MAGPIE

SMART GREEN PORTS

Risks of ammonia bunkering in ports

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RISKS OF AMMONIA BUNKERING IN PORTS

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2. Executive Summary

Ammonia bunkering has been studied with regard to risks posed to the surrounding population of the location where the bunkering takes place (societal risk) as well as the risks for the bunkering operators. These analyses have been carried out by engineering firms Royal Haskoning DHV (R) and Peutz (P) as subcontractors to the Netherlands Organisation for Scientific Research (TNO) and by American Bureau of Shipping (ABS) as subcontractor to Maersk Mc-Kinney Moller Center for Zero Carbon Shipping. The study is part of the EU project MAGPIE. A summary and assessment of the results are reported in the current document .

This report is about risk analyses on five typical bunker operations, in this document referred as bunker cases; small pressurised, medium pressurised, large pressurised and medium refrigerated and large refrigerated. Small, medium and large refer to the size of the receiving ship.

The main findings regarding risk to the surrounding population for the situation where all five bunker cases take place at one terminal throughout the year, is that the 10-6/year location specific individual risk (LSIR) maximum distances are 738 m (R) and 1030 m (P).

A distinction has been made between pressurized and refrigerated ships of which both the LSIR and the 1 % fatality distances have been determined.

For bunkering of pressurised ammonia the 10-6/year LSIR maximum distances are 747 m (R) and 1015 m (P). For bunkering of pressurised ammonia the largest 1 % fatality contour distances of 1865 m (R) and 891 m (P) were calculated.

A location specific individual risk of bunkering refrigerated ammonia of 10-6/year at distances of 490 m (R) and 345 m (P) were calculated. For bunkering of refrigerated ammonia the largest 1 % fatality contour distances were calculated as 919 m (R) and 596 m (P).

Regarding risk to bunkering operators the conclusion of the HAZID is that ''risk is high and additional control is required to manage risk''.

3. Introduction

3.1 Goal

An international community of ship owners and port authorities wishes to use ammonia as a fuel for ships. The main driver is to achieve zero carbon emissions. Unfortunately ammonia is a hazardous substance which needs to be handled accordingly. Probably the most hazardous handling operation is ammonia fuel bunkering. Therefore ammonia bunkering has been studied with regard to risks posed to the surrounding population of the location where the bunkering takes place, as well as the risks for the bunkering operators. There is also the intention to conduct a bunkering demo in the Port of Rotterdam. Therefore for analysis of the risks to the surrounding population the analysis tools as required by the Dutch law for handling of hazardous substances on factory and storage premises have been used. These analysis have been carried out by engineering firms Royal Haskoning DHV (RHDHV) and Peutz as subcontractors to TNO. For the risks to the bunkering operators a hazard identification HAZID has been conducted in accordance with recommendations issued by the major classification societies. This work has been facilitated and reported by American Bureau of Shipping as subcontractor to Maersk Mc-Kinney Moller Center for Zero Carbon Shipping. The participants in the HAZID are listed in the Appendix.

The work is done within the framework of the EU-research and innovation project MAGPIE, which aims at forcing a breakthrough in the supply and use of green energy carriers in transport to, from and within ports. Further details can be found on the project web pages [1].

A summary and assessment of the results are reported in the current document

3.2 Risk

The process of risk control is often depicted with the diagram shown in figure 1. It starts with a system description. Then hazards are identified. For each of the hazards their probability of occurrence is determined together with the severity of the consequences of occurrences. Probability of occurrence and severity constitute the risk, which is assessed with regard to tolerability. At the start of a design and building process initial risks will be identified which are considered too high and risk reduction measures will be taken. After a number of iterations, risks will have reduced to an acceptable level and the design will be consolidated.

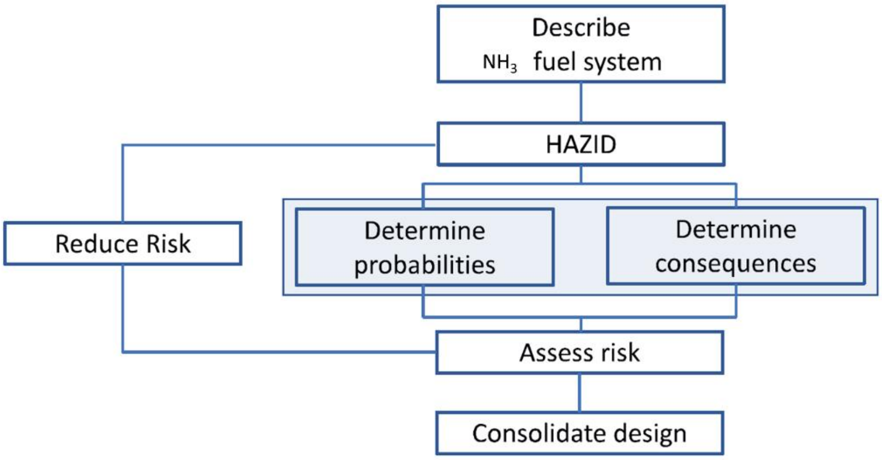


Figure 1 Risk assessment and control.

Many risks can conveniently be visualised as a risk matrix as shown in figure 2, taken from IACS recommendation 146 on how to conduct risk assessments for on board low flashpoint fuels [12]. The blue cross shows the (10^{-6} probability, single fatality) locus which is further explained in section 4.1. A more detailed risk matrix which was used for the HAZID is shown in the Appendix.

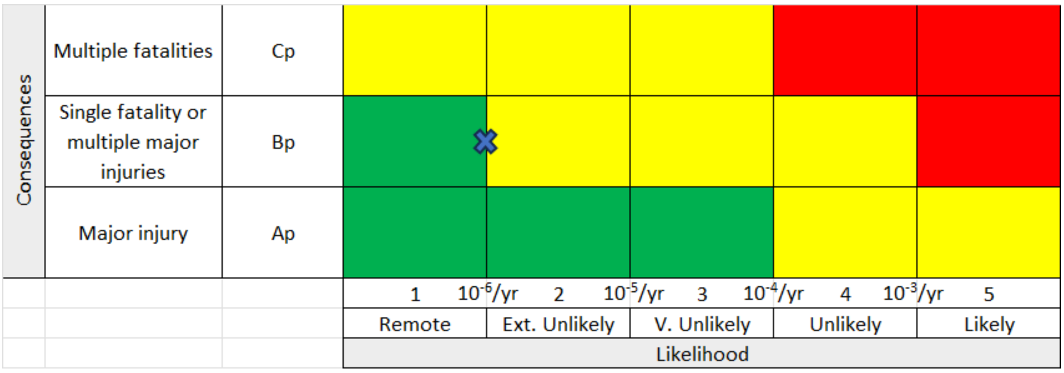


Figure 2 Risk matrix for persons [12].

The Dutch legislator requires this process to be carried out for industrial establishments which handle hazardous substances. The procedure is described in a manual for risk calculations (*Handleiding Risicoberekeningen Bevi* [2]). It details how probabilities and consequences are to be determined/ calculated. The Dutch legislator also prescribes the use of a software package called SAFETI-NL which follows the manual. The prescribed procedure only covers risks to the area surrounding the establishment handling the hazardous substances. This risk is referred to as **external risk**. It is not applicable to risks inside the establishment. It is noted that an analyst wishing to use and report on the SAFETI-NL software is legally obliged to take a training course.

It is noted that ship to ship bunkering occurs while moored at a quay, jetty or mooring buoy, which from a judicial point of view may not belong to an establishment. Hence strictly spoken using the manual for risk calculations is not legally required. Obviously from a physics, chemistry and statistics point of view legal distinctions are irrelevant, therefore the manual is quite suitable.

