2020]. Potential mitigation measures like room inerting, water sprays, active ventilation or pressure relief panels will all be much less efficient for hydrogen than for methane. While Inergen (or nitrogen) can make a room inert by reducing oxygen concentration below 12% (still safe to breath), oxygen level must be reduced below 5% to inert hydrogen (too low to survive). At these concentrations the most popular (reasonably priced) catalytic and semiconductor hydrogen gas detectors will not work, and significantly more expensive detection systems will be required.

For releases outdoors the situation will be much better for hydrogen, as a) the very strong buoyancy will quickly lead gas away (upwards), and b) the high stoichiometric concentration combined with the high sonic release velocity, will quickly dilute the release to less reactive concentrations <15%. Large release events will therefore be required for a serious incident to happen outdoors.

Ammonia, on contrary, is much less reactive than methane. The reported minimum ignition energy required for ammonia is more than 2000 times higher than for methane. While ammonia may burn at concentrations above 15% in air, the reactivity of ammonia at stoichiometric concentration of 22.0%, is much too low to fear any significant flame acceleration. Explosion pressures should only be feared for very enclosed volumes at concentrations close to stoichiometry. Note that the low reactivity is also a concern for internal combustion engines as there may be a need for a pilot flame or hydrogen injection to prevent misfiring and incomplete combustion.

The normal gas flame propagation mode in which the flame front is accelerated by turbulence ahead of flame, is called a deflagration. In a deflagration, a volume of gas will normally only burn fast enough to generate significant blast waves if there is partial confinement or significant turbulence ahead of the flame front. Turbulence can be generated if the flame burns through arrays of turbulence generating objects/obstructions which split the flame into multiple smaller parts and strongly enhance the flame surface area and reaction rate. With increasing gas reactivity flames may transition to detonation, a supersonic flame propagation mode (1500-2000 m/s) in which gas heating by shockwave interference

ignites unburnt gas ahead of flame, typically generating overpressures of 15-20 bar in the flame front. One important difference between deflagration and detonation is the much higher flame speeds and pressure levels normally seen in a detonation, a deflagration will normally stop accelerating once the flame enters open space, so that gas volumes out in the open will not tend to contribute to any significant blast waves. Outdoors a detonation will therefore tend to be a much more severe incident than a deflagration. Indoors there are also important differences. Due to the supersonic flame propagation in a detonation, the detonating flame front propagates much faster than the speed of sound in air and will therefore not be influenced by the presence of vent openings in a building. Traditional explosion mitigation methods like pressure relief panels (soft walls) may not be of much help protecting the structures, deflagrations have even transitioned to detonation (DDT) through vent openings.

Table 2.2 – Relevant flammability properties of hydrogen and ammonia compared to methane

Properties	Hydrogen	Ammonia	Methane
Flammable range in air (LFL -UFL)	4%-75%	15%-28%	5%-15%
Stoichiometric concentration in air	29.6%	22.0%	9.5%
Maximum burning velocity	3.0 m/s	0.07 m/s[#]	0.4-0.45 m/s
Closed room combustion pressure	7.1 barg	5.4 barg	7.9 barg
Minimum ignition energy (MIE)	0.017 mJ	680 mJ[#]	0.29 mJ
Autoignition temperature (AIT)	~550°C	~650°C	~580°C
Fraction added N_2 in air to inert	73%	~ 18%[°]	37%
Minimum oxygen level combustion	5%	~ 13.3%[°]	12%
Detonation initiation energy	1 g TNT	N/A	1000 g TNT
Detonation cell size	1 cm	N/A	30 cm
Concentrations that may detonate	15-60%	N/A	5-15%
Combustion energy (HHV)	142 MJ/kg	19 MJ/kg	56 MJ/kg
Combustion energy Stoich & LFL	3.4 & 0.5 MJ/m^3	2.9 & 1.9 MJ/m^3	3.4 &1.8 MJ/m^3
Flame temperature (adiabatic)	2254°C	1800°C	1963°C
Flame colour	Not visible	Yellow-green	Blue to orange
Flame radiative fraction	~5-10%		~10-20%
Superheat limit (BLEVE potential)	-240°C (29.7 K)	89.8°C	-102°C (171 K)

[#] Some sources [Verkamp et al., 1967] report ammonia to have MIE around 8 mJ and burning velocity around 0.15 m/s. These results do not seem consistent with majority of sources. In other studies, much lower MIE has been reported in NH_3-N_2O mixtures, see e.g. discussion in [Pfahl and Shepherd, 1997]

[°] Estimated by comparison with properties of other gases

The propensity of a gas to detonate is described by parameters like the detonation initiation energy and the detonation cell size. The detonation cell size λ is a measure of the distance between the shock-ignition nodes in a detonation, the higher reactivity of the gas, the shorter the distance between the ignition nodes. To initiate a detonation a hot-spot high pressure region in a flame front covering a certain number of ignition nodes is required. Thus, the detonation initiation energy is proportional to the square of the detonation cell size $E \sim \lambda^2$. For hydrogen λ=1 cm while for methane λ=30 cm, therefore it requires roughly 1000 times higher energy to initiate a methane detonation than a hydrogen detonation.

This fact is also reflected in the attitude within the process industry and accident statistics. Methane detonations are not considered possible, or at least not credible, within the process industry. Within the coal mine industry, however, where large gas clouds may develop in long confined tunnels, detonations are reported. Large scale experiments with methane dominated natural gas have also led to DDT and detonations, both in long pipes and test rigs reflecting oil rig modules, see [Hansen and Johnson, 2015] and discussion about experiments in section 2.4.

A consequence of the higher reactivity and smaller detonation cell size is that hydrogen detonations can take place at 30 times smaller linear scale than methane detonations. Thus, while methane detonations should only be feared as very unlikely events at very large industry scale facilities or in mines, hydrogen detonations can happen at small scale, and must be considered when evaluating risk for local hydrogen infrastructure units. In the 2019 Kjørbo incident a hydrogen release into the open from a relatively small storage container at a hydrogen refuelling station likely detonated [Hansen, 2019].

Ammonia has much too low a reactivity to detonate.

Like previously mentioned, hydrogen and methane releases from same pressure and hole size, whether as liquid or as compressed gas, will have a similar maximum combustion energy. The energy content at the lower flammability limit, LFL, is however much lower for hydrogen (0.5 MJ/m^3) than methane (1.9 MJ/m^3), thus the potential flammable cloud will typically be much larger for hydrogen. While the reactivity of lean hydrogen clouds between LFL (4%) and 8% is very low, and of limited concern as flames outdoors will only burn upwards, not sideways or down, the cloud above 8% concentration would normally still be significantly larger than a flammable methane cloud. For liquid releases the balance can be even worse as LNG will have a greater tendency to form pools which may limit the flammable cloud size and hazard distances.

Ammonia will have a 20% higher release rate at the same pressure and hole size compared to LNG. The combustion energy per kg is however only 1/3rd for ammonia. The much higher LFL for ammonia (15%) compared to methane (5%) makes the flammable cloud much smaller for ammonia. For ammonia the flammability is however of secondary concern, the primary concern is the toxic effects. With extended exposure above 2500 ppm (0.25%) the fatality risk may be significant, while exposure of 40,000 ppm (4%) can give immediate fatality. Thus, hazard zones from ammonia releases may extend well beyond those for methane.

The flame temperature of hydrogen jet-fires may be higher than for methane, hydrogen flames may also be invisible in daylight, which may represent an additional hazard to people. On the other hand, hydrogen flames are generally reported to give significantly less radiation than methane flames, thus as long as direct flame exposure is prevented the hazards from flame radiation should be less compared to methane. DNV GL has however reported test in which radiative fraction for hydrogen jet-fires seemed comparable to that for methane jet-fires [Allason et al., 2019]. To the extent ammonia flames will represent a hazard, an even lower radiation than for hydrogen jet-fires should be expected, since the combustion products from ammonia are the same as for hydrogen, but the flame temperature significantly lower.

Boiling liquid expanding vapour explosion (BLEVE) is a physical explosion due to immediate rapid boiling at loss of pressure of a pressurized liquid stored at temperatures well above its boiling point. The main risk is usually related to flammable liquids, where the physical explosion can be followed by a major flame ball burning for several seconds, giving very high radiation, see Figure 2-9. BLEVE can further be highly relevant for water boilers as well as toxic substances like ammonia. For a proper BLEVE to take place the liquid temperature at the time of pressure loss must be above the T_{SHL}, the Reid superheat limit, normally estimated to be around $0.895\ T_{CRIT}$, the critical temperature. At suck temperatures there will be a homogenous nucleation at loss of pressure leading to immediate explosive boiling all over the liquid. For temperatures above the atmospheric boiling point, but below the T_{SHL}, pressure loss will also lead to spontaneous boiling of parts of the liquid. The event will be gradually less explosive with reduced temperature, reducing blast pressures, vaporization and spread of liquid particles/flame ball.

For methane the T_{SHL} is 171 K, or 60 K above the boiling point, at storage pressure of around 24 bar. For LNG is storage pressure usually around 5 bar or lower with typical tank around 10 bar. A tank experiencing uncontrolled pressure increase due to failure in pressure venting will then be expected to fail before the pressure can reach 24 bar, if so, the BLEVE risk should be limited.

For LH2 the T_{SHL} is estimated to 29.7 K (7.7 bar), which is only 9.3 K above the boiling point and below the typical tank design pressures. The potential for a tank-failure at temperature above T_{SHL} may thus be higher, resulting in a BLEVE scenario. How a BLEVE would develop is however highly unclear, the volume expansion at phase change is only about factor 50 (compared to 250 for LNG), and the expelled LH2-particles would quickly evaporate while condensing/freezing air on its way. If the LH2 and frozen air mixture would ignite, very high explosion loads could be feared. Due to the high uncertainty and potential for severe scenario, it is important to ensure that LH2 BLEVEs will not happen.

For ammonia the T_{SHL} is around 90 °C (48 bar), which is much higher than ambient temperatures and storage temperatures (and pressures). The BLEVE risk for ammonia is therefore assumed limited. While the explosive BLEVE is unlikely, a pressurized ammonia tank rupture at e.g. 25 °C could still be catastrophic as 9% of the ammonia would immediately flash, and expand 700 times, which could expel significant additional quantities of ammonia. For comparison, propane, with a significantly higher BLEVE risk, has a T_{SHL} of 53 °C (18 bar), much closer to extreme ambient temperatures and tank design pressures.

For the accident scenarios discussed the risk will generally tend to increase with the degree of confinement, i.e. any release and accumulation of flammable or toxic gases will be much more critical to people present inside a building where a release would happen.

Similarly, many incident scenarios which outdoors could be dramatic, but not life-threatening, could have disaster potential inside a long tunnel or enclosed deck on a ferry. This would e.g. apply to any major release from a road tanker transporting flammable or toxic fuel.

Figure 2-9   BLEVEs in hydrogen and ammonia would likely have quite different characteristics from each other, and from propane BLEVEs. Left photo shows propane BLEVE testing at Queens University, Canada, right photo shows Sunrise BLEVE-accident in Toronto (2008).

2.4 Relevant experiments

2.4.1 Hydrogen

Research into hydrogen safety has been carried out for several reasons, both related to nuclear plant safety, to understand LH2 as propellant, and to investigate hydrogen properties as a potential future energy carrier.

Among the interesting research is the experimental research by [Little, 1960], see Figure 2-10, to understand hazards and properties of LH2 to be used as rocket propellant, including vapour dispersion behaviour, reactivity exploring LH2 flash-fire, deflagration and detonation, and hazards related to solid/liquid air deposits generated from LH2 releases. Later large scale LH2 spill experiments (~10 kg/s) were performed by NASA [Witcofski and Chirivella, 1984] studying cold hydrogen plume spread in varying wind and humidity. Both test series demonstrated that LH2-vapour could remain dense near the ground for 100-200m prior to becoming buoyant and lift off the ground.

After nuclear accidents of Three Mile Island and Chernobyl, large-scale hydrogen explosion experiments were carried out, Sandia National Laboratories performed hydrogen explosion testing in the FLAME facility, a 30m long tunnel geometry [Sherman et al., 1989]. These tests looked into effect of obstructions, gas concentration and venting, interesting observations included the very low reactivity below 8% concentration, and also observed DDT and detonations at concentrations as low as 15% hydrogen. The initiation of DDT related to vent openings, well before significant pressures and flame speeds had developed, was also observed in one test. In Germany other large-scale experiments were performed at Fraunhofer ICT including explosions in a 20m diameter hemispherical balloon [Pförtner and Schneider, 1983] and experiments investigating DDT related to pre-ignition turbulence or explosion venting [Pförtner and Schneider, 1984], see Figure 2-11. Major test programs were also carried out in Russia (e.g. NRC Kurchatov Institute) and elsewhere.

Research into hydrogen safety after 2000 has mainly focused on hydrogen as an emission free energy carrier. Experimental activities within indoor/outdoor dispersion and explosion tests continued through numerous initiatives within EU (e.g. Hysafe-project with 25 partners from 12 countries, www.hysafe.net), USA (various DoE-funded national laboratories, with Sandia NL being among the more active) and elsewhere, with coordination and information exchange through IEA-HIA expert groups and other channels. Most research was focusing on compressed hydrogen. Recently there has been more focus on LH2 for use in the maritime, and in 2019 LH2 safety tests have been carried out at HSL and KIT within the EU project PresLHy (www.preslhy.eu) and at DNV GL test site in the UK on behalf of Norwegian Public Road Authorities. Both test campaigns have presented interesting preliminary results.

The significant array of available tests, combined with 3D modelling, give a good basis to build understanding of most aspects of the physics related to hydrogen releases, dispersion, explosion and fires.

Figure 2-10   Very impressive test program into LH2 hazards by AD Little Company for US Air Force in 1960 studying release, dispersion, deflagration and detonation. The test procedures may give the impression that LH2-handling is free of hazards, which is far from the case.
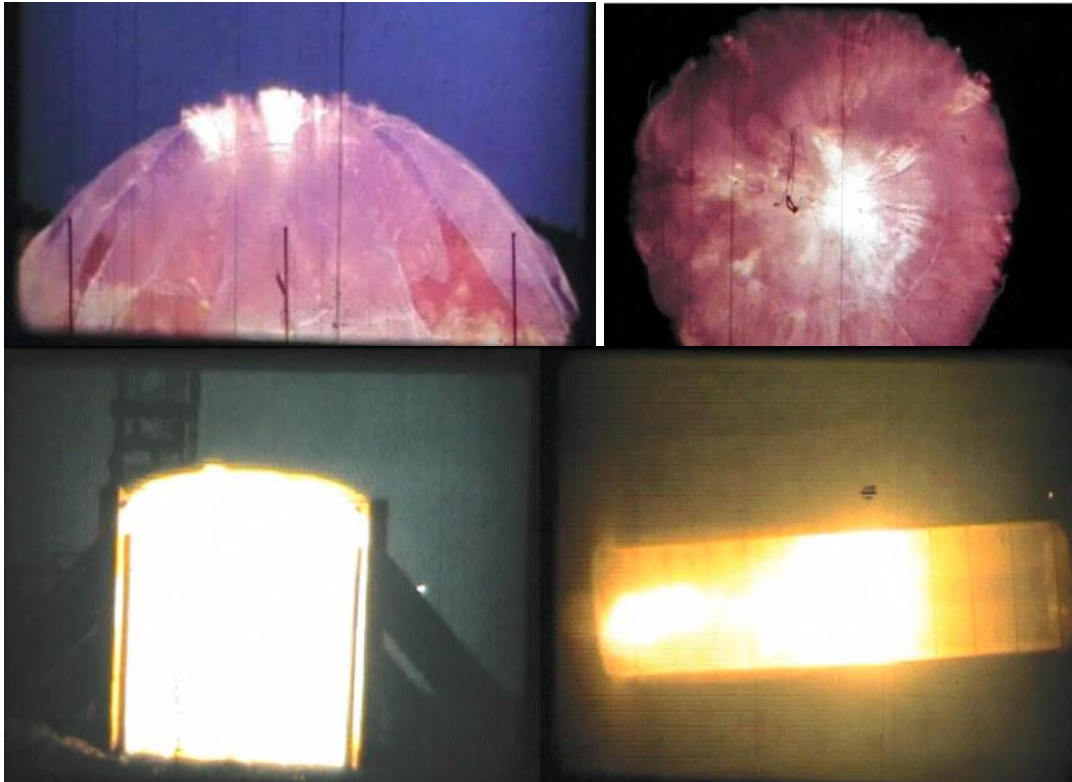
Figure 2-11   Experiments at Fraunhofer-ICT, Germany, 20m hemispherical balloon test (upper) and Lane experiments (lower) investigating DDT in vented explosions.
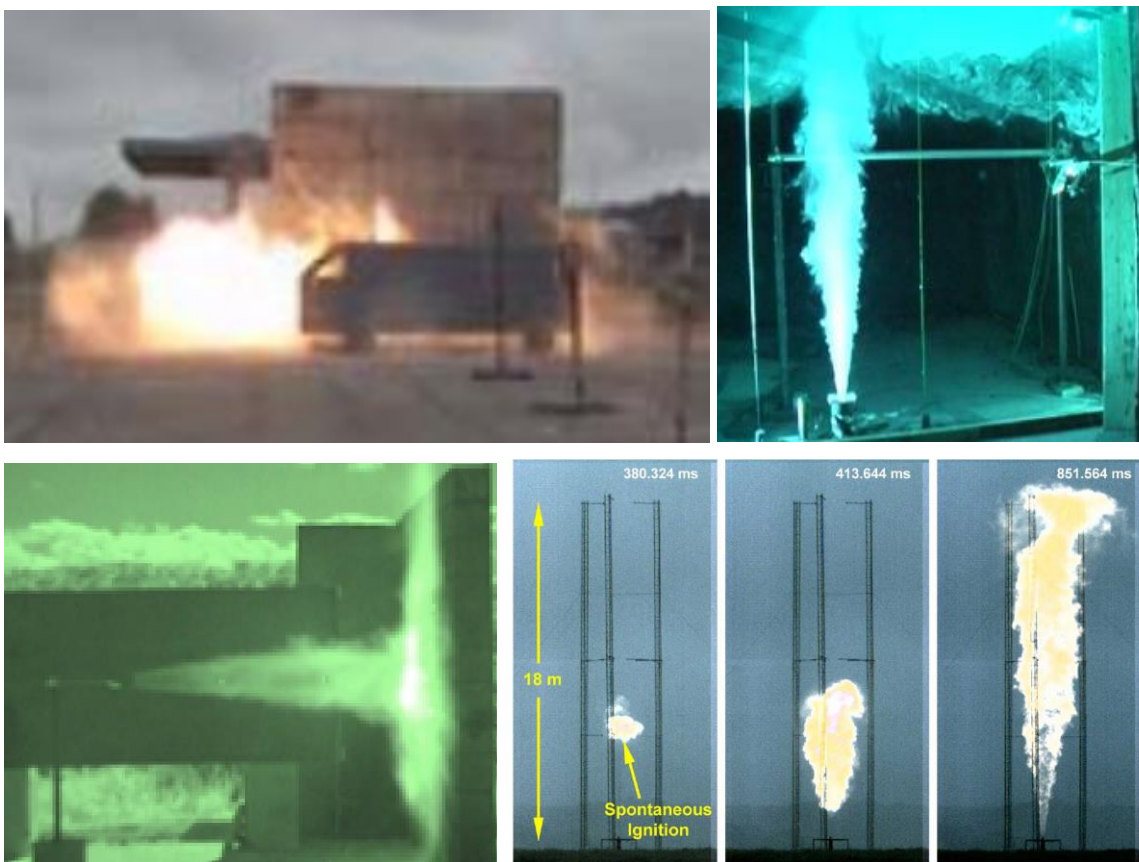

Figure 2-12   Experiments after 2000, ignited jet explosion test by Shell/HSL (upper left), dispersion test by INERIS (upper right), ignited release tests by Sandia/SRI (lower left/right).

2.4.2 Ammonia

Experimental research within ammonia safety is mostly related to release and dispersion research, less regarding explosion properties as this risk is secondary. One major test campaign is the 1983 Desert Tortoise test series by LLNL at Frenchman Flats, Nevada, USA [Goldwire et al., 1985]. Four tests were performed with 10-13 bar pressurized ammonia releases (80-130 kg/s) over 2 to 6 minutes (10-40 tons released). The releases were directed horizontally downwind in winds from 4.5 to 7.4 m/s, temperature around 30°C and low humidity. Reported concentrations were 6-10% at 100m distance, up to 1.6% at 800m distance and 0.5% at 3.4 km distance. Significant pools were seen for some tests, the two first tests were performed onto very wet soil due to prior rain, while the last two on dry soil.

On a significantly smaller scale the Fladis experiments [Nielsen and Ott, 1996] were performed by Risø in Denmark with partial support from a European Union project. 27 flashing release experiments were performed with release rates from 0.25-0.50 kg/s and duration up to 40 minutes.

INERIS performed a series of large-scale tests in France in 1996-1997 [INERIS, 2005] with release rates up to 4.5 kg/s. Tests included impinged releases giving reduced downwind concentrations, and retention dikes, which could collect significant amounts of the ammonia. Water curtains were tested and had limited effect on the dispersion.

