External safety study - bunkering of alternative marine fuel for seagoing vessels

Port of Amsterdam

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Objective: to investigate the external safety risks (determination of location-specific individual risk and focus areas) of bunkering future alternative marine fuels, such as methanol, ammonia and hydrogen to seagoing vessels.

This report is a translation of the original Dutch DNV report: “Onderzoek externe veiligheid bunkeren van alternatieve brandstoffen voor de zeescheepvaart”, Report No: 10246009-1, Rev. 1, Document No: 11HYLEZF-2, Date: 2021-04-19

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0	2021-04-19	Translation of original final Dutch report (revision 1) into English and added 10^{-5}/year LSIR distances	N. Wessels & Alinea Lingua (translation company)	D. van der Meulen	R. van der Spek

Table of contents

EXECUTIVE SUMMARY

Introduction

Havenbedrijf Amsterdam N.V. (Port of Amsterdam) is preparing for a sustainable future, which includes bunkering of seagoing vessels with alternative fuels. Ship-to-ship bunkering of LNG has already been made possible in the port of Amsterdam. In 2017, DNV conducted an LNG toolkit study for the Port of Amsterdam. In this study, the location-specific individual risk associated with planned LNG bunkering operations in the Port of Amsterdam was calculated to better understand the risk profile of the activities. This has also been used to support the development of an LNG bunker map showing locations where bunkering is allowed. The results of this study are reported in DNV report: 'LNG toolkit for the port of Amsterdam' (Ref. /1/).

The Port of Amsterdam would like to gain an understanding of the space required in the land-use planning to allow for bunkering of alternative fuels, such as methanol, ammonia and hydrogen. Ship-to-ship bunkering falls under the regime of the Port Bye-laws and not under the External Safety (Establishments) Decree (Bevi) or in the future Environmental and Planning Act, which comes into force in January 2022[1]. However, due to the 'Level playing field' principle, the Port of Amsterdam wants to apply the same rules with regard to external safety as for activities with hazardous substances on land. This requires the determination of external safety distances and focus areas (a new concept in the Environmental and Planning Act 2022).

The Port of Amsterdam has requested DNV to carry out this study for the purpose of making a comparison of safety distances for bunkering of alternative fuels with those for the bunkering of LNG. The following fuels are considered in this study:

- LNG;
- Methanol;
- Ammonia (pressurized and refrigerated);
- Gaseous hydrogen (gaseous at different pressures and flow rates);
- Liquid hydrogen.

Objectives

The objectives of this study are:

1. To determine external safety distances for the ship-to-ship bunkering of alternative fuels;
2. To define the focus areas;
3. To compare the results with each other and with those for bunkering of LNG.

Study approach

The study is carried out by making use of the approach and starting points in the LNG toolkit study as much as possible. The starting points are defined in consultation with the Port of Amsterdam. A quantitative risk analysis (QRA) is drawn up for calculating external safety distances. The risks are calculated in Safeti 8.3, using the guidelines in the Reference Manual Bevi Risk Assessments, version 4.3 (hereinafter referred to as: Reference Manual). The focus areas are also calculated in Safeti-NL 8.3 and are based on the same scenarios as those included in the QRA.

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[1] And the applicable Living Environment (Activities) Decree (Bal) and the Decree on the quality of the living environment (Bkl)

Results and Conclusions

The study showed that bunkering of gaseous hydrogen is not likely to be used for shipping, in view of the low energy density and the relatively low bunkering flow rates that are mentioned in literature. This makes the time required for bunkering unrealistically high in order to satisfy the energy demand. For this reason, no risk contours are calculated for bunkering of gaseous hydrogen, assuming a low flow rate from the literature (60 g/s). Instead, effect distances are calculated in order to still obtain an insight into the possible maximum external safety distance (regardless of bunkering duration).

However, there is a party that claims that gaseous hydrogen can be bunkered at 3,000 kg/h without problems being caused by the rapid heating of the storage system by adiabatic compression. This claim is not further examined in terms of feasibility. However, if such bunkering flow rates are feasible, it is helpful to understand the safety distances because then the bunkering duration is more realistic. This does not mean to say that bunkering seagoing vessels with this high flow rate will be more likely, considering the low energy density and the required bunkering volumes.

Location-specific individual risk/external safety distances

The results for the location-specific individual risk show that the external safety distances (10^{-6}/year) for bunkering of methanol and gaseous hydrogen are much smaller (a factor of 3-5) than those for LNG. For refrigerated ammonia and liquid hydrogen, the safety distances are similar to those for LNG, and for pressurised ammonia, the distances are about three times as large due to the generation of a large toxic cloud in the event of a hose rupture. The external safety distances for bunkering the different alternative fuels are provided in Table 0-1. The maximum effect distance for bunkering of gaseous hydrogen at 700 bar and 1000 bar is about 50 m when assuming that due to the low ignition energy, the immediate ignition probability equals 1 and a jet fire always occurs (in accordance with the current assumption used by the RIVM, see further Sections 6.4.3 and 7.3) and 100 m, when a possible delayed ignition possibly leading to an explosion is taken into account[2]. By definition, the external safety distance can be no greater than these values, regardless of bunkering duration.

If a composite hose is used instead of a metal hose for bunkering operations, the risk will decrease because of the lower failure frequency for the rupture scenario of a composite hose. It is expected that the calculated 10^{-5}/year and 10^{-6}/year location-specific individual risk will decrease by a factor of 10. Therefore, as an indication, the calculated 10^{-5} per year location-specific individual risk contour can be used to determine the external safety distance for bunkering with a composite hose. The 10^{-5}/year distances are included in Table 0-1.

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[2] The accuracy of the immediate ignition probability of gaseous hydrogen has recently been called into question in the Hydrogen Safety Innovation Programme (‘Waterstof Veiligheid Innovatie Programma’, WVIP) following an explosion that took place at a hydrogen refuelling station in Norway. This incident suggests that delayed ignitions (and explosions) may well be relevant for modelling in a QRA.

Table 0-1: Location-specific individual risk distances (distance up to the 10^{-6} and 10^{-5} per year contour)

Bunkering scenario	Distance to 10^{-6}/year LSIR contour		Distance to 10^{-5}/year LSIR contour	
	Low flow rate (400 m^3/h)[1]	High flow rate (1000 m^3/h)[1]	Low flow rate (400 m^3/h)[1]	High flow rate (1000 m^3/h)[1]
	LSIR distance (m)	LSIR distance (m)	LSIR distance (m)	LSIR distance (m)
LNG (-146 °C)	321	- [2]	210	- [2]
LNG (-159 °C)	231	344	188	285
Methanol	68	98	56	85
Ammonia (refrigerated)	255	427	153	246
Ammonia (pressurized)	793	973	405	556
Hydrogen (liquid)	214	273	159	198
Hydrogen (gaseous) – (3 t/h)	87	- [2]	87[3]	- [2]
Hydrogen (gaseous) – 700 bar (60 g/s)	- [2]	- [2]	- [2]	- [2]
Hydrogen (gaseous) – 1000 bar (60 g/s)	- [2]	- [2]	- [2]	- [2]

[1] Bunkering flow rates apply to liquid fuels. The flow rate for gaseous fuels is shown in the scenario name

[2] An explanation of the table can be found under Table 7-1 in Section 7.1

[3] For bunkering of hydrogen with 3 tonnes per hour the calculation assumes a high annual bunker duration. This causes the location-specific individual risk contour of 10^{-5}/year to be of almost equal size to the 10^{-6}/year and the influence area (see also Appendix A).

Focus areas

Focus areas are areas that visualise where without additional measures, people are insufficiently protected indoors against the consequences of accidents involving hazardous substances. In the new Environmental and Planning Act 2022, a distinction will be made between three types of focus areas:

- Fire focus area;
- Explosion focus area;
- Toxic cloud focus area.

Table 0-2 shows the maximum distances (measured from the bunker hose) for the focus areas. The results show that the focus areas for ammonia are by far the largest because of the large toxic effect. The focus areas for bunkering LNG are in the same order of magnitude as those for liquid hydrogen. The focus areas for bunkering methanol and gaseous hydrogen are 3 to 6 times smaller compared to LNG. According to current insights for calculating the risks of gaseous hydrogen, explosion focus areas do not really apply to bunkering of gaseous hydrogen because the RIVM states that the immediate ignition probability for the continuous flow of hydrogen gas is equal to 1 and therefore no explosion can occur (see also above). For this reason, no explosion focus areas for bunkering of gaseous hydrogen are included in Table 0-2. However, should this insight change in the future, it may be relevant to consider explosions. Then, the explosion focus area for bunkering gaseous hydrogen is about 110-150 m for the bunkering scenarios considered in this study.

Table 0-2: Maximum distance from bunker hose to focus area boundary

		Focus area distance (m)		
Fuel	**Flow rate**	**Fire**	**Explosion**	**Toxic**
LNG	400 m^3/h (-146 °C)	249	274	- [1]
LNG	400 m^3/h (-159 °C)	330	295	- [1]
Methanol	400 m^3/h	102	- [1]	22
Ammonia (refrigerated)	400 m^3/h	- [1]	- [1]	1446
Ammonia (pressurized)	400 m^3/h	- [1]	- [1]	1478
Hydrogen (liquid)	400 m^3/h	239	283	- [1]
Hydrogen (gaseous)	3 t/h	87	- [1]	- [1]
Hydrogen (gaseous)	700 bar (60 g/s)	55	- [1]	- [1]
Hydrogen (gaseous)	1000 bar (60 g/s)	55	- [1]	- [1]
LNG	1000 m^3/h	448	229	- [1]
Methanol	1000 m^3/h	154	- [1]	34
Ammonia (refrigerated)	1000 m^3/h	- [1]	- [1]	2624
Ammonia (pressurized)	1000 m^3/h	- [1]	- [1]	2060
Hydrogen (liquid)	1000 m^3/h	324	338	- [1]

[1] The justification as to why no distances are calculated can be found under Table 7-3 in Section 7.2

The results of this study provide an initial insight into the external safety of bunkering of alternative fuels to seagoing vessels and the necessary space required that has to be taken into account in the land-use planning. However, much remains unknown as to how the bunkering of these fuels will exactly be performed. It is therefore recommended to examine the study starting points and assumptions at a future date (when the market is further developed) and if necessary, to update them in the context of, for example, the development of bunker maps.

1 INTRODUCTION

Havenbedrijf Amsterdam N.V. (Port of Amsterdam) is preparing for a sustainable future, which includes bunkering of seagoing vessels with alternative fuels. Ship-to-ship bunkering of LNG has already been made possible in the port of Amsterdam. In 2017, DNV conducted an LNG toolkit study for the Port of Amsterdam. In this study, the location-specific individual risk associated with planned LNG bunkering operations in the Port of Amsterdam was calculated to better understand the risk profile of the activities. This has also been used to support the development of an LNG bunker map showing locations where bunkering is allowed. The results of this study are reported in DNV report: 'LNG toolkit for the port of Amsterdam' (Ref. /1/).

The Port of Amsterdam would like to gain an understanding of the space required in the land-use planning to allow for bunkering of alternative fuels, such as methanol, ammonia and hydrogen. Ship-to-ship bunkering falls under the regime of the Port Bye-laws and not under the External Safety (Establishments) Decree (Bevi) or in the future Environmental and Planning Act, which comes into force in January 2022[3]. However, due to the 'Level playing field' principle, the Port of Amsterdam wants to apply the same rules with regard to external safety as for activities with hazardous substances on land. This requires the determination of external safety distances and focus areas (a new concept in the Environmental and Planning Act 2022).