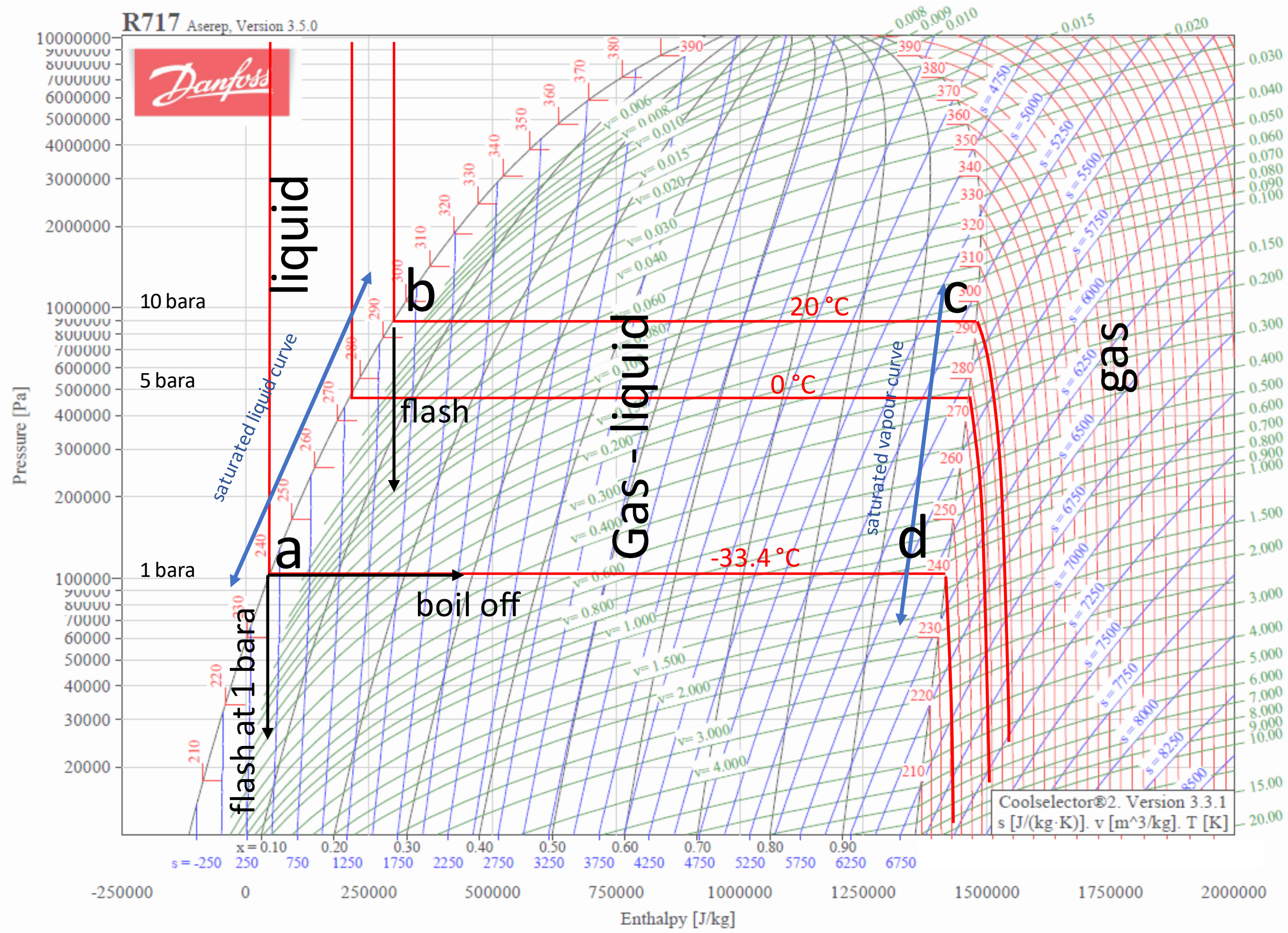
Currently there are no dedicated Dutch requirements for bunkering of ammonia. Therefore some data published in the Dutch interim calculation method for LNG bunker facilities (*Interim calculation method LNG bunker stations* [3]) has been used.

3.3 Ammonia

Thermodynamic behaviour

figure 3 shows the pressure – enthalpy (p-h) chart for ammonia ([9] the engineering mindset web site). In Northen Europe, ammonia is transported as a saturated liquid, at temperatures ranging from -33.6 °C up to 20 °C.

When the ammonia is refrigerated down to a temperature of -33.6°C, the saturation pressure is 1 bara, i.e. atmospheric. Preferably the ammonia is present in the tank as liquid (locus **a** in the p-h chart). The attractiveness of refrigerated transport is that tank pressures can be kept at around ambient, which allows for prismatic tanks to be used. The downside is that insulation is required in order to prevent excessive **boil off** due to heat input from the environment (see p-h chart). It means that part of the liquid ammonia evaporates into gas. This gas needs to be removed from the tank in order to prevent pressure build up. Preferably the removed gas is used for energy generation. In emergencies however the gas is vented through pressure relief valves. Were all liquid to evaporate while the pressure is kept at 1 bara, the ammonia mass would be at locus **d** in the p-h chart.



https://theengineeringmindset.com/r717-ammonia-pressure-enthalpy-chart/

Figure 3 Pressure enthalpy diagram ammonia

Safety data

Within the HAZID study task (HAZID report [8]) a list of hazards has been compiled which is reproduced here.

Key ammonia related risks are:

- NH_3 exposure to human:
  - Toxicity – to human
  - Corrosive to the respiratory tract, skin and eyes
  - Fatal if inhaled
  - Causes severe skin burns and eye damage
  - Can harm respiratory system if long-term exposure occurs
  - Can cause lung injury
  - Repeated or prolonged exposure on the skin will cause dermatitis.

- NH_3 exposure to the marine environment may lead to long lasting toxicity effect on aquatic life.
- Due to its alkalinity & corrosiveness, NH_3 exposure on equipment can lead to equipment damage including stress corrosion cracking in storage tanks and process equipment.
- Due to its flammability and explosiveness, loss of containment of NH_3 can lead to pool fire, flash fire, and explosion.
- The following NH_3 characteristics can contribute to major hazards:
    - NH_3 auto-ignition temperature is 650 °C
    - NH_3 liquid to gas expansion ratio is 800:1
    - In an oxygen rich environment, NH_3 can undergo a Rapid Phase Transition (RPT) leading to detonation
    - NH_3 is highly attracted to water, with a water absorption ratio of 200:1
    - If exposed to heat, large NH_3 leaks can lead to Boiling Liquid Expanding Vapor Explosion (BLEVE) of storage tank
    - Can react violently with certain chemicals and materials if exposed
    - At high temperature:
        - NH_3 can decompose into a flammable gas, hydrogen, and toxic nitrogen dioxide
        - NH_3 can continuously evaporate to form boil-off gas (BoG), leading to increased pressure in the storage tanks
    - At low temperature, continuous NH_3 exposure on equipment can lead to low temperature embrittlement equipment damage.

It is noted that NH_3 also 'reacts' with water, when it dissolves in water heat is generated. Human exposure limits for inhalation of ammonia are as listed in table 1. AEGL stands for acute exposure guideline limits ([11] EPA web site).

Table 1 Acute Exposure Levels - Standards and Guidelines copied from [8]

	Exposure limit [ppm]				
	10 min	30 min	1 hour	4 hours	8 hours
AEGL-1	30	30	30	30	30
AEGL-2	220	220	160	110	110
AEGL-3	2700	1600	1100	550	390

AEGL-1 level means: Notable discomfort, irritation, or certain asymptomatic non-sensory effects. Effects are not disabling and are transient and reversible upon cessation of exposure.
AEGL-2 level means: Irreversible or other serious, long lasting adverse health effects of an impaired ability to escape.
AEGL-3 level means: Life-threatening health effects or death.

It is noted that the quantitative risk analyses reported in sections error! reference source not found. and error! reference source not found., are based on a more sophisticated lethality parameter, known as *probit*. For further explanation please refer to [2] (Handleiding Risicoberekening Bevi).

3.4 Five bunker cases

The project work group has decided to investigate five bunker cases, of which three refer to pressurised ammonia and two to refrigerated.

A typical arrangement for bunkering pressurised ammonia is shown in figure 4. A (small) bunker barge (Ammonia Bunker fuel Vessel, ABV) is moored alongside a (larger) fuel receiving ship (Ammonia Fuelled Vessel, AFV). The fuel receiving ship may be moored at a quay or at an anchoring buoy.

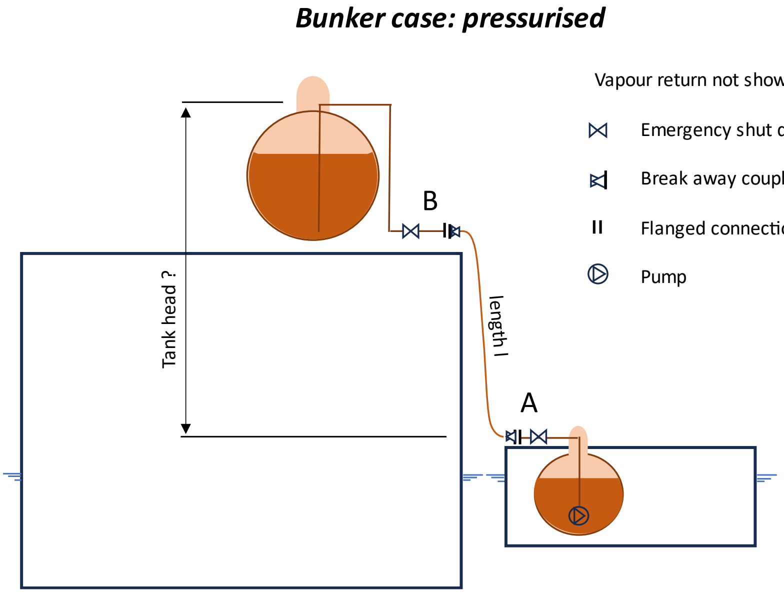


Figure 4 Bunkering pressurised ammonia. ABV on the right, AFV on the left.