In 2010 US DHS performed pressurized ammonia and chlorine release experiments within the Jack Rabbit test programme [Fox et al., 2011], with 1 to 2 tons of ammonia released downwards within 45s (~45 kg/s) under, concentrations were reported at various downwind distances.
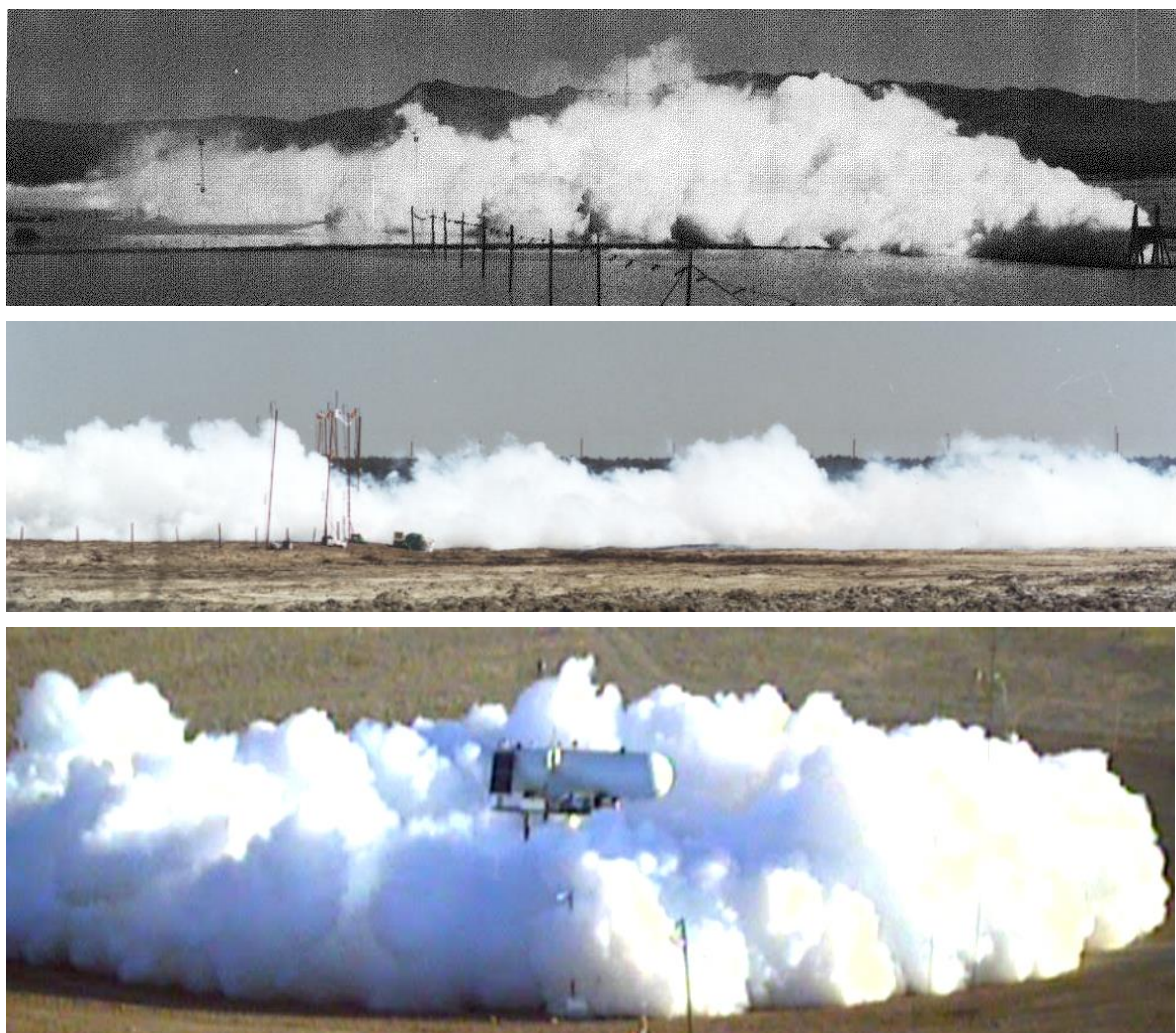

Figure 2-13   Photo from Test 2 of Desert Tortoise (upper), INERIS experiments (middle), and Jack Rabbit tests (lower)

2.4.3   Methane / natural gas

Serious research and testing into methane and natural gas explosion safety mechanisms followed the development of the oil and gas industry around the North Sea. As a response to fatal accidents on the Norwegian Continental Shelf explosion tests were initiated at Chr. Michelsen Institute (CMI, now Gexcon) late 1970s to build understanding of explosion mechanisms relevant for oil platform geometries. From 1980 large joint industry projects supported by major oil companies were initiated at CMI, see e.g. [Moen et al. 1982, Hjertager et al.,1982]. Several smaller or larger explosion incidents during the 1980s culminating with the Piper-Alpha explosion 1988, killing 167 oil workers, increased the interest and importance of this research. Similar research activities were performed in the Netherlands (TNO) and UK (British Gas, Shell). After the Piper-Alpha accident large research projects were initiated at the BG Spadeadam test site (Now DNV GL). Through this research lots of phenomena were investigated including explosion severity as function of congestion, gas concentration, confinement, scale, pre-ignition turbulence and water mitigation. Tests were both performed with idealized homogeneous gas clouds and by igniting high pressure gas releases. For some of the large-scale explosions, deflagration to detonation transition, at least locally, seems to have taken place [Hansen and Johnson, 2015]. In Figure 2-12 some pictures of test rigs and explosions are shown.

Figure 2-14   Photos from CMI (Gexcon) testing activities in 1970s-80s (upper) and Advantica (DNV GL) experiments 1990s (lower).

While the focus on the understanding of natural gas explosion phenomena may have been less in the USA, there was a significant activity investigating LNG releases through large scale experiments Burro, Coyote and Falcon through the 1980s [Koopman et al., 1982, Goldwire et al., 1983, Brown et al., 1990]. In these experiments 100-200 kg/s LNG was released to study vapour dispersion and LFL hazard distances. In the early 1980s large scale test series Burro and Coyote with release rates up to 130 kg/s into a pond in the desert were performed by Lawrence Livermore National Laboratories at China Lake, California. In 1987 LLNL also performed the Falcon experiments with release rates up to 200 kg/s inside a vapour fence at the Nevada test site. These experiments gave a good understanding of dispersion behaviour of LNG.

Figure 2-15   LNG release tests from Burro experiments (left) and Falcon experiments (right).

2.5   Vulnerability of people and structures

In a risk assessment, not only the consequences matter but also the vulnerability of people to exposure of hazards like cryogenic loads, toxicity, flames, radiation, explosion pressures and impact from failing structures or projectiles. In the Lloyd's Register report for DSB, '*Guidelines for quantitative risk analysis of facilities handling hazardous substances'*, [Lloyd's Register, 2019], vulnerability criteria are described for various hazards. For toxic, heat and pressure loads, the fatality risk depends not only on the maximum pressure, heat or concentration of a substance, but also the duration of exposure (often expressed as dose or impulse). Criteria for toxicity are usually developed based on animal testing, the same applies for the blast vulnerability, in addition observations from major accidents are used when concluding the vulnerability of people. The Lloyd's Register guidance report recommends using the TNO Green Book [TNO, 1992] being the best source for vulnerability criteria. Criteria will be presented in the following sections.

2.5.1   Explosions

The fatality rate for explosions depends on many factors in addition to the direct effects on people of overpressure, e.g. impact of projectiles, collapse of buildings and people thrown against hard surfaces. These indirect effects of an explosion can result in fatalities at much lower overpressures than blast impact to people and are very site and scenario specific.

For direct causes to fatalities like overpressures causing injury to lungs, there are well-established probit functions estimating no fatalities for overpressure less than 1 barg, and 50% fatality rate for pressures of 4 barg. The relevance of these vulnerability criteria is limited around a plant, using the TNO '*Whole body impact'* probit function is instead recommended. This assumes that fatalities occur as a result of head injuries, because the shockwaves from the explosion knock the person to the ground. This probit function is dependent on both overpressure and impulse. The first (current) version of the LR guidance suggested conservatively to assume infinite impulse duration resulting in a 50% fatality risk for a blast wave of 74 mbar. For the short durations of pressure waves from unconfined explosions, in particular hydrogen explosions, this criterion is much too conservative. To obtain a more correct estimate of risk, the impulse should be taken into consideration. Doing so, the 50% fatality criterion for blast waves of duration 200ms is more than 1 barg, for shorter duration blast from hydrogen explosions the tolerable loads would be even higher, see Figure 2-16. To reflect the indirect effects mentioned of projectiles and collapse of buildings, a 50% fatality criterion for blast of around 0.3-0.4 bar is considered reasonable. Lloyd's Register is currently updating the DSB guidance report, in the revised version the recommended blast criterion for 50% fatality risk will likely be 0.35 barg. This level is more consistent with the criterion recommended by the Association of Oil and Gas Producers of 500 mbar [OGP, 2010].

Pressure levels of 0.35 bar would only be feared in the near vicinity of facilities for outdoor scenarios related to hydrogen infrastructure. For scenarios inside tunnels or buildings the blast loads will extend much further, and the fatality risk is higher.

Blast pressures vulnerability

— TNO 50% fatality threshold

Green Book P-I-relation
reformatted to P-Δt

OGP 434-14

H_2 scenarios
Δt ~ 2-20ms

HC on oil platform
Δt ~ 50-250 ms

Pressure		Damage
Psig	kPa	
0.02	0.14	Annoying noise (137 dB if of low frequency 10-15 Hz)
0.03	0.21	Occasional breaking of large glass windows already under strain
0.04	0.28	Loud noise (143 dB), sonic boom, glass failure
0.1	0.69	Breakage of small windows under strain
0.15	1.03	Typical pressure for glass breakage
0.3	2.07	"Safe distance" (probability 0.95 of no serious damage[1] below this value); projectile limit; some damage to house ceilings; 10% window glass broken
0.4	2.76	Limited minor structural damage
0.5-1.0	3.4-6.9	Large and small windows usually shattered; occasional damage to window frames.
0.7	4.8	Minor damage to house structures
1.0	6.9	Partial demolition of houses, made uninhabitable
1.0-2.0	6.9-13.8	Corrugated asbestos shattered; corrugated steel or aluminium panels, fastenings fail, followed by buckling; wood panels (standard housing) fastenings fail, panels blown in
1.3	9.0	Steel frame of clad building slightly distorted
2	13.8	Partial collapse of walls and roofs of houses
2.0-3.0	13.8-20.7	Concrete or cinder block walls, not reinforced, shattered
2.3	15.8	Lower limit of serious structural damage
2.5	17.2	50% destruction of brickwork of houses
3	20.7	Heavy machines (3000 lb) in industrial building suffered little damage; steel frame building distorted and pulled away from foundations
3.0-4.0	20.7-27.6	Frameless, self-framing steel panel building demolished; rupture of oil storage tanks
4	27.6	Cladding of light industrial buildings ruptured
5	34.5	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building, slightly damaged
5.0-7.0	34.5-48.2	Nearly complete destruction of houses
7	48.2	Loaded, lighter weight (British) train wagons overturned
7.0-8.0	48.2-55.1	Brick panels, 8-12 inch thick, not reinforced, fail by shearing or flexure
9	62	Loaded train boxcars completely demolished
10	68.9	Probable total destruction of buildings; heavy machine tools (7,000 lb) moved and badly damaged, very heavy machine tools (12,000 lb) survive
300	2068	Limit of crater lip

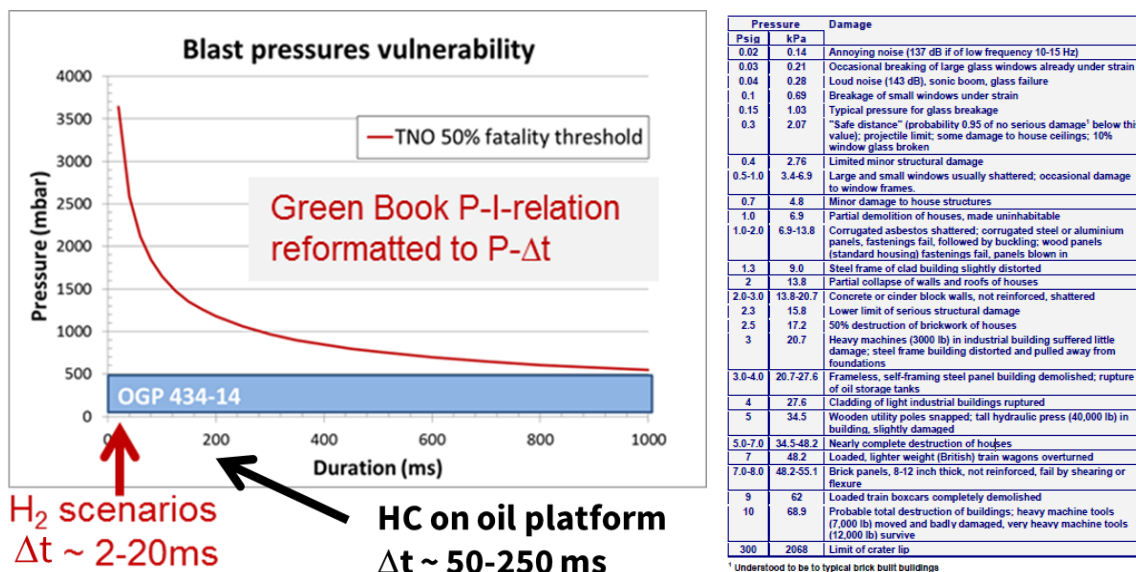[1] Understood to be to typical brick built buildings

Figure 2-16   Left plot shows TNO 50% fatality threshold for full body impact recalculated as pressure versus duration diagram assuming idealized triangular pressure wave (original curve is expressed as pressure versus impulse). Right table shows old data for vulnerability of buildings [Clancey, 1972]

2.5.2   Fires

For hydrocarbons like methane, people being trapped inside a flash-fire, jet-fire or pool-fire will be assumed fatally injured, as the temperature in the flame at LFL will be as high as 1300°C. For hydrogen the criterion should be adjusted as the flame temperature at LFL (4%) is only 370°C, and flames will only burn upwards when hydrogen concentration is below 8%. A more reasonable fatality criterion for hydrogen may therefore be at 8% hydrogen concentration where the flame temperature is around 700°C, much lower than LFL for methane. Since only upwards flame propagation can be expected below 8% concentration, this criterion must still be considered reasonable, but possibly still quite conservative relative to the hydrocarbon criterion. For ammonia the LFL concentration of 15% is immediately fatal, thus people trapped in an ammonia flashfire may already be fatally injured before the flame arrives.

For radiation outside the flame, TNO gives the following probit function for fatality due to exposure of bare skin

$$\text{Probit} = -12.8 + 2.56 \ln (t\, q^{4/3}) \qquad \text{with } t \text{ in seconds and } q \text{ in kW/m}^2$$

The correlation between heat flux and duration corresponding to the 50% fatality rate (i.e. Probit = 5) is shown in Figure 2-17. For moderate jet-flame sizes radiation from hydrogen is generally known to be significantly lower than for hydrocarbons. [Allason, 2019] presented large scale hydrogen experiments indicating that radiation from hydrogen could be similar to that of methane (radiative fraction ~0.13). In most cases related to flame scenarios of infrastructure it can be expected that the exposure to high radiation levels from hydrogen flames will be short, both because people may move away from a heat source, and because many hydrogen releases will be very transient as segment empties. For such cases the use of radiation fatality thresholds of 15-25 kW/m^2 may be justified.
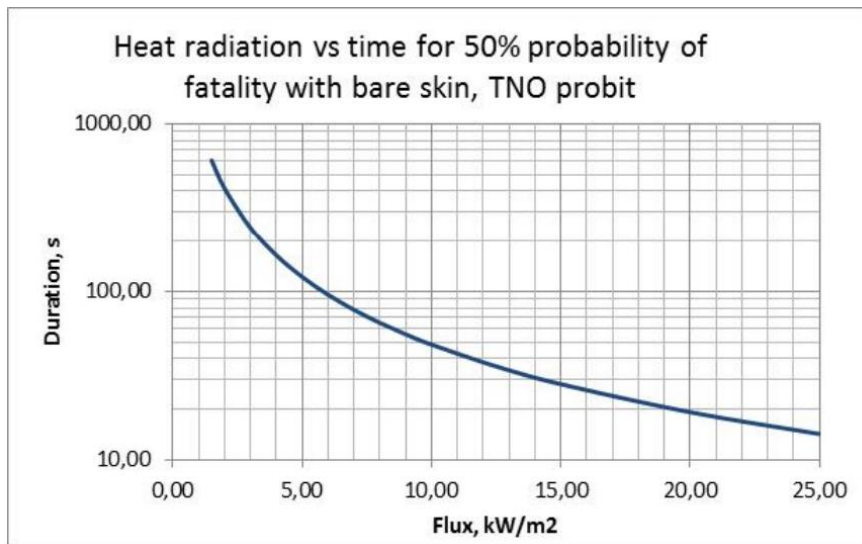
Figure 2-17   Heat radiation versus time for 50% fatality with bare skin

2.5.3 Toxicity

For toxicity, probit functions are typically used to conclude fatality risk. For ammonia the RIVM [RIVM, 2017] has concluded the following probit function for ammonia based on 3 animal studies on experiments in rats and mice correlated with human observations:

Probit = -16.5 + 0.99 x ln($C^{2.02}$ x t)   with C in mg/m^3 and t in min

Setting Pr=5 (50% fatality rate) and multiplying by ~1.4 to convert from mg/m^3 to ppm (at 20°C) this gives the concentration time relation seem in Figure 2-18. These exposure levels and times are very high, e.g. for 10 min exposure the 50% fatality rate is predicted for 10,000 ppm or 1% concentration. The curve is confirming the observations from accidents e.g. in Houston, that fatalities are only to be expected for very high concentrations very near the incident.
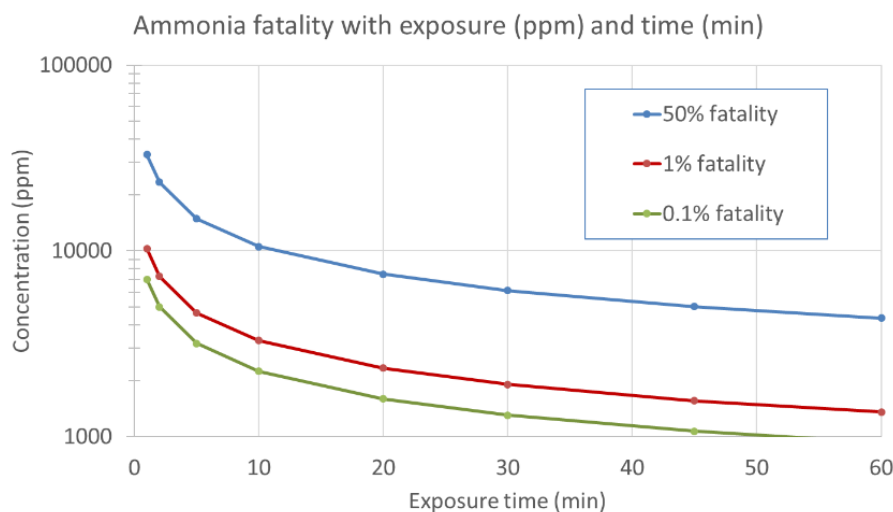
Figure 2-18   Probit curves for different fatality rates, exposure (ppm) versus exposure time (min) for ammonia [RIVM, 2017]

Other relevant thresholds are shown in Table 2.3. The AEGL-values are from the Environmental Protection Agency (EPA, USA) and give three exposure levels where discomfort (AEGL-1), potential for irreversible health effects (AEGL-2), and life-threatening condition or death (AEGL-3) can be feared.

Much used is also the IDLH (National Institute for Occupational Safety and Health, NIOSH, USA) which indicates the concentration where people can fear irreversible health effects after 30 min.

Quite interesting is also the list of expected effects of ammonia exposure to people from the former President of IIAR, the International Institute of Ammonia Refrigeration, [Anderson, 2017], see Table 2.4.

Table 2.3 – Ammonia vulnerability

	10 min	30 min	Comment
AEGL-1	30 ppm	30 ppm	Discomfort, irritation
AEGL-2	220 ppm	220 ppm	Irreversible health effects
AEGL-3	2700 ppm	1600 ppm	Life threating or death
IDLH		300 ppm	NIOSH, irreversible health effects or dead with prolonged exposure (30 min)

Table 2.4 – Ammonia effects [Anderson, 2017]

	Immediate
5-50 ppm	Odour threshold
>100 ppm	Uncomfortable
150-200 ppm	General discomfort – eye tearing
300-500 ppm	Unbearable
700 ppm	Eye damage begins
1,700 ppm	Coughing, bronchial spasms
2,500 ppm	May be fatal 30 min or less
10,000 ppm	Skin damage
>10-40,000 ppm	Visible cloud with moisture
40,000 ppm	Immediately fatal

3 Rules and guidance related to infrastructure in Norway

In this chapter different rules and regulations applicable to various situations are discussed, including regulations for land-based facilities handling dangerous substances like the flammable and toxic fuels being focus of this report. Transport of dangerous substances by land (ADR/RID), by sea (IMDG, ICG-code) or use as a fuel (IGF-code) are also discussed.

3.1 Facilities handling dangerous substances

For most land facilities handling dangerous substances in Norway the Directorate for Civil Protection (DSB) is the regulator. The exception is a selection of larger petroleum facilities downstream of the offshore activities on the Norwegian Continental Shelf which are regulated by the Norwegian Petroleum Safety Authority. This includes facilities at Kårstø, Sture, Kollsnes, Mongstad, Tjeldbergodden, Melkøya and a few more, including related pipeline systems.

Information about regulations and guidance around the use of, handling, storage, and transportation of dangerous good can be found on DSB website, see Figure 3-1. The law regulating most of this field is in short called 'Brann- og eksplosjonsvernloven', the more extensive name is 'Lov om vern mot brann,

eksplosjon og ulykker med farlig stoff og om brannvesenets redningsoppgaver' . For this report the most relevant regulations include the sections around *dangerous substances (farlige stoffer)*, *transport of dangerous goods (transport av farlig gods (ADR(RID, see later section)*, *major accidents (storulykke)*, *pressure equipment* (trykkpåkjent utstyr) and *health, environment and safety (Helse, miljø og sikkerhet)*. Some of the most relevant regulations will be discussed in the following.

For hydrogen the HyLaw-website (www.hylaw.eu) has a good overview of relevant legislation, not only in Norway but in most parts of Europe, see Figure 3-2.
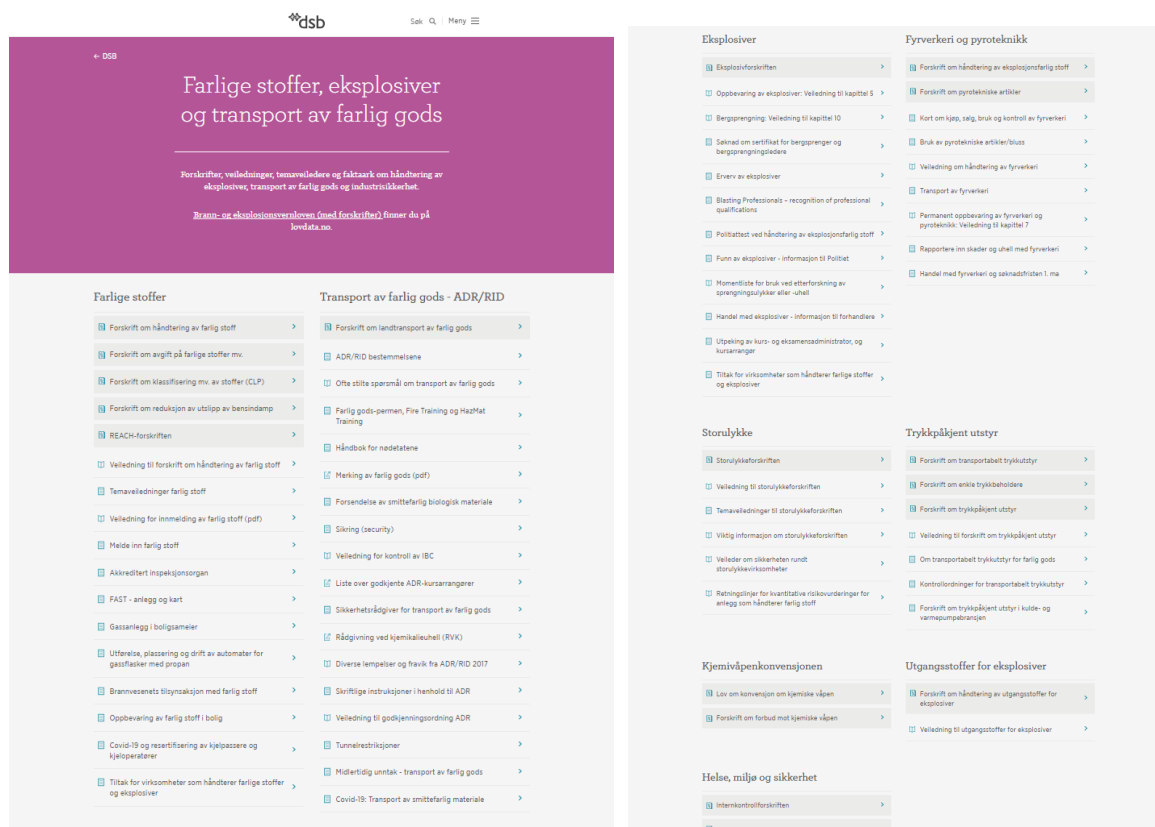
Figure 3-1   From DSB website (https://www.dsb.no/lover/farlige-stoffer/) about dangerous goods legislation and guidance.