The Port of Amsterdam has requested DNV to carry out this study for the purpose of making a comparison of safety distances for bunkering of alternative fuels with those for bunkering of LNG. The bunkering of the following fuels is considered in this study:

- LNG;
- Methanol;
- Ammonia (pressurized and refrigerated);
- Gaseous hydrogen (gaseous at different pressures and flow rates);
- Liquid hydrogen.

The study is carried out by making use of the approach and starting points in the LNG toolkit study as much as possible.

1.1 Objectives

The objectives of this study are:

1. To determine external safety distances for the ship-to-ship bunkering of alternative fuels by means of a QRA;
2. To define the focus areas;
3. To compare the results with each other and with those for bunkering of LNG.

1.2 Scope limitations

The determination of the external safety distances involves solely the determination of the location-specific individual risk and thus the distance to the 10^{-6}/year risk contour. The societal risk is not included as a consideration in the allocation of bunker locations in the port area due to the area's

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[3] And the applicable Living Environment (Activities) Decree (Bal) and the Decree on the quality of the living environment (Bkl)

character and the relatively low number of people present. In addition, in the new Environmental and Planning Act, the societal risk will be replaced by focus areas.

External domino effects (such as failing wind turbines) and damage (collisions) are not considered. The collision risk in the LNG toolkit study had a limited contribution on the total risk. The Port of Amsterdam has indicated that this is not intended to be a detailed study, but to allow an indication with some margin as to what the relationship will be between LNG and alternative fuels. The collision risks are therefore not considered in this study.

The risk results must be as much as possible independent of the location, so that they are applicable to the entire Amsterdam port area. Location-specific conditions, which may increase the risk locally, are not taken into account. These are ship collisions, external domino effects such as failing wind turbines, plane crashes (the approach routes of Schiphol) and the hazards from companies in the area that work with hazardous substances.

In determining the location-specific individual risk, no further investigation is made into the risk driving scenarios, the risk drivers (parameters) and the impact of mitigating measures.

No specific sensitivity analyses are conducted to better understand the impact of certain parameters on the risk. However, in the determination of the scenarios/parameters, account is taken of the fact that, for example, bunkering can be performed at different flow rates. It is known from the 2017 LNG toolkit that bunkering flow rate has a significant influence on the calculated risk, thus a distinction is made herein in the characterisation of bunkering scenarios. For the liquid fuels, a high and low bunkering flow rate is assumed.

The calculation of the risk caused by the transport of the alternative fuels by water is outside the scope of this study.

1.3 Report structure

The report has the following structure:

- Chapter 2 discusses the legal framework and explains some relevant concepts;
- The starting points for bunkering operations are described and worked out in Chapter 3;
- A description of the general hazardous properties of the different fuels is given in Chapter 4;
- The approach of the study (methodology) is detailed in Chapter 5;
- Chapter 6 gives further substance to the steps that are followed in order to calculate the risk in a QRA study (scenario definition, probability of occurrence, measures, modelling and parameters);
- The location-specific individual risk results and the focus areas (with corresponding distances) are presented in Chapter 7;
- The report concludes with a conclusion (Chapter 8) and a list of references (Chapter 9).

2 LEGAL FRAMEWORK AND CONCEPTS

The external safety risk standards for companies with hazardous substances are legally defined in Bevi. Bevi aims to ensure a minimum level of protection for both individuals and groups of citizens from accidents involving hazardous substances[4]. Primarily, Bevi obliges the competent authorities (municipalities and provinces) to keep a distance between sensitive (vulnerable and less vulnerable) objects and high-risk companies.

High-risk activities that take place on the water within a harbour area, and not within an establishment, such as ship-to-ship (STS) bunkering, are not strictly subject to Bevi. The competent authority in this matter is the Central Nautical Management North Sea Canal Area ('Centraal Nautisch Beheer Noordzeekanaalgebied'), which must approve or issue a permit for the activity. There is therefore no legal framework for calculating the risks for these activities. The standards in Bevi can of course be used for the activities, if the risks are calculated in a similar way as for an establishment. In this manner, the Port of Amsterdam can provide substance to the spatial planning by determining the minimum distance between the vulnerable objects and the high-risk activity. In this way, a minimum level of protection is guaranteed.

The norms in Bevi are not effect-oriented, but based on a probability approach, i.e. the probability of death as a direct result of an accident involving hazardous substances. This does not include health damage, probability of injury or property damage. The Bevi distinguishes between two types of risk: location-specific risk and societal risk. In the future, in the new Environmental and Planning Act, the societal risk will be replaced by focus areas. The societal risk is not considered because the calculation thereof is not part of the scope of this study. Focus areas are calculated however.

In addition, Bevi also employs the term area of influence. The area of influence, the location-specific individual risk and focus areas are discussed below.

2.1 Location-specific individual risk

The location-specific individual risk (LSIR) (risk at a specific location) is the probability per year of a single fatality involving an unprotected individual who is outdoors for 24 hours per day (365 days per year) at a location outside the establishment, arising from the fatal harmful effects of an unusual incident (accident scenario) within the establishment under consideration.

The location-specific individual risk is visualised by LSIR contours. For instance, the 10^{-6} LSIR contour shows those locations where the probability of death of an individual is one in a million per year. The LSIR is independent of the actual population distribution in the vicinity of the establishment.

The Bevi norm further states that the limit value for vulnerable objects (such as dwellings in residential areas, hospitals, schools, large offices etc.) is equal to 10^{-6} per year. For less vulnerable objects (such as scattered dwellings, smaller offices, sports complexes etc.) a target value of 10^{-6} per year is defined. This means that there may be no vulnerable objects within the 10^{-6} LSIR contour of an establishment. For less vulnerable objects, it should be ensured that these objects do not fall within the 10^{-6} LSIR contour; a higher risk may be permitted, if it is sufficiently motivated.

Vulnerable and less vulnerable objects are, by definition, located outside of the (own) risk-causing Bevi establishment (or activity). Vulnerable and less vulnerable objects that are part of another Bevi establishment, such as an office building, are not considered as a (less) vulnerable object for the location-specific individual risk on the basis of Article 1, paragraph 2 of Bevi.

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[4] Source: https://www.infomil.nl/onderwerpen/hinder-gezondheid/veiligheid/bevi-revi/hoofdpunten-bevi/ (visited on 17/07/2017)

The table below gives an overview of objects that are considered to be vulnerable and less vulnerable.

Table 2-1: Overview of vulnerable and less vulnerable objects

Vulnerable objects	Less vulnerable objects
Residential areas (dwellings); Hospitals, retirement homes and nursing homes; Schools and day care of minors; Office buildings and hotels with a gross floor area of more than 1500 m^2; Shopping centres (more than 5 shops and with a floor area greater than 1000 m^2) and shops with a total floor area of more than 2000 m^2; Campsites and other recreational areas intended for accommodating more than 50 people over several consecutive days.	Scattered dwellings (Max. 2/ha); Other office buildings (<1500 m^2); Other hotels and restaurants; Other shops; Gymnasiums, sports fields, swimming pools and playgrounds; Other campsites and other recreational areas; Industrial buildings; Equivalent objects; Objects with a high infrastructure value.

2.2 Focus areas

Focus areas are areas around activities with hazardous substances that visualise where people are insufficiently protected indoors against the consequences of accidents involving hazardous substances, without additional measures. That means that in the event of an accident with hazardous substances, life-threatening hazards to people in buildings can occur. A distinction is made between three types of focus area:

- Fire focus area;
- Explosion focus area;
- Toxic cloud focus area.

The focus areas provide an insight into the potential hazards in an area and where attention should at least be paid to extra protection. In its environmental vision and environmental plan, the competent authority makes and motivates its choices about what is sufficiently safe and how health and the environment are protected. The competent authority also evaluates whether, and if so what measures are needed to sufficiently protect people in focus areas.

2.3 Area of influence

The area of influence is based on the area from the source to the greatest effect distance. The maximum 1% lethal effect distance is the distance to the location where an unprotected person has a 1% probability of death, given all possible scenarios.

3 DETAILING OF BUNKERING OPERATIONS

For the ship-to-ship bunkering of liquid fuels, the following two scenarios are considered:

1. Ship-to-ship bunkering with a low flow rate (400 m3/hour);
2. Ship-to-ship bunkering with a high flow rate (1000 m^3/hour).

These scenarios are not applicable to bunkering of gaseous hydrogen, because the flow rates are much higher than what is realistically feasible for gaseous hydrogen. The MariGreen report 'Perspectives for the use of hydrogen as fuel in inland shipping' (Ref. /2/) mentions a maximum bunkering flow rate for gaseous hydrogen of 60 g/s. At higher bunkering flow rates, problems arise with rapid excessive heating of the storage system by adiabatic compression.

However, there is a party that claims that gaseous hydrogen can be bunkered at 3,000 kg/h without problems being caused by adiabatic compression. This claim is not further examined in terms of feasibility.

For bunkering of gaseous hydrogen, three scenarios are considered:

1. Bunkering of gaseous hydrogen (700 bar) at 60 g/s;
2. Bunkering of gaseous hydrogen (1000 bar) at 60 g/s;
3. Bunkering of gaseous hydrogen (350 bar) at 3 t/h;

Given the low energy density and relatively low bunkering flow rates mentioned in literature, the duration that is required for bunkering is unrealistically high in order to satisfy energy demand. For this reason, no risk contours are calculated for the first two bunkering scenarios where a low flow rate from the literature (60 g/s) is assumed. Instead, effect distances are calculated in order to still obtain an insight into the possible maximum external safety distance (regardless of bunkering duration).

However, for the higher bunkering flow rate (3 t/h) scenario, it is helpful to understand the risk distances because bunkering duration is more realistic with this flow rate. This does not mean to say that bunkering seagoing vessels with this high flow rate will be likely, considering the low energy density and the required bunkering volumes.

To be able to determine the risk contours, it is necessary to characterise the activities. The technical and operational starting points and parameters (hose diameters, pump flow rate, pressure, ESD system, etc.) are of importance in this respect. The bunkering operations are further detailed in the following paragraphs. The configurations, bunkering scenarios and technical/operational starting points are discussed.

3.1 Bunkering scenarios and configurations

For bunkering of the different fuels, a distinction is made between two bunkering scenarios per fuel. For each fuel, a 'low flow rate' and a 'high flow rate' scenario is defined, in which a distinction is made in bunkering flow rate, hose size and bunkering duration. The risk for all bunkering scenarios are calculated separately. The technical and operational starting points (e.g. flow rates) that are used for the scenario parameters of each bunkering scenario are described in the following section.

3.2 Technical and operational starting points

The required technical and operational starting points and parameters for the risk calculation are defined in consultation with the Port of Amsterdam. The study starting points for LNG bunkering are taken from the LNG toolkit study of 2017 (Ref. /1/). The assumptions regarding the presence of technical measures (repressive systems) are described in Section 6.1.3.

In order to calculate the risks of bunkering, details about the bunkering operation are required. Some relevant parameters are included in the tables below. In reality, the values for the parameters are highly dependent on the design of the bunker vessel and receiving ship and the specific details of the bunkering operation. In practice, the values could be different and a range is normally applicable. However, only one (conservative) value for each parameter can be assumed per risk calculation, which is to reduce the number of risk calculations and not to underestimate the risk of possible future situations.