Delivering tank and receiving tank are both pressurised with pressures ranging from 4 to 13 barg. A submerged pump inside the delivering tank pumps the liquid ammonia towards the receiving tank. Piping on the delivering ship and the receiving ship is fixed and rigid. Between location A on the delivering ship and location B on the receiving ship a temporary flexible hose is rigged. At locations A and B closing devices are provided which are operated remotely with an emergency button. They can be activated from the delivering ship as well as from the receiving ship. There is also a vapour return line between delivering tank and receiving tank (not shown in the figure). Further details are listed in table 2.

figure 5 shows a typical arrangement for bunkering of refrigerated, atmospheric ammonia. The mooring arrangement is equal to the arrangement described for the pressurised case. The ammonia is now refrigerated to a temperature of -33.4 °C.

Bunker case: refrigerated

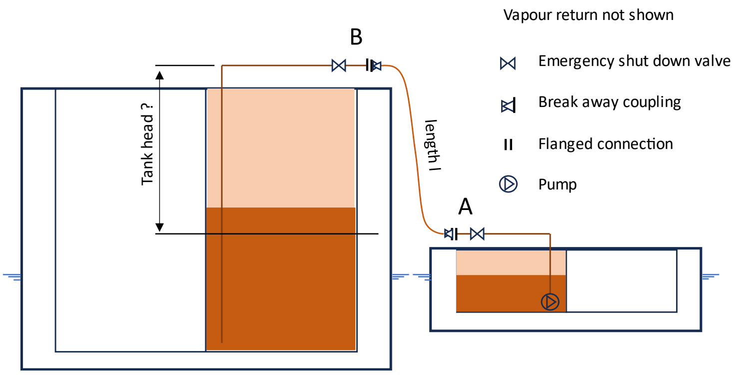


Figure 5 bunkering refrigerated ammonia

The ammonia mass is liquid at ambient (atmospheric) pressure of 1 bara. The fuel transfer system is similar to the system for pressurised ammonia, albeit that the average pressure in the tanks is only a few millibar above atmospheric pressure. An important difference is the ammonia temperature. There is a potential risk of excessive heat transfer from the environment into the liquid ammonia via the manifolds and hose causing ammonia to evaporate with subsequent pressure build-up in the transfer lines. Here also (emergency) closing arrangements are provided at locations A and B, similar to the pressurised case. There is also a vapour return line between delivering tank and receiving tank (not shown in the figure). Further details are listed in table 2.

Table 2 characteristics five bunker cases (differences in grey)

	Royal Haskoning DHV					Peutz				
	pressurised			refrigerated		pressurised			refrigerated	
	small	medium	large	medium	large	small	medium	large	medium	large
# Bunker events /year	150	150	150	100	150	300	300	150	100	150
Bunker volume per year [m^3/year]	22,500	22,500	1,290,000	330,000	2,400,000	45,000	900,000	1,290,000	330,000	2,400,000
Bunker volume /bunkering event [m^3/event]	150	3,000	8,600	3,300	16,000	150	3,000	86,000	3,300	16,000
Bunker line diameter [inch]	6	6	8	6	8	6	6	8	6	8
# Bunker lines	1	1	2	1	2	1	1	2	1	2
Bunker rate [m^3/hour]	80	300	500	450	1,000	80	300	500	450	1,000
Bunker duration /bunker event [hour]	1.88	10.00	17.20	7.33	16.00	1.88	10.00	172.00	7.33	16.00
Bunker duration /year [hour]	281	75	2580	733	2400	563	3000	2580	733	2400
Bunker flow velocity [m/s]	1.22	4.57	2.14	6.85	4.28	1.22	4.57	2.14	6.85	4.28
Pump pressure during bunkering [barg]	11	11	11	7	7	13	13	13	4	4
Fuel temperature [°C]	5	5	5	-33.4	-33.4	5	5	5	-33	-33

In table 2 the characteristics of the five bunker cases are given. As said in the introduction, two engineering firms have conducted quantitative risk analysis calculations, i.e. Royal Haskoning DHV and Peutz. Some discrepancies between both firms have slipped into the input as highlighted in the table with grey. In the first row, the number of bunker events per year, for pressurized small and medium, RHDHV lists 150 whereas Peutz lists 300. This is due to confusion between the maximum number of events per terminal per year (150) and the maximum number of bunker events in the whole Port of Rotterdam area (300). The number of 22,500 m³ under RHDHV, pressurized medium is obviously a typo; that should have been 450,000.

As will become clear in chapter 5 on *risk calculation results*, bunkering of large pressurised and large refrigerated volumes yield the largest hazard distances.

4. Method and criteria

In this report risk to population is the risk that an individual member of the general public gets killed as a consequence of an accident with a system that handles ammonia. This individual has no involvement whatsoever with the ammonia handling system and is not in the neighbourhood of the system in any professional capacity.

4.1 10^{-6}/year contour

Risk to the surroundings can conveniently be expressed as the yearly probability that an individual will get killed as a consequence of a spill of hazardous substance when being present at a given distance from the location where this spill takes place. This individual is present at this location 24/7 throughout a year without any special protection. This probability is called the location specific individual risk (LSIR). Most authorities consider a value of 10^{-6}/year as allowable.

4.2 1 % lethality contour

The 1 % lethality contour indicates the maximum effect distance from the source of a spill of a hazardous substance at which 1 in 100 of those exposed will suffer fatal consequences ([4] *Reference Manual Bevt*).

4.3 Calculation software and input data

As already mentioned, the risk to the population is calculated in compliance with regulations in the Netherlands regarding spatial planning when handling of hazardous substances is involved. These regulations are described in *Interim calculation method LNG bunker stations* [2], which is in Dutch. Fortunately the methods and principles are also described in English in *Reference manual Bevt* [4]. The Dutch legislator requires the compulsory use of the software package SAFETI-NL when analysing risks within the context of spatial planning. From a legal point of view ships moored at an establishment are not part of that establishment. Obviously physics, chemistry, weather behaviour, dispersion etc. do not stop at judicial boundaries. Therefore the bunkering process is regarded as just another handling of a hazardous substance at an establishment.

Input data regarding process parameters (e.g. pressure and temperature), probabilities of component failure and weather conditions, used in the calculations are listed in table 3.

Table 3 Calculation input (grey indicate different values between contractors)

	Royal Haskoning DHV					Peutz				
	pressurised			refrigerated		pressurised			refrigerated	
	small	medium	large	medium	large	small	medium	large	medium	large
Emergency shut down response time [s]	30									
Fuel pressure in tank [barg]	4.15	4.15	4.15	1	1	5	5	5	1	1
Probability hose rupture [/hour]	4.0E-06					4.0E-06				
Probability hose 10% of diameter leakage [/hour]	4.0E-05					4.0E-05				
Hose leakage diameter (10% of hose nominal diameter) [m]	0.015	0.015	0.020	0.015	0.020	0.020	0.020	0.020	0.020	0.020
Probability closures hose at 'A' and 'B' *work* [ ]	9.9E-01					9.8E-01				
Probability closures hose at 'A' *works* at 'B' *fails* [ ]	not considered					9.9E-03				
Probability closures hose at 'A' *fails* at 'B' *works* [ ]	not considered					9.9E-03				
Probability closures hose at 'A' and 'B' *fail* [ ]	1.0E-02					1.0E-04				
Flow rate increase at hose rupture	50%									
Outflow (spill) duration when closure/shut down works [s]	60 (1 min)					60 (1 min)				
Outflow (spill) duration when closure/shut down fails [s]	300 (5 min)					300 (5 min)				
Weather statistics location	weather station Hoek van Holland					weather station Rotterdam				

Emergency shutdown response time is reported only by RHDHV. It is probably not necessary to report this value because this value is included in the *outflow (spill) durations* listed in table 3. As is the case with *fuel pressures in tank* they were decided by the working group. It is unclear why RHDHV use a fuel pressure of 4.15 barg while Peutz use 5 barg. The effect of this difference on the final outcome of the calculations is probably not very big. The hose leakage values (10 % of nominal diameter) are taken from the regulations ([2] *Handleiding risicoberekening*). The values used by Peutz for pressurised small and medium and for refrigerated medium should have been 0.015 m, apparently they took an 8 inch hose for all cases. It is noted that leakage does not dominate the outcome of the risk calculations. The flow rate increase at hose rupture is according to ref. [2], (*Handleiding risicoberekening*).

In the reports by Peutz and RHDHV weather condition codes are sometimes referred to. An explanation of these codes can be found in ref. [10]. They are not used in the document at hand however.

The last parameter to be mentioned is the probability that closure devices at each end of the ammonia fuel hose will actually close in case of an incident. The work group members have decided that the probability that a closure will be activated successfully in case of an incident equals 0.99. Interestingly two different interpretations were adopted. In case of Peutz the interpretation was that closures A and B (see figure 4 and figure 5) will be successful simultaneously. So the probability that closure A and closure B will both close equals 0.99. Hence the probability that closure A and closure B will both fail to close equals 0.01. The events *closure A works and closure B fails* and *closure A fails and closure B works,* do not exist with this interpretation. Please refer to the table below (column indicated with Peutz). The RHDHV interpretation identifies four events as indicated in the table below in the RHDHV column.