The Major Accident Directive (Storulykkeforskriften / Seveso-Directive):

For facilities handling larger quantities of dangerous substances particular rules are applicable as described in '*Storulykkeforskriften*'. Upper-tier establishments (storing/processing more than 50 ton of hydrogen or 200 ton of ammonia) have a number of responsibilities in addition to those applicable to smaller facilities. The permitting process must include the national authorities/regulator to whom they must produce a specified safety report and deploy major accident prevention policies, produce internal emergency plans and provide information to authorities and local community in case of accidents.

Lower-tier establishments storing or processing more than given quantities of listed chemicals (e.g. 5 ton of hydrogen or 50 ton of ammonia) must notify the national regulator (DSB) about the amounts of hazardous substances stored on their site. Except for this, their duties will be similar to the duties of other facilities handling dangerous substances, with permitting processes primarily towards the local municipality.
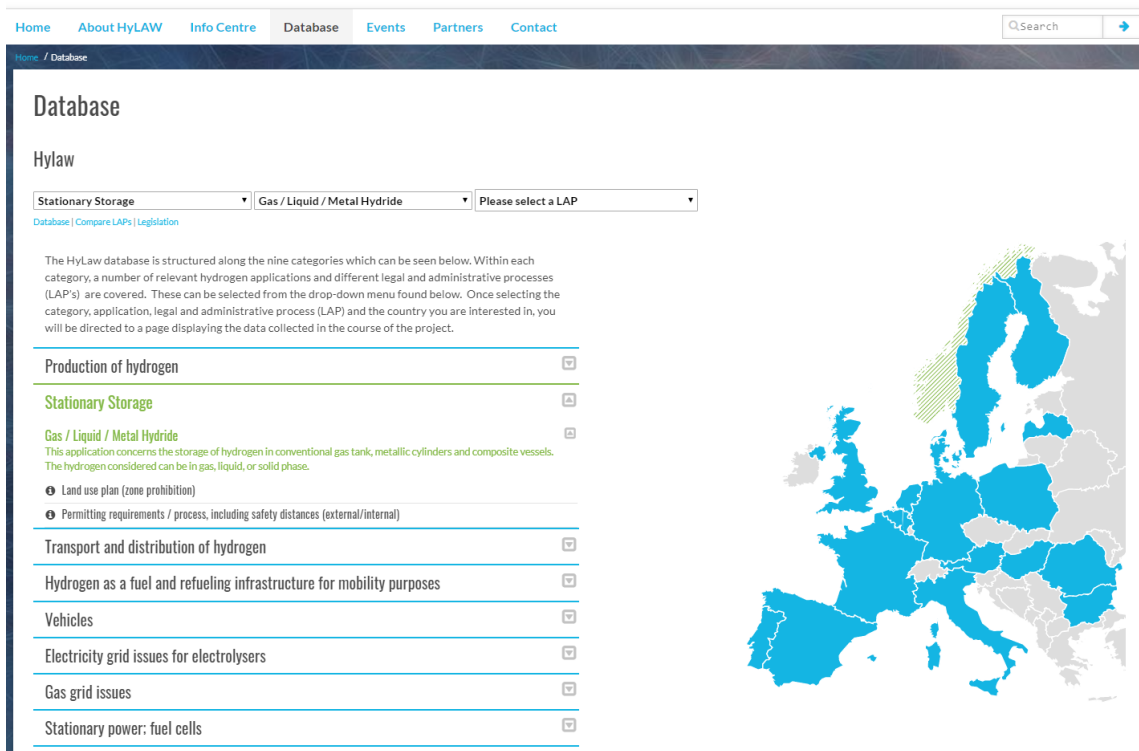
Figure 3-2   View of the HyLaw website (www.hylaw.eu) which gives a good overview of legislation and permitting processes across Europe.

Facilities handling dangerous substances

For facilities handling smaller quantities of substances than specified in the major accident directives there is also a reporting threshold applicable for informing the authorities about the storage ('*innmelding*' at www.altinn.no). For hydrogen and ammonia gas the threshold for reporting are storage volumes of $0.4m^3$ or higher.

For certain activities DSB may define "*Samtykkekrav*", this can be related to recent changes in regulatory regime or particular situations where an incident may have a significant impact on third-person or society as a whole. For these situations the facility must fulfil a particular reporting to DSB and get a permit to operate prior to start-up or reopening an operation. Examples of activities that currently require "*samtykke*" include:

- facilities handling flammable, reactive or pressurized substances at levels higher than lower tier threshold of the major accident directive (5 ton hydrogen or 50 ton ammonia or LNG)

- Ship to ship bunkering within 12nm zone

- Pipeline transport of dangerous goods at pressures above 16 bar

- Bunkering of flammable gases (including hydrogen) from road tanker or terminal to ship

- Reopening of hydrogen refuelling stations for vehicles (after Kjørbo-accident)

In Europe, ammonia is classified as a toxic rather than a flammable gas, and a facility storing less than 50 tons of ammonia would likely not technically fall under the '*samtykke*' requirement. Since all types of flammable gas bunkering currently require '*samtykke*', and toxic risks from ammonia would likely not be considered significantly lower than flammability risks from LNG, it would be expected that ammonia bunkering would also be included in the list of activities requiring '*samtykke*' when this becomes relevant.

It should also be mentioned that '*brann- og eksplosjonsvernloven*' also has a number of explicit requirements to facilities handling explosive gases, including requirement for overpressure venting, active ventilation to ensure safe operation and rupture valves on piping, whether all of these will have optimal mitigation effect against hydrogen explosions in any situation is unclear.

Risk assessment for land-planning purposes

For facilities handling dangerous substances a risk assessment will be required to document risk contours for land-planning purposes according to the DSB guidance [DSB, 2013]. Further guidance to risk assessments is also provided in a report written by Lloyd's Register for DSB [Lloyd's Register, 2019]. Areas with annual individual fatality risk higher than 1×10^{-5} would be defined as an inner zone to be controlled by the company for land planning purposes, this area should normally be kept within the property limits and fenced to prevent unauthorized access. Beyond the inner zone a middle zone with annual fatality risk higher than 1×10^{-6} should be defined, within which e.g. no private homes, shops or hotels would be accepted. Public roads and industry/offices will however be acceptable. Outside the middle zone an outer zone with individual fatality risk above 1×10^{-7} should be defined, here private homes, shops and smaller guesthouses will be accepted. Particularly vulnerable objects (kindergartens, schools, hospitals, larger arenas, shopping malls and hotels etc.) should be outside this outer zone.

The risk contour concept around a facility applicable in Norway is illustrated in Figure 3-3, and the zones are defined in Table 3-1. The acceptable fatality risk for the inner, middle and outer zones are all significantly lower than the average risk for dying for other reasons (natural causes or accidents) for any age group and gender in the society.
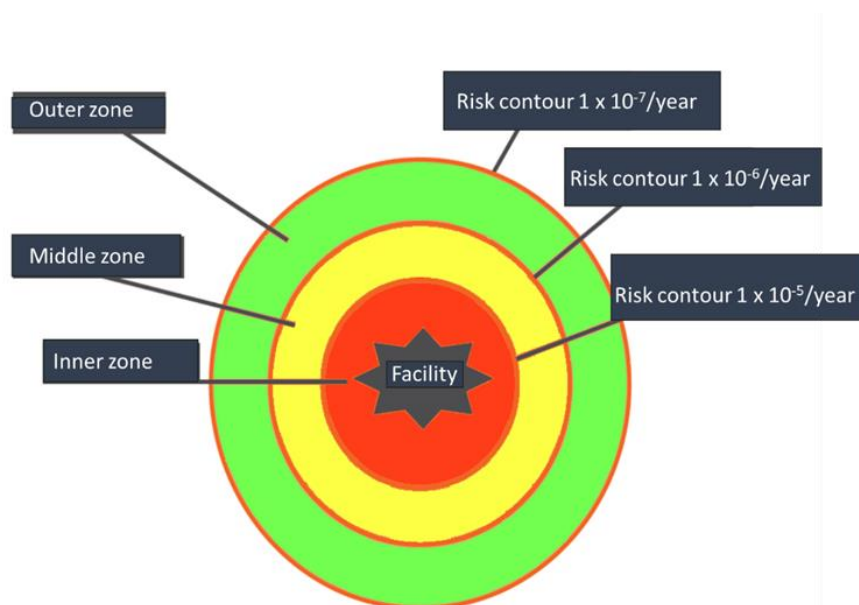

Figure 3-3 – Illustration of tolerable fatality risk for inner zone (red), middle zone (yellow) and outer zone (green) around a facility handling hazardous materials. In the illustration the zones are circular, in reality distances to zones may vary in different directions.

In addition to the individual risk criteria the ALARP (As Low As Reasonably Practicable) principle also applies, i.e. that the risk shall be reduced to the lowest level that with reasonable effort can be achieved. While the risk levels and approaches described are applicable for Norway, the principles are applicable all over Europe due to European directives and legislation, and in several countries (Denmark, UK, Netherlands and Flandern in Belgium) similar zone concepts and risk thresholds are applied or recommended, see [Duijm, 2008]. In UK the COMAH regulation outer zone risk level is 3×10^{-7} instead of 1×10^{-7}, see https://www.hse.gov.uk/landuseplanning/methodology.pdf.

In 2019, with the aim of reducing the threshold for establishing smaller facilities handling flammable materials, DSB asked DNV GL to perform a study that should lead to guidelines for standard table values

for inner, middle and outer zones for certain types of facilities [DNVGL, 2019]. For some of the facility types, e.g. hydrogen refuelling stations, the proposed zones ended up prohibitive (e.g. inner zone a minimum of 63m). For ammonia the study considered a refrigeration facility, which may be far from relevant for the ammonia facilities considered in this report. It seems highly likely that further iterations may be done before the recommended safety distances, see Figure 3-4, will end up as guidance.

Pressure equipment directive (PED)

The pressure equipment directive is a European directive which applies to the design, manufacture and conformity assessment of stationary pressure equipment with a maximum allowable pressure greater than 0.5 bar. The directive aims at guaranteeing free movement of products in its scope while ensuring a high level of safety. The Norwegian regulation related to the PED is called '*Forskrift om trykkpåkjent utstyr*' and describes obligations of the different market players, classification, conformity evaluation (CE-marking), technical control body and safety requirements.

ATEX-directives (workplace and equipment)

The EU-workplace directive was introduced to protect employees working at businesses with potential explosion risk. This specifies that the employer must identify and assess explosion risks and document the explosion risks at the workplace in a dedicated explosion protection document.

The ATEX Directive 2014/34/EU covers equipment and protective systems intended for use in potentially explosive atmospheres, to ensure that the equipment is explosion proof and certified for the use.

The employer will have further obligations to ensure a safe workplace through '*internkontroll forskriften*'.
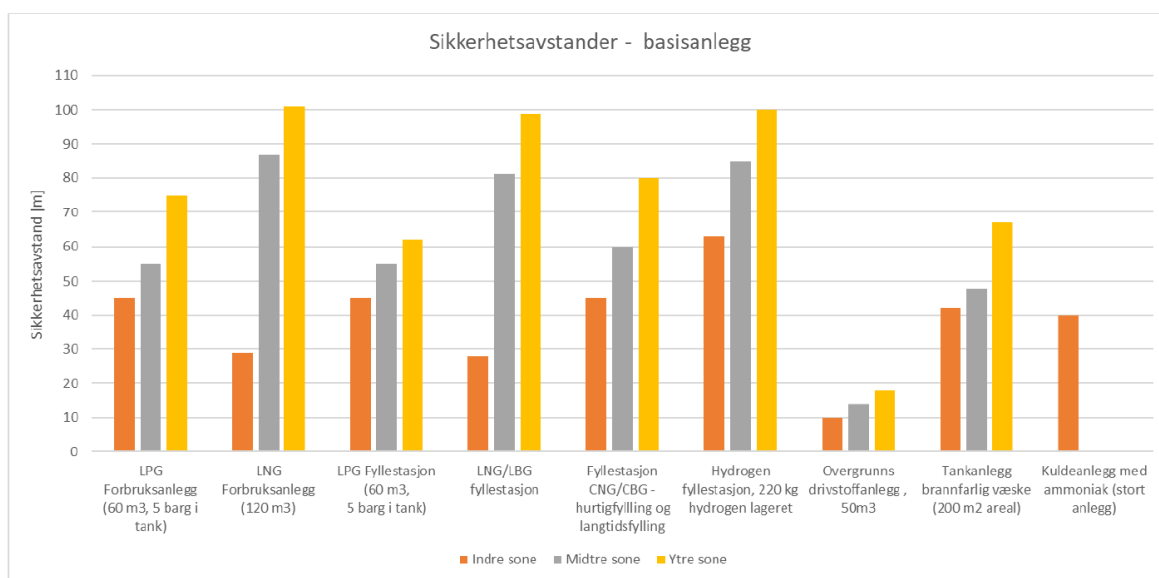

Figure 3-4 – Standard zones for various facility types proposed by [DNV GL, 2019]

Table 3-1   Description inner, middle and outer zones for area planning [DSB, 2013]

Zone	Fatality risk [1/year]	Regulation
Inner zone	1×10^{-5}	This should as a main rule be within the facility property limits, however, exception exists for certain public areas with limited presence of people for shorter periods of time. It is expected that a person spending all his/her time on this contour will die from a facility related accident once every 100.000 years.
Middle zone	1×10^{-6}	Public roads, railway stations, quay, offices or industry can be within this zone, private homes, guesthouses or accommodation should not be within the middle zone. It is expected that a person spending all his/her time on this contour will die from a facility related accident once every 1.000.000 years.
Outer zone	1×10^{-7}	Areas regulated for homes and general use by population can be within the outer zone, including shops and guesthouses. It is expected that a person spending all his/her time on this contour will die from a facility related accident once every 10.000.000 years.
Beyond outer zone		Schools, kindergarten, hospitals, care homes and similar, shopping centres, hotels and arenas should be placed beyond outer zone.

3.2   Bunkering

For bunkering of LNG from terminals or road tankers DSB has recently requested compliance with the ISO20519:2017 standard. A hazardous area (per IEC60079-10-1:2015), a safety area and a monitoring and security area shall be established based on a risk/consequence assessment. For bunkering of liquid hydrogen, it has been suggested to apply the same standard.

The ISO20519 standard suggests two alternative approaches for documenting the risk. One option is a '*credible release approach*' in which the safety area to be closed off for non-essential personnel is defined to be the maximum LFL-distance for typical credible release scenarios identified in a HAZID (constant release through a failing instrument connection or release from the hose after ESD is closed are suggested scenarios). The monitoring and security area would be defined based on best judgement. The second option is to perform a typical facility risk assessment of the bunkering site and establish inner, middle and outer exclusions zones (*hensynssoner*) in addition to the hazardous area. The safety area would then cover the entire inner zone, while the monitoring and security area should cover the middle zone. In both cases, there should be ignition source control in the safety area during bunkering, i.e. that electrical equipment potentially being an ignition source can temporarily be powered off.

For compressed hydrogen bunkering operations, it is assumed that a dispenser concept similar to a truck or bus dispenser could be applied. For such a system it would be assumed that the risk assessments could be somewhat simpler than for liquid hydrogen.

The most recent feedback from the DSB regarding bunkering operations is that they work to harmonize the bunkering operation with the standard hazardous substance facility siting regulations. This likely means that the risk contour approach will be requested for the bunkering risk assessment in the future.

Like discussed in the previous section, there is requirement for '*samtykke*' for bunkering operations these days, thus before planning such in detail it will be recommended to approach DSB to get their feedback on documentation requirements.

3.3 Transport of dangerous substances on land (ADR/RID-directives)

To regulate inland transport of dangerous goods the 2008/68/EC Directive of the European Union (The joint ADR/RID-Directive) is applicable in Norway. ADR is acronym for '*the European Agreement concerning the International Carriage of Dangerous Goods*' while the RID is acronym for '*the Regulations concerning the International carriage of Dangerous goods by rail*'. The regulator responsible for enforcing the ADR/RID in Norway is the DSB (https://www.dsb.no/lover/farlige-stoffer/artikler/adrrid/).

The directive contains an introductory overview, description of how substances shall be classified, listing of dangerous goods and quantities required to be regulated, description of how various goods must be secured, the responsibility of the various parties, how to prepare a shipment with documentation and visible signs, handling of goods, training of drivers, and requirements and authorizations to vehicles used to transport dangerous goods according to the directives.

Both hydrogen and ammonia (and LNG) are included among the listed dangerous goods. There are some restrictions that it may be useful to be aware of for owners of facilities depending on road transports of dangerous goods.

According to the ADR-directive the various national regulators can put restrictions on transport through tunnels. While such restrictions are quite common within the European Union, the only tunnels in Norway which have restrictions are Ellingsøytunnelen and Valderøytunnelen near Ålesund where restrictions according to Tunnel Category D are applicable daily from 7-9 and 14-18. Further, for the Hvaler tunnel near Fredrikstad road authorities must be informed prior to arrival and tunnel will be closed for other traffic when dangerous goods are transported.

While there are few tunnel restrictions in Norway, there may be additional limitations if the road transportation depends on ferry crossings, as this is regulated by the IMO IMDG-code. This code is overseen by the NMA (Sjøfartsdirektoratet), see next section.

3.4 Transport of dangerous substances by sea (IMDG-code, IGC-code)

For transport of dangerous goods on Norwegian vessels the IMO SOLAS convention '*the International Maritime Dangerous Goods Code*' (the IMDG-code) is applicable. The interpretation of the IMDG-code is handled by the Norwegian Maritime Authority (Sjøfartsdirektoratet) and described in '*Forskrift om farlig last på norske skip*'. For several years until the revision in 2017, the transport industry experienced severe challenges when transporting LNG and other ADR-goods along roads with ferry connections due to restrictions on the number of passengers on the ferry with ADR-vessels on board. Transport vehicles could experience long waiting times as the ferry companies often prioritized normal passengers during busy periods rather than running half-empty with an ADR-vehicle on board.

In 2017 the interpretation of the regulation was somewhat relaxed. Steel roro-ferries being part of the national road system, with proper fire protection systems installed, could now transport up to four ADR-vehicles on open decks, or two on closed decks, outside the IMDG-regulations, provided a number of conditions are fulfilled. This seems to have solved the main challenges for the transport companies.

For vessels transporting dangerous goods as bulk '*the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk*', the so-called IGC-code, is applicable. The intention of the code is to ensure safety for the ship, crew and environment related to transport of low flashpoint flammables. It is worthwhile to observe that gases transported as cargo may be used to fuel

the vessel, except if the fuel has toxic properties. With the current regulation it is thus not allowed for an ammonia transport vessel to use ammonia from the cargo as fuel.

3.5   Use of low flashpoint gases as maritime fuel (IGF-code)

'The International Code of Safety for Ships using gas or other low-flashpoint fuels' (the IGF Code) are the applicable rules when designing vessels fuelled by flammable gaseous fuels like hydrogen and ammonia. Most of the code (Section A-1) contains detailed LNG-rules, for all other gases the so-called alternative design approach will apply. For alternative design there are a number of goals and functional requirements to be fulfilled, in addition to demonstrating that the vessel has an equivalent level of safety to a modern, conventionally fuelled vessel.

The goal of the IGF-code is to ensure a safe and environmentally friendly design, construction and operation of the ship. 18 functional requirements are stated to ensure that the safety and reliability of the systems are equivalent with new and comparable oil-fuelled machinery, incidents or the risk reducing measures shall not lead to unacceptable loss of power, the hazardous areas minimized, unintended accumulation of flammable gas shall be prevented, systems shall be protected against external damage, ignition sources to be minimized, appropriate gas and fire detection to be installed, and a single failure of a technical system shall not lead to an unsafe situation.

The IGF-code requires that a risk assessment is carried out to eliminate or mitigate any adverse effect to the persons on board or the environment of the ship. Eight prescriptive requirements for explosion protection are also listed, including that explosions shall be kept local (not impact other areas), not lead to flooding, and not impact life-saving equipment or evacuation.

For the risk assessment the equivalent safety criterion can be challenging to interpret and live up to. For passenger transport, the NMA had for many years (2002-2016) regulations with a quantitative criterion that stated that for a vessel with new technology it was acceptable with 1.0 additional fatality per 1000 million passenger km compared to the conventionally fuelled vessels currently operating on the route. For a gas fuelled vessel, a criterion to keep fatalities related to fuel and fuel systems below 1.0 per 1000 million km is therefore considered to be a reasonable criterion. An alternative criterion for vessels not transporting passengers could be to keep the fatal accident rate for crew below 1.0. The FAR-value is defined as fatalities per 100 million work hours, the EU-average is slightly below 1.0, average in Scandinavian countries is below 0.5.

4   Risk assessments

A guidance for performing facility risk assessments can be found in Lloyd's Register Consulting report for DSB [Lloyd's Register, 2019], below is a brief summary on how a risk assessment is typically performed.

4.1   Methodology

A traditional risk assessment approach is illustrated in Figure 4-1. The different steps in the procedure are described below:

System Description

The facility, including the processes (chemicals, flow rates/volumes, pressures, temperatures and pipe/vessel dimensions), facility layout and robustness, safety/mitigation systems and vulnerable objects in the surroundings, should be properly documented and described.