Table 3-1: Starting points for the different bunkering operations

	High flow rate				**Low flow rate**			
	Pressure (barg)	**Temp (°C)**	**Flow rate (m^3/hour)**	**Internal hose dia. (mm)**	**Pressure (barg)**	**Temp (°C)**	**Flow rate (m^3/hour)**	**Internal hose dia. (mm)**
LNG	0.224	-159*	1000	200	0.224	-159	400	150
Methanol	atm	20	1000	200	atm	20	400	150
Ammonia (pressurized)	9	20	1000	200	9	20	400	150
Ammonia (refrigerated)	atm	-34	1000	200	atm	-34	400	150
Hydrogen gas 700 bar (60 g/s)	-	-	-	-	700	20	5.65**	25
Hydrogen gas 1000 bar (60 g/s)	-	-	-	-	1000	20	4.54**	25
Hydrogen gas – (3 t/h)	-	-	-	-	380	20	122	50
Liquid hydrogen	atm	-253	1000	200	atm	-253	400	150

* In the LNG toolkit, a situation with -146 °C was also calculated. This is recalculated in this study.
** flow rate is based on 60 g/s (Ref. /2/)

Furthermore, for all bunkering operations, a metal bunker hose is assumed. To make a meaningful comparison between the safety distances of the different fuels, it is assumed that an equivalent amount of energy is bunkered on an annual basis for all fuels. Since the different fuels have different energy densities, this means that there are different bunkering durations between the various fuels. No account is taken of other parameters (e.g. engine efficiency), which may affect how often a ship needs to be bunkered in reality.

LNG bunkering of 250 hours per year is assumed. The bunkering duration for alternative fuels is determined so that the amount of energy that is bunkered for the alternative fuel is equal to the amount of energy that is bunkered with LNG. Because of the low bunkering flow rate of gaseous hydrogen (60 g/s), this approach results in a very high bunkering duration for bunkering of gaseous hydrogen at 60 g/s (>> 8,765 hours per year). Therefore, for bunkering gaseous hydrogen only effect distances instead of the location-specific individual risk is considered (the number of hours needed for bunkering per year exceeds the number of hours in a year).

Table 3-2 bunkering duration for equivalent amounts of energy bunkered

	Energy density [1] MJ/l	Energy factor[2] (-)	High flow rate		Low flow rate	
			Flow rate factor[2] (-)	Bunkering duration[2] (hours/year)	Flow rate factor[2] (-)	Bunkering duration[2] (hours/year)
LNG	22.4	1	1	250	1	250
Methanol	15.6	0.70	1	359	1	359
Ammonia (pressurized)	12.7	0.57	1	442	1	442
Ammonia (refrigerated)	11.3	0.50	1	495	1	495
Hydrogen gas 700 bar (60 g/s)	4.6	0.20	-	-	0.014	86,605[3]
Hydrogen gas 1000 bar (60 g/s)	5.7	0.25	-	-	0.011	86,605[3]
Hydrogen gas – (3 t/h)	3.0	0.13	-	-	0.30	6,236
Liquid hydrogen	8.5	0.38	1	660	1	660

[1] Excl. the volume of the storage system

[2] The bunkering duration for alternative fuels is determined based on an equivalent amount of bunkered energy with respect to the LNG scenarios. In order to determine this, the 'energy factor' and the 'flow rate factor' are defined. The energy factor is the energy density of an alternative fuel divided by that of LNG. The flow rate factor is the flow rate of the alternative fuel divided by the flow rate for bunkering of LNG. Dividing bunkering duration for LNG by these two factors calculates a bunkering duration for which the same amount of energy is bunkered for the alternative fuel as for LNG.

[3] Due to the low bunkering flow rate, the number of bunkering hours per year is unrealistic. No LSIR is calculated for these scenarios, but only effect distances. The location-specific individual risk contour can never be greater than the maximum effect distance. The effect distances can therefore be considered as the maximum safety distance.

4 GENERAL HAZARDOUS PROPERTIES

This chapter describes what can happen if fuels are released into the atmosphere and the possible resulting effects. The general hazardous properties of the fuels are described. Next, the various effects that can occur, such as fire, explosion and toxic exposure are discussed.

4.1 Fuels

4.1.1 LNG

The composition of LNG varies and depends on the gas field or other source from which it is recovered. LNG consists primarily of methane (natural gas). In addition, LNG contains higher hydrocarbons (such as ethane) and inert gases (such as nitrogen).

The general hazardous properties for LNG are described in PGS 33-1 (Ref. /3/). Some relevant properties are described below.

Natural gas is not toxic, no limit is set, but in high concentrations, it poses a risk of suffocation (by displacing the air). Under atmospheric conditions, a natural gas/air mixture is ignitable between a percentage volume of 4.4 vol% and 16.5 vol% natural gas in air (PGS 33-1 has limits between 4.5 vol% and 14 vol%).

Natural gas is naturally odourless. For CNG, there is a legal obligation to add an odouriser to warn end users for any leaks. It is not possible to add an odour to LNG.

Under atmospheric conditions at ambient temperatures, natural gas is lighter than air and will therefore rise and dissipate when released. However, if LNG is released, the gas first behaves like a heavy gas and stays near the ground or water surface. It will then accumulate in low-lying and poorly ventilated locations, thereby replacing the ambient air and causing suffocation. The cold vapour will only begin to rise if it is heated by the outdoor air to above −113 °C.

Because of the low temperature, the skin will freeze (so-called ‘cold burn’) upon contact with the cold liquid or vapour. Inhalation of the cold vapour can cause freezing of the lungs and airways. Materials can become brittle at low temperatures and lose their strength and thereby their functionality.

When LNG is released on a surface or in the water, this will have an impact on the rate at which LNG expands to a gaseous form. An intensive boiling process will occur where the LNG hits the surface. During the evaporation of larger amounts of released LNG, the cold vapour will condense the water vapour in the outside air. This can be accompanied by the formation of a white cloud of fog, until the gas warms up, dilutes and dissolves in the outside air.

When LNG is released into water (or comes into contact with water) explosive forces may occur. This phenomenon is called rapid phase transition (RPT). There is no combustion with RPT. The pressure wave that is created by small quantities of liquid material vaporising instantaneously when overheating occurs due to mixing with water, will propagate with the speed of sound and deteriorate like any other pressure pulse. Usually no specific modelling is carried out for RPT, because it is improbable that the effects of RPT make a significant contribution to the total danger area of a large leak that has already taken place.

4.1.2 Methanol

Methanol (methyl alcohol) is a colourless, volatile liquid. Methanol is flammable with a Lower Flammable Limit (LFL) of 7.3 vol% , and an Upper Flammable Limit (UFL) of 36 vol%. Methanol is mainly toxic when ingested, causing blindness and possibly death. Although methanol is also classified as toxic by inhalation (Hazard statement H331), the degree of toxicity by inhalation is minimal[5]. Methanol also has a high life-threatening value (LBW) (1-hour exposure) of 20,248 ppm, indicating that a person must be exposed to high concentrations before death can occur. The RIVM has not defined any probit functions for methanol, and toxic risks are therefore not considered in Dutch Quantitative Risk Assessments (QRAs). However, there is a probit function available in the calculation program Safeti. Because of the existence of a probit function, an LBW value, and the classification with H-statement H331, methanol is also considered (in addition to flammable) as a toxic substance in this study.

4.1.3 Ammonia

The general hazardous properties for ammonia are described in PGS 12 (Ref. /4/). Some relevant properties are reproduced below.

Ammonia is a colourless, toxic gas with a strong pungent odour. The gas itself is lighter than air (vapour density of 0.6 with respect to air), but when it is released into the air, a vapour can arise that is heavier than air (see further below). By compressing or cooling, the gas can be condensed into a liquid. Liquefied ammonia can cause caustic irritation and severe burns on contact with the skin.

The action of ammonia vapour on the respiratory system is usually limited to the upper respiratory tract, because the gas dissolves well in water and moreover it generates strong reflexes so that one immediately holds one's breath. At very high concentrations, ammonia can get into the deeper airways. The consequences are extremely serious, such as damage to the lungs (pulmonary oedema) and possible death as a result.

With the release of liquefied ammonia gas, due to the presence of water vapour in the air (such as at high humidity), vapours are generated that are heavier than air. These toxic vapours can spread at ground level or in low-lying areas with poor ventilation, potentially exposing people to harmful (lethal) concentrations. So if large amounts of ammonia are released (as in the scenarios in this study), this can create a large ammonia cloud, which is toxic upon inhalation up to great distances from the scenario. As this cloud is heavier than air and spreads at ground level, people can be exposed to high concentrations and there can be a high risk of mortality.

Ammonia is not very flammable. A cold boiling ammonia pool does not burn in a self-sustaining way, like most hydrocarbons. This is caused because insufficient heat from the flames is radiated into the pool. The flames are very transparent. When heat is applied by another means, for example, from the ground or with water, sufficient ammonia can evaporate to maintain the fire. A possible ammonia fire gives only a limited hazard, because only very little heat radiation occurs from the fire to the environment. The probability of a fire or explosion arising exists almost exclusively in poorly ventilated spaces. The minimum ignition energy is 680 mJ (this is approximately 10,000 times as large as for hydrogen).

Quantitative risk analyses therefore only consider the toxic effects of ammonia. Ammonia has an LBW value (1-hour exposure) of 1,495 ppm.

4.1.4 Hydrogen

The general hazardous properties for hydrogen are described in PGS 35 (Ref. /5/). Some relevant properties are reproduced below.

Hydrogen is a flammable gas with an LFL concentration of 4.0 vol% and a UFL concentration of 75 vol% in the air. Hydrogen is not toxic. Because of the small molecule, hydrogen penetrates almost everywhere, is lighter than air (about 14 times) and is also odourless. Little energy is needed to ignite the gas. Depending on the pressure and the discharge flow rate, hydrogen can be ignited with very low

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[5] 'Serious intoxication after inhaling methanol' https://www.ntvg.nl/system/files/publications/2006112980001a.pdf

energy, creating a jet fire. In addition, there is a risk of explosion in case of accumulation of hydrogen in confined spaces.

Hydrogen has a colourless, hardly visible flame and has virtually no heat radiation. Human senses cannot easily detect a hydrogen flame. With a larger leak in a pipe or hose, at a pressure of 700 bar, in the case of fire, virtually invisible and powerful jet fires can occur.

Hydrogen has a high ignition probability due to the low ignition energy. In order to be able to ignite hydrogen, only 0.02 mJ energy is required. The probability of immediate ignition of liquid hydrogen is somewhat lower than in the case of gaseous hydrogen. Liquid hydrogen is stored thermally insulated and under low pressure, so that the velocity and corresponding energy at which hydrogen outflows will be lower and delayed ignition could take place. Cold hydrogen can still ignite at a distance after evaporation.

Liquid hydrogen is a cryogenic liquid. Hydrogen is pressurised and cooled to minus 252.8 °C (at 1013 mbar). On exposure to the ambient air, oxygen and nitrogen can condense from the ambient air. With very rapid evaporation, liquid hydrogen may pose a risk of freezing. In addition, the release of liquid hydrogen in water can lead to an RPT, just as for LNG (see Section 4.1.1 above).

4.2 Fire and explosion

The release of flammable materials can result in a fire or explosion. By mixing the gas with air, a gas becomes flammable when its concentration in air is between the LFL and UFL. If there is less air, there will be too little oxygen for a flame, while with more oxygen the gas will be too diluted to ignite.

4.2.1 Flash fire

A flash fire is a non-explosive combustion of a flammable vapour cloud (i.e. the concentration in air is between the LFL and UFL). In general, a flash fire occurs when a vapour cloud encounters a source of ignition (such as a naked flame, combustion engine, sparks etc.). So in this case there is delayed ignition. The vapour cloud is often ignited on the edge (where the concentration is lower), after which the fire spreads to all the flammable mass and then continues burning up to the UFL until all the mass is burned. So different flame fronts can exist.

4.2.2 Jet fire

A jet fire can arise when a continuous outflow of flammable material ignites. In the case of immediate ignition, there is always a jet fire.