Table 4 Closure probabilities at locations A and B (indicated in figure 4 and figure 5)

		RHDHV				Peutz	
closure	works	0.9801	0.0099	***closure***	works	0.9900	
at 'A'	fails	0.0099	0.0001	***at 'A'***	fails		0.0100
		works	fails			works	fails
		closure at 'B'				***closure at 'B'***	

The consequence of the RHDHV interpretation is that the event *both closures work* has now a probability of 0.99 x 0.99 = 0.9801. The event *both closures fail* now has a probability of 0.01 x 0.01 = 0.0001, i.e. 100 times smaller than in case of the Peutz interpretation! See chapter 5 for the effect of these different probabilities.

4.4 Risk on board, HAZID bunkering pressurised ammonia medium sized ship

Regarding risks on board, a hazard identification (HAZID) has been carried out following a process in accordance with common practice in the maritime domain. The HAZID was facilitated by American Bureau of Shipping. Assessment of risks was done qualitatively only.

The HAZID process which was followed is shown in figure 6. In principle four consequence categories have been considered:

1. Asset.
2. Environmental effects.
3. Community/ Government/ Media/ Reputation.
4. Injury and Disease.

However the fourth category, injury and disease, seems to be governing.

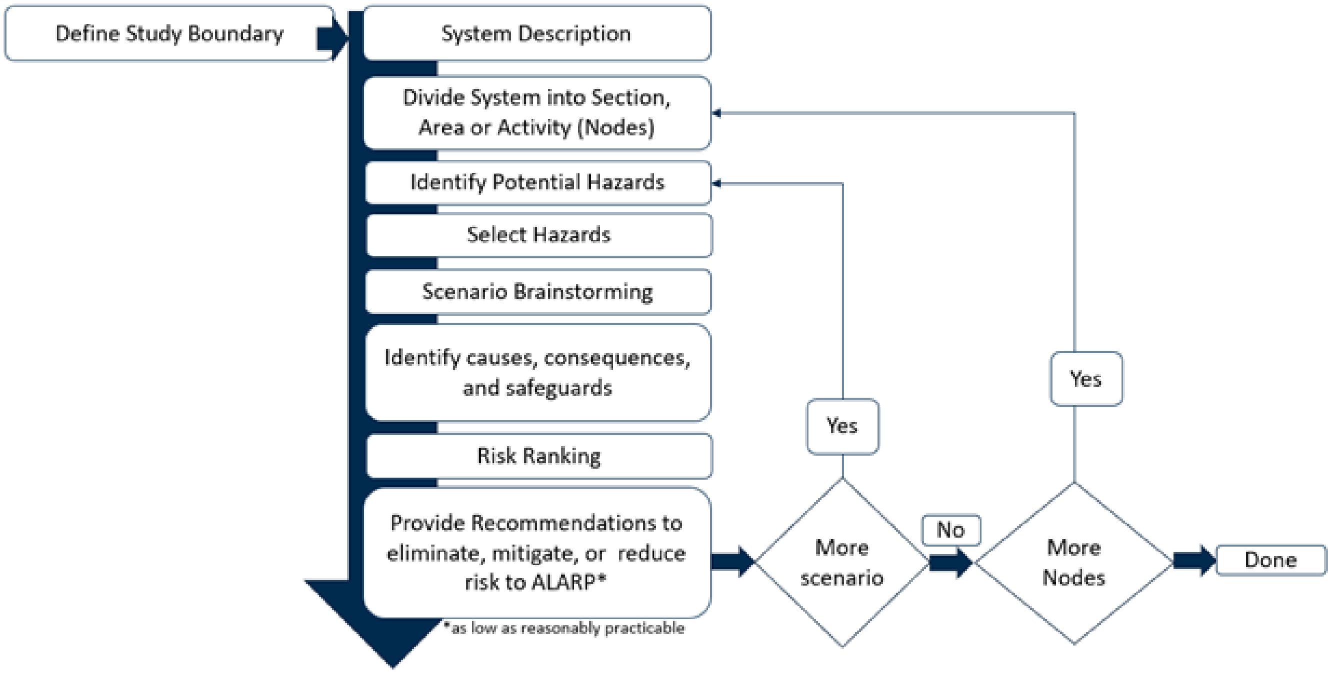


Figure 6 Hazard identification, risk ranking and risk control process (copied from HAZID report [8])..

The adopted risk matrix can be found in the Appendix. The full report of this effort can be found in the HAZID report [8].

Only the bunker case *pressurised medium* size has been studied, because this is expected to become the demonstrator case in the port of Rotterdam.

The general arrangement and the process & instrumentation diagram (P&ID) are shown in figure 7 and figure 8. Large printouts were used during the HAZID.