Hazard identification (HAZID):

In a hazard identification workshop a group composed of people with necessary expertise and knowledge of the systems, operation and potential hazards, should go systematically through the

process of the facility with the aim to identify all significant hazards that can contribute to the risk at the facility.
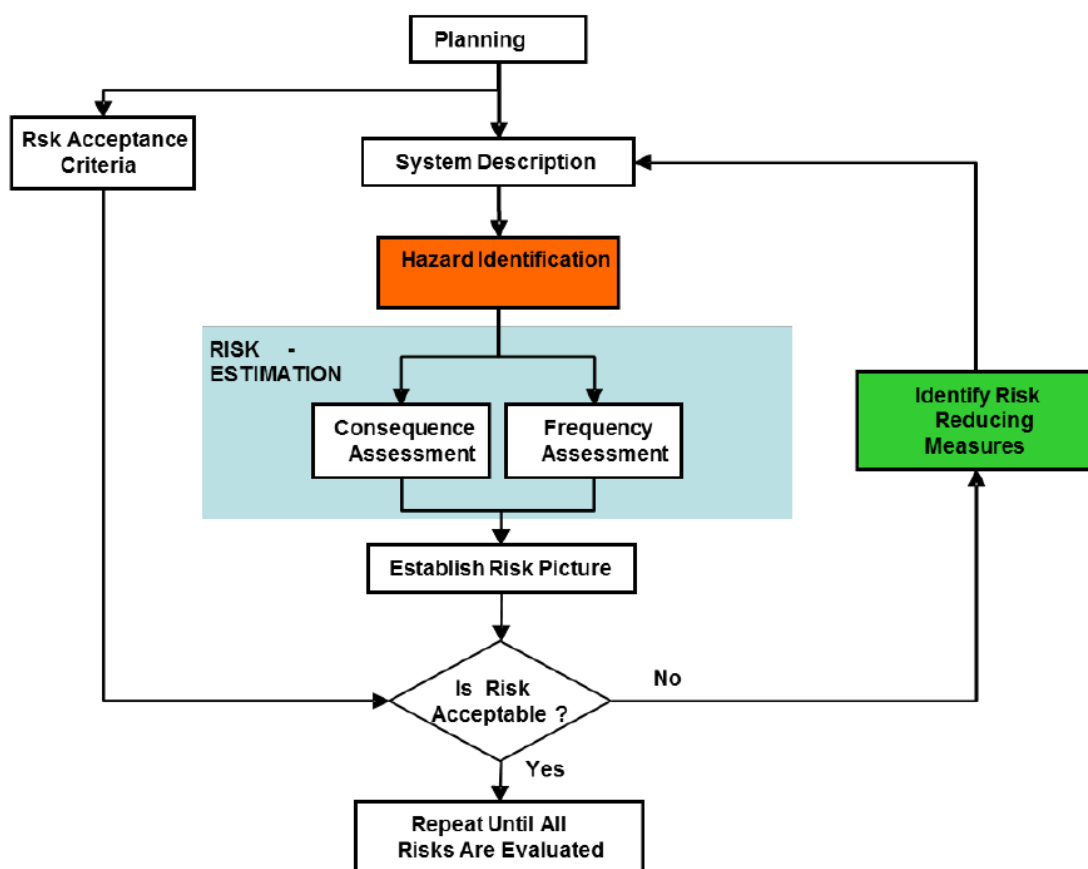

Figure 4-1– Systematic illustration of a risk assessment approach in line with ISO 31000:2009

Risk acceptance criteria:

The risk acceptance criteria will depend on setting. For facilities on land the DSB-critieria, [DSB, 2013], will be applicable, in which annual individual fatality risk outside the property fence shall be less than $1x10^{-5}$ in industrial areas, roads and infrastructure points, below $1x10^{-6}$ in areas with private homes, guesthouses and local shops, and below $1x10^{-7}$ for particularly vulnerable objects like schools, hospitals, kindergartens etc. attracting vulnerable groups or a large number of people. Other risk acceptance criteria are applicable in the petrochemical industry or in the maritime industry. It is not uncommon that larger companies may define their own risk acceptance criteria which are stricter than the requirements from the authorities.

Frequency assessment:

In the frequency assessment the frequency (per year or operation) for all significant hazards should be estimated. For a given hazard frequencies for maximum release (full bore rupture) as well as a few smaller hole sizes, are typically estimated. The most used leak frequency models for analysing land-based facilities include:

- RIVM [RIVM, 2005]– widely used, based on TNO Purple Book
- HSE [HSE, 2012]– widely used, data from facilities in the UK (more detailed than RIVM)
- OGP [OGP, 2010] – Data from offshore/onshore hydrocarbon exploration and process industry
- PLOFAM [Lloyds' Register, 2018a] – Comprehensive offshore model also used onshore
- Sandia [Sandia, 2017] – Model with dedicated hydrogen leak frequencies

For smaller infrastructure facilities RIVM, HSE and Sandia (Hydrogen) may be the most appropriate sources of data.

For the developing gas cloud ignition probability models will also be required to estimate risk for fires and explosions. Models of varying detail level can be found from RIVM, OGP, MISOF [Lloyd's Register, 2018b]. For hydrogen releases ignition probability can be high and depending on whether releases take place indoor or outdoor, and none of the mentioned models seem to reflect this properly. For studies at LR an internally developed ignition model has been proposed and used [Aarskog et al., 2020].

Consequence assessments:

The consequence assessments will for all scenarios estimate transient leak rates, evaporation (pool or flashing for liquids), gas dispersion, fire, explosion and blast propagation. Calculation tools at varying level of detail can be used, including;

- Spreadsheet-based simple models (e.g. hydrogen-tool used at LR). For many scenarios these can provide quite accurate and immediate estimates of consequences of e.g. transient release rates, free jet hazard distances (LFL, flash-fire, fire radiation), gas accumulation in ventilated rooms, blast and vessel rupture. If geometry or site-layout will influence results output can in some cases be manually adjusted to reflect e.g. the effect of barrier walls on radiation or pressures, or the scenarios can be modelled using CFD-models.

- Integral models like Phast/Safeti, FRED/Shepherd and Effects/Riskcurves can predict a wider range of events than simple spread-sheet models and can also efficiently generate risk contours. Limitations are however the same as for the spread-sheet models, the ability to represent effects of 3D layout or detailed mitigation measures is limited and CFD-models are required to improve such predictions. Due to the more complex architecture of the models, the output is more challenging to combine with CFD-calculations. The final result curves may also be more challenging to decompose/verify (black-box model) due to the extensive number of models and correlations behind. Further, as these models are developed to work for a large number of chemicals, models are not always accurate for hydrogen with its extreme properties.

- CFD tools like FLACS, if properly validated (see section 4.4), can predict consequences from given scenarios with good precision, including effects of geometry layout, transient leak rates, leak position and direction relative to geometry and wind, pool spread in bund, air humidity, ignition point and time, and a lot more. The main challenge is that it takes skills and time to prepare and run a given scenario, and results may change significantly due to small parameter variations. A good study must include simulations that can span the result space, i.e. give insight in worst-case consequences, but also in the expected variability of consequences. A good understanding of the phenomena is therefore required to perform a study using CFD.

All tools will require experienced users that both know how to use the tools for the particular application, how to define input parameters, and understand the validity and limitations of the selected tool. While it is possible to perform full studies using the simpler tools, overly conservative or non-conservative predictions may be seen for some cases which may limit the value of the assessment. Similarly, it may require too much resources and time to only use CFD-models in a study. To assess benefit of various mitigation measures, CFD-models will often be required.

Risk estimate:

The estimated risk is a combination of frequency for events and their consequences. This can be expressed as individual fatality risk contours around the site, or fatality risk for workers on the site.

Risk treatment / mitigation

If the risk is not within the risk acceptance criterion, or a potential for risk reduction is identified (e.g. through an ALARP process), mitigation measures or design changes may be proposed and implemented, and the risk reassessed.

4.2   Uncertainties

Many assumptions in a risk analysis will have uncertainties, including:

- Leak frequencies (estimates of leak points, dimensions and choice of leak frequency model)

- Estimate of transient leak profiles, phase of leak (vapour and aerosol remaining airborne, liquid entering pool)

- Distribution of assumed leak locations and directions

- Choice of or distribution of weather condition (wind direction, strength, profile, temperature, humidity, atmospheric stability)

- Precision of 3D geometry modelling (if the modelling approach considers topography and geometry at all)

- Choice of transient ignition model (ignition probability with time and location)

- Are the consequence tools used correctly? Are guidelines (input parameters, grid resolution, domain, boundary conditions and time step for CFD-models) understood and followed?

- Does the modeller understand and use the modelling tool within its validity and limitations? What is the precision of the model if used correctly?

- Resolution of assessment, how many scenario variations (leak rates, leak positions, directions, wind conditions, ignition positions/times) are assessed? Does the modeller understand the phenomena well enough to be confident that low frequency high consequence scenarios are included?

- Are the models for vulnerability of people or structures sufficiently accurate?

The assessment should preferably present the most accurate, unbiased risk picture. There may be millions of different scenario combinations to be evaluated, tools may be difficult to use, and not always accurate. The risk analyst must usually choose between performing a high number of estimates using simpler consequence models (e.g. spreadsheet models or integral models like Phast/FRED/Effects) or a lower number of calculations using CFD-tools like FLACS or similar validated CFD-tools. In many cases a combination of these approaches will be the optimal, where the simpler models are used (slightly conservative) for scenarios where precision is sufficient, while more accurate CFD-modelling is used to model scenarios where proper precision is required, either because the scenario has a high frequency, a high consequence or both.

Uncertainties are part of the risk picture, the higher the uncertainties, the higher the estimated risk should be assumed. As part of a risk assessment the list of possible uncertainties should be checked, and if there is a significant doubt about the precision of assumptions or the modelling approach, a sensitivity assessment should be considered to be able to quantify the impact the uncertainty may have on the risk prediction.

4.3   Probabilistic, Maximum credible or (Realistic) Worst-case approach

Around the world and across industries there are different risk assessment approaches, some of these are discussed in the following.

Probabilistic Assessment to comply with Performance-Based risk acceptance criteria

This type of assessment is common within the oil and gas offshore industry (NORSOK Z-13), but also to establish risk contours/exclusion zones for land-based risk assessments [DSB, 2013]. For an IGF-type risk assessment a probabilistic risk study should be performed to demonstrate that the risk is sufficiently low relative to the '*Equivalent Safety*' criterion of IGF. The probabilistic study will aim at evaluating the consequences from all scenarios with a significant frequency and/or a significant consequence, and from these evaluate whether the risk (= Σ Frequency x Consequence) is within the risk acceptance criteria, or

to establish exclusion zones for land planning purposes as per [DSB, 2013] or other national implementations of the Seveso-Directive. Characteristic for this type of assessment using performance-based criteria is a significant level of freedom with regard to how to minimize risk. By assessing worst-case events in addition to numerous events with lower consequences, it will be possible to understand the severe incidents and take precautions to mitigate/reduce consequences if these would happen.

If performed properly the probabilistic risk assessment approach will be the most cost-efficient for the society, and the risk-owner can to a great extent choose how to design and operate the facility to limit risk. This will ensure that the safeguards are better or safety distances longer where the probability for an accident is higher, or where the potential losses are higher, while less costly safeguards or smaller exclusion zones may be acceptable where severe incidents are less likely or surroundings less vulnerable. The challenge with the probabilistic approaches is that studies may require a higher competence to perform and will require a higher skill level by the regulator overseeing that rules are followed.

Maximum Credible Event (MCE)

An alternative risk assessment approach is the assessment of Maximum Credible Events (MCE). This is e.g. applied as one option (to a probabilistic assessment) in the ISO 20519 bunkering standard for LNG (safety area to be established based on LFL-distance from credible releases) and in the NFPA-59A LNG standard (LFL-distance from 'design spill' to remain within property limits). Maximum Credible Events are used extensively in risk and safety studies in the USA, e.g. in API-RP 752 for process plant safety studies.

The legal system is one important reason why MCE approaches are popular in the USA. While industry (and the society as a whole) in Norway acknowledge the fact that there may be a residual risk (low frequency high consequence events) which cannot cost-effectively be designed against, plant owners in the USA would hesitate to admit the same. If an accident would happen and they would admit they were aware that a worse disaster scenario than assessed in their analyses could develop which they had not prevented, legal claims for compensation from relatives of victims (or from authorities for environmental damage) could be extremely high. For example, after Deepwater Horizon accident BP losses were estimated to around 65 billion USD, or 1/3rd of their share value (similar to the full value of Statoil/Equinor at that time). In this setting it is convenient for companies operating in the USA to design their facility 'safe' based on MCE-approaches and claim not to be aware that worse things could happen. If a worse accident than the MCE would still happen, they can claim to be surprised, that this was unprecedented, and that they have done what was expected from them following best industry practice and standards.

For the mentioned LNG-standards the MCE is a dispersion event and the consequences the LFL-distance, and the consequences of the MCE simplification may be limited. For explosion scenarios of the API-RP 752 the MCE approach may be less suitable.

In the API-RP 752 the maximum credible event is defined as **the event with the maximum consequence among the major scenarios evaluated, which should all be realistic, and have a reasonable probability of occurrence** *considering the chemicals, inventories, equipment and piping design, operating conditions, fuel reactivity, process unit geometry industry incident history, and other factors.*

One main problem with this approach is to define the credible worst-case scenario with a reasonable probability of occurrence, as this will be highly subjective. For example, users could be limited by what has happened in the past 10 years within a specific industry/technology and geographical region.

For explosion studies an MCE approach can be highly questionable. For enclosed scenarios it is well known that the worst-case explosion is not from the largest leak, but from any leak rate that can fill the room volume to the optimal (stoichiometric) gas concentration before igniting. Also, for the unconfined scenarios the MCE approach has severe weaknesses, as is illustrated by the example in Figure 4-2.

The purple line illustrates a typical leak hole size frequency distribution (fraction of leaks smaller than given hole size). With the circle the chosen maximum credible hole size of 2" (50mm) is indicated, this is

the 95-percentile among leaks with hole size of 10mm or larger, this is common approach in the USA, see e.g. [Marx and Nicotra, 2016]. This hole size may correspond to a 10 kg/s release of gas phase propane, the maximum leak rate of 100 kg/s is assumed for hole sizes larger than 100 kg/s (~150mm). The leak rate goes with the square of the hole size up to 100 kg/s, see orange curve in the plot. Flammable clouds from a high-pressure jet release can expand in three directions and the explosive cloud volume tends to increase to the third power relative to the hole size, see blue line (MCE cloud size is only 3.2% of maximum). The ignition probability will also depend strongly on the leak rate, see green curve for large onshore gas plant [OGP, 2010]. For MCE the ignition probability is 2.5%, while it is more than 50% for the largest releases.

By combining the leak frequencies for the various hole sizes with the ignition probabilities a frequency distribution of ignited cloud sizes can be plotted. The red curve shows the fraction of explosions expected to be equal to or larger than the explosions from the given hole size. Thus, while only 5% of the significant leaks have a diameter larger than 2" (50mm) as much as 76% of the explosions will be larger (and mostly significantly larger) than for the MCE. Thus, the MCE design will only protect plant and neighbours against 1 of the next 4 explosions.
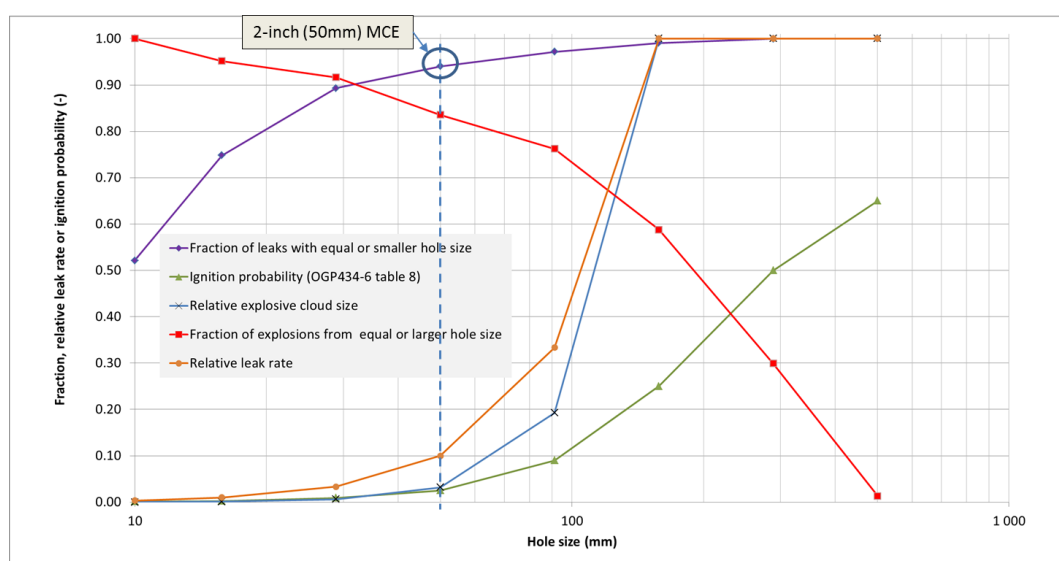
Figure 4-2– Illustration of possible relation between hole size distribution (purple), leak rate (orange), explosion cloud size (blue) and ignition probability (green). The red curve shows the probability that an explosion will be from a given hole size or larger.

Within the hydrogen industries similar differences in approach are seen. In Figure 4-3 a slide presented by Ethan Hecht, Sandia National Laboratories, USA, at the SH2IFT/PRESLHY liquid hydrogen workshop in Bergen March 6, 2019, is shown. Here he describes the process behind chosen methodology for 'setback distances' (exclusion zones) for a hydrogen facility in the NFPA-2, the main industry standard for hydrogen facilities in the USA. Based on a guideline criterion to keep fatality risk outside a facility below 2 x 10^{-5}/year example risk studies of four standard storage facilities were performed, and it was concluded that the setback distances of NFPA-2 could be estimated as the LFL-distance for leaks from 3% pipe cross-section (this was changed to 1% in 2020 version of NFPA-2 to reduce conservatism). This would for example mean that the distance from 200 bar piping with diameter 7.9mm to property limit should be at least 3.0m (LFL-distance from a 0.79mm leak). Only jet-fire and flash-fire risk were considered, not explosions (deflagration/detonation) or burst of storage cylinders.

The advantages with this type of approach is that the exclusion zones (distance to fence or property limit) are easy to calculate, this lowers the barriers when building hydrogen facilities. Provided the demonstration risk studies used to calibrate the approach are done properly and the facilities reflect the

actual facilities well, the fenced area may not be too different compared to a similar facility in Europe (1×10^{-5}/year instead of 2×10^{-5}/year is used in Norway and some other EU-countries).

This MCE approach or risk informed safety distances may have the following main weaknesses:

- The approach lacks frequency considerations and will give similar results no matter the number of pipes and systems at the facility, while the probability for a leak exceeding the MCE 1% hole size, and thus risk, may increase proportionally to the number of pipes and connections. To limit exclusion zones developers may optimize facility designs with a higher complexity (=higher leak probability) than for the sites of the example studies used to calibrate the safety distances.

- The simplified approach with distances does not consider incidents like explosions (deflagration/detonation) or high-pressure tank failures.

- Authorities in Europe tend to require annual fatality risk contours 10^{-5}, 10^{-6} and 10^{-7} (3×10^{-7} in UK) around a facility to define threshold for property fence, residential areas and particularly vulnerable objects. These exclusion zones will increase due to increased frequency when system complexity increases. A very low frequency event like tank burst would influence the risk contours for residential areas if the number of tanks were significant, with the MCE approach this is not the case.

- Using this type of simplified assessment, the facility owners are not required to understand the risk drivers and will thus not optimize the layout, mitigation measures or system design to minimize risk. If worst-case events were assessed, and the hazards understood, measures may be identified to mitigate these risks.

For LH2-storage facilities NFPA-2 similarly has a table of prescribed minimum distances, for storage facilities with up to 284 m³ LH2 (20 ton) car parks should be at least 7.6m away, open flames and welding at least 15m away and locations for public assembly at least 23m away. Again, these hazard distances are irrespective of activity level of a site. For an active bunkering facility with several vessels bunkering LH2 daily, and similarly several truckloads being delivered every day, the frequency for leaks may be significant and the prescribed exclusion zones by NFPA-2 seem very low.
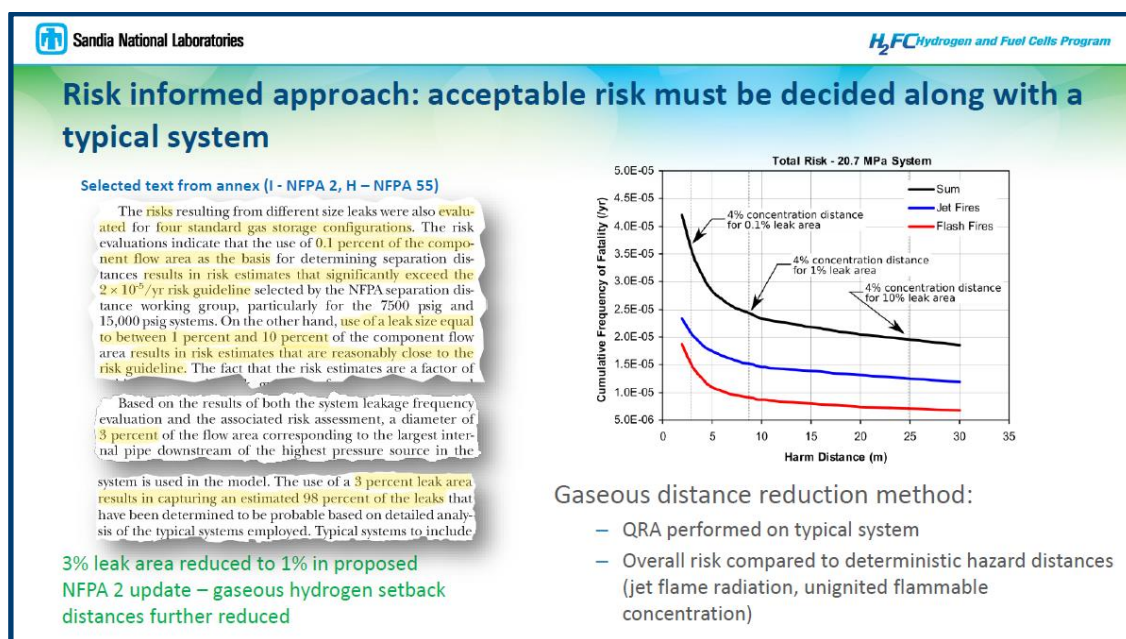

Figure 4-3– Handout from Ethan Hecht, Sandia National Laboratories, presenting at SH2IFT-PRESLEY liquid hydrogen seminar in Bergen March 6, 2019. In his slides about 'Risk informed approach' it is explained how (maximum credible) leak area in the NFPA-2 standard is reduced from 3% to 1% of pipe cross-section.

'Realistic' Worst-Case

A worst-case approach in a risk assessment will give the highest estimated exclusion zones. In such an assessment the worst possible event is assessed, this could be e.g.

- Full bore rupture of pipe (jet-fire, flash-fire or explosion)

- Full bore leak from tank connections (jet-fire, flash-fire or explosion)

- Pressurized tank rupture with delayed ignition

- Worst-case explosion inside a container or building handling hydrogen

The 'realistic' dimension of such an assessment has to do with removing impossible scenarios, e.g. if the total amount of hydrogen is 0.15 kg only (1x10L bottle @ 200 bar) a release cannot fill the containing room to a reactive concentration, then the worst-case explosion of the room filled with hydrogen will not be considered. Taking into account transient leak profiles or reduced leak rates due to pressure loss in pipes may also be part of such an assessment.

In many cases this approach is still attractive as the residual risk, i.e. probability that a scenario worse than designed for, will happen, shall be zero.

When performing an IGF-assessment of a hydrogen fuelled vessel with hydrogen stored below deck, a study may aim to demonstrate 'equivalent risk' to a modern vessel operating on conventional fuels. While this would technically be a probabilistic assessment (e.g. using criteria FAR < 1.0 or increase in fatality rate < 1.0 per 1000 million passenger km) it would in reality be a realistic worst-case assessment because from experience practically any foreseeable scenario of concern (that could lead to loss of life) would give a risk contribution higher than acceptable. Unprovoked catastrophic tank failures may be a possible exception.