4.2.3 Pool fire

A pool fire occurs when a liquid pool ignites flammable material, or when the flammable vapour cloud is ignited above the pool. In the latter case, the flash fire will ignite the pool. Pool fires cause a lot of thermal radiation which decreases as the distance to the pool increases.

4.2.4 BLEVE/fireball

A fireball is an extremely fast combustion process, usually associated with 'Boiling Liquid Expanding Vapour Explosions' (BLEVE), which can occur with pressurized (boiling) liquids that are released instantaneously. Such effects are only relevant for instantaneous failure of pressurized storage on land and not with ship-to-ship bunkering.

4.2.5 (Semi) confined vapour cloud explosion

A vapour cloud explosion can occur when a large quantity of gas is ignited in a confined or semi-confined space.

4.3 Toxic exposure

Both ammonia and methanol are toxic if inhaled. This can be lethal for persons exposed to prolonged toxic concentrations. It should be noted, however, that methanol is much less toxic on inhalation than ammonia, and that, even with long-term exposure to high concentrations in the open air, death is unlikely to occur (see also Section 4.1.2). In case of the release of large amounts of ammonia, a large toxic cloud forms that is accompanied with a high risk of death over large distances (see Section 4.1.3).

5 METHODOLOGY

The risk calculations are carried out by making use of the approach and starting points in the LNG toolkit study as much as possible, which was developed at the request of the Port of Amsterdam (Ref. /1/). The starting points and scenarios for LNG bunkering are taken from this study and the risks are recalculated in the latest version of Safeti (8.3)[6].

Similar starting points are adopted for the other fuels. Because the calculations are carried out in the latest version of Safeti, there may be slight differences in the calculated risk distances. This approach follows broadly the methodology of a QRA. The main principles of the QRA process are outlined in this chapter. In addition, the used QRA guidelines and calculation methods (in which it is explained how the risks should be calculated) are provided and explained. The calculation of risk also requires a calculation program. The choice of the calculation program is explained in this chapter. Furthermore, it is discussed how the risk calculation is carried out, which results are generated, and what analyses are carried out on the results.

5.1 QRA process

A QRA is a tool to make the risks of the use, transport and storage of hazardous substances transparent. To determine the risks to external safety, both the probabilities and the hazardous effects of incidents involving hazardous substances are calculated in a QRA. The results of a QRA can be used to determine e.g. risk distances from the source of the incidents to the LSIR contours (Ref. /7/).

Generally, conducting a QRA comes down to the following. First, a selection is made of the installations (or process components with hazardous material) that are relevant to external safety. Accident scenarios are subsequently worked out for each installation/component. This relates to both the probability as well as the effects of the scenarios. Further, it is examined whether measures are in place that can reduce the probability of the scenario or that can control its effects, after which it must be determined whether and how these measures can be given a place in the QRA. Finally, to calculate the risks, data on the environment, such as weather data (meteorology) are relevant[7]. All this leads to calculation results in the form of an LSIR that can be assessed based on the requirements of Bevi (Ref. /7/). A schematic overview of the QRA process or methodology is displayed in Figure 5-1.

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[6] It should be noted in this respect that the LNG toolkit distances were calculated in a previous version of the software (7.21). For a good comparison, the distances are therefore recalculated in version 8.3. This may result in slight differences with respect to the calculated distances in the toolkit.

[7] This study only calculates the LSIR, other environment data, such as population and ignition sources in the vicinity of the activity is irrelevant for the calculation of the LSIR.

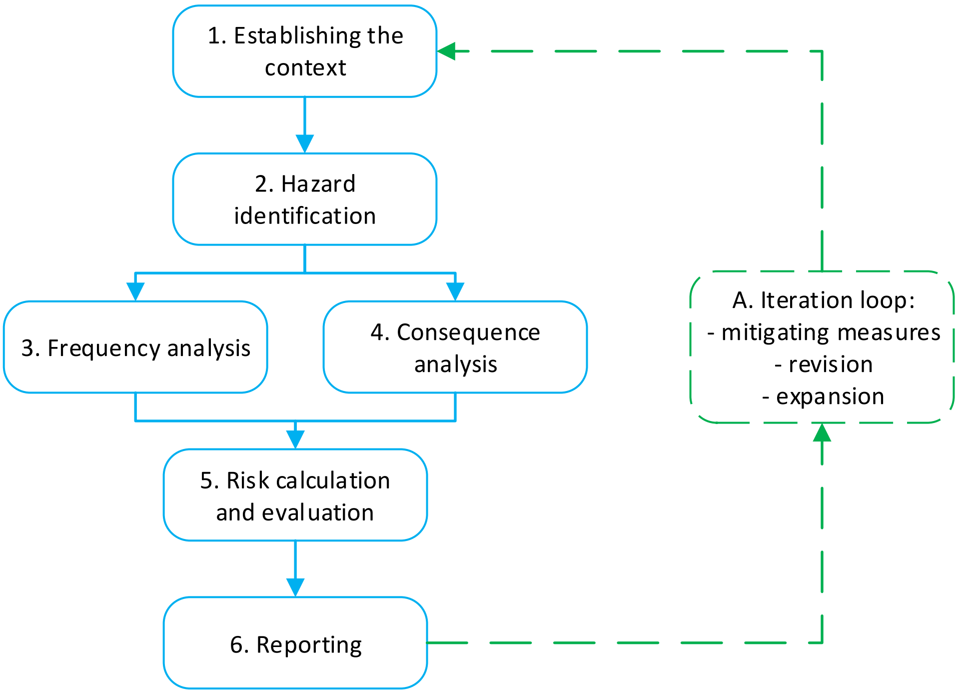


Figure 5-1: QRA methodology

The various process steps in Figure 5-1 are briefly explained below with reference to the chapter/section in the report where they are detailed.

Establishing the context, hazard identification and frequency analysis

The description and selection of process components and the associated failure scenarios are included in Chapter 6.1. The selection of relevant components is carried out in Section 6.1.1. Next, failure scenarios with associated standard failure frequencies are defined for the relevant components. The standard failure frequency must then be multiplied by the annual duration of the operation to calculate the final failure frequency. The latter is explained in Section 6.1.4.

Mitigating measures

The repressive measures are described in Section 6.1.3. These are technical measures to limit the outflow and/or the effects (such as an automatic isolating system or a non-return valve). There are also preventive measures that reduce the probability of a scenario (e.g. the use of a special type of hose). In addition, mitigating measures can also fail and the probability of failure on demand of these measures has in turn an impact on the overall frequency of the scenario.

Consequence analysis

The consequences are calculated with the aid of the computer program that is described in Section 5.3 based on the failure scenarios as defined in Section 6.1 and the model and environmental parameters in Chapter 6.4. Consequence results are not reported.

Risk calculations

The risk is calculated using the same calculation program as that used for calculating the consequences. No assessment is made of the risk, instead, the LSIR results and focus areas are generated, reported and subsequently analysed. How the results are generated and determined etc. is explained in Section 5.4. The results are included in Chapter 7.

Data on population and ignition sources in the vicinity of the activity are not relevant for the calculation of the LSIR. The method for determining the probability of delayed ignition for the calculation of the LSIR is independent of the presence of sources of ignition in the vicinity.

The meteorological data and other environmental parameters used, such as the roughness length of the surroundings, are described in Section 6.4.1.

5.2 Guidelines

The risks are calculated using the Reference Manual Bevi Risk Assessments, version 4.3 (Ref. /6/). In the Reference Manual, the parameters are specified that are to be entered into the calculation program. Strictly speaking, the Reference Manual is only applicable to the risk calculation for establishments with hazardous substances. However, the scenario and model parameters and the modelling philosophy in the Reference Manual is of general use for the risk calculation of an activity with hazardous substances (establishment or not). For the risks associated with bunkering of LNG, use is made (as in 2017), of the available LNG calculation method: Calculation methodology for LNG bunkering stations (Ref. /7/). The RIVM memo: Risk and effect distances for hydrogen refuelling stations (Ref. /8/) is used to calculate the risks associated with bunkering hydrogen.

5.3 Calculation program

In order to be able to assess risks against Bevi norms use should be made of the Bevi method of calculation. The Bevi calculation method consists of the calculation program Safeti-NL and the Bevi Reference Manual. Safeti-NL 8.3 is currently the program prescribed in the Netherlands to carry out a QRA for establishments. As the activities take place on the water and do not belong to an establishment, it is chosen to use the calculation package Safeti 8.3 developed by DNV. This is in fact the mother program of Safeti-NL, where there are no input restrictions for changes in model parameters (as is the case in the NL version). The model parameters that are specific for a QRA in the Netherlands are in a large part taken from Safeti-NL 8.3 (see also the Reference Manual). The focus areas are calculated in Safeti-NL, because this version has an added option that is necessary for the calculation of the focus areas which is not available in the standard version of Safeti.

5.4 Risk calculation

5.4.1 Location-specific individual risk

After determining and calculating the probabilities and effects, the LSIR contours are calculated in Safeti. The LSIR contours are reported as contours on a map. These contours are used to determine the external safety distances (distance to 10^{-6}/year).

5.4.2 Focus areas

In the calculation of focus areas, a distinction is made between three types of focus area:

- Fire focus area;
- Explosion focus area;
- Toxic cloud focus area.

These are explained in the following sections.

5.4.2.1 Fire focus area

For the calculation of the fire focus area, use is made of the fire effect areas in a QRA. The fire focus area is the area around an activity in which, as a result of the activity, heat radiation effects in excess of 10 kW/m^2 are possible. Upon prolonged exposure to heat radiation above 10 kW/m^2, buildings may collapse and anyone who is indoors may die as a result.

5.4.2.2 Explosion focus area

The explosion focus area is determined as the area in which excess overpressures of more than 0.1 bar are possible as a result of the activity. In the calculation of the location-specific individual risk, it is assumed that people are outside. The criterion for death due to overpressure for people outside is 0.3 bar. But because focus areas are focused on people who are indoors, lethality could already occur at overpressures from 0.1 bar. At 0.1 bar overpressure, structural damage to the building can occur and people who are indoors may die, through the (partial) collapse of the building.

Further, for the location-specific individual risk, a vapour cloud explosion is assumed as soon as the vapour cloud has reached its maximum size. This is considered too conservative for determining the explosion focus areas. For the determination of the explosion focus area, it is assumed that a vapour cloud explosion will occur if the centre of the cloud passes the ‘site boundary’. For this study, the site boundary is defined as a boundary around the two vessels (the fuel-receiving ship and the bunker vessel).

5.4.2.3 Toxic cloud focus area

The toxic cloud focus area is defined as the area in which a toxic concentration of 2.53 times the LBW value (1-hour exposure) of a substance can occur. The RIVM has determined that if the concentration of a substance outside is equal to 2.53 x LBW, concentrations equal to LBW can occur indoors. The 1-hour LBW value of a substance is the air concentration above which possible lethality or life-threatening conditions can occur, as a result of one hour of exposure.

Within the toxic focus area, people who are indoors can therefore be exposed to life-threatening toxic concentrations.

5.4.2.4 Calculation of the size of the focus area

The effect areas for the different focus areas are shown for a probability of 1x10^{-20} per year and are shown as contours on a map. The distance from the bunker hose to the contour is measured and shown as the distance for the focus area.

5.4.3 Area of influence

A calculation of the area of influence (or: maximum 1% lethal effect distance) is relevant due to the following:

- Insight into the maximum effect area that can arise. On this basis, it can be determined by the Port of Amsterdam whether, at a later stage, a calculation of the societal risk is considered necessary on the basis of the number of people present within the area;
- The area of influence also shows the theoretical maximum size of the 10^{-6}/year contour independent of the annual duration of an activity.

The area of influence for all considered activities is displayed on the figures with a location-specific individual risk contour of 10^{-30} per year.