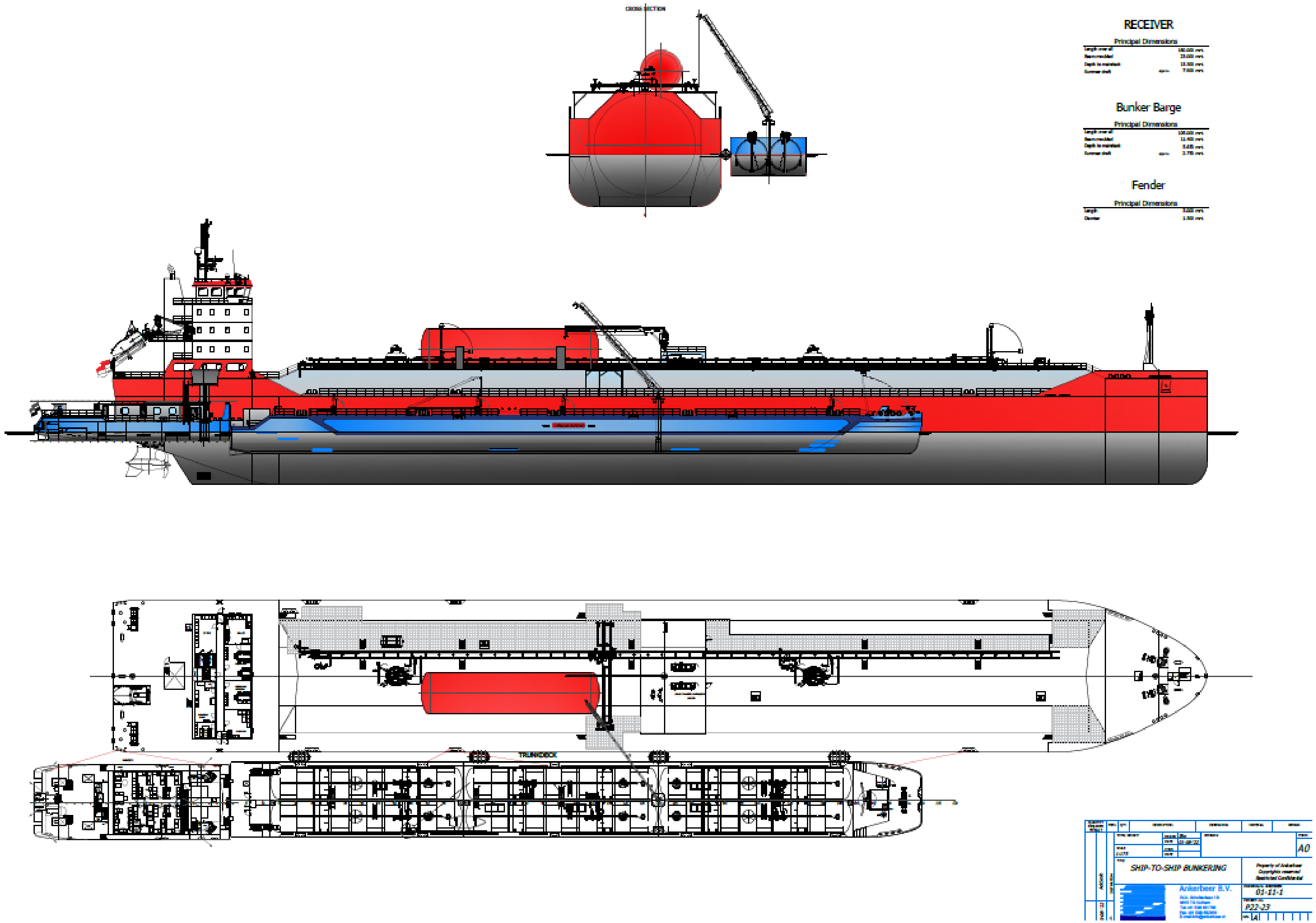


Figure 7 General arrangement bunker case pressurised medium

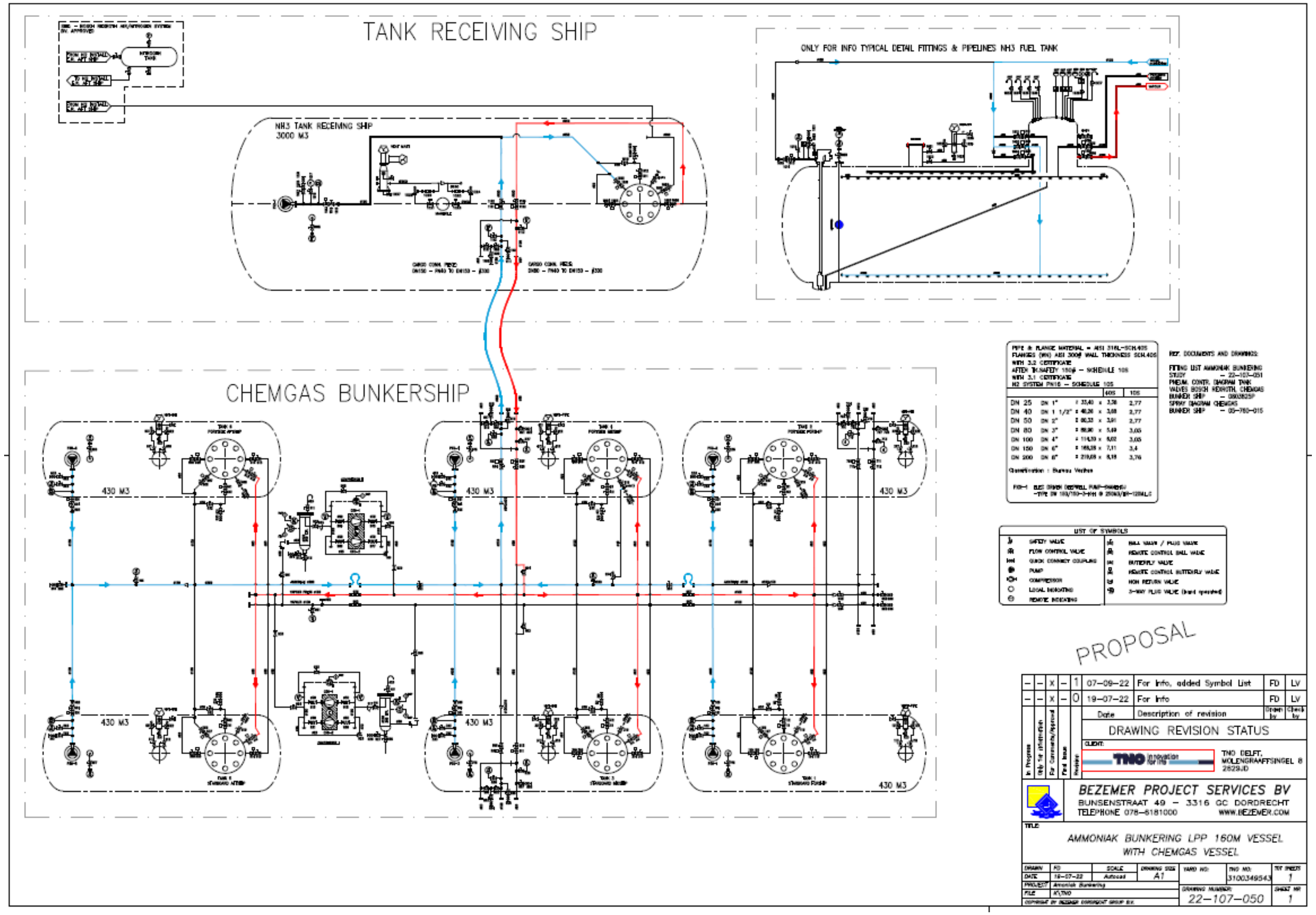


Figure 8 Process & Instrumentation Diagram (P&ID) bunker case pressurised medium

The general assumptions during the HAZID are copied from HAZID report [8]. They are based on submitted documents and drawings in order to conduct a high-level but also practical HAZID study:

- Ammonia Fuelled Vessel (AFV) (the ship that receives the fuel) and Ammonia Bunker Vessel (ABV) (the ship that delivers the fuel) used in ship-to-ship bunkering DEMO and future bunkering activities in the port are in compliance with class society rules and regulatory requirements.
- Prior to ship-to-ship bunkering DEMO, the ABV will receive NH_3 at NH_3 terminal during normal operation. This is outside the scope of the HAZID study.
- This HAZID study focuses on the risks related to the Ammonia Bunkering DEMO which will be conducted using pressurized ammonia gas. Considerations for semi-refrigerated or refrigerated ammonia fuel bunkering process is outside the scope of this study.
- The maximum bunker pressure is 5 barg at a temperature between 5 °C to 6 °C.
- No tug needed for berthing.
- ABV will provide fender and crane to handle bunker hoses.
- ABV mooring line will be used for mooring with AFV.
- For NH_3 ship-to-ship bunkering DEMO, the proposed ABV has the following specifications:
    - ABV is a single propeller vessel or a double propeller vessel (to be determined for DEMO)
    - ABV contains 6 Type-C storage tanks in the cargo hold with a total capacity between 2000 m^3 to 3000 m^3.
    - Each Type-C storage tank has a tank capacity between 380 m^3 to 550 m^3.
    - The tank design temperature range is -10 °C to 40 °C.
    - The Maximum Allowable Relief Valve Setting (MARVS) of the tank is 1.58 MPa (15.8 bar).
    - The vessel bunker manifold/cargo manifold has a liquid line and a vapor line.
    - There is no refrigeration equipment.
- For ship-to-ship bunkering DEMO, the proposed AFV has the following specifications:
    - AFV contains 1 Type-C storage tank on deck.
    - The tank storage capacity is 3000 m^3 and it can store refrigerated or semi-refrigerated cargo.
    - The tank minimum design temperature is -33 °C, and its MARVS is approximately 15 bar.

Any equipment tags referenced in the drawings and workshop discussions are to serve as examples for workshop discussion only. Actual equipment tags may differ based on selection of vessel and associated drawings for DEMO.

5. Risk to population - results

The results of the risk calculations related to population who might become exposed to hazardous gas concentrations after accidents related to ammonia bunkering are reported in the sections error! reference source not found. and error! reference source not found. for the LISR and 1 % lethality contours respectively as done by RHDHV and Peutz.. Although there are some discrepancies between the input used by both companies, it is still meaningful to report the results next to each other which enables easy comparing. The risk results are expressed as 10^{-6}/year location specific individual risk contour (LSIR) and 1 % lethality contour distances. Please note that in the Netherlands the procedure for calculating these risks is referred to as quantitative risk assessment (QRA).

5.1 10^{-6}/year LSIR contours

table 5 and table 6 show the results for the 10^{-6} location specific individual risk (LSIR) distances as calculated by Peutz ([5] and [6]) and RHDHV ([7]) respectively. figure 9 shows these distances on a map.
"Simultaneously" in table 5 and table 6 refers to the situation that all five bunker cases may take place in one terminal, throughout a year.

Table 5 Location specific individual risk 10^{-6} contour 'radius', calculated by Royal Haskoning DHV

Royal Haskoning DHV				
10-6 contour 'radius' LSIR for each bunker case [m]				
pressurised			refrigerated	
small	medium	large	medium	large
732	744	747	239	345
all 5 bunker cases simultaneously				
738				

Table 6 Location specific individual risk 10^{-6} contour 'radius', calculated by Peutz

Peutz				
10-6 contour 'radius' LSIR for each bunker case [m]				
pressurised			refrigerated	
small	medium	large	medium	large
450	630	1015	320	490
all 5 bunker cases simultaneously				
1030				

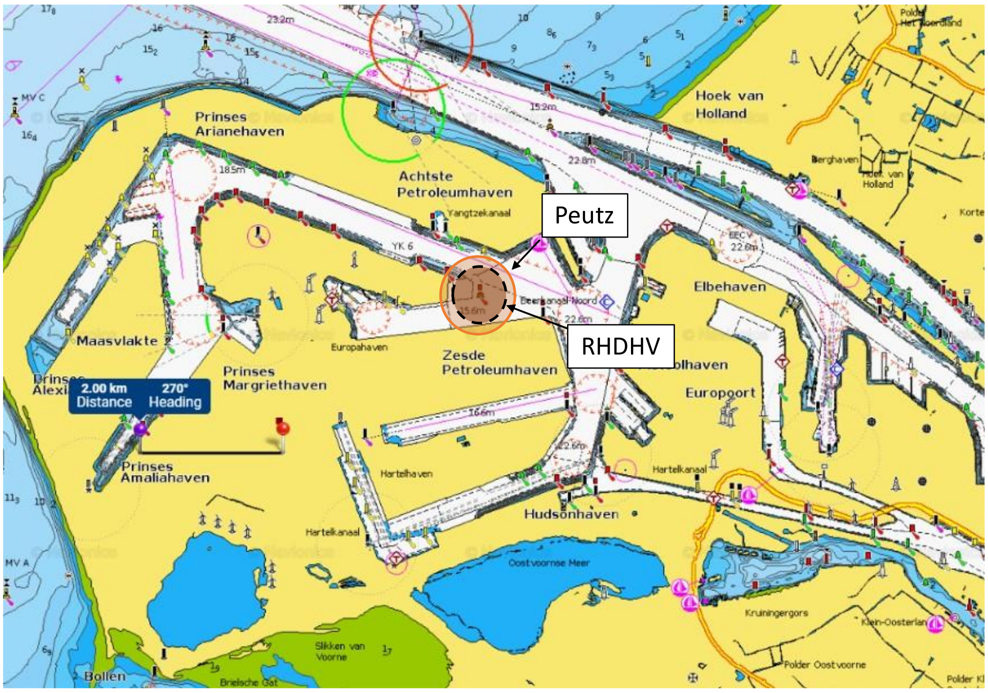


Figure 9 *Location Specific Individual Risk (LSIR) 10-6/year contour for 5 cases simultaneously, outer circle (Peutz) inner circle (RHDHV)*

Both Peutz and RHDHV report the contribution of hose ruptures and hose leakages to the LSIR ([5], [6] and [7] respectively). These are shown in table 7 and table 8.