4.4 Phenomena and consequence model validation and accuracy

The precision and ability of consequence models, if used correctly, to predict the various phenomena, are important elements of a risk assessment. Below is an overview of phenomena with indication of model validity for simple spread-sheet models, integral models and CFD. Among the CFD models the FLACS-model is mostly discussed. For certain tasks, like dispersion and fire scenarios, other CFD tools could be used provided these are properly validated and have proper used guidelines. For hydrogen explosions, FLACS should be a preferred tool.

Transient outflow rate compressed hydrogen and natural gas:

Both simple spreadsheet tools, integral models and CFD-tools will usually be able to predict compressed gas outflow rates with reasonable precision. For compressed hydrogen real gas behaviour and compressibility effects ($Z \neq 1$) will have a significant effect on storage density and outflow rates, models for this are normally not included in consequence models like the jet utility program of the FLACS CFD model. It is possible to manually compensate for these effects by adjusting the storage volume and hole size to get a near correct transient leak profile. Models limiting maximum outflow rates due to pipe-friction and pressure losses will also be important in many cases, such are normally not included in consequence models and effects must be calculated outside the integral tools or CFD-tools.

Transient outflow rate LH2, ammonia and LNG:

For gases in liquid phase like LH2, ammonia and LNG outflow rates can be estimated using the Bernoulli equation. This gives a conservative estimate of the outflow rate and velocity. For a real scenario, in particular for LNG and LH2, there is a possibility for pressure loss in piping due to friction or flow acceleration, and partial flashing prior to the leak orifice due to this pressure loss or due to heat ingress through the pipe walls. This may significantly reduce the outflow rates. For a real system this effect can be challenging to estimate.

Pool spread and evaporation ammonia and LNG:

For simplified models, including integral models, pool spread, and evaporation can be estimated simplistically by assuming a (transient) pool area and evaporation rate. Using a CFD model it is possible to calculate the pool spread, transient evaporation rate and gas dispersion for ammonia and LNG more accurately, see e.g. [Hansen et al., 2010a]. LH2 pool spread in air atmospheres is considered a less likely scenario and would require significant spills straight onto the ground. If a pool would form the freezing of air would complicate the detailed modelling. The modelling of ammonia sprays/spills in FLACS is possible but challenging, while much of the necessary functionality is included in FLACS, functionality is not always in the same FLACS version but spread among different versions of FLACS which are not yet properly integrated (dispersion, spray and pool-models).

Flashing gas release and dispersion (LNG, LH2, ammonia):

Flashing release source terms can be estimated using homogeneous equilibrium model assumptions, this can both be done in simple spread-sheet models, integral models and CFD-models. While the simpler models may predict gas dispersion in wind-field without 3D geometry [Witlox, 2010], only the CFD-model can model the following gas dispersion among 3D obstructions with good precision. Example of CFD model validation against experiments includes [Hansen et al., 2010a] predicting Falcon LNG-tests, [Ichard et al., 2009] and [Gavelli et al., 2010] modelling Desert Tortoise and Jack Rabbit ammonia experiments, in all these cases FLACS was used.

Outdoor dispersion and LFL or toxic distance and cloud size development:

For compressed hydrogen releases outdoor simple free jet models can predict LFL-distances with reasonable precision, see e.g. tables in NFPA-2 standard. Integral models like Phast, have been validated/calibrated against numerous idealized experiments. For precise predictions the model will need to assume the correct momentum of the release, and the terrain has to be flat. For a real scenario with terrain, walls and obstructed plant areas a CFD model will be required for accurate CFD-modelling. Example of atmospheric dispersion validation of FLACS CFD-model includes [Hanna et al., 2004] for general dense/neutral gas dispersion, [Hansen et al, 2010a] simulating the LNG model evaluation protocol (first and only CFD model that has been through the evaluation and been PHMSA accepted for use towards NFPA-59A), and [Middha et al., 2009a] simulating hydrogen dispersion experiments.

Indoor dispersion and cloud size development in ventilated room:

For indoor dispersion in ventilated spaces of limited size from high pressure releases of hydrogen accurate predictions can be obtained with very simple stirred tank reactor models, either in a spreadsheet or an integral model. With larger room volumes, geometry models, lower release momentum and density gradients, CFD-models will be required for more accurate predictions. Validation work for CFD has been performed by [Middha et al. 2009a] and [Middha et al., 2010] for hydrogen, and [Hansen et al. 2013] for natural gas. [Venetsanos et al., 2009], see Figure 4-4, present a more extensive blind benchmark exercise which gives some perspectives around validation of models and competence of modellers, with 17 different modellers trying to blind-predict a simple dispersion experiment. The conclusion from this work must be that a CFD tool must be properly validated for the application and have clear validation-based user guidelines.

Vessel rupture compressed hydrogen gas:

It is possible to establish simple models to predict blast from a bursting high pressure vessel, such a model is not included in the Phast model. With special settings such scenarios can be modelled with CFD-tools. In [Aarskog et al., 2020] examples both of simple models and use of CFD for catastrophic tank ruptures can be found. Examples of validation includes prediction of vapour head blast from BLEVEs [Hansen and Kjellander, 2016], the FLACS model has also been checked against hydrogen car tank rupture tests [Stephenson, 2005].

BLEVE LH2, LNG, ammonia:

For BLEVEs simple relations exist to predict blast, projectiles and flame radiation. None of these are expected precise or particularly valid for LH2-BLEVEs. [Hansen and Kjellander, 2016] developed a CFD modelling approach for blast waves from (unignited) BLEVEs. For traditional BLEVEs blast is generally of secondary interest to flame radiation or toxicity for unconfined BLEVEs. Indoor or in tunnels the risk from blast could be more of a concern, here the simpler models will no longer be valid.
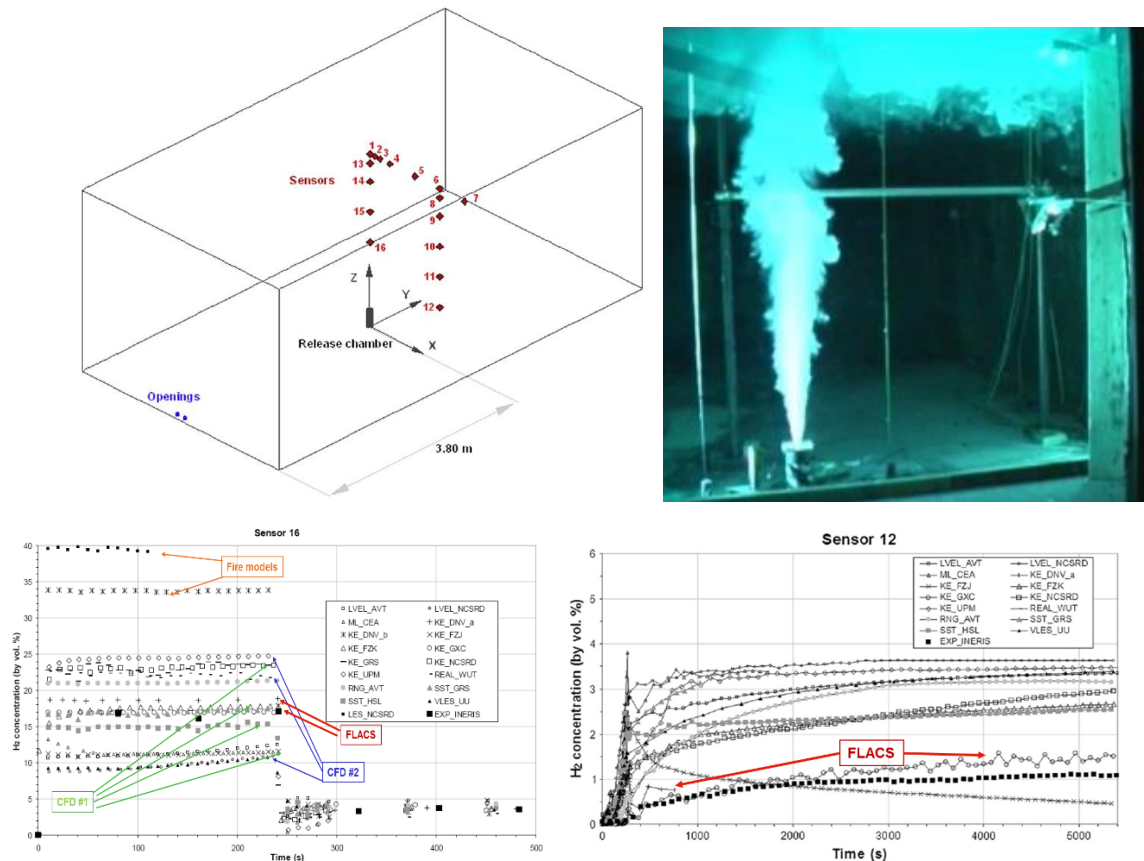
Figure 4-4– Blind-benchmark simulation exercise carried out as part of the HySafe project with 2 g/s hydrogen released for 240s inside a garage sized room. The experiment was thereafter performed by INERIS. Lower left plot shows predicted hydrogen concentrations 1m above the release first 6 min by 17 partners (experimental results shown as black squares), while lower right plot shows predicted hydrogen concentration 0.9m above the floor near. FLACS was used by two groups with good results, for some of the other CFD-tools used a significant user dependency was seen. For more details see [Venetsanos et al., 2009]

Deflagration hydrogen, natural gas and ammonia:

Simpler models for deflagration are of mixed quality and value. Vent guidelines exist for idealized rooms with vent openings, e.g. in standard NFPA-68 and EN14491, given room size is limited and gas cloud is homogeneous and filling the room and not particularly turbulent. For far-field blast predictions simple models exist in which the cloud size and explosion strength are required as input, the most popular among these models is the Multi-energy method [van den Berg et al.,1985 and 1996]. Both spread-sheet models and integral models may include such models. For the accurate prediction of a general deflagration scenario with a gas release indoors or outdoors a comprehensive, purpose-made CFD-model will be required. The CFD explosion model FLACS, developed since 1980 through JIPs with major oil companies, has been the globally leading deflagration prediction model since1990. The extensive validation effort against experiments is a main reason for the position, see e.g. [Hansen and Åsheim,

1995], [Foisselon et al., 1998], [Hansen et al., 1999] and [Hansen et al., 2013] for natural gas explosion validation, and [Hansen et al., 2005], [Middha et al. 2007, 2009b] for hydrogen explosion validation. No dedicated ammonia explosion models exist. While it is possible to define ammonia as an explosive substance in FLACS, this is not usually done due to the low reactivity of ammonia.

Jet-fire and flash-fire:

Free jet-fire length and radiation can be predicted either with simple models, integral models or CFD. For hydrogen jet-fires tabulated values for jet-fire length and radiation can also be found in NFPA-2. For jet-fires impinging onto walls and other geometries a dedicated CFD-model is required for proper prediction of flow patterns and heat loads. KFX has traditionally been the most comprehensive dedicated fire model, a range of other models like ANSYS-CFX/FLUENT, FDS and FLACS are also used for such predictions. Simplified models can still be useful to estimate radiation e.g. outside a fenced area.

Detonation hydrogen (and natural gas):

For hydrogen, and for certain large-scale natural gas scenarios, DDT and detonation may be a risk. The challenge is both to predict where and when a DDT may take place, and how this will influence explosion loads (pressures and impulse). While simplified models can predict near-field and far-field pressures, CFD-tools will be required to predict whether or not a DDT will take place for the realistic scenario. Models to predict DDT was developed in FLACS around 2005 [Middha and Hansen, 2008]. FLACS is not a detonation model, however, with special settings it is also possible to predict detonation flame development and pressures [Hansen and Johnson, 2015]. In Figure 4-5 this approach is used to simulate a detonation with FLACS with the aim to model the likely explosion dynamics of the Kjørbo-incident [Hansen, 2019].
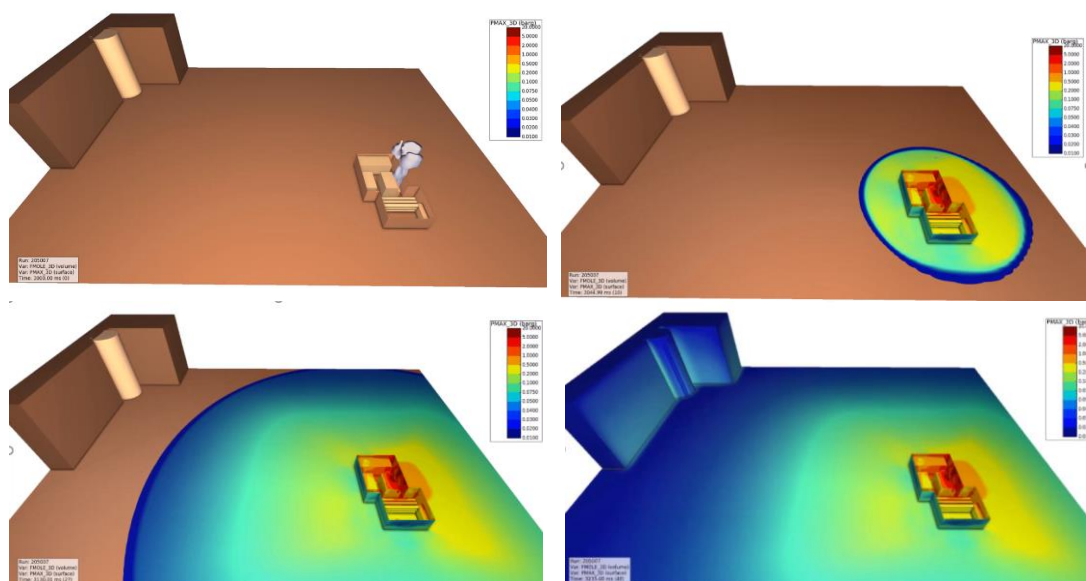

Figure 4-5– CFD-simulation of assumed hydrogen release and detonation [Hansen, 2019] in the Kjørbo accident, first frame shows predicted hydrogen cloud (>15%) at ignition, the other frames show maximum received blast pressures after 45ms, 130ms and 275ms.

Far-field blast calculations:

Idealized far-field blast calculations can be done with spreadsheet models and integral models using e.g. the Multi-energy model. For situations where gas clouds are elongated, inhomogeneous, or with asymmetric ignition point, CFD-tools have to be used for directional blast predictions. The majority of CFD-tools, including FLACS if used according the standard guidelines, will have a tendency to smear blast-waves from strong explosions, and this way underpredict blast loads. By improved time resolution and decent grid resolution, blast predictions can be quite accurate, see [Hansen et al. 2010b] and [Hansen and Johnson, 2015]

Mitigation (detection/ESD/others)

There are many ways to eliminate or mitigate risk. Both for simple spreadsheet models, integral models and CFD-models various mitigation methods can be assessed. For quite a few of the mitigation methods only detailed modelling will have the required precision and modelling capability to properly assess detector placement, detection time and effect of ESD on gas cloud build-up.

4.5   Who owns the risk?

Risk management in the society is an interaction between the facility owner, typically one or more companies, and the regulator. For most land facilities in Norway DSB is the regulator. In Norway there is a tradition for a goal setting regime in which the goals are defined by the authorities, while the operator has a significant freedom on how to achieve these goals, see e.g. [Rui and Søreide, 2019] discussing this regime in the offshore petroleum industry. It is thus the facility owners' responsibility to understand and manage the risk on the site, and to document that the risk is properly understood and kept within tolerable limits by preparing ATEX Explosion Protection Documents and Risk Assessments. The regulator shall guide and help the companies to fulfil their responsibilities and may also perform controls when required. When necessary if a site owner does not comply with the requirements, the regulator has the authority to stop the operation or give fines.

In Norway it is generally recognized that costs could be prohibitive if the goal would be to prevent all incidents and accidents, and there is an acceptance for a limited residual risk (e.g fatality risk outside the property of a facility may be up to 10^{-5}/year). Thus, even if the operator has done everything right, accidents may happen. If a severe accident would happen it will therefore be important for the operator that the risk documentation of the facility is of good quality confirming that the risk is well understood, and that the site has operated according to the procedures and standards described in the risk reports and internal governing documents. If there are significant weaknesses in the documentation that may indicate that the site risk was not properly understood, or procedures and requirements not followed, the operator or those responsible may risk fines, or at worst, face criminal prosecution for negligence.

In many parts of the world there is a greater element of prescriptive rules stated by the regulators. If an accident happens, and it is later concluded that the prescriptive rules were not good enough, there could be an element of blame sharing in court between regulator and company having the accident. This could for instance be for a situation where authorities inspired by NFPA-2 have prescribed minimum safety distances from e.g. an LH2 storage facility to a parking lot of 7.6m. If a release would then happen and ignite from a car injuring people at the parking lot by blast and fires, the authorities could be claimed to have shown negligence if the justification for the 7.6m exclusion zone is weak.

It should also be mentioned that numerous industry standards exist internationally as well as in various countries. Sometimes these are harmonized, while at other times there can be significant deviation in philosophy and content. Industry standards are generally developed by industrial players on their own cost of participation, many of those who participate may have commercial interests for their companies as first priority, rather than the safety of workers and neighbours of facilities. Following recommendations in a standard therefore does not guarantee that a plant or facility is safe.

Finally, some words of wisdom….

- *Do you think safety is expensive? Try an accident!*

5 Modelling examples

In this section some CFD modelling examples of accidental releases are performed to illustrate possible hazards from typical small-scale storage or processing facilities. The gases investigated include:

- ammonia stored as refrigerated (-33.4°C)
- ammonia stored pressurized (ambient temperature 20°C)
- liquid hydrogen
- compressed hydrogen
- LNG (for comparison)

For all cases the assumed tank dimension and tank connection piping are selected based on typical expected storage need and realistic bunkering rates. The storage site is surrounded by a 3m tall fence, and 2 m/s wind (5 m/s for selected cases) is assumed in the modelling, this wind strength will in many cases give the maximum hazard distances.

5.1 Refrigerated ammonia

For spills with refrigerated ammonia the release is at its boiling point and when released there will be no immediate evaporation of ammonia. Ammonia will fall to ground, generate a pool at -33.4°C which will spread and gradually evaporate due heat transfer while cooling the ground. The boiling rate per area of pool will gradually reduce with the cooling of the ground. The 100m³ tank is placed into the ground surrounded by a concrete bund. A 100mm connection (bunker line) was considered reasonable to be able to bunker a typical vessel in 1-2 hours. Hole sizes of 100% (full bore), 10% (31mm) and 1% (10mm) were simulated using the FLACS simulation tool.

No pressurization of the tank is assumed, thus when a release happens the ammonia is forced out by gravity only. Assuming a connection failure/hole below the tank a 3m liquid column is assumed (P=0.2 barg), giving a leak rate of 38.6 kg/s for the full-bore leakage, 2.4 kg/s for the 31mm hole size and 0.24 kg/s for the 10mm hole size. The concrete below the tank is assumed to be at temperature 15°C prior to the release. In Figure 5-1 the development of the IDLH plume (300 ppm) for the case with 31mm hole size (2.4 kg/s spill) is shown after 10s, 50s, 100s and 200s. In the first 5 seconds the evaporation rate is 10-15 g/m²s, around 30s it has fallen to 5-6 g/m²s and further reduced to about half of that after 120s once the ground has cooled.

In Figure 5-2 the evaporation rates for the three cases are shown. For the highest spill rate the maximum evaporation rate is 0.5 kg/s. As the large release quickly spreads to cover the entire floor of the bund and cools the concrete, the evaporation rate drops after 20-30s. The 2.4 kg/s spill reaches a maximum evaporation rate of 0.3 kg/s after 80s before falling as the entire floor has been covered and the heat transfer falls due to cooling of ground. The smallest release (0.24 kg/s) reaches a maximum evaporation rate of 0.18 kg/s after 150s. Despite the very significant difference in release rate the pool evaporation is not substantially different as most of the ammonia is collected in the bund.

In Figure 5-3 the predicted ammonia plumes 1.25m above the ground are plotted for the three cases after 200s simulation. For all cases the IDLH plume (300 ppm) reaches beyond 200m, but only in a rather narrow tongue. For the larger release rates this plume extends beyond 250m and might stretch even further. The 1000 ppm plume reaches 100-150m, while the 3,000 ppm plume is predicted 10-25m outside the fence (and up to 30m outside in the early stages of the largest release).

It would be quite unlikely to see fatalities outside the fence from this type of releases, the 3,000 ppm plume (AEGL-3 level) extended 10-30m outside fence for all cases, still the exposed area is limited, and it will be highly likely that people exposed would manage to get out of the exposed plume to safety. Exposure times of the order 30 minutes or more would normally be required to be fatally injured. People inside the entire IDLH plume will feel a significant discomfort, and would be likely to seek

medical check, and there would be potential for some non-reversible injuries if people would be trapped inside the cloud for several minutes. Due to the narrow plume it would be very likely that concentration levels at the worst exposed places would fluctuate due to normal wind variations, so that the average concentrations at a location downwind would not be as high as predicted.
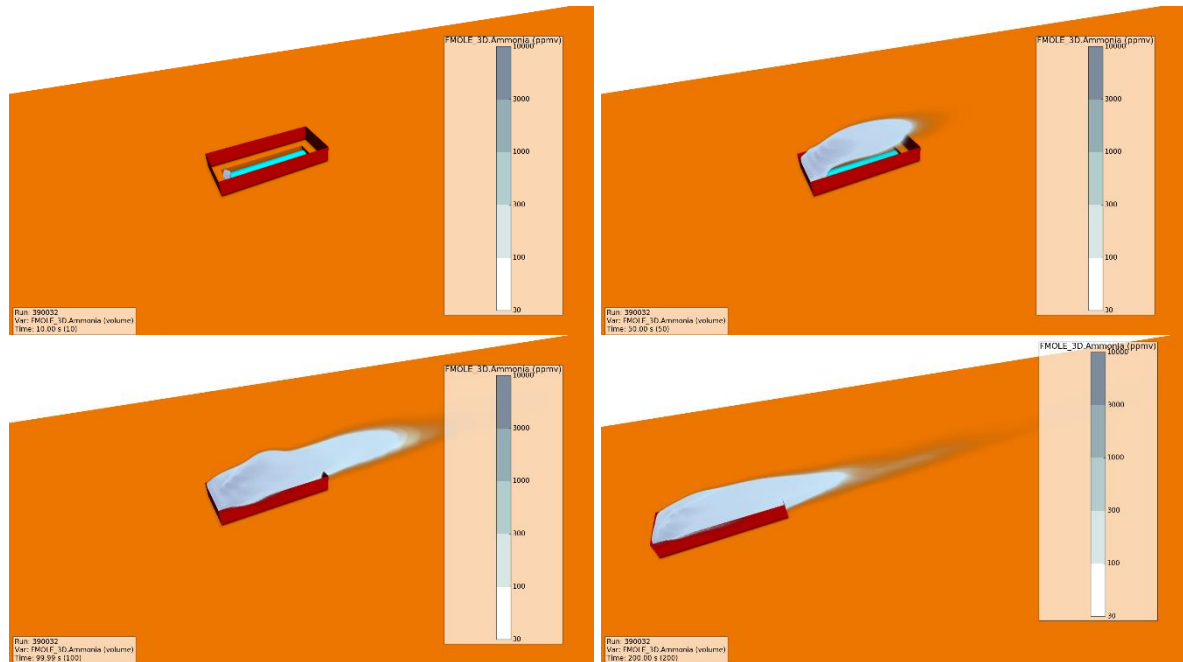

Figure 5-1 Pool evaporation and gas dispersion from 31mm hole (10%) for refrigerated ammonia, 3D plume odour level (30 ppm) shown after 10s, 50s, 100s and 200s.