6 QRA STUDY

6.1 Loss of Containment scenarios

This section defines and elaborates the LoC scenarios. First, a selection is made of the risk-relevant components where fuel may possibly be released. For the relevant components, the LoC scenarios are defined according to the Reference Manual and the Interim Calculation Method for LNG bunkering stations. Also the measures (repressive systems) that are taken into account are described. The section concludes with a calculation of the probability of failure per scenario.

6.1.1 Selection of relevant components

This section provides an overview of which components are or are not selected for the risk analysis. A justification is given if components are not selected for the QRA.

It is not yet known for all types of fuels which components will be present on a ship. A number of standard components are identified that may possibly be present on a ship, where fuel may potentially be released. For the risk calculations, it is assumed that all fuels are bunkered ship-to-ship by means of a metal hose. In reality, it is not expected that gaseous hydrogen will be bunkered ship-to-ship, considering the low energy density and bunkering volumes required. To calculate the risk distances, however, it makes little difference whether bunkering is ultimately done from a land-based installation or from a ship.

STS bunkering

- Bunker vessel's cargo tank;
- Receiving ship's fuel tank;
- Bunker hose;
- Possible vapour return hose;
- Fuel piping and other equipment which contains fuel on the bunker vessel or the receiving ship;
- Bunker vessel's fuel pump;
- Pressure relief devices/vent stack on the bunker vessel and the receiving ship.

Of the above process equipment, the following components are not considered in the QRA:

- Bunker vessel's cargo tank and receiving ship's fuel tank:

  The failure of a cargo tank does not need to be considered in a QRA (Ref. /7/, /6/). It is assumed that bunkering takes place during most of the time the bunker vessel is present at the quay, and that bunker scenarios (hose failure) dominate the risk of the operation.

  The only scenarios for tank failure that are relevant to bunkering are collision scenarios, where the tank is damaged by a collision with another ship. Since collision risks are very location-dependent, and the LNG toolkit showed that they have only a minor effect on the ultimate risks, it is chosen not to take these risks into consideration for this study. Therefore, no scenarios are included for the failure of the bunker vessel's cargo tank or the receiving ship's fuel tank.

- Possible vapour return hoses:
  The only scenarios that should be included in the QRA for bunkering operations are a rupture and leakage of the loading/unloading hose (Ref. /6/). A vapour return line (or hose) may be used in a

bunkering operation, but for that, no additional scenarios are specified in the Reference Manual. The reason for this follows from the calculation method LNG fuelling stations (Ref. /12/). The calculation method specifies that the risk caused by the vapour return hoses is negligible compared with the liquid hoses. In the case of liquid discharges, this is a reasonable assumption as the mass flow rate through the vapour return hose is much lower due to the difference in the density of liquid and gaseous substances.

- Fuel piping and other equipment which contains fuel on the bunker vessel or the receiving ship:

  It is assumed that the operation takes place during most of the time that a ship is present, and the mechanical handling scenarios (failure of the hose) are dominant with respect to the failure of other components on the ship, such as piping, etc.

- Bunker vessel's fuel pump:

  It is assumed that the pump or pumps on the supply vessel are either:

  1. on the deck above the cargo tanks (and thus above the maximum liquid level of the tank) and/or have no bottom connection with the cargo tank (not allowed according to the ADN), or;

  2. submerged in the cargo tank (in a 'well').

  In both cases, catastrophic failure of the pump will not lead to a discharge of liquid to the atmosphere. An outflow of gas is only possible in the case of option 1, which is not a relevant risk given the difference in density.

- Pressure relief devices/vent stacks:
  The effects and risks of blow-off points at ground level are considered irrelevant for the external safety (and specifically the 10^{-6}/year LSIR) because of the blow-off height, direction, frequency and the amount that can be released, and hence the maximum effect distances. Here it is assumed, in accordance with the Reference Manual, that the opening of the pressure relief device and/or discharge from the vent stack does not lead to an emission with risks to the environment and therefore the scenario is not included in the risk analysis.

Selected components for the risk analysis
Below it follows that only the risks associated with the failure of the bunker hose are selected as a relevant risk to the various bunkering operations. The definition of the standard LoC scenarios of the bunker hose with associated failure probabilities is provided in the following sections.

6.1.2 Bunker hose

The standard scenarios with associated standard failure frequencies for a bunker hose as defined in the interim calculation method for LNG bunkering stations (Ref. /9/ are included in the table on the next page. For all bunkering operations, a metal hose is assumed by default (an indication is given for the results when a composite hose is employed).

Table 6-1: Standard scenarios for the fuel hose (Ref. /9/)

Scenario	**Standard failure frequency (h^{-1})**
Metal hose	
S.1 Hose rupture	$4,00*10^{-6}$
S.2 Hose leakage with an effective diameter of 10% of the nominal diameter, maximum 50 mm	$4,00*10^{-5}$
Composite hose	
S.3 Hose rupture	$4,00*10^{-7}$
S.4 Hose leakage with an effective diameter of 10% of the nominal diameter, maximum 50 mm	$4,00*10^{-5}$

6.1.3 Repressive measures

This section describes the repressive measures that are included in the risk analysis. Repressive measures (or repressive systems) may restrict the outflow duration of the failure scenarios, thereby limiting the harmful effects of a given Loss of Containment.

It is assumed that there is an automatic isolating system (ESD system) present with a reaction time of 120 s and a reliability of 0.01 probability of failure on demand (PFD).

It is assumed for the risk analysis that this automatic isolating system will only be effective in the event of a hose rupture. In accordance with the Interim Calculation Method for LNG bunkering stations (Ref. /9/) no intervention by the ESD system is modelled in the event of a small leakage. The method provides the following three reasons for this:

1. It is difficult to prove that leakages will be detected quickly;
2. Even when the leaking part is isolated, any fuel still present in the system will continue to discharge for a longer period of time;
3. The effect distances of leakages are often less relevant for the external risk.

So for a small hose leakage (10% of the diameter) a maximum outflow duration of 30 minutes is assumed.

A non-return valve is also included in the risk analysis for bunkering, which may limit the backflow from the fuel tanks (for example, in the case of a rupture of the hose during bottom filling of the fuel tank). It is assumed that the non-return valve is regularly tested and may therefore be included in the risk analysis. A reaction time of 5 seconds is assumed and a PFD of 0.06. These are default values from the Reference Manual.

Breakaway couplings are considered standard provisions. The Reference Manual assumes that the presence and proper working of these provisions are included in the failure frequencies. For this reason, breakaway couplings are not included as repressive measures in the risk analysis.

6.1.4 Failure frequencies

For the LoC scenarios, the final failure frequencies (probability of occurrence) need to be calculated. The frequencies of the scenarios depend on the time that a particular activity takes place at a particular location, the standard failure frequency as given in the preceding sections and the probability of failure of the repressive systems.

As described in Section 3.2, bunkering duration for the different scenarios is defined such that an equivalent amount of energy is bunkered. In the table below, the number of bunkering hours per fuel is given again that are used to determine the failure frequencies.

	High flow rate	**Low flow rate**
	Bunkering duration (hours/year)	**Bunkering duration (hours/year)**
LNG	250	250
Methanol	359	359
Ammonia (pressurized)	442	442
Ammonia (refrigerated)	495	495
Hydrogen gas 700 bar (60 g/s)	-	-
Hydrogen gas 1000 bar (60 g/s)	-	-
Hydrogen gas - 3 t/hour	-	6,236
Liquid hydrogen	660	660

6.2 Domino effects and damage

The occurrence of damage and domino effects is not included in the standard failure frequencies. This study does not take into account the occurrence of external damage or domino effects, because these are very location-dependent and they should really be assessed on a case-by-case basis in the site selection. This section gives a qualitative consideration of domino effects and when these may lead to a significant increase in the risk. Based on these considerations, the Port of Amsterdam can, at a later stage, assess whether a specific risk calculation is required for a particular location.

6.2.1 External damage

According to the Reference Manual (Ref. /6/), scenarios such as external damage resulting from ship collisions are relevant to consider in the calculation of the risk. These are very strongly determined by the local situation. In the case of a ship in a (small) harbour outside the transportation routes, the probability of a collision that leads to an outflow is so small that it doesn’t need to be considered. In other cases, based on the specific waterway, the base failure frequency of accidents needs to be determined, which depends on how long the bunker vessel is present and the number of ship passages per year. This last parameter is location-dependent.

The LNG toolkit of 2017 (Ref. /1/) includes the collision risks for various nautical situations. In the toolkit, collision risks only had a limited effect on the calculated risk distances. It is therefore decided to disregard collision risks in this study.

6.2.2 Internal domino effects

Internal domino effects arise when the failure of one installation with hazardous substances leads to the failure of another installation with hazardous substances. The probability of internal domino effects is normally minimised by a good layout of the ship (arrangement of the components). Domino effects may also be (partly) included in the standard failure frequencies. For this reason, internal domino effects are not explicitly included in a QRA, unless there are situations where the failure of one component clearly leads to the failure of another component. Even though this might be the case, according to the Reference Manual, it should be assumed that the contents of the largest reservoir (tank) is released.

6.2.3 External domino effects

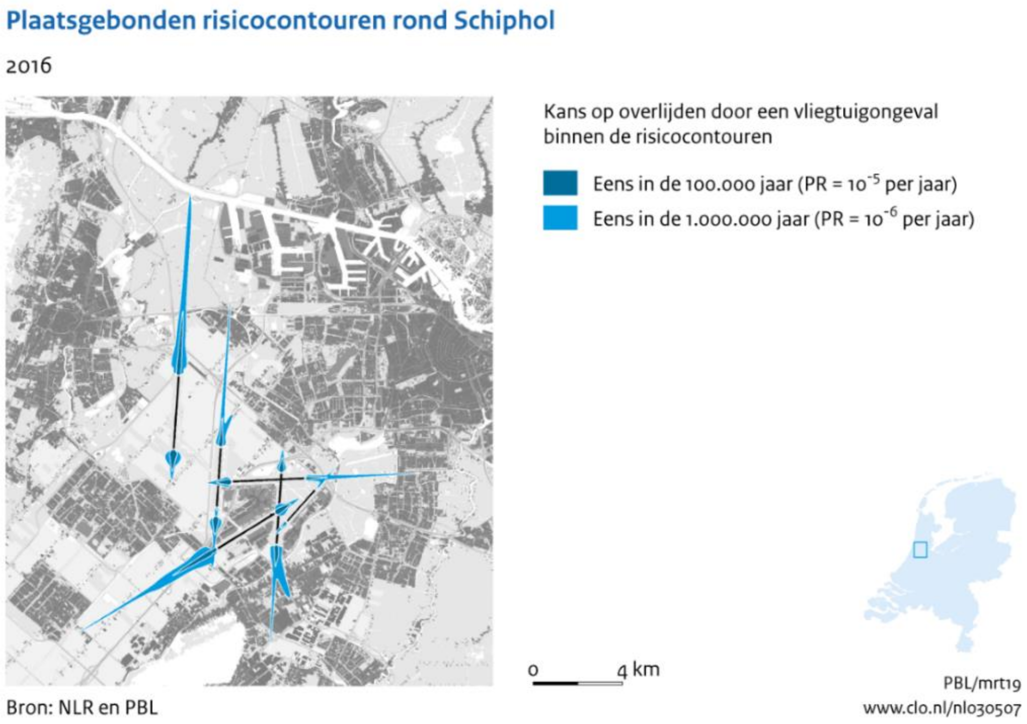
Other domino effects that should normally be considered are objects falling on components of the establishment (e.g. plane crashes), failing wind turbines and potential external domino effects caused by activities in the surrounding area. In accordance with the Reference Manual, it should be assessed whether external domino effects could lead to a significant increase in the external risks.