Table 7 *contribution closure failures to location specific individual risk (RHDHV results)*

		Royal Haskoning DHV									
		contribution to LSIR (10-6) for each bunker case									
		pressurised						refrigerated			
		small		medium		large		medium		large	
		hose rupture									
		closure at hose connection 'B'									
		works	*fails*	*works*	*fails*	*works*	*fails*	*works*	*fails*	*works*	*fails*
closure at hose connection 'A'	*works*	0	0.74	0.92	0.02	0.91	0.02	0	0.71	0	0.14
	fails	0.24	0.01	0.06	0	0.01	0	0	0.29	0.86	0
		hose leakage									
		0		0		0.06		0		0	

RHDHV have calculated all four bunker hose closure scenarios, as shown in the table. Please also refer to section 4.3 for some further considerations regarding scenario assumptions. The fact that the (fail, fail) combinations of RHDHV contribute very little to the LSIR can be explained by their assumption that the probability of this scenario is 100 times smaller than what was considered by Peutz (see section 4.3).

Table 8 contribution closure failures to location specific individual risk (Peutz results)

		Peutz									
		contribution to LSIR (10-6) for each bunker case									
		pressurised						refrigerated			
		small		medium		large		medium		large	
		hose rupture									
		closure at hose connection 'B'									
		works	*fails*	*works*	*fails*	*works*	*fails*	*works*	*fails*	*works*	*fails*
closure at hose connection 'A'	*works*	0.59		0		0		0.18		0	
	fails		0.41		1		1		0.16		1
		hose leakage									
		0		0		0		0.66		0	

It is noted that Peutz have not calculated the (*fail, work*) and (*work, fail*) scenarios, which is in line with the assumption that both bunker hose closures either work or fail simultaneously.

It is also noted that according to Peutz' calculations the hose leakage contributes substantially to the LSIR in the refrigerated medium case. According to RHDHV's calculations, only a minor contribution by hose leakage is reported for the pressurized large case. A satisfactory explanation for these discrepancies is not available yet. However, intermediate results of the calculations by Peutz and RHDHV show considerable differences in calculated total outflow masses for the hose leakage case. This needs to be further investigated.

5.2 1 % lethality contours

table 9 and table 10 show the results for the 1 % lethality contours as calculated by Peutz and RHDHV respectively ([5], [6] and [7] respectively). figure 10 shows these distances on a chart.

Table 9 largest 1 % lethality contour distance, calculated by Peutz

Peutz				
largest distance 1% lethality for each bunker case [m]				
pressurised			refrigerated	
small	medium	large	medium	large
1269	1470	1865	591	919
max. of all five bunker cases				
1865				

Table 10 largest 1 % lethality contour distance, calculated by RHDHV

Royal Haskoning DHV				
largest distance 1% lethality for each bunker case [m]				
pressurised			refrigerated	
small	medium	large	medium	large
576	742	891	505	596
max. of all five bunker cases				
891				

It is remarkable to see that for pressurised bunkering differences range from 693 m to 974 (1865 – 891) m, while for refrigerated they are 85 m and 323 m (919 – 596).

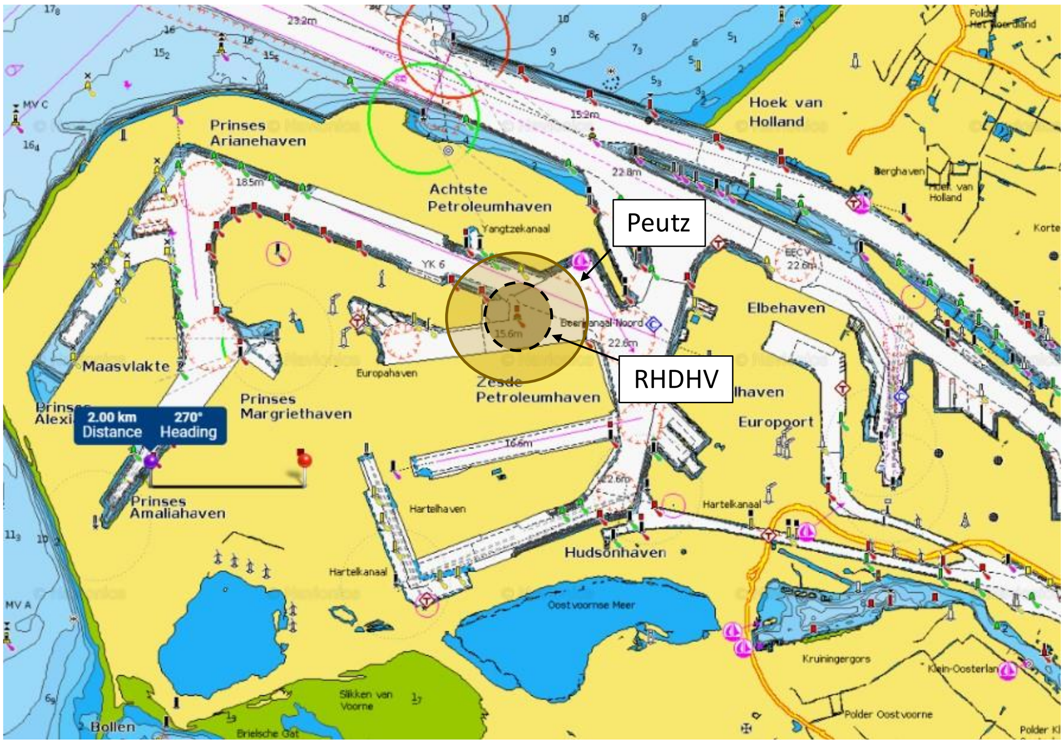


Figure 10 1 % lethality contour, outer circle (Peutz) inner circle (RHDHV)

6. Risk on board: HAZID study pressurised ammonia medium sized ship - results

table 11 shows a summary of the results of the HAZID on the bunker case pressurised medium, taken from the HAZID report [8]. The colours yellow, green, blue and red refer to the risk levels low, moderate, high and extreme respectively. Low requires no actions, moderate requires no further actions either but monitoring is required to ensure no changes in circumstances occur, high requires additional control to manage risk and extreme is not tolerable and therefore requires mitigation. The numbers refer to the number of hazards identified.

Table 11 HAZID Risk ranking summary, bunker case pressurised medium [8]

Node #	Key system level HAZID nodes	Unmitigated Risk Ranking				Mitigated Risk Ranking			
		L	M	H	E	L	M	H	E
1	Shore to Ship Transfer	3	4			4	3	-	-
2	Voyage from Terminal to Bunkering Pier	-	-	-	-	-	-	-	-
3	Bunkering Phase 1 - Berthing Preparation	3	1	-	-	4	-	-	-
4	Bunkering Phase 2 - Mooring & Coming-along-side	-	7	-	-	4	3	-	-
5	Bunkering Phase 3 - Pre-Meeting	-	2		-	1	1	-	-
6	Bunkering Phase 4 - Hose Connection	1	2	1	-	3	1	-	-
7	Bunkering Phase 5 - Hose Purging and Leak Testing	-		2	-	2	-	-	-
8	Bunkering Phase 6 - Measurement	-	-	-	-	-	-	-	-
9	Bunkering Phase 7 - ESD system functional test at ambient temperature (hot condition)	-	-	-	-	-	-	-	-
10	Bunkering Phase 8 - Line cooldown in case of ammonia bunker in refrigerated state	(excluded from DEMO scope & this study)							
11	Bunkering Phase 9 - ESD system function test at low temperature	(excluded from DEMO scope & this study)							
12	Bunkering Phase 10 - Start Bunker Transfer-	-	4	5		2	5	-	-
13	Bunkering Phase 11 - Steady State Bunker Transfer	-	-	24		4	20	-	-
14	Bunkering Phase 12 - Bunker Transfer Completion	-	-	-	-	-	-	-	-
15	Bunkering Phase 13 - Drain and Liquid Purging	-	-	-	1		1	-	-
16	Bunkering Phase 14 - Measurement	-	-	-	-	-	-	-	-
17	Bunkering Phase 15 - Vapor Purging	-	-	-	-	-	-	-	-
18	Bunkering Phase 16 - Hose Disconnection	-	5	-		5	-	-	-
19	Bunkering Phase 17 - Meeting After Completion of Bunker Transfer	-	-	-	-	-	-	-	-
20	Bunkering Phase 18 - Vessel Departure	-	1	-	-	-	1	-	-
21	Demo - Vessel General Arrangements	-	-	-	-	-	-	-	-
22	Demo - Manifold and Piping Arrangement	-	-	-	-	-	-	-	-
23	Demo - Safety Systems	-	1	1	-	1	1	-	-
24	Demo - Operational Safety	-	-	-	-	-	-	-	-
25	Nearby vessels at the port	-	2	2	-	-	2	2	-
Total		7	29	35	1	30	38	2	0
(1): L=Low, M= Medium, H = High and E = Extreme									

As can be seen, initially 35 safety hazards were identified in the high risk category, and 1 (*draining and liquid purging*) in the extreme category. After a risk mitigation brainstorm most of the issues in the high category could be shifted to medium while 2 issues remained; *mooring line failure* and *crew exposure to NH_3* (node 25). The issue in the extreme category could be mitigated. Further details are reported in the HAZARD report [8].