Run: 390012, 390032, 390102
Var: RATE_RT
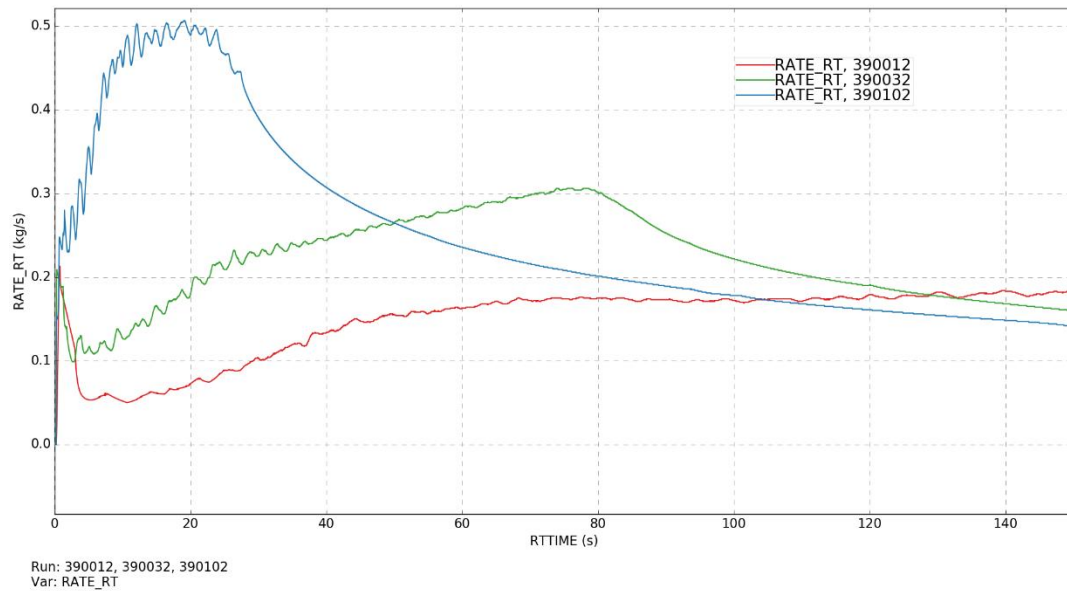
Figure 5-2 Pool evaporation rate (kg/s) with time for spills with refrigerated ammonia with leak rate of 38.6 kg/s (full bore - blue), 2.4 kg/s (31mm - green) and 0.24 kg/s (10mm - red)

It can be noted that ammonia evaporating from a pool is significantly lighter than ambient air and will rise upwards. An initial plume rise is also seen above the pool. In the wind-field the plume quickly gets diluted down below 10,000 ppm (1%) and at this concentration the buoyancy effect of the plume is secondary to wind and wake effects, and the ammonia plume is in reality neutral density blowing with the wind outside the fence.
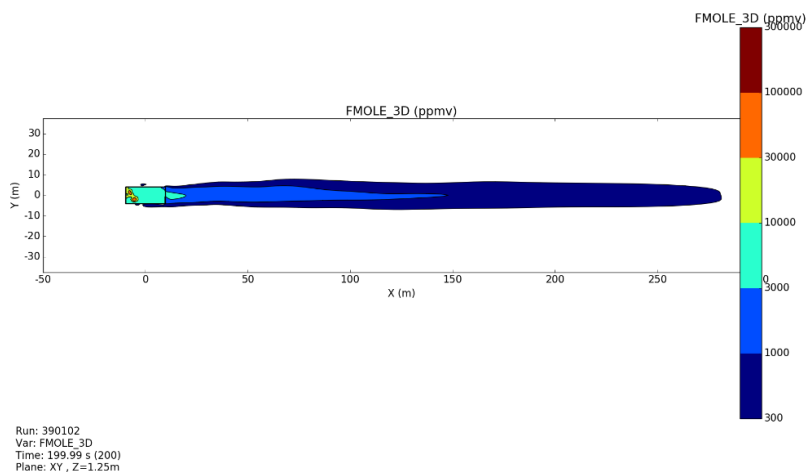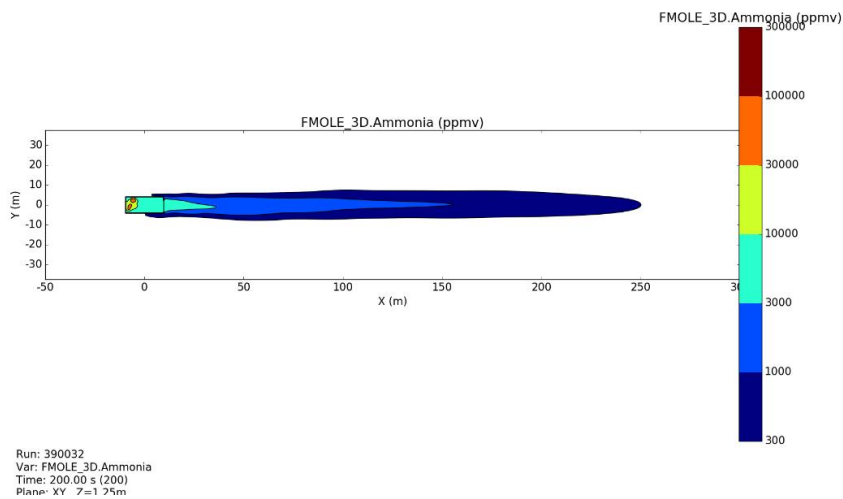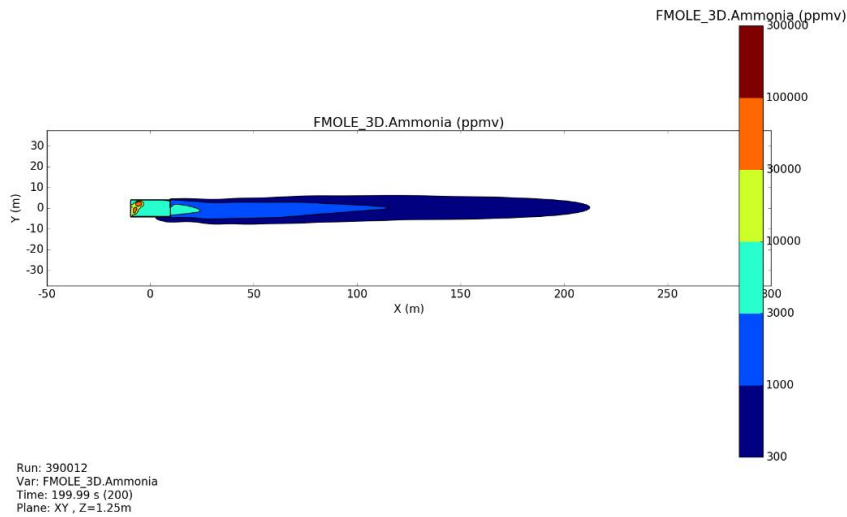
Figure 5-3 Ammonia concentration with distance at 200s near ground for 2 m/s wind for refrigerated spill from 10mm hole (upper), 31mm hole (middle) and full-bore rupture (lower) of the pipe connection.

The simulated spills from the refrigerated ammonia storage indicated that the fatality hazard beyond the fenced area is not significant. For an actual storage and bunkering site there would be further transfer operations from road tanker and bunkering transfer to the vessels which would need to be assessed, together with their frequency, before the risk contours or safety zones can be defined.

5.2   Pressurized ammonia

For the second case it is assumed that the ammonia is stored pressurized at ambient temperature. In the example it is assumed that the ammonia and bund temperature is 15°C, while the air is slightly warmer, 20°C. The release dynamics is primarily governed by the temperature and pressure of the ammonia, at 15°C temperature the vapour pressure is 8.6 bar (7.6 barg). The liquid density at this temperature is 610 kg/m^3 and the predicted outflow velocity 50 m/s.

This gives estimated ammonia release rates of 1.4 kg/s for the 10mm release, 14 kg/s for the 31mm release, and 140 kg/s for the 100mm release (in this case discharge coefficient Cd=0.62 is assumed for all releases). At this temperature 8% of the ammonia will immediately flash when the pressure is reduced to ambient, as ammonia at this temperature will expand 710 times from storage density as a liquid to vapour at its boiling point, it is estimated that this rapid flashing outside the release will create fine aerosol mist of 55% of the remaining liquid, which will remain airborne and evaporate when further diluted and heated by air. The remaining 35-40% of ammonia is assumed to form a pool, parts of this may also evaporate.

The flashing release scenarios are simulated using the FLACS homogeneous equilibrium model specifying a gas+mist release rate just above 0.8, 8 and 80 kg/s for the 3 cases, with another 0.6, 6 and 60 kg liquid ammonia deposited into the pool. During the evaporation of the ammonia droplets in the plume, the temperature falls well below the boiling point of ammonia (to almost -70°C) and the plume is significantly denser than ambient air due to the cooling of air during evaporation of mist.

In Figure 5-4 3D plots of the ammonia plume exceeding IDLH for the medium release rate scenario are shown after 10s, 50s and 100s simulation. First 10s the plume stays within the fence, thereafter the 300 ppm plume spreads well outside the fences. Due to the high release momentum and impingement of the release onto the fences, the plume has a significant lateral spread.
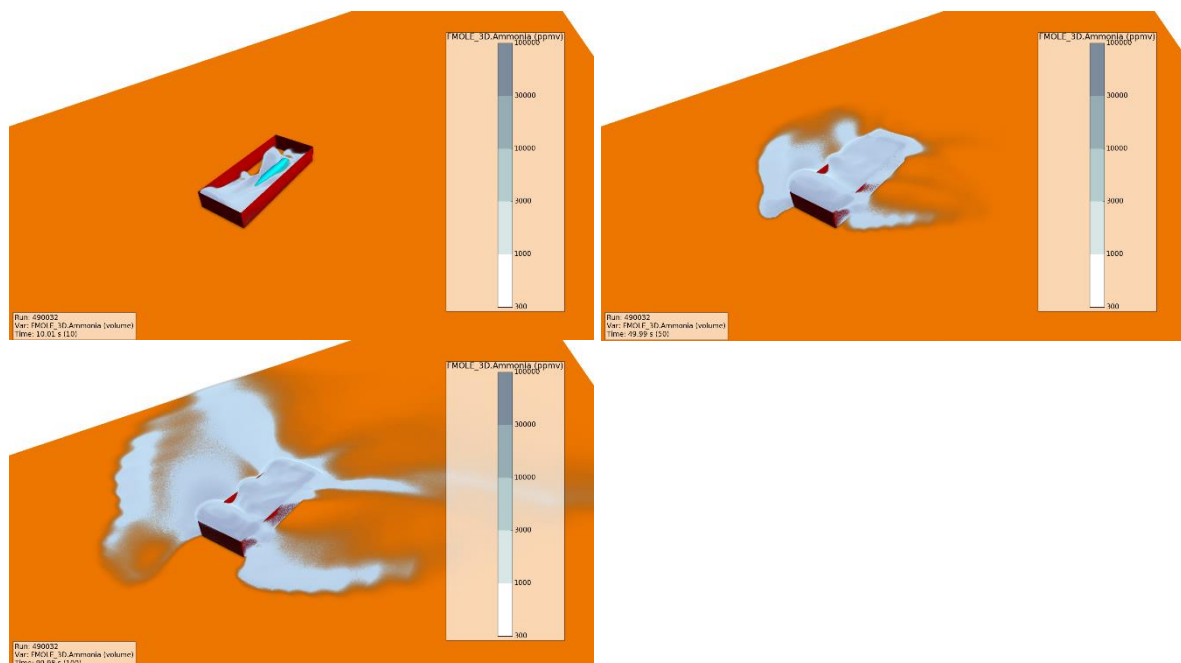

Figure 5-4   Gas dispersion from flashing release from 31mm hole (10%) for ambient pressure ammonia, IDLH level shown after 10s, 50s and 100s.

In Figure 5-5 the evaporated ammonia rates are shown for the three cases, this is practically identical to the gas+aerosol release rate, the pool evaporation has only a secondary impact for the smaller release rates. In contrary to pure gas releases, where release rate will quickly be reduced for larger releases, the release rate for liquid releases can remain practically unchanged for a significant time as the tank volume reduction for liquid releases is low and liquid will evaporate to compensate the pressure reduction during the release.

The evaporation rates for the flashing releases are much higher than evaporation rates from the pool spills for refrigerated releases. A similar release from of ammonia stored at 0°C would have 33% lower release rate with an estimated gas+aerosol release rate about half compared to a release at 15°C.
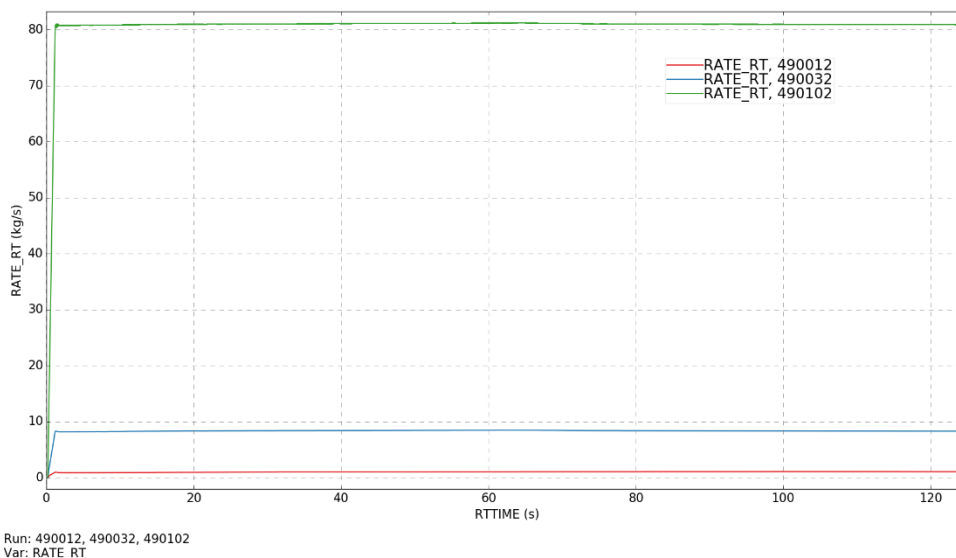

Figure 5-5   Evaporation rate (kg/s) for releases with time for spills with refrigerated ammonia with leak rate of 80 kg/s (full bore - blue), 8 kg/s (31mm - green) and 0.8 kg/s (10mm - red)

In Figure 5-6 ammonia plumes 1m above ground are shown for the three simulated hole sizes, the plots for the two smaller release rates are shown at time 200s, while the largest release is shown after 100s. The release rate for the largest release is too high for the simulation domain chosen. The gas cloud quickly reaches the simulation domain boundaries and the precision in the prediction near the boundaries will be influenced by this.

For the smallest hole size the hazard distances are similar to what was predicted in the pool spill scenarios with the 3,000 ppm plume extending roughly 50m, the 1,000 ppm plume 100m and the 300 ppm plume around 200m. The plume is 4-5 times wider than for the pool scenarios, thus this release from the smallest release rate would have a higher impact than any of the pool spill cases. The 10,000 ppm plume also extends 5-10m outside the fence, this was not seen for any of the refrigerated releases.

In the simulations the flashing release is directed against the wind direction hitting the fence and spreading laterally. For the larger releases this gives a significant lateral spread of the plume, e.g. for the 31mm plume this gives a bifurcated main plume 150m wide, with 10,000 ppm contours predicted 250m away from the release, and also the 30,000 ppm plume is seen well outside the fence. For the full-bore rupture case the predicted plume is even worse, filling almost the entire simulation domain. The plume is more than 150m wide with concentrations more than 30,000 ppm 200m downwind of the release.

Expected outcome from these releases might be that the 10mm release would probably give lighter injuries. The medium size release could lead to fatalities, but more likely irreversible injuries, while the largest release could well lead to multiple fatalities and serious, permanent injuries.

The risk contours around such a site would depend on the combined risk from filling operations from road tankers, the bunkering operations to a ship/vessel, and their frequencies, however, the simulations presented indicate very significant hazard distances for the larger releases which will very likely influence the risk contours and lead to restrictions on placement of such a facility and simultaneous operations.
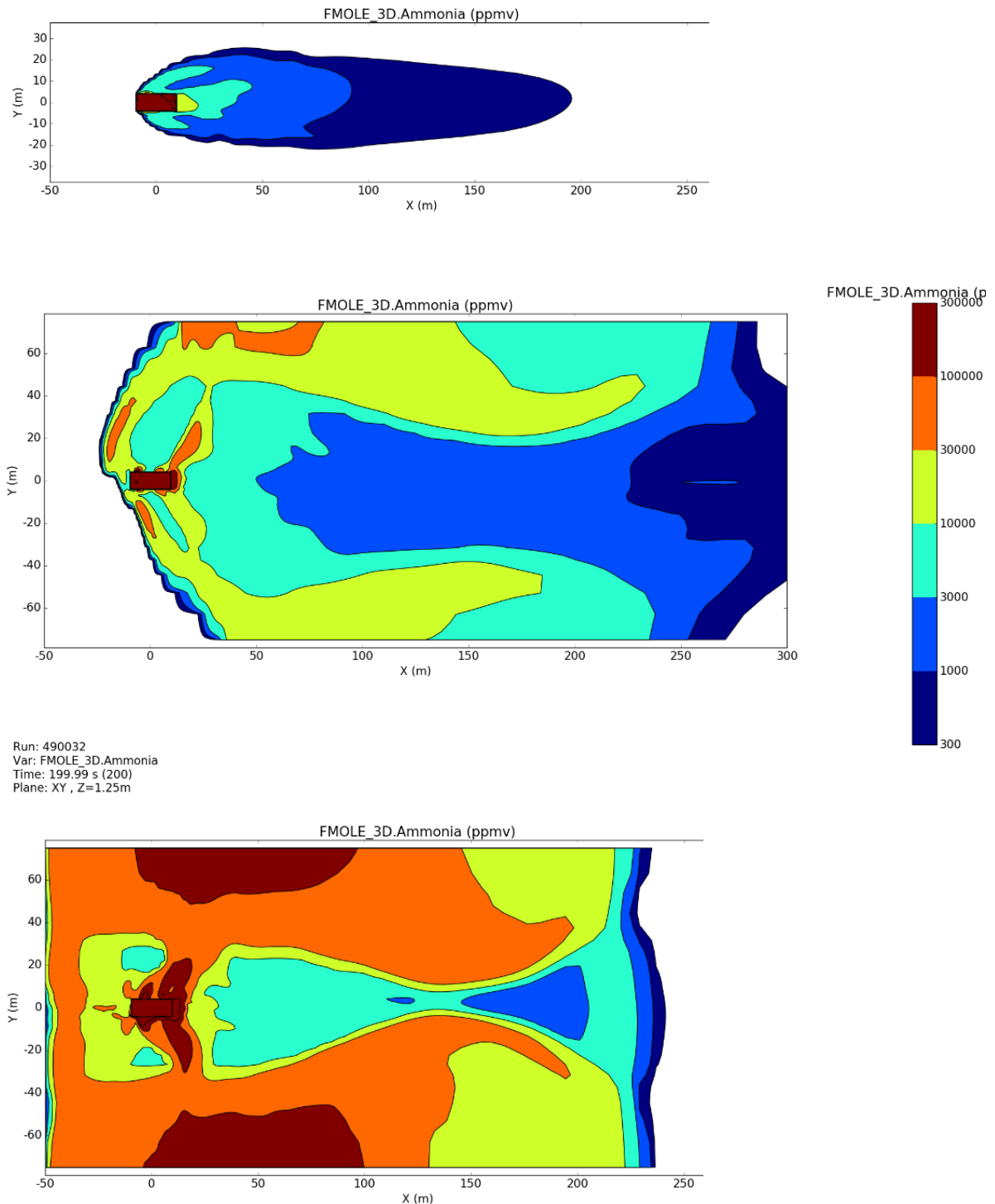

Figure 5-6 Ammonia concentration with distance near ground for 2 m/s wind for 10mm hole (top, 200s), 31mm hole (middle, 200s) and full-bore rupture (bottom, 100s) of connecting pipe.

5.3   Liquid hydrogen

For the liquid hydrogen storage two vertical storage tanks, each with capacity to store 4-5 tons, are modelled. The bunkering line from the tanks is 50mm diameter and a release from the upwind tank directed horizontally towards the downwind tank has been simulated assuming full bore rupture (50mm), 10% hole size (16mm) and 1% hole size (5mm). The modelling approach described by [Hansen, 2020] is used in which an LH2 source term of cold evaporated hydrogen mixed with some entrained air assuming the condensed/frozen air particles will remain in the air and evaporate when diluted with further ambient air. For all releases simulations are performed in 2 m/s wind conservatively assuming no humidity in air, for the medium size release (16mm) a sensitivity simulation has been performed with humid air (50% relative humidity at 20°C), while for the largest release a sensitivity simulation is performed with 5 m/s wind. Like shown in [Hansen, 2020] LH2 spray releases into air are initially denser than ambient air. Once diluted below stoichiometric concentration the density gradually becomes neutral relative to ambient air. In humid air, however, fog generation in the cold air will heat the air and give the plumes positive buoyance at leaner hydrogen concentrations. In low wind the hydrogen plume in humid air will therefore lift off the ground when diluted. In stronger wind it will take longer until the buoyancy effect kicks in, and the plume may remain at ground level longer.

The temperature of the leaking tank is assumed to be 25 K, i.e. 4.6 K above the boiling point of hydrogen. At this temperature the saturation pressure is 2.2 barg and the hydrogen density 64.7 kg/m³. Due to the low density of hydrogen the liquid level in the tank has barely any effect on the release pressure, a 6m liquid level of LH2 would add only 0.04 bar to pressure behind the release. The LH2 leak rates for the full-bore release (Cd=1.00 assumed) is 10.5 kg/s, for the 16mm release it is 0.665 kg/s and for 5mm release it is 0.065 kg/s, for the two smaller releases a discharge coefficient Cd=0.62 is assumed.