The Reference Manual states that the additional risk of these domino effects should be considered if the risk contribution thereof can contribute at least 10% at the standard frequency of catastrophic failure of an installation component with hazardous substances. The reason that only catastrophic scenarios are looked at is because in the case of an external domino effect (e.g. an incident with air traffic or a wind turbine failure involving blade throw) there will never be a small incident/small leakage.

As part of this study, it could for example concern the additional failure probability of the failure of the bunker hose (hose rupture) for which the 10% criterion of relevance is often not achieved because of the already high standard failure frequency.

6.2.3.1 Aircraft crashes

The figure below (Source: Environmental Data Compendium, http://www.clo.nl/) shows the location-specific individual risk contours surrounding Schiphol airport. The contours only slightly overlap the Amsterdam port area ('small strips'). In addition, the location-specific individual risk in the port area does not exceed 10^{-6}/year, making it improbable that the risk as a result of aircraft crashes will significantly increase the 10^{-6}/year risk of bunkering.



Location-specific individual risk contours around Schiphol
Probability of death due to an airplane accident inside the risk contours
Dark blue: Once in 100,000 years (LSIR = 10^{-5} per year)
Light blue: Once in 1,000,000 years (LSIR = 10^{-6} per year)
Source: NLR and PBL

Figure 6-1: Location-specific individual risk contours around Schiphol[9]

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[9] Downloaded from https://www.clo.nl/sites/default/files/infographics/0305_011k_clo_07_nl.png via http://www.clo.nl/indicatoren/nl0305-veiligheid-rondom-schiphol (visited on 2020-09-07)

6.2.3.2 Failing wind turbines

If there is a wind turbine in the vicinity of bunkering operation, the failure of this turbine could lead to the failure of components with fuel. An example of such a scenario is the breaking off of a turbine blade which then hits the bunker vessel or the bunker hose. For this purpose, the hit frequencies of such an impact are normally calculated based on the different components that can be hit. Such a wind turbine analysis should be carried out in accordance with the 'Handboek Risicozonering Windturbines' [Dutch wind turbine risk manual] (Ref. /11/). According to this manual, the following scenarios should be considered:

- Blade breakage;
- Mast breakage;
- Nacelle and/or rotor break off.

On the basis of these scenarios, a hit frequency is calculated for each component and compared with the initial frequency of catastrophic failure of the exposed component. If it is found that the additional failure frequency of a particular failing component as a result of a wind turbine impact is significant (> 10%, see also above), relative to the standard frequency of catastrophic failure, this is included as a separate domino scenario in the risk analysis (QRA).

The relevance of turbine failure on the 10^{-6}/year bunkering contour is often limited. It is often assumed that the failure of a wind turbine (e.g. blade breakage) does not lead to such damage to the ship that fuel can be released from the cargo tank when, for example, the tank is installed under the deck. It is therefore unknown which failure scenarios should be defined, as the standard failure scenarios for ships are only related to a collision (and not intrinsic failure). When the cargo tank (or fuel tank) is on the deck, the influence of wind turbine failure may become more relevant. Furthermore, for the failure of the hose, the 10% criterion of relevance is often not met.

As a first screening step to assess whether the wind turbine influence could be relevant, it could be examined whether bunkering operations are within the blade throw effect distance (throw distance) at the rated speed. Outside this effect distance, the risk contribution is often irrelevant because the hit frequency as a result of the blade throw scenario is much lower at overspeed, and thus does not contribute significantly to the 10^{-6}/year location-specific individual risk. Generic throw distances at nominal speeds are given in Table 2 of the Dutch wind turbine risk manual (Ref. /11/) and range from about 131 to 245 m depending on the type of wind turbine, the power and IEC class[10].

6.2.3.3 Domino-effects as a result of activities in the surrounding area (establishments)

Establishments that work with hazardous (flammable) substances and that are located in the vicinity of bunkering operation, may cause domino effects as a result of an incident within the establishment, resulting in a fire or explosion. Experience shows that potential external domino effects of this nature often make no relevant contribution to the risk of the bunkering operation, given the limited duration of the operation and the low probability of occurrence of possible explosions and fires with effect distances that can reach bunkering operation.

Typically, an analysis is made on the basis of the risk map (www.risicokaart.nl) to identify which establishments with hazardous substances are present in the vicinity of the bunkering operation (e.g. Brzo (Seveso) establishments). Subsequently, based on the risk contours of this establishment, an initial

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[10] This is a classification of the location based on wind data in accordance with the description in IEC 61400-1. For more information, reference is made to the Dutch wind turbine risk manual (Ref. /11/)

assessment is made as to whether there may be a risk-relevant contribution in the context of domino effects.

The bunkering operations could theoretically take place anywhere and the relevance of external domino effects caused by activities in the area would therefore have to be assessed on a case-by-case basis.

6.3 Modelling

6.3.1 System reactions

The presence of pumps that are used for bunkering is included in the calculation of the outflow. When the pump is not capacity controlled and does not shut off, in the event of a hose rupture, the outflow rate is equal to 1.5 × the pump flow rate (Ref. /9/). This takes into account a 50% increase in flow rate due to loss of back-pressure. It is uncertain how the pump will react in the case of a hose rupture, and whether it is pressure or capacity controlled. Therefore, the response of the pump is conservatively taken into account and it is assumed that the pump continues to run. For an idle pump, the outflow rate would in fact be much smaller, since the pre-pressure in the cargo tank (and tank head) is low, and because of the resistance of the idle pump, not much fuel will flow through the pump.

For gaseous fuels, it is assumed that bunkering will be performed on the basis of differential pressure, and not by means of a pump. For these scenarios, no system response is therefore included in the calculations.

6.3.2 Subsequent delivery

Upon the failure of a component, the subsequent delivery of other system components may take place that are associated with that component. If the quantity of subsequent deliveries is significant[11], this must be taken into account in the scenario.

Possible subsequent delivery is not accounted for in the hose rupture scenario. The effects of measures on the outflow, such as closing valves, are included. The closing of a valve after e.g. 120 s is modelled for this scenario by reducing the content that can be released so that the outflow stops after 120 seconds (Ref. /6/). In reality, after closing the valves after a hose rupture, the contents of the hose could also be released. In the Interim Calculation Method for LNG bunkering stations (Ref. /9/) no account is taken in the determination of the content that can be released. While bunkering, the content of the hose is also insignificant with respect to the total outflow. In addition, strictly speaking, only the subsequent delivery of other components and not the failing component itself (after intervention by the isolating system) should be taken into account.

6.3.3 Backflow

6.3.3.1 Liquid fuels

In the case of a hose rupture during bunkering, an outflow can take place from both sides of the rupture, namely outflow from the cargo tank on the bunker vessel, and backflow from the fuel tank. When the contributions from both sides of the hose rupture at the outflow are relevant (> 10% of the flow rate or outflow from one side), this must be taken into account in the modelling.

The rupture scenario is modelled with an effective diameter of the hose (in accordance with Ref. /6/, /9/) wherein the outflow rate corresponds to the sum of the flow rates from both sides.

Backflow of fuel from the fuel tank for the hose rupture scenario should be considered in the QRA. Whether or not a fuel tank is filled up via a bottom or top line is important in the determination of

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[11] Significant here means more than 10% of the amount from the failing component is released.

possible backflow. If the tank is filled up via a top line, gas can only flow back in the case of a hose rupture. When filling through a line at the bottom of a fuel tank, the contents of the fuel tank can flow back. For a number of bunkering operations, a mix of bottom and top filling is used. First, filling is done from the top in order allow the tank to be cooled and to lower the pressure in the tank. Subsequently, the rest of the filling of the tank is done via the bottom of the tank. The table below shows which assumptions are made with respect to bottom or top filling.

Table 6-2: Bottom or top filling for different alternative fuels.

	Top filling %	**Bottom filling %**	**Explanation**
LNG	25	75	Assumption from LNG toolkit
Methanol	100	0	Methanol is similar to diesel fuel and can simply be bunkered through the top. Backflow is irrelevant.
Ammonia (pressurized)	0	100	A conservative assumption is made of 100% bottom filling
Ammonia (refrigerated)	25	75	Cooled liquid, it is assumed that this is comparable with LNG bunkering
Liquid hydrogen	25	75	Cooled cryogenic liquid, it is assumed that this is comparable with LNG bunkering

For bunkering configurations where backflow is possible, the maximum amount of material that can flow back then needs to be determined. For all configurations, it is assumed that the tank is filled to 50% and that therefore 50% of the tank contents can flow back. This comes down to 175 m^3 of fuel.

In the calculation of the backflow flow rate, a liquid level of 6 metres in the tank is assumed for all fuels. Further, the calculations assume a 20-metre filling pipe from the fuel tank to the rupture (in reality, this could be longer, this is a conservative assumption). The conditions in the fuel tank for the calculation of the backflow are provided in the table below.

Table 6-3: Conditions in the fuel tank for the calculation of backflow

	Temperature in fuel tank (°C)	**Pressure in fuel tank (barg)**
LNG	-154	2
Ammonia (pressurized)	20	9
Ammonia (refrigerated)	-32.1	0.068
Liquid hydrogen	-245	4.9

6.3.3.2 Gaseous hydrogen

For the LSIR calculations of gaseous hydrogen, a probability of immediate ignition of 1 is used. As a result, the risks for bunkering of gaseous hydrogen are determined entirely by the jet fire. In order not to overestimate the risks of the jet fire, the LSIR calculations for gaseous hydrogen assume single-sided outflow (the jet fires from both ends are in opposite directions and are not added together).

In addition to the LSIR calculations, effect calculations for gaseous hydrogen are also carried out. In the effect calculations, the effects are also calculated in the case of a delayed ignition (flash fire and vapour cloud explosion). In the calculation of these effects, two-way outflow is assumed. The outflow is calculated on the basis of an effective diameter, and it is assumed that a maximum of 1000 kg of hydrogen gas can flow back (the content of a number of cylinders). When bunkering gases, top or bottom filling is irrelevant, since gas flows back in both situations.

6.4 Parameters

This chapter presents some relevant environmental and model parameters that are important for the risk analysis.

6.4.1 Environmental parameters

Environmental parameters, such as population data and ignition sources, are not relevant to the calculation of the location-specific individual risk. The only environmental parameters that are relevant are weather information, atmospheric parameters and roughness length of the surroundings.

6.4.1.1 Weather information (meteorological)

The data from the Schiphol meteorological station are used. The Schiphol meteorological station is expected to be closest to the future bunker locations as the crow flies. Besides, the choice between the meteorological stations of Schiphol or IJmuiden is not expected to make much difference because the maximum risk distance is measured in each wind direction.

6.4.1.2 Atmospheric parameters

For the atmospheric parameters (atmospheric temperature and pressure, etc.), the data are used from the Reference Manual (specifically for the Netherlands).

6.4.1.3 Roughness length of the surrounding area

The roughness length is (an artificial) linear measurement indicating the influence of the surrounding area on the wind velocity (Ref. /6/). The roughness length of the surrounding area in the Netherlands is standard 300 mm. This may be adjusted based on the distance between obstructions and the height of these obstructions in the vicinity of the establishment. For a city centre with high and low-rise buildings, a roughness length of 3 metres is usually assumed, and for industrial estates typically 1 metre.

It is expected that most of the bunker locations will be on or in the vicinity of an industrial area. Therefore, a roughness length of 1 metre is assumed.

6.4.2 Model parameters

Virtually all model parameters, specifically for a QRA in the Netherlands, are taken directly from the Reference Manual and/or Safeti-NL 8.3. The deviations are justified in this section.