7. Discussion, conclusions, recommendations

7.1 Individual risk (QRA)

The calculated 10^{-6} per year location specific individual risk (LSIR) distances by both subcontractors, 1030 m and 738 m, are more or less in the same ball park, which is reassuring.

With the results regarding 10^{-6}/year LSIR distances it seems possible to find locations in the port of Rotterdam where ammonia bunkering is possible in compliance with the Dutch requirements for establishments.

It is noted however that the calculated LSIR distances depend heavily on the assumptions regarding the probability that closure devices will be activated when required and will actually work, which is currently set at 0.99 (Peutz) or 0.98 (RHDHV) (table 4). It is noted that Dutch regulations for QRA (ref. [2] *Handleiding risicoberekening Bevi*) specify a probability of 0.90. Diverting from the 0.9 value however is acceptable provided that the chosen value can be substantiated.

It is also noted that Peutz reports that, in case of *pressurised large and refrigerated large*, the 10^{-6}/year LSIR contour is dominated by the ***hose closure fails at both ends*** scenario. RHDHV reports dominance for ***hose end closure working at both ends*** for *pressurised large* and ***closure delivering end fails, receiving end fails*** for *refrigerated large*. The RHDHV results are entirely due to the low probability of ***closure of both ends failing*** which is 0.0001! Please refer to table 7 and table 8 about contributions of closure failures to LSIR risk and table 4 about closure probabilities.

In case of refrigerated ammonia there is no overpressure in the tanks. It can therefore be argued that when there is a rupture at location A, backflow will not occur. It is important to note that syphoning cannot take place because that would require an under-pressure (pressure < 1 bara) in the piping and hose sections which are above the liquid level in the receiving tank, indicated as syphoning height in figure 11.

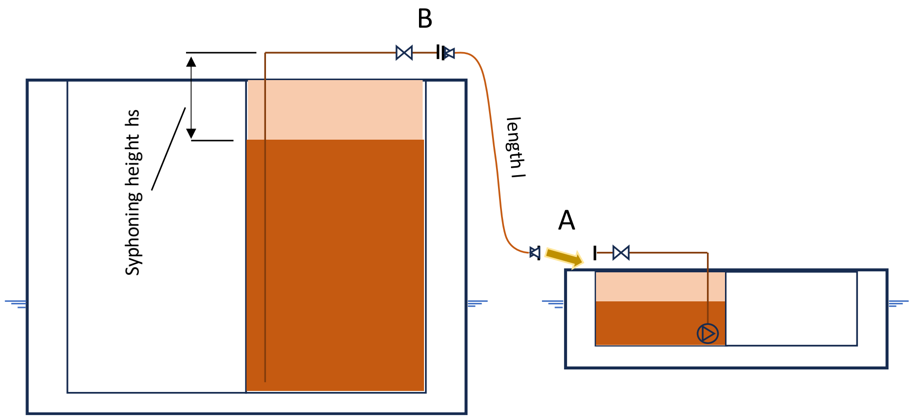


Figure 11 Syphoning in case of refrigerated ammonia fuel

This will cause immediate evaporation because the ammonia is boiling at saturation. In the pressure – enthalpy chart this is indicated by *flash at 1 bara*. As soon as gas develops in the liquid inside the piping/ hose, the syphoning mechanism becomes impossible. It is therefore argued that the probability of *closure at B* may even be set at 1. The liquid present in the hose at rupture can still be spilled.

The other assumptions which greatly influence the calculated LSIR distances are outflow durations, which are currently set at 60 and 300 s, for successful closures of hose connections and failing closures respectively (table 3). It is noted that Dutch regulations for QRA (ref. [2] *Handleiding risicoberekening Bevi*) specify outflow durations of 120 s and 1800 s respectively. Again, diverting from this value however is acceptable provided that the chosen value can be substantiated, which is currently not the case.

The contributions of hose leakage to the LSIR differs between RHDHV and Peutz. This requires further investigation.

Finally it is noted that it is currently unclear to what extend the calculation software SAFETI-NL takes the solubility of water into account. A brief investigation into this matter has been reported by RHDHV ([7]). Both input options *release on land* and *release on water* were calculated which yielded negligible differences. Because ammonia is highly soluble in water and the heat conductivity of water is much higher one would expect differences.

Given the considerations above, it is recommended that closure probabilities at both hose end connections be further substantiated.

It is also recommended that closure response time and subsequent outflow (spill) durations be further substantiated.

The calculated location of the maximum 1 % lethality distance by both subcontractors, i.e. 1875 m and 891 m, show a discrepancy which justifies further investigation. Especially the solubility property requires further attention

7.2 Risk on board (HAZID)

The risk ranking as shown in table 11 is based on the risk matrix as included in the appendix to this report. The core of the matrix is reproduced in figure 12. It has been extended by the authors

Likelihood	Low (1)	Minor (2)	Moderate (3)	Major (4)	Critical (5)
Almost Certain (E) Occurs 1 or more times a year	High	High	Extreme	Extreme	Extreme
Likely (D) Occurs once every 1-10 years	Moderate	High	High	Extreme	Extreme
Possible (C) Occurs once every 10-100 years	Low	Moderate	High	Extreme	Extreme
Unlikely (B) Occurs once every 100-1000 years	Low	Low	Moderate	High	Extreme
Rare (A) Occurs once every 1000-10000 years	Low	Low	Moderate	High	High
Occurs once every 10^{-5}-10^{-6} years					

Figure 12 Risk matrix used for risk ranking.

The cross at the bottom indicates the locus of the 10^{-6} LSIR (location specific individual risk), shown for reference only.

There is a methodological observation to be made. Let's take for explanation purposes node 13 from table 11. It says there are 20 moderate risk scenarios (after mitigation). Suppose 10 of these are in the cell indicated (B,3). The question arises in this case weather the probabilities of these 10 cases should be added, resulting in a joint probability which may end up 10 times higher, pushing the joint risk into a high risk cell. It is currently not clear how to handle joint (cumulative) risk of multiple scenarios.

The general assumptions made for the HAZID study regarding the bunker demo in the port of Rotterdam state that *the tank storage capacity is 3000 m³ and it can store refrigerated or semi-refrigerated cargo.* This may be a bit confusing. At the time of the study the intention was to conduct a demo with pressurised ammonia only, refrigerated and semi-refrigerated are not covered in the HAZID, which is clearly stated in section 2.2 of the HAZID report.

The 35 high risk issues initially identified during the HAZID could be reduced to 2 while the extreme risk issue could be mitigated. The remaining moderate risks are:

1. Collision damage to ammonia fuel delivering vessel (ABV).
2. NH_3 spill due to hose damage.

Both are caused by nearby vessels colliding with ABV (delivering vessel) and impacting bunker operations (e.g. drifting vessel) (node 25 in HAZID report ref. [8]).

The worst thing that can happen regarding collision damage is rupture of the NH_3 tank of the ABV (delivering vessel). This scenario is possible when a large (sea ship) collides. Traffic control and selection of suitable bunkering locations can greatly reduce this risk. It is noted that collision energy absorbing capacities are known for inland waterway gas tankers which can be compared with collision energies with which the ABV may be collided into by other ships nearby.

The other risk is the ABV being dragged away by the colliding ship, cause rupture of mooring lines and consecutively rupture of the bunker hose. Emergency closure arrangements and break away systems will be in place dealing with preventing excessive spills.

There is also is a list of 72 recommendations for attaining this risk reduction down to moderate. These 72 recommendations require a successful follow-up.

Finally in the conclusions of the HAZID report it is said that *in some cases, selected scenarios were discussed but were not risk-ranked or developed further by the team because the necessary information was unavailable, or recommendations were generated for further analysis or design considerations*.

It is recommended to further discuss and decide how to handle joint risk of multiple scenarios.