In Figure 5-7 simulation results (3D) are shown for some of the simulations. For the 5mm release the entire flammable plume (>4%) remains inside the fence, thus there is no flammability risk outside the fence. For the 16mm release in dry air the flammable plume extends around 50m outside the fence and has a relatively wide footprint due to the wake behind the fenced area. When the same release is simulated in humid air (50% relative humidity in 20°C) the plume lifts off after climbing the 3m fence, thus there is no flammable cloud at ground level outside the fence. For the 50mm release a large cloud is formed extending far beyond the fenced area.
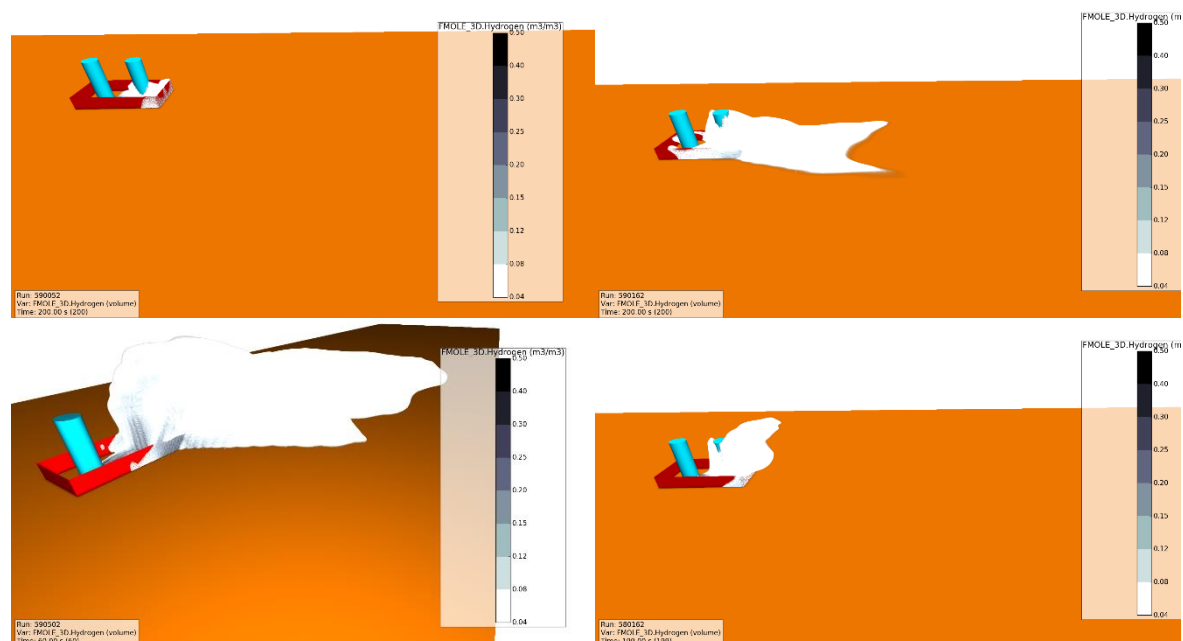

Figure 5-7   Gas dispersion from liquid hydrogen 5mm release (upper left), 16mm release in dry air (upper right), 16mm release in humid air (lower right) and 50mm release lower left.

In Figure 5-8 the release rate profile for the LH2-releases is shown. For LH2-spray leaks at 25 K 10% of the LH2 will immediately flash. Compared to the ammonia release, in which flashing liquid would expand 700 times, hydrogen at this temperature will only expand 50 times. Despite limited expansion it can be expected that no LH2 will deposit at the ground and form a pool. Reasons for this is that LH2 cannot coexist with air, thus it will immediately evaporate and freeze the air when in contact with air. Further, the very high release velocity and low density of LH2 droplets will make it unlikely with any significant pool-generation of LH2, unless the release is immediately at ground level with limited momentum.

Run: 590052, 590162, 590502
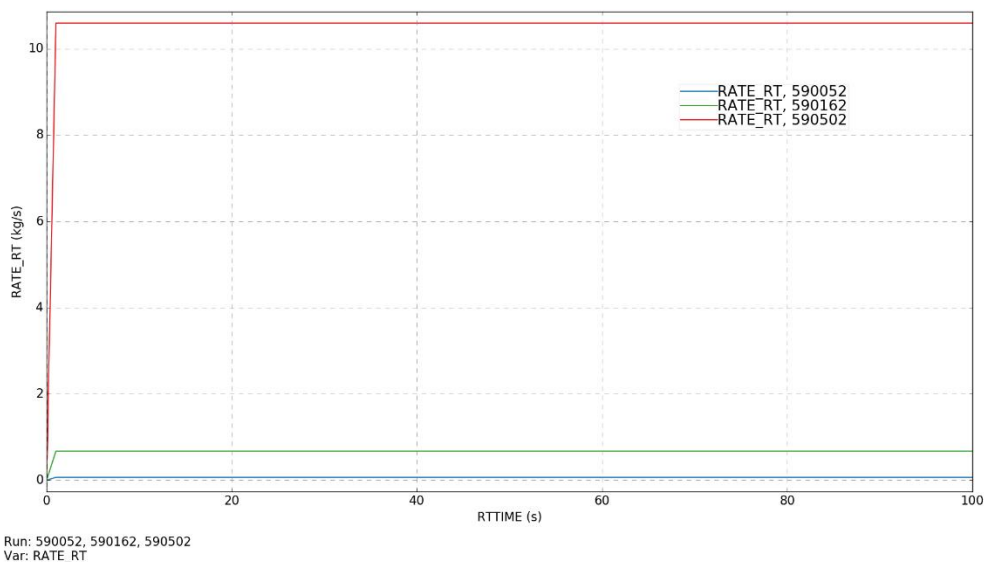Var: RATE_RT

Figure 5-8   Flash evaporation rate (kg/s) with time for liquid hydrogen releases with leak rate of 10.5 kg/s (full bore - red), 0.66 kg/s (16mm - green) and 0.065 kg/s (5mm - blue)

In Figure 5-9 cold hydrogen concentrations at ground level are shown for selected simulations. In the upper two plots the 16mm release is shown with humid air (left) and dry air (right), it is clearly seen that the plume with humid air lifts off the ground when passing the fence, with no gas 1m above ground outside the fence. LFL contour 4% (ignition risk) extends 60m beyond fence, 8% contour (flashfire risk) only around 20-25m beyond fence. Concentrations outside fence are below 20%. In the lower plots the 50mm release is shown in 2 m/s wind (left) and 5 m/s wind (right), both assuming dry air. With 2 m/s wind the 8% contour (flashfire risk) covers a large area and extends beyond the end of domain 300m from the release, while reactive concentrations above 20% hydrogen extend almost 50m outside the fence. For the same simulation in 5 m/s wind the 4% LFL concentration extends almost 300m from the release, the 8% (flashfire risk) concentration around 150m downwind, while the 20% contour goes almost 50m beyond the fence.

The risk from the smallest hydrogen release is negligible, the flammable cloud is primarily inside the fence and too small to generate any explosion consequences of concern outside.

For the 16mm hydrogen release there is flash-fire risk at ground level 20-25m downwind for the dry air scenario, nothing for the humid air case. The predicted reactive cloud size (>15% hydrogen concentration) and the estimated equivalent stoichiometric cloud size Q9, see [Hansen, 2013] is of the order 400m^3 (~10 kg H$_2$) for the dry air case, but only around 100-150m^3 (~3 kg H$_2$) for the humid air case, see Figure 5-10. If there are limited density of object/obstructions inside the fence, an explosion in such an open cloud will likely not be very strong and detonation will be unlikely, at least not for the humid air case. An important reason for this is the significantly lower jet turbulence for the 2.2 barg LH2 release compared to releases from compressed gas storage (release exit velocity ~80 m/s compared to ~1200 m/s). If a strong explosion would happen, this could give blast pressures of the order double of those likey seen in the Kjørbo-incident. With a higher wind speed the effect of humidity will be less, and the 8% (flashfire) plume could extend outside the fence, this would be more diluted than for 2 m/s,

thus distances would be shorter than the 20-25m predicted with 2 m/s wind. In case of a strong explosion the distance to predicted blast load of 0.35 bar, the expected adjusted criterion for 50% fatality, would be 20m (humid air) and 28m (dry air), respectively. Broken windows could be feared 200-300m away.
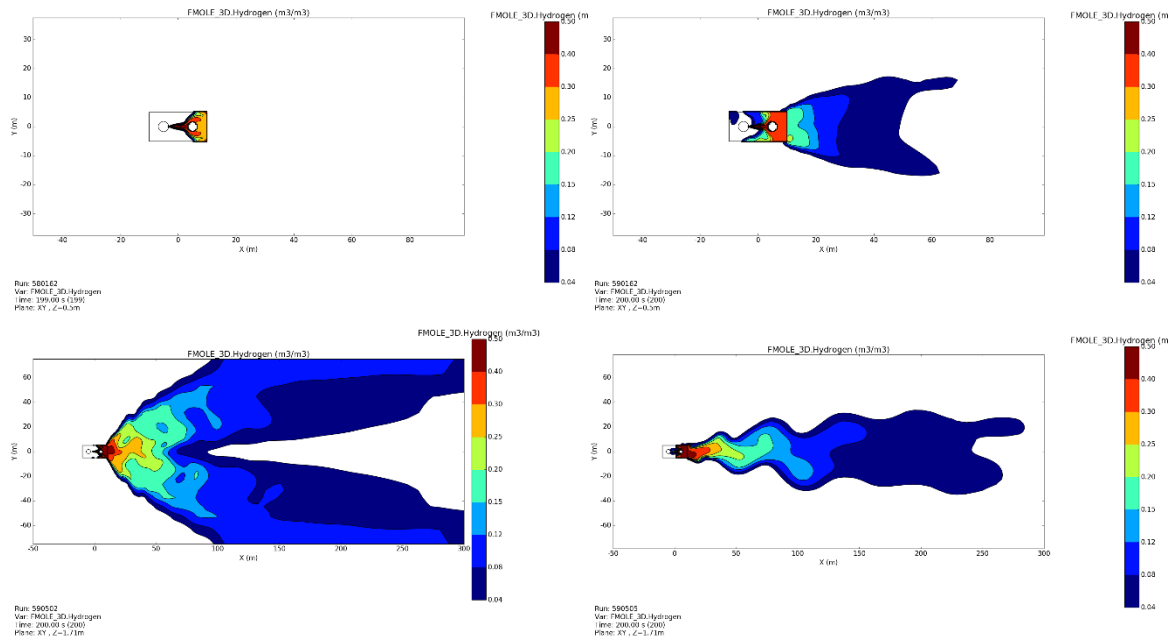

Figure 5-9   Ground concentrations from LH2 release from 16mm (10%) hole in humid air (upper left) and dry air (upper right), and full bore (50mm) release in 2 m/s wind (lower left) and 5 m/s (lower right)

For the largest release, 50 mm full bore, the flashfire distance (8%) could extend 300m away or more, and a reactive gas cloud of the order 10,000m^3 could result with 2 m/s wind, and half the cloud size with 5 m/s wind. If ignited the chances that this scenario would develop into a strong explosion and possible detonation would be significant, estimated distance to 0.35 bar blast pressure would in that case be 80m from the most reactive part of the gas cloud with potential for windows shattering more than 1 km away.

The risk contour around the site would depend on the frequency of filling operation from road tanker as well as bunkering operations. The medium sized releases would not contribute significantly to the risk contours beyond the fence if normal humid days can be assumed. The catastrophic scenario with full bore release which cannot be stopped may give severe consequences, however, the frequency of such incidents should be low. For a busy LH2 bunkering site a controlled area of the order 70-100m away from the operation may be expected, possibly more.
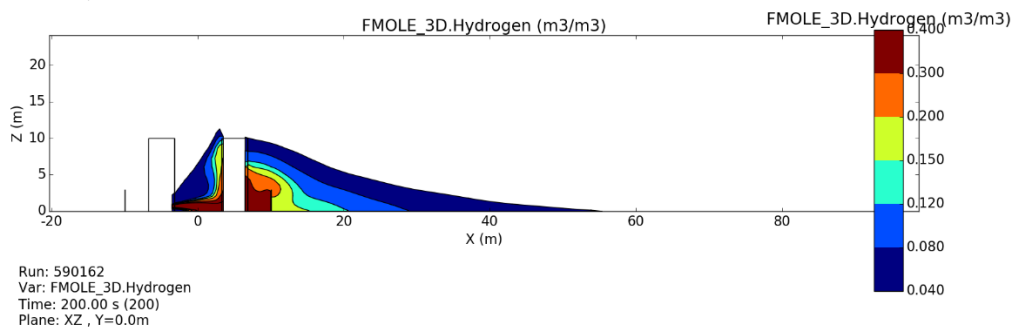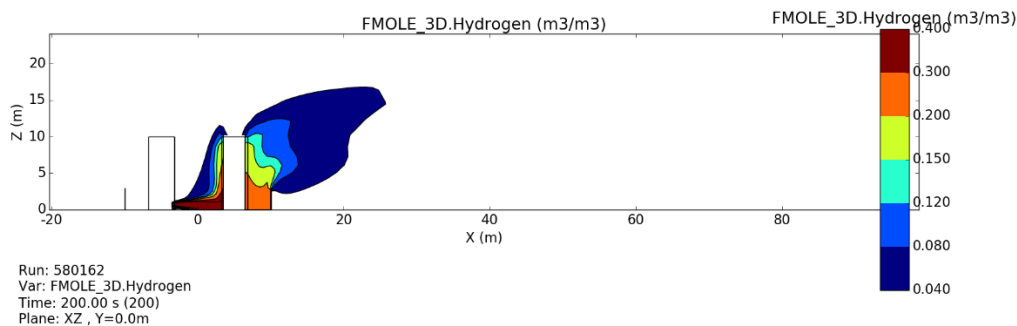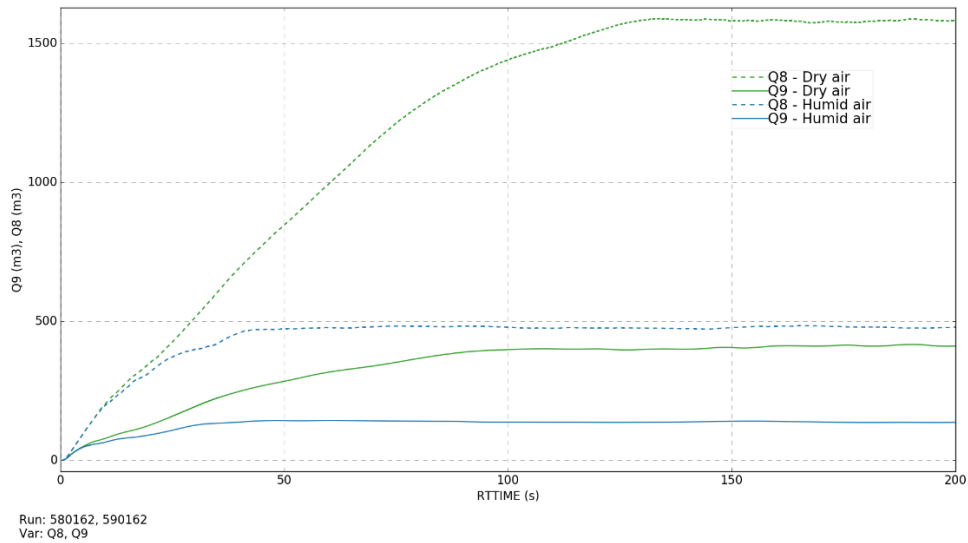
Figure 5-10   Reactive cloud sizes development Q8 and Q9 for the 31mm release (upper) and vertical plot of concentration for humid and dry air case (middle and lower)

5.4   Compressed hydrogen

For the compressed hydrogen storage five transport units are placed inside the 3m tall fence, each unit consisting of 3x3 1650L tanks which could fit inside a 20ft container. A tank pressure of 350 bar is assumed, giving a capacity of 40 kg per tank, 360 kg per unit and 1800 kg in total. These tanks could either be used for compressed gas bunkering, or as swap-tanks for vessels.

For the assessment it is assumed that a severe leak (20mm diameter) takes place through the tank connection, this gives an initial release rate of 5.9 kg/s out from the tank, reduced to half in about 5-6s. The release hits straight into the fence, deflects and seeks upwards due to buoyancy when losing momentum. Depending on the design of the tanks the maximum release through the tank connection could be significantly higher, e.g. if the tank connection is double diameter, i.e. 40mm, and blows out, the release rate will be four times higher and the time to empty the tank four times faster. This can have significant impact on the maximum gas cloud size and potential explosion loads if ignited. For this case, like for the other cases, a 2 m/s wind is assumed. The effect of moderate wind is however limited due to

the strong buoyancy of the plume, the reactive cloud size will be only moderately influenced, but a certain tilt of the flammable plume can be seen, see Figure 5-11.

Due to the strong reduction of release rate with time, the most reactive plume will be seen early during the release, within the first 5s, at this time roughly 150m³ volume (~3 kg H₂) is filled with reactive gas above 15% concentration. For such a high-pressure release among a number of cylindrical tanks, there would be a significant risk for DDT and detonation if the release is ignited during the first 5-10 seconds. A strong explosion involving this amount of hydrogen could give overpressures of 0.35 bar at around 20m distance, however, as most of the reactive gas is near ground level inside the fence, the distance to the 0.35 bar contour is expected to be shorter than 20m as the fence will limit the blast pressures outside the fence. This could be demonstrated in a CFD-calculation. Broken windows may be seen up to 200m away.

No flammable gas is predicted near ground level outside the fence, thus there is limited flash-fire risk outside the fence.

To conclude, the risk related to a high-pressure storage of hydrogen could to a great extent be kept within the enclosure. For the largest releases there may be a fatality risk from blast a limited distance outside the fence. If tank design could ensure that the tank connections were kept as small as possible, and that any leak through the orifices are rapidly deflected upwards, the risk for DDT and detonations, and thus strong explosion, should be kept low. Tank burst, normally assumed to have a very low frequency, is a potential high consequence scenario. To ensure that the risk from such a scenario is kept low, it would be important to protect the tanks from dropped objects and impact, as well as from flame impingement from leaks from other bottles. If this is done properly, it is believed that this type of facility could be possible in the vicinity of jetties where boats operate.
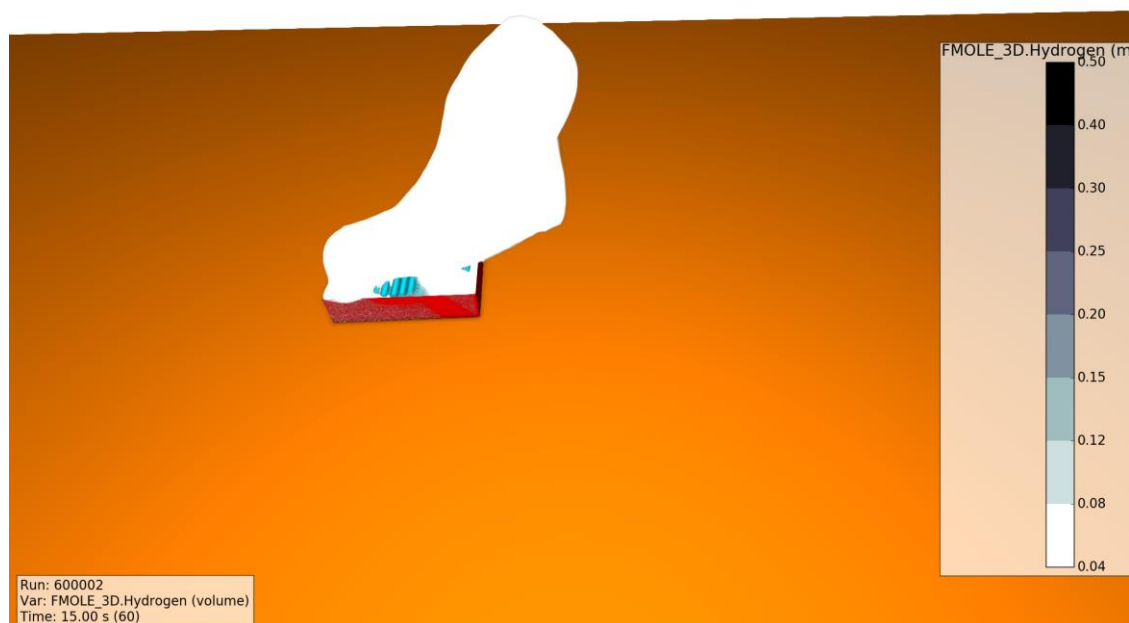

Figure 5-11   Flammable cloud from a 20mm diameter release of a 350 bar tank storing 40 kg hydrogen, maximum cloud size 15s after the start of the release is shown.

5.5   LNG

The last simulation example is the comparative assessment looking at LNG. The LNG-tank is for simplicity assumed placed inside a concrete bund into the ground, the size and layout are the same as for ammonia. The LNG composition is 92% methane, 4% ethane, 2% propane and 2% butane (MW=18) stored at -150°C, giving a liquid density of 443 kg/m³. At this temperature the vapour

pressure is 2.3 bar (1.3 barg) giving a flow velocity for a liquid leak of 24 m/s. At this temperature an estimated 7.1% of the LNG would immediately flash when released to atmospheric pressure, and 16% of the remaining liquid is assumed to be broken into fine aerosol mist and remain airborne as LNG is expanding 225 times when evaporating at this temperature. The LNG bunker line is assumed to be 100mm diameter, for a full bore release the leak rate would be 84 kg/s (Cd=1.00), a slightly lower rate of 52 kg/s (Cd=0.62) was simulated, with 12 kg/s assumed gas+mist and 40 kg/s to form a pool. A 10% hole would have a diameter of 31mm and leak rate of 5.22 kg/s (Cd=0.62) with 1.22 kg/s being a flashing jet and 4.0 kg/s entering a pool. The 1% hole size, 10mm diameter, has a leak rate of 0.52 kg/s.

For the full-bore release an up to 50m wide LFL-plume extending around 100m downwind was predicted.

From experiments with LNG releases with a slightly higher evaporation around 25 kg/s (Maplin Sands, see e.g. model validation study in [Hansen et al., 2010a], LFL-distances of up to 200-250m were reported. This was however in completely flat area above water, without the fence of the site studied, and the observed plume was only 10-20m wide. The somewhat shorter hazard distances therefore make sense.

For the 31mm release around 1.22 kg/s LNG is assumed to form a gas+mist plume developing into a dense vapour cloud when diluted with air, while 4.0 kg/s LNG is assumed to fall into the concrete bund and form an LNG pool. The flammable plume from this simulation is seen in Figure 5-12. Due to the flow pattern inside the fence the dense vapour escapes the fence primarily in the corners of the enclosure, and the plume behind the fenced area is irregular. In Figure 5-13 the LNG evaporation rate is shown. While the gas+mist release is only the 1.22 kg/s the evaporation rate is generally around 3 kg/s peaking at 3.7 kg/s after 130s, the main contribution coming from the pool evaporation which is high during the pool spread and reduces once the concrete bund is cooling down.

In Figure 5-14 the maximum LFL-plume during the simulation is shown, extending around 40m beyond enclosure. Due to low reactivity of LNG vapour there is no risk from explosion pressures for such a plume, however, there will be a limited fatality risk related to being trapped in a flash-fire within the LFL-plume. As the developing LNG vapour plume will be highly visible due to the white fog generated when cooling humid air, the likelihood that people will get trapped inside the plume may be low. For the largest catastrophic release, however, there will be a somewhat higher possibility for being trapped inside a flash-fire.