Probability of an explosion

For the determination of the overpressure effects of a vapour cloud explosion, by default, Safeti-NL 8.3 uses the TNO Multi-Energy explosion model in its calculations, which works with explosion strength curves (1-10) in order to indicate the strength of an explosion depending on the degree of confinement (congestion) and reactivity of the substance (shows the degree of sensitivity for flame acceleration). The higher the curve, the greater the overpressure effects. In the open field, the overpressure effects that are modelled with the TNT equivalent model correspond with the TNO Multi-Energy model curves 6-10 (these curves converge in the far field).

The degree of congestion in an area (or the possibility of confinement) where a flammable cloud may be able to come, plays a large part in the amount of pressure build-up as a result of an explosion. When bunkering in the open air, in the majority of cases, the fuel released will ignite (if it ignites), which will be accompanied by low overpressure effects (this is often modelled as a flash fire). If more confinement can occur (unlikely on water), higher overpressures may arise. Due to the limited degree of confinement in the vicinity of STS bunkering operations, an explosion with overpressures of 300 mbar or higher is not considered realistic. The probability of lethality for people standing outside as a result of overpressure is

0 for overpressures below 300 bar (Ref. /6/). In short, an explosion is not expected to contribute to the location-specific individual risk.

It is decided not to include an explosion in the LSIR calculations. This means specifically that in the case of a delayed ignition, the consequence probability of a flash fire is set to 1 and an explosion to 0 (in the event tree).

However, for explosion focus areas, explosions are relevant from 100 mbar overpressure. At 100 mbar overpressure, structural damage to buildings can be caused and there is a chance that people will die in the building. Since overpressures of greater than 100 mbar cannot be ruled out on the basis of the possible presence of (limited) confinement, explosions are still relevant in determining focus areas. Therefore, explosion focus areas are defined. In defining these areas, use is made of the standard event tree.

6.4.3 Ignition probabilities

The RIVM modelling is followed (Ref. /8/) for the ignition probabilities of the continuous release of hydrogen. For gaseous hydrogen, a probability of 1 for immediate ignition is used in the calculations. For liquid hydrogen, an immediate ignition probability of 0.9 is used.

7 RESULTS

7.1 Location-specific individual risk

The risk contours for bunkering of the alternative fuels and bunkering scenarios are shown in Appendix A. For illustration, Figure 7-1 shows the calculated location-specific individual risk of bunkering of liquid hydrogen at 1000 m^3/h on a map. The red contour is the 10^{-6}/year location-specific individual risk. The maximum distance from the hose to the 10^{-6} per year LSIR contour (i.e. the external safety distance) is 273 metres. The area of influence for the activity is shown as the black 10^{-30} per year contour.

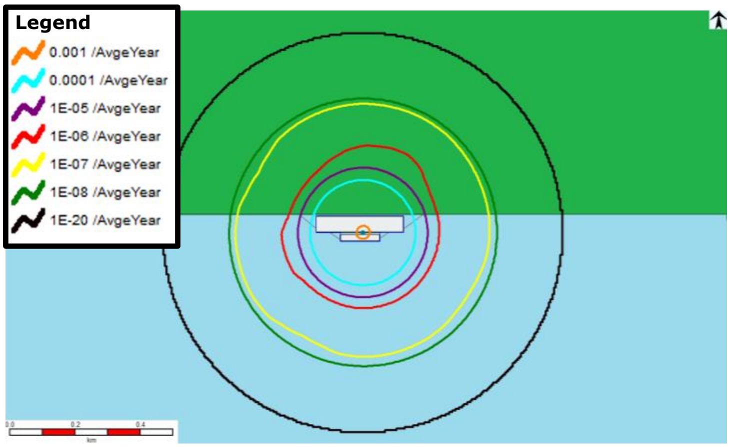

Figure 7-1: The location-specific individual risk for 'bunkering liquid hydrogen at a high flow rate'

The risk distances for bunkering the different alternative fuels are given in Table 7-1. The risk distances for methanol and gaseous hydrogen are much smaller (a factor of 3-5) than those for LNG. For refrigerated ammonia and liquid hydrogen, the distances are similar to those for LNG, and for pressurised ammonia, the distances are about three times as large due to the generation of a large toxic cloud in the event of a hose rupture.

Table 7-1: Distance to the 10^{-6} per year LSIR contour

Bunkering scenario	Low flow rate (400 m^3/h)[1]	High flow rate (1000 m^3/h)[1]
	LSIR distance (m)	LSIR distance (m)
LNG (-146 °C)	321[2]	-[3]
LNG (-159 °C)	231[4]	344[5]
Methanol	68	98
Ammonia (refrigerated)	255	427
Ammonia (pressurized)	793	973
Hydrogen (liquid)	214	273
Hydrogen (gaseous) –3 t/hour	87	-
Hydrogen (gaseous) – 700 bar (60 g/s)	- [6]	-
Hydrogen (gaseous) – 1000 bar (60 g/s)	- [6]	-

[1] Bunkering flow rates apply to liquid fuels. The flow rate for gaseous fuels is shown in the scenario name
[2] 346 m in the LNG toolkit (Ref. /13/)
[3] The risk distances with a higher LNG temperature (-146 °C) are based on a situation in which inland waterway bunker vessels supply fuel to seagoing vessels. In this study, it is not considered likely that inland waterway bunker vessels could supply fuel at a flow rate of 1000 m^3/hour. Therefore, only the situation with 400 m^3/hour is considered (Ref. /13/).
[4] 223 m in the LNG toolkit (Ref. /1/)
[5] 339 m in the LNG toolkit (Ref. /1/)
[6] Because of the unrealistically high bunkering duration required, only the effect distances are calculated

If a composite hose is used instead of a metal hose for bunkering operations, the risk decreases considering the lower failure frequency for the rupture scenario of a composite hose (a factor 10 with respect to a metal hose). It is expected that the calculated 10^{-5}/year and 10^{-6}/year location-specific individual risk will decrease by a factor of 10. Therefore, as an indication, the calculated 10^{-5} per year LSIR contour can be used to determine the external safety distance for bunkering with a composite hose. To verify this, the scenario 'ammonia (pressure) – low flow rate' is calculated using a composite hose for comparison with the metal hose scenario.

The 10^{-5} per year contour in the scenario with a metal hose, has a maximum distance to the scenario of 405 metres. The scenario with a composite hose results in exactly the same distance to the 10^{-6} per year contour. The 10^{-5} per year contours calculated in this study can therefore be used as an indication for the 10^{-6} per year contour (and external safety distance) when bunkering with a composite hose instead of a metal hose.

The distances to the 10^{-5}/year contour for all the alternative fuels are shown in Table 7-2.

Table 7-2: Distance to the 10^{-5} per year LSIR contour

Bunkering scenario	**Low flow rate (400 m^3/h)[1]**	**High flow rate (1000 m^3/h)[1]**
	LSIR distance (m)	**LSIR distance (m)**
LNG (-146 °C)	210	-[2]
LNG (-159 °C)	188	285
Methanol	56	85
Ammonia (refrigerated)	153	246
Ammonia (pressurized)	405	556
Hydrogen (liquid)	159	198
Hydrogen (gaseous) –3 t/hour	87	-
Hydrogen (gaseous) – 700 bar (60 g/s)	- [3]	-
Hydrogen (gaseous) – 1000 bar (60 g/s)	- [3]	-

[1] Bunkering flow rates apply to liquid fuels. The flow rate for gaseous fuels is shown in the scenario name

[2] The risk distances with a higher LNG temperature (-146 °C) are based on a situation in which inland waterway bunker vessels supply fuel to seagoing vessels. In this study, it is not considered likely that inland waterway bunker vessels could supply fuel at a flow rate of 1000 m^3/hour. Therefore, only the situation with 400 m^3/hour is considered (Ref. /13/).

[3] Because of the unrealistically high bunkering duration required, only the effect distances are calculated

7.2 Focus areas

The following figures show (as illustration) the focus areas for the scenario: liquid hydrogen bunkering with a high flow rate. It can be read from the figures below that the fire focus area is 324 metres from the bunker hose. The extent of the explosion focus area is no more than 338 metres from the bunker hose. The contours for the focus areas for all alternative fuels are shown in Appendix B.

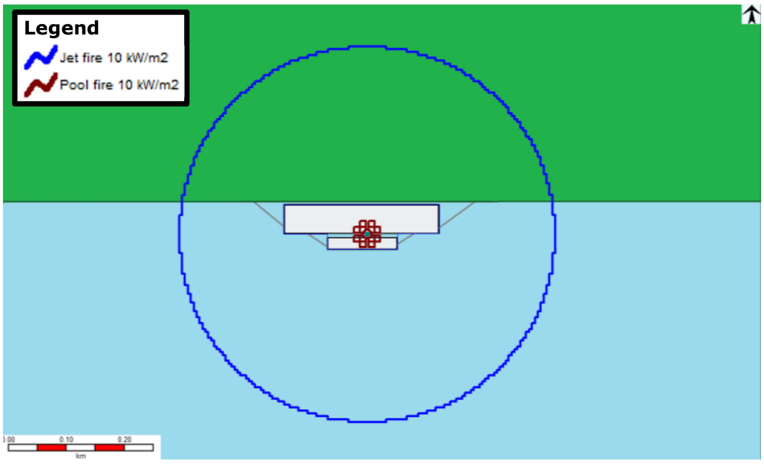

Figure 7-2: Fire focus area: 10 kW/m^2 contours for pool fire and jet fire for the scenario: liquid hydrogen bunkering with a high flow rate

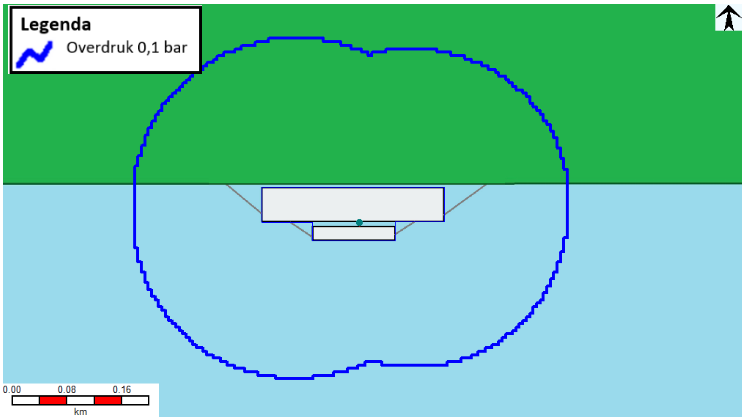

Figure 7-3: Explosion focus area: 0.1 bar overpressure contours for the scenario: liquid hydrogen bunkering with a high flow rate

Table 7-3 includes the maximum distances (measured from the bunker hose) for all focus areas. It should be noted that no explosion focus area is calculated for bunkering of gaseous hydrogen, because it is assumed that the immediate ignition probability is equal to 1, and a jet fire always occurs. It is possible that in the future, this assumption will change and an explosion focus area will still have to be calculated. In that case, the maximum distance from the bunker hose to the boundary of the explosion focus area is about 110-150 m for the bunker scenarios considered in this study.