It is recommended to further investigate the collision scenarios with respect to ABV NH_3 tank rupture.

It is recommended to further investigate the collision scenarios with respect to hose rupture or break away.

It is recommended to further deal with the list of 72 recommendations given in table 5 of the HAZID report.

It is also paramount that the scenarios/ issues ***not yet risk ranked***, as listed below, be further investigated. Figures between brackets refer to Item number in Risk Register in HAZID report [8].

1. Hose Connection (6.2)
2. Hose Purging and Leak Testing (7.1, 7.2)
    a. Water inside hose (7.1).
3. ESD System Functional Test (9.1).
4. Start Bunker Transfer (12.3).
5. Bunker Transfer Completion (14.1)
    a. Overfilling of tank (14.1).
    b. Over pressurisation of the line (14.1).
    c. Human error (14.1).
6. Drain and Liquid Purging (15.1, 15.2).
    a. Nitrogen supply for purging (15.1).
    b. Nitrogen supply (15.1).
    c. Draining (15.2).
7. Hose disconnection (18.3).
8. Emergency shut down (23.1).
9. Firefighting systems (23.3).
10. Safety equipment (eyewash, shower) (23.4).
11. Ammonia detection (23.5).
12. SIMOPS (24.1).

Emergency situations on ABV or AFV (24.2)

8. References

[1] https://www.magpie-ports.eu/magpie-project/presentation/, consulted 02-02-2024

[2] Handleiding Risicoberekening Bevi, Ministerie van Infrastructuur en Milieu, RIVM, https://www.rivm.nl/documenten/handleiding-risicoberekeningen-bevi-v43, consulted 02-02-2024

[3] Interim Rekenmethode LNG-bunkerstations (*Interim calculation method LNG bunker stations*), Ministerie van Infrastructuur en Milieu, RIVM – Centrum Veiligheid, 18 december 2014, https://www.rivm.nl/documenten/20141218-interim-rekenmethode-lng-bunkerstations, 20141218 Interim rekenmethode LNG-bunkerstations | RIVM , consulted 02-02-2024

[4] Reference Manual Bevt Risk Assessment Guidelines for calculating external risk for transporting hazardous substances by road, rail and water, RIVM report 2022-0168, https://www.rivm.nl/documenten/handleiding-risicoanalyse-transport-hart-v1-2, consulted 02-02-2024

[5] *External safety in relation to the bunkering of ammonia, quantitative Risk Analysis (QRA)*, Report number F 22435-3E-RA-002 of 26 September 2022, issued by Peutz BV

[6] Note titled *External safety in relation to the bunkering of ammonia, quantitative Risk Analysis (QRA)*, Reference TKr/TJo/TvdE/F 22435-5E-NO-002 of January 16 2024, issued by Peutz BV

[7] *Location-specific individual risk contours for the bunkering of ammonia*, Reference BI4427IBRP001F01, 3 November 2023, issued by Royal HaskoningDHV

[8] *HAZID Report: Project MAGPIE DEMO Ammonia Bunkering HAZID Study*, 6 March 2023, submitted to Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, issued by American Bureau of Shipping, Spring, TX 77389 (USA)

[9] https://theengineeringmindset.com/r717-ammonia-pressure-enthalpy-chart/, consulted 08-02-2024

[10] Real-time Environmental Applications and Display sYstem, https://www.ready.noaa.gov/READYpgclass.php, consulted 05-02-2024

[11] https://www.epa.gov/aegl/about-acute-exposure-guideline-levels-aegls, consulted 09-02-2024

[12] IACS recommendation Rec. No. 146, Risk assessment as required by the IGF Code

Annex 1: HAZID background info

Participants in HAZID bunkering *pressurised medium*

First Name	Last Name	Company	Job Title	Role
Harish	Patel	ABS	Senior Technical Advisor	Facilitator
An	Nguyen	ABS	Senior Risk Engineer	Scribe
Jun	Kato	CENTER/NYK	Naval Architect	Represents ship designer. Provides input on NH3 bunkering system design and Operational feedback.
Jun	Ito	CENTER/NYK	Naval Architect	Represents ship designer. Provides input on NH3 bunkering system design and Operational feedback.
Peter Lystrup	Christensen	CENTER	Technology Manager	MAGPIE Bunker Demo lead. Assists facilitator and ensures workshop is covering all necessary aspects for overall objectives.
Shinichi	Iwamoto	CENTER/NYK	Chief engineer	Have experience of LPG operations. Provides input and reflections LPG standard operations
Koichi	Sato	CENTER/NYK	Naval Architect	Represents ship designer. Provides input on receiving vessel design, safety systems and vessel limitations.
Matt	Dunlop	CENTER/Vgroup	Director of Sustainability & Decarbonization	Represents receiving vessel. Provides input on operation procedures, receiving vessel crew competences, limitations and training needs for bunkering process.
Cheng	Liang	Proton Ventures		Represents ammonia terminal design body. Provides inputs on ammonia system design and ammonia safety considerations.
Lex	Vredeveldt	TNO	Senior scientist, naval architect	Represents research laboratory. Ensures sound technical evidence and risk definition are used.
Reinier	Sterkenburg	TNO	Senior scientist	Represents research laboratory. Ensures sound technical evidence and risk definition are used.
Cees	Boon	Port of Rotterdam		Representing PoR. Ensures all aspects are covered towards later obtaining approval for Ammonia bunkering demo.
Marika	Hoedemaeker	TNO		
Dennie	Van Kempen	Chemgas	Project Manager , QHS	In charge of the management of the MAGPIE project within TNO. Represents gas tanker operator. Provides input on vessel design, equipment, and standard bunkering procedures.
Klaas	Vandijk	Vanoord shiping		
Takima	Danieru Hosokawa	NYK	Captain	Have experience of LPG operations. Provides input and reflections LPG standard operations

Note: there's a small error in the table; the Job Title and Role of Marika Hoedemaeker were merged into the row of the next person

Risk matrix used in HAZID, bunkering *pressurised medium*

Category	Consequence Severity				
Asset	No shutdown, costs less than $10,000 to repair	No shutdown, costs less than $100,000 to repair	Operations shutdown, loss of day rate for 1-7 days and/or repair costs of up to $1,000,000	Operations shutdown, loss of day rate for 7-28 days and/or repair costs of up to $10,000,000	Operations shutdown, loss of day rate for more than 28 days and/or repair more than $10,000,000
Environmental Effects	No lasting effect. Low level impacts on biological or physical environment. Limited damage to minimal area of low significance.	Minor effects on biological or physical environment. Minor short-term damage to small area of limited significance.	Moderate effects on biological or physical environment but not affecting ecosystem function. Moderate short-medium term widespread impacts e.g., oil spill causing impacts on shoreline.	Serious environmental effects with some impairment of ecosystem function e.g., displacement of species. Relatively widespread medium-long term impacts.	Very serious effects with impairment of ecosystem function. Long term widespread effects on significant environment e.g., unique habitat, national park.
Community/ Government/ Media/ Reputation	Public concern restricted to local complaints. Ongoing scrutiny/ attention from regulator.	Minor, adverse local public or media attention and complaints. Significant hardship from regulator. Reputation is adversely affected with a small number of site focused people.	Attention from media and/or heightened concern by local community. Criticism by NGO's. Significant difficulties in gaining approvals. Environmental credentials moderately affected.	Significant adverse national media/public/ NGO attention. May lose license to operate or not gain approval. Environment/ management credentials are significantly tarnished.	Serious public or media outcry (international coverage). Damaging NGO campaign. License to operate threatened. Reputation severely tarnished. Share price may be affected.
Injury and Disease	Low level short-term subjective inconvenience or symptoms. No measurable physical effects. No medical treatment required.	Objective but reversible disability/impairment and/or medical treatment, injuries requiring hospitalization.	Moderate irreversible disability or impairment (<30%) to one or more persons.	Single fatality and/or severe irreversible disability or impairment (>30%) to one or more persons.	Short- or long-term health effects leading to multiple fatalities, or significant irreversible health effects to >50 persons.
	Low (1)	Minor (2)	Moderate (3)	Major (4)	Critical (5)
Likelihood: Almost Certain (E) Occurs 1 or more times a year	High	High	Extreme	Extreme	Extreme
Likelihood: Likely (D) Occurs once every 1-10 years	Moderate	High	High	Extreme	Extreme
Likelihood: Possible (C) Occurs once every 10-100 years	Low	Moderate	High	Extreme	Extreme
Likelihood: Unlikely (B) Occurs once every 100-1000 years	Low	Low	Moderate	High	Extreme
Likelihood: Rare (A) Occurs once every 1000-10000 years	Low	Low	Moderate	High	High

Cross indicates 10^{-6}/year fatality risk.

Action Key		
	Low	No action is required, unless change in circumstances
	Moderate	No additional controls are required, monitoring is required to ensure no changes in circumstances
	High	Risk is high and additional control is required to manage risk
	Extreme	Intolerable risk, mitigation is required