The smallest release did not generate flammable plumes outside the fence.

Figure 5-12   Gas dispersion from LNG spray release from 31mm hole (10%) for LNG at minus 150°C, LFL plume shown after 2 minutes.
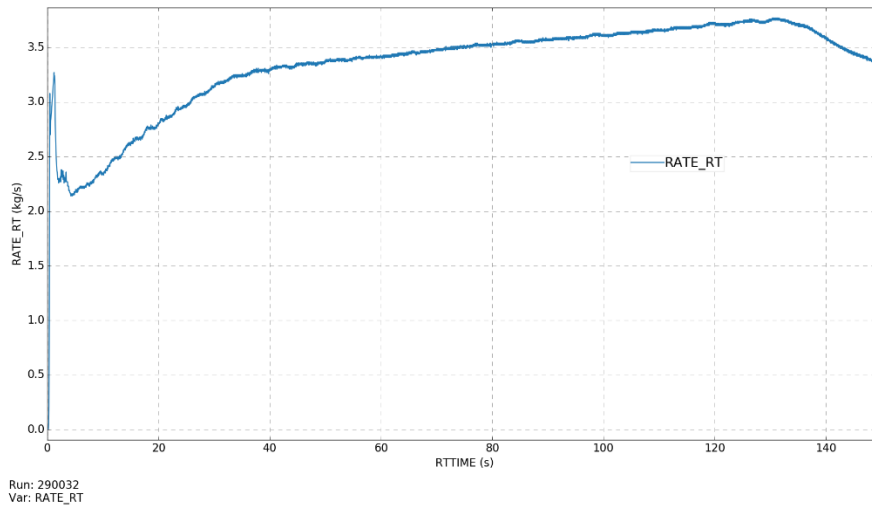
Run: 290032
Var: RATE_RT

Figure 5-13 LNG evaporation rate (kg/s) for a spill with an estimated 1.22 kg gas and aerosol plume and 4.0 kg/s spill entering the pool in the concrete bund below the tank
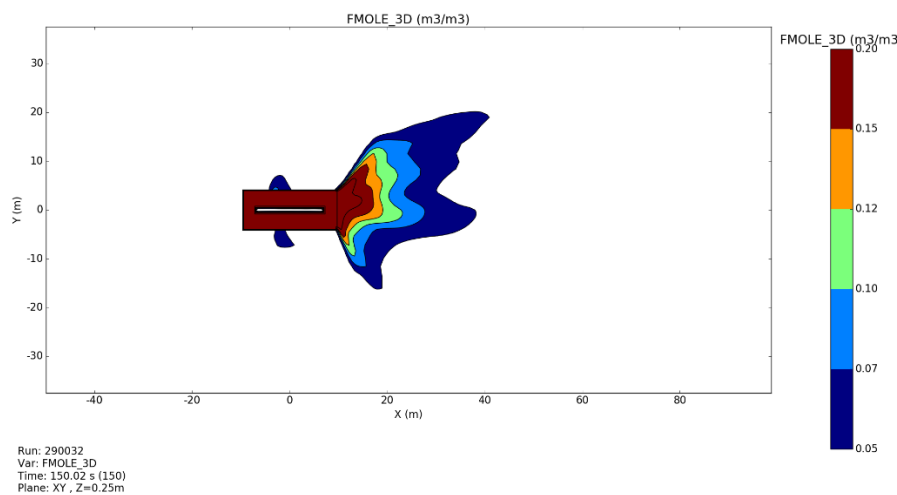

Run: 290032
Var: FMOLE_3D
Time: 150.02 s (150)
Plane: XY , Z=0.25m

Figure 5-14 Maximum LFL-plume at ground level for LNG-spill from 31mm diameter LNG release (10%) in 2 m/s wind.

5.6 Summary consequence assessment

The simplified assessment only considered releases from a typical bunker line, both full-bore release, 10% cross-section and 1% cross-section release, and mainly for moderate wind speeds (2 m/s). If it can be assumed that the release frequencies for these hole sizes are of the same order of magnitude for the different cases, potential consequences can still be compared. In an attempt to compare the consequences two different levels of severity are compared, these are life-threatening consequences (flash-fire, 350 mbar blast or AEGL-3 of 2700 ppm ammonia), and an injury threshold (20 mbar blast potentially breaking windows or IDLH of 300 ppm ammonia). A coarse evaluation of the simulated scenarios gives the assessment as seen in Table 5.1.

Here there are several issues to be kept in mind. For the compressed hydrogen case it is assumed that a full-bore bottle connection leak has diameter of 60mm, which may be realistic, however, it should be highly possible to design and operate bottles with opening dimension of 10mm. If this is done, together with measures to prevent impact loads or impinging jet fires onto the bottles (and a few more things) risk related to releases from these bottles could be reduced to a more limited level. It should also be taken into account that for the refrigerated ammonia releases (and a few more cases) the dispersed plume is narrow, so even if there may be a risk for injuries 250m away, this risk is negligible due to the

narrow plume. Given a release the likelihood that this will hit a person 250m away is small, and it takes little effort to escape from the plume. For comparison the potential for broken windows from the larger LH2 and compressed hydrogen explosions will be applicable in all directions from the site, thus a direct comparison based on the limited simulations performed is challenging.

While pressurized ammonia has been handled with few severe accidents in the past, and the probability for severe leaks may be low, the situation with regular bunkering of vessels may be more leak exposed than many other transfer operations of ammonia. Thus, it is definitely recommended to consider whether ammonia can be handled as a refrigerated liquid instead of pressurized. If not, it will be quite important to consider safety measures to prevent or mitigate significant leaks.

For comparison two risk assessments related to the use of ammonia as fuel were performed in Denmark [Duijm et al., 2005] and the USA [Quest, 2009].

The Danish study concludes that the production risk is acceptable the way ammonia is produced today, the risks related to road transport higher, but still acceptable in the transport quantities foreseen. For refuelling stations, it is concluded that smaller releases will give hazard distances up to 150m (compared to 40m for LPG) and that additional safeguards may be required. In the Danish study pressurized ambient temperature ammonia is assumed. To limit risk the study proposes to transport ammonia as refrigerated, to add sufficient safety zones between refuelling stations and residential areas/public areas, and to add technical measures and regulations to avoid releases in maintenance workshops and prevent unauthorized maintenance on the ammonia fuel systems.

In the study from USA ammonia as fuel was compared to gasoline and LPG as fuel for cars, looking into transport, storage and dispensing of the fuels. Also, this study concludes that risk from transport of fuel remains acceptable. For the total chain of transport, storage and dispensing this study is assuming ammonia to be refrigerated. It is then concluded that LPG (pressurized) represents the highest risk, ammonia (refrigerated) medium risk, and gasoline the lowest risk.

The conclusions from the studies in Denmark and USA seem to be in line with conclusions in this report, that refrigerated ammonia will represent moderate risk, while pressurized ammonia can represent a significant risk.

To summarize, the assessment in this report indicated that it may be feasible with bunkering of refrigerated ammonia and compressed hydrogen with moderate hazard distances, such operations could possibly take place at port where the vessel is normally docked. For LH2 and LNG the potential for significant incidents is larger, and the largest releases could give unacceptable hazard distances. Proper safety measures are therefore essential to be able to bunker the vessel at port. Smaller vessels should preferably bunker at protected site nearby, while the larger vessels could possibly obtain satisfactory safety distances to operations in port by doing ship-to-ship transfer on the outside of the vessel. For compressed ammonia even medium sized releases end up with large hazard distances which put extra requirements to prevent such releases. It may seem likely that such operations will require a dedicated bunkering location properly separated from other operations.

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

Hazard distance	Fatality potential			Injury potential		
Scenario	Full bore	10%	1%	Full bore	10%	1%
Refrigerated NH$_3$	25m	25m	10m	280m	250m	220m
Compressed NH$_3$	~2,000m	270m	30m	>10,000m	~2,000m	200m
Liquid H$_2$	~300m	25m	N/A	~1,000m	300m	N/A
Compressed H$_2$	~30-40m	20m	N/A	~300m	200m	50m
LNG	>200m	35m	N/A	>200m	35m	N/A

6 References

Aarskog, F. G., Hansen, O. R., Strømgren, T., & Ulleberg, Ø. (2020). Concept risk assessment of a hydrogen driven high speed passenger ferry. International Journal of Hydrogen Energy, 45(2), 1359-1372.

Allason, D., Jenney, L. and Acton, M.R., 2019, Thermal Radiation Properties of Large Hydrogen Leaks from Gas Distribution Networks, International conference of hydrogen Safety ICHS2019, Adelaide, September 2019 (https://hysafe.info/iahysafe/wp-content/uploads/2019_papers/203.pdf)

Anderson, Kent, 2017, Ammonia safety, a global perspective, presentation at Technion Ammonia Conference, November 2017 (http://chemeng.technion.ac.il/wp-content/uploads/2017/11/M.-Kent-Anderson.pdf)

Aursand, E., & Hammer, M. (2018). Predicting triggering and consequence of delayed LNG RPT. Journal of Loss Prevention in the Process Industries, 55, 124-133.

Bjerketvedt, D., 2014, Explosions, Incidents and Experiments, Presentation at Lloyds' Register Seminar at Herøya, 29 October, 2014 (https://www.slideshare.net/LloydsRegister/2014-10-29dbjlloyds-reg-herya)

Brown, T. C., Cederwall, R. T., Chan, S. T., Ermak, D. L., Koopman, R. P., Lamson, K. C., McClure, J.W. & Morris, L. K. (1990). Falcon series data report: 1987 LNG vapor barrier verification field trials (No. UCRL-CR-104316; GRI--89/0138). Lawrence Livermore National Lab., CA (USA).

Clancey, V.J., 1972, Diagnostic features of explosion damage, 6th Int Meeting of Forensic Sciences, Edinburgh.

CSB, 2014, Tesoro Refinery Fatal Explosion and Fire, US Chemical Safety Board Investigation (https://www.csb.gov/tesoro-refinery-fatal-explosion-and-fire/)

CSB, 2015, Millard Refrigerated Services Ammonia Release, US Chemical Safety Board Investigation (https://www.csb.gov/millard-refrigerated-services-ammonia-release/)

DNV GL, 2019, Sikkerhetsavstander ved anlegg for farlig stoff, DNV Report.: 2018-1200, Rev. 0, Document no: 244733, Report to DSB with appendices dated 7 October 2019

DSB, 2013, Sikkerheten rundt anlegg som håndterer brannfarlige, reaksjonsfarlige, trykksatte og eksplosjonsfarlige stoffer. Kriterier for akseptabel risiko. Guidance from Directorate for Civil Protection and Preparedness available at: https://www.dsb.no/rapporter-og-evalueringer/sikkerheten-rundt-anlegg-som-handterer-brannfarlige-reaksjonsfarlige-trykksatte-og-eksplosjonsfarlige-stoffer/

Duijm N.J, Markert, F. and Paulsen, J.L. 2005, Safety assessment of ammonia as a transport fuel, Risø report Risø-R-1504(EN)

Duijm, N.J., 2008, Acceptkriterier i Danmark og EU, Report for Miljøstyrelsen Denmark, 15 September, 2008, ISBN 978-87-7052-815-3

Foisselon, P., Hansen, O.R. and van Wingerden, K., 1998, Detailed Analysis of FLACS Performance in Comparison to Full-Scale Experiments, Christian Michelsen Research Report CMR-98-F30058 for Gas Safety Programme 97-99, November 1998 (Available to users of FLACS Software)

Fox, S. B., Storwold, D., & Center, W. D. T. (2011). Project Jack Rabbit: Field Tests. Chemical Security and Analysis Center, Science and Technology Directorate, US Department of Homeland Security, CSAC, 11-006. (https://www.dhs.gov/sites/default/files/publications/csac-11-006_r1_project_jack_rabbit_field_tests_pr-508c.pdf)

Gavelli, F., Ichard, M., Davis, S., & Hansen, O. R. (2011, January). CFD simulations of the Jack Rabbit ammonia and chlorine release experiments using FLACS. In 91st American Meteorological Society Annual Meeting, Special Symposium on Applications of Air Pollution Meteorology (pp. 23-27).

Goldwire Jr, H. C., Rodean, H. C., Cederwall, R. T., Kansa, E. J., Koopman, R. P., McClure, J. W., McRae; T.G., Morris, L.K., Kamppinen, L. & Kiefer, R. D. (1983). Coyote series data report LLNL/NWC 1981 LNG spill tests dispersion, vapor burn, and rapid-phase-transition. Volume 1.[7 experiments with liquefied natural gas, 2 with liquid methane, and one with liquid nitrogen] (No. UCID-19953-Vol. 1). Lawrence Livermore National Lab., CA (USA).

Goldwire Jr, H. C., McRae, T. G., Johnson, G. W., Hipple, D. L., Koopman, R. P., McClure, J. W., Morris, L.K. & Cederwall, R. T. (1985). Desert Tortoise series data report: 1983 pressurized ammonia spills (No. UCID-20562). Lawrence Livermore National Lab., CA (USA).

Hanna, S. R., Hansen, O. R., & Dharmavaram, S. (2004). FLACS CFD air quality model performance evaluation with Kit Fox, MUST, Prairie Grass, and EMU observations. Atmospheric Environment, 38(28), 4675-4687.

Hansen, O.R. and Åsheim, 1995, Simulation of Explosion Experiments using FLACS93 version 2.0, Christian Michelsen Research Report CMR-95-F20004 for the Gas Safety Programme 1993-1996, July 1995. (Available to users of FLACS Software)

Hansen, O. R., Storvik, I., & van Wingerden, K. (1999, September). Validation of CFD-models for gas explosions, where FLACS is used as example; model description and experiences and recommendations for model evaluation. In Proceedings European Meeting on Chemical Industry and Environment III, Krakow, Poland (pp. 365-382).

Hansen OR, Renoult J, Sherman MP, Tieszen S., 2005, Validation of FLACS-hydrogen CFD consequence prediction model against large scale H2 explosion experiments in the FLAME facility. ICHS2005, Pisa, Italy; September 2005. (https://h2tools.org/sites/default/files/2019-09/120075.pdf)

Hansen, O. R., Gavelli, F., Ichard, M., & Davis, S. G. (2010a). Validation of FLACS against experimental data sets from the model evaluation database for LNG vapor dispersion. Journal of Loss Prevention in the Process Industries, 23(6), 857-877.

Hansen, O. R., Hinze, P., Engel, D., & Davis, S. (2010b). Using computational fluid dynamics (CFD) for blast wave predictions. Journal of Loss Prevention in the Process Industries, 23(6), 885-906.

Hansen, O. R., Gavelli, F., Davis, S. G., & Middha, P. (2013). Equivalent cloud methods used for explosion risk and consequence studies. Journal of Loss Prevention in the Process Industries, 26(3), 511-527.

Hansen, O. R., & Johnson, D. M. (2015). Improved far-field blast predictions from fast deflagrations, DDTs and detonations of vapour clouds using FLACS CFD. Journal of Loss Prevention in the Process Industries, 35, 293-306.

Hansen Olav R., Kjellander M., 2016, CFD Modelling of Blast Waves from BLEVEs, Chemical Engineering Transactions, 48, 199-204 (https://www.cetjournal.it/index.php/cet/article/view/CET1648034)

Hansen, O.R. (2019), Hydrogen Safety: Kjørbo Incident, overview and perspectives, presentation at MoZEES Workshop October 23, 2019, (https://mozees.no/wp-content/uploads/2019/10/Hansen_Hydrogen-safety_Kjoerbo-incident-overview-and-perspectives.pdf)

Hansen, O. R. (2020). Liquid hydrogen releases show dense gas behavior. International Journal of Hydrogen Energy, 45(2), 1343-1358.

HJERTAGER, B. H. (1982). Simulation of transient compressible turbulent reactive flows. Combustion Science and technology, 27(5-6), 159-170.

HSE, 2012, Failure Rate and Event Data for use within Risk Assessments (28/06/2012).

Ichard, M., Hansen, O. R., & Melheim, J. (2010). Releases of pressurized liquefied gases: simulations of the Desert Tortoise test series with the CFD model FLACS. American Meteorological Society.

INERIS, 2005, Ammonia, Large-scale atmospheric dispersion tests, INERIS report No 10072, December 20, 2005.

Koopman, R. P., Cederwall, R. T., Ermak, D. L., Goldwire Jr, H. C., Hogan, W. J., McClure, J. W., McRae, T.G., Morgen, H.C., Rodean, H.C. & Shinn, J. H. (1982). Analysis of Burro series 40-m3 LNG spill experiments. Journal of Hazardous Materials, 6(1-2), 43-83.

Little, A. D. Inc. An investigation of hazards associated with the storage and handling of LH2. Final Report. Contract No. AF-18 (600)-1687 (AD-324194), 1960.

Lloyds Register Consulting, 2018, Process leaks for offshore installations frequency assessment model - PLOFAM(2), report no 107566/R1: Rev. Final for Equinor, December 6, 2018 (https://www.norskoljeoggass.no/contentassets/9972d6e9f1b74f158931aac3b462770e/107566_r1_final.pdf)

Lloyds Register Consulting, 2018, Modelling of ignition sources on offshore oil and gas facilities – MISOF(2), report no 107566/R1: Rev. Final for Norwegian Oil and Gas Association, November 20, 2018 (https://www.norskoljeoggass.no/contentassets/067198d80b9c4b039b879bd0c8ae42bf/107566_r2_final_.pdf)

Lloyds' Register, 2019, Guidelines for quantitative risk analysis of facilities handling hazardous substances, LR report 106535/R1 Final Rev A (English version), May 6, 2019 (https://www.dsb.no/globalassets/dokumenter/rapporter/prj11089512_r1_final.pdf)

Marx. J.D. and Nicotra, A., 2016, Is a Two-Inch Hole Adequate for a Siting Study?, Presented at 12th Global Congress on Process Safety, Loss Prevention Symposium, Houston, Texas, April 11-13 2016.

Middha, P., Hansen, O. R., & Schneider, H. (2007, May). Deflagration to detonation transition (DDT) in jet ignited hydrogen-air mixtures: large scale experiments and FLACS CFD predictions. In Proceedings of 12th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Edinburgh, UK.

Middha, P., & Hansen, O. R. (2008). Predicting deflagration to detonation transition in hydrogen explosions. Process Safety Progress, 27(3), 192-204.

Middha, P., Hansen, O.R. & Storvik, I.E. (2009a). Validation of CFD-model for hydrogen dispersion. Journal of Loss Prev. in the Process Industries, 22: 1034-1038

Middha, P., & Hansen, O. R. (2009). Using computational fluid dynamics as a tool for hydrogen safety studies. Journal of Loss Prevention in the Process Industries, 22(3), 295-302.

Middha, P., Hansen, O.R., Grune, J. & Kotchourko, A. (2010). CFD calculations of gas leak dispersion and subsequent gas explosions: Validation against ignited impinging hydrogen jet experiments. Journal of Hazardous Materials, 179: 84-94.

Moen, I. O., Lee, J. H. S., Hjertager, B. H., Fuhre, K., & Eckhoff, R. K. (1982). Pressure development due to turbulent flame propagation in large-scale methane air explosions. Combustion and Flame, 47, 31-52.

Nielsen, M. & Ott, S. (1996), Fladis Field Experiments, Final Report, RIS0-R-898(EN)

OGP Risk Assessment Data Directory Report No. 434, March 2010, Int. Association of Oil and Gas Producers

Pfahl, U., & Shepherd, J. E. (1997). Flammability, ignition energy and flame speeds in NH3–H2–CH4–N2O–O2–N2 mixtures. Report FM97-4R1, Explosion Dynamics Laboratory, California Institute of Technology.

Pförtner, H., & Schneider, H. (1984). Tests with jet ignition of partially confined hydrogen air mixtures in view of the scaling of the transition from deflagration to detonation, Final report for Interatom GmbH, Bergisch Gladbach, Germany, Oct. 1984. Fraunhofer ICT Internal Report.

Pförtner, H., & Schneider, H. (1983). Ballonversuche zur Untersuchung der Deflagration von Wasserstoff/Luft4Gemischen (Abschlußbericht). Fraunhofer4institut fur treib4und explosivstoffe, ICT4Projektforschung, 19-83.

PTIL, 2020, Risikonivå i petroleumsvirksomheten norsk sokkel, RNNP Hovedrapport 2019 (ptil.no), April 2, 2020

Quest Consultants Inc., 2009, Comparative quantitative risk analysis of motor gasoline, LPG and anhydrous ammonia as an automotive fuel, Report for Iowa State University, June 17, 2009

RIVM, 2005, Guideline for quantitative risk assessment –'Purple book' CPR 18E, RIVM

RIVM, 2017, 20170606-ammonia-interim, 6 June, 2017, http://www.rivm.nl/

Rui, J. P., & Søreide, T., (2019), Governments' Enforcement of Corporate Bribery Laws. Tidsskrift for Rettsvitenskap, 132(02), 132-162. (https://www.idunn.no/tfr/2019/02/governments_enforcement_of_corporate_bribery_laws)

Sandia, 2017, Groth, K.M., Hecht, E.S., Reynolds, J.T., Blaylock, M.L., Carrier, E.E, Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.1 tech. ref. manual, Sandia Report SAND2017-2998, March 2017

Sherman, M. P., Tieszen, S. R., & Benedick, W. B. (1989). FLAME facility: The effect of obstacles and transverse venting on flame acceleration and transition on detonation for hydrogen-air mixtures at large scale (No. NUREG/CR--5275). Nuclear Regulatory Commission.

Stephenson, R.R., 2005, Fire Safety of Hydrogen-fueled Vehicles: System-level Bonfire Tests, International Conference on Hydrogen Safety, Pisa Italy, September 2005

TNO, 1992, Green Book, Methods for the determination of possible damage. Rep CPR E, 1989, 16.

Van den Berg, A. C. (1985). The multi-energy method: a framework for vapour cloud explosion blast prediction. Journal of Hazardous Materials, 12(1), 1-10.

Venetsanos, A. G., Papanikolaou, E., Delichatsios, M., Garcia, J., Hansen, O. R., Heitsch, M., ... & Ledin, H. S. (2009). An inter-comparison exercise on the capabilities of CFD models to predict the short and long term distribution and mixing of hydrogen in a garage. International Journal of Hydrogen Energy, 34(14), 5912-5923.

Verkamp, F. J., Hardin, M. C., & Williams, J. R. (1967, January). Ammonia combustion properties and performance in gas-turbine burners. In Symposium (International) on Combustion (Vol. 11, No. 1, pp. 985-992). Elsevier.

Witcofski, R. D., & Chirivella, J. E. (1984). Experimental and analytical analyses of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills. International journal of hydrogen energy, 9(5), 425-435.

Witlox, H. W. (2010). Overview of consequence modelling in the hazard assessment package Phast. American Meteorological Society (https://ams.confex.com/ams/90annual/techprogram/program_587.htm)

Zipf, R. K., Sapko, M. J., & Brune, J. F. (2007). Explosion pressure design criteria for new seals in US coal mines. Pittsburgh, PA, US Dept. HHS, NIOSH IC, 9500, 76.