Table 7-3: Maximum distance from bunker hose to focus area boundary

		Focus area distance (m)		
Substance	**Flow rate/pressure**	**Fire**	**Explosion**	**Toxic**
LNG	400 m^3/h (-146 °C)	249	274	- [4]
LNG	400 m^3/h (-159 °C)	330	295	- [4]
Methanol	400 m^3/h	102	- [3]	22
Ammonia (refrigerated)	400 m^3/h	- [1]	- [1]	1446
Ammonia (pressurized)	400 m^3/h	- [1]	- [1]	1478
Hydrogen (liquid)	400 m^3/h	239	283	- [4]
Hydrogen (gaseous)	3 t/h	87[2]	- [5]	- [4]
Hydrogen (gaseous)	700 bar	55	- [5]	- [4]

Substance	Flow rate/pressure	Focus area distance (m)		
		Fire	Explosion	Toxic
Hydrogen (gaseous)	1000 bar	55	- [5]	- [4]
LNG	1000 m^3/h	448	229	- [4]
Methanol	1000 m^3/h	154	- [3]	34
Ammonia (refrigerated)	1000 m^3/h	- [1]	- [1]	2624
Ammonia (pressurized)	1000 m^3/h	- [1]	- [1]	2060
Hydrogen (liquid)	1000 m^3/h	324	338	- [4]

[1] Only toxic effects are considered for ammonia, and no flammable effects, see Section 4.1.3
[2] The fire focus area for this scenario is larger because of the assumption that a larger diameter hose is employed
[3] The LFL for methanol does not reach the 'site boundary' (see Section 5.4.2.2), therefore no explosion is calculated
[4] The immediate ignition probability for gaseous hydrogen is 1 (see the RIVM study), therefore, no explosion is calculated
[5] LNG/H2 are not toxic

7.3 Effect distances for bunkering of hydrogen gas

Because of the low bunker rate (60 g/s), which is assumed for bunkering scenarios with a pressure of 700 bar and 1000 bar, no LSIR calculations are carried out. For bunkering of an equivalent amount of energy, more hours are needed than there are in a year. In order to still give an understanding of the risks associated with bunkering of gaseous hydrogen, the effect distances are calculated. The 10^{-6}/year risk distance can, by definition, never exceed the maximum effect distance.

In accordance with the memo of the RIVM with a QRA for hydrogen refuelling stations (Ref. /8/), for the continuous release of gaseous hydrogen, an immediate ignition probability of 1 is assumed, which will implies that there is always a jet fire. The accuracy of the immediate ignition probability of gaseous hydrogen has recently been called into question in the Hydrogen Safety Innovation Programme (Waterstof Veiligheid Innovatie Programma, WVIP) following an explosion that took place at a hydrogen refuelling station in Norway. This incident suggests that delayed ignitions (and explosions) may well be relevant for modelling in the QRA. It is therefore decided to also calculate the distances to the effects arising from delayed ignition (flash fire and explosion). The effect distances are shown in the table below.

Table 7-4: maximum effect distances for bunkering of gaseous hydrogen

Effect	700 bar (m)	1000 bar (m)
Jet fire - 3 kW/m^2	68	68
Jet fire - 10 kW/m^2	53	53
Jet fire - 35 kW/m^2	41	42
Flash fire	78	80
Worst-case explosion 0.02 bar	339	344
Worst-case explosion 0.1 bar	134	136
Worst-case explosion 0.3 bar	98	100

The limit value for lethality for the different effects on the LSIR calculations are:

- 10 kW/m^2 for exposure to heat radiation;
- 0.3 bar for exposure to overpressure;
- Flame contact for exposure to a flash fire.

When an immediate ignition probability of 1 is assumed (current assumption), the maximum effect distance for bunkering of gaseous hydrogen at 700 bar and 1000 bar is about 50 metres (10 kW/m^2 for the jet fire).

If delayed ignition is taken into account, and the possibility of an explosion, the maximum effect distance for bunkering of gaseous hydrogen is about 100 metres (0.3 bar overpressure). By definition, the external safety distance can be no greater than these values, regardless of bunkering duration.

8 CONCLUSION

The Port of Amsterdam is preparing for a sustainable future, which includes bunkering of seagoing vessels with alternative fuels. In 2017, DNV conducted an LNG toolkit study for the Port of Amsterdam. In this study, the location-specific individual risk associated with planned LNG bunkering operations in the Port of Amsterdam is calculated to better understand the risk profile of the activities and to support the development of an LNG bunker map in order to allocate bunker locations.

Similarly, the Port of Amsterdam wants to gain an understanding of the space required in the land-use planning (in terms of external safety) to allow for bunkering of alternative fuels, such as methanol, ammonia and hydrogen. The Port of Amsterdam has requested DNV to carry out this external safety study for the purpose of making a comparison of safety distances for bunkering of alternative fuels with those for bunkering of LNG. In the study, the external safety distances (10^{-6}/year location-specific individual risk distances) and focus areas (a new concept in the new Environmental and Planning Act 2022) are calculated.

The following fuels are considered in this study:

- LNG;
- Methanol;
- Ammonia (pressurized and refrigerated);
- Gaseous hydrogen (gaseous at different pressures and flow rates);
- Liquid hydrogen.

The study showed that bunkering of gaseous hydrogen is not likely to be used for shipping, in view of the low energy density and the relatively low bunkering flow rates that are mentioned in literature. This makes the time required for bunkering unrealistically high in order to satisfy the energy demand. For this reason, no risk contours are calculated for bunkering of gaseous hydrogen, assuming a low flow rate from the literature (60 g/s). Therefore, effect distances are calculated in order to still obtain an insight into the possible maximum external safety distance (regardless of bunkering duration).

However, there is a party that claims that gaseous hydrogen can be bunkered at 3,000 kg/h without problems being caused by the rapid heating of the storage system by adiabatic compression. This claim is not further examined in terms of feasibility. However, if such bunkering flow rates are feasible, it is helpful to understand the safety distances because then bunkering duration is more realistic. This does not mean to say that bunkering seagoing vessels with this high flow rate will be more likely, considering the low energy density and the required bunkering volumes.

Location-specific individual risk/external safety distances

The results for the location-specific individual risk show that the external safety distances (10^{-6}/year) for bunkering of methanol and gaseous hydrogen are much smaller (a factor of 3-5) than those for LNG. For refrigerated ammonia and liquid hydrogen, the safe distances are similar to those for LNG, and for pressurised ammonia, the distances are about three times as large due to the generation of a large toxic cloud in the event of a hose rupture. The external safety distances for bunkering the different alternative fuels are shown in the table on the following page. The maximum effect distance for bunkering of gaseous hydrogen at 700 bar and 1000 bar is about 50 m when assuming that due to the low ignition energy, the immediate ignition probability equals 1 and a jet fire always occurs (in accordance with the current assumption used by the RIVM) and 100 m when account is taken of a possible delayed ignition and the possibility of an explosion[12]. By definition, the external safety distance can be no greater than these values, regardless of bunkering duration.

If a composite hose is used instead of a metal hose for bunkering operations, the risk will decrease considering the lower failure frequency for the rupture scenario of a composite hose. It is expected that the calculated 10^{-5}/year and 10^{-6}/year location-specific individual risks will decrease by a factor of 10. Therefore, as an indication, the calculated 10^{-5} per year LSIR contour can be used to determine the external safety distance for bunkering with a composite hose.

Table 8-1: Location-specific individual risk distances (distance up to the 10^{-6} and 10^{-5} per year contour)

Bunkering scenario	Distance to 10^{-6}/year LSIR contour		Distance to 10^{-5}/year LSIR contour	
	Low flow rate (400 m^3/h)[1]	High flow rate (1000 m^3/h)[1]	Low flow rate (400 m^3/h)[1]	High flow rate (1000 m^3/h)[1]
	LSIR distance (m)	LSIR distance (m)	LSIR distance (m)	LSIR distance (m)
LNG (-146 °C)	321	-[2]	210	-[2]
LNG (-159 °C)	231	344	188	285
Methanol	68	98	56	85
Ammonia (refrigerated)	255	427	153	246
Ammonia (pressurized)	793	973	405	556
Hydrogen (liquid)	214	273	159	198
Hydrogen (gaseous) – (3 t/h)	87	-[2]	87[3]	-[2]
Hydrogen (gaseous) – 700 bar (60 g/s)	-[2]	-[2]	-[2]	-[2]
Hydrogen (gaseous) – 1000 bar (60 g/s)	-[2]	-[2]	-[2]	-[2]

[1] Bunkering flow rates apply to liquid fuels. The flow rate for gaseous fuels is shown in the scenario name
[2] The justification as to why no distances are calculated can be found under Table 7-1 in Section 7.1
[3] For bunkering of hydrogen with 3 tonnes per hour the calculation assumes a high annual bunker duration. This causes the location-specific individual risk contour of 10^{-5}/year to be of almost equal size to the 10^{-6}/year and the influence area (see also Appendix A).

Focus areas

Focus areas are areas that visualise where without additional measures, people are insufficiently protected indoors against the consequences of accidents involving hazardous substances. In the new Environmental and Planning Act 2022, a distinction will be made between three types of focus areas:

- Fire focus area;
- Explosion focus area;
- Toxic cloud focus area.

The table below shows the maximum distances (measured from the bunker hose) for the focus areas. The results show that the focus areas for ammonia are by far the largest because of the great toxic effect. The focus areas for bunkering LNG are in the same order of magnitude as those for liquid hydrogen. The focus areas for bunkering methanol and gaseous hydrogen are 3 to 6 times smaller compared with LNG. According to current insights for calculating the risks of gaseous hydrogen, explosion focus areas do not really apply to bunkering of gaseous hydrogen because the RIVM states that the immediate ignition probability for the continuous flow of hydrogen gas is equal to 1 and therefore no explosion can occur (see also above). For this reason, no explosion focus areas for

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[12] The accuracy of the immediate ignition probability of gaseous hydrogen has recently been called into question in the Hydrogen Safety Innovation Programme (Waterstof Veiligheid Innovatie Programma, WVIP) following an explosion that took place at a hydrogen refuelling station in Norway. This incident suggests that delayed ignitions (and explosions) may well be relevant for modelling in the QRA.

bunkering gaseous hydrogen are included. However, should this insight change in the future and it may be relevant to consider explosions, then the explosion focus area for bunkering gaseous hydrogen is about 110-150 m for bunkering scenarios considered in this study.

Table 8-2: Maximum distance from bunker hose to focus area boundary

Fuel	**Flow rate**	**Focus area distance (m)**		
		Fire	**Explosion**	**Toxic**
LNG	400 m^3/h (-146 °C)	249	274	- [1]
LNG	400 m^3/h (-159 °C)	330	295	- [1]
Methanol	400 m^3/h	102	- [1]	22
Ammonia (refrigerated)	400 m^3/h	- [1]	- [1]	1446
Ammonia (pressurized)	400 m^3/h	- [1]	- [1]	1478
Hydrogen (liquid)	400 m^3/h	239	283	- [1]
Hydrogen (gaseous)	3 t/h	87	- [1]	- [1]
Hydrogen (gaseous)	700 bar (60 g/s)	55	- [1]	- [1]
Hydrogen (gaseous)	1000 bar (60 g/s)	55	- [1]	- [1]
LNG	1000 m^3/h	448	229	- [1]
Methanol	1000 m^3/h	154	- [1]	34
Ammonia (refrigerated)	1000 m^3/h	- [1]	- [1]	2624
Ammonia (pressurized)	1000 m^3/h	- [1]	- [1]	2060
Hydrogen (liquid)	1000 m^3/h	324	338	- [1]

[1] The justification as to why no distances are calculated can be found under Table 7-3 in Section 7.2

The results of this study provide an initial insight into the external safety of bunkering of alternative fuels to seagoing vessels and the necessary space required that has to be taken into account in the land-use planning. However, much remains unknown as to how the bunkering of these fuels will exactly be performed. It is therefore recommended to examine the study starting points and assumptions at a future date (when the market is further developed) and if necessary, to update them in the context of, for example, the development of bunker maps.

9 REFERENCES

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/11/ Handboek Risicozonering Windturbines, Dutch wind turbine risk manual, prepared by DNV KEMA at the request of AgentschapNL, version 3.1 released September 2014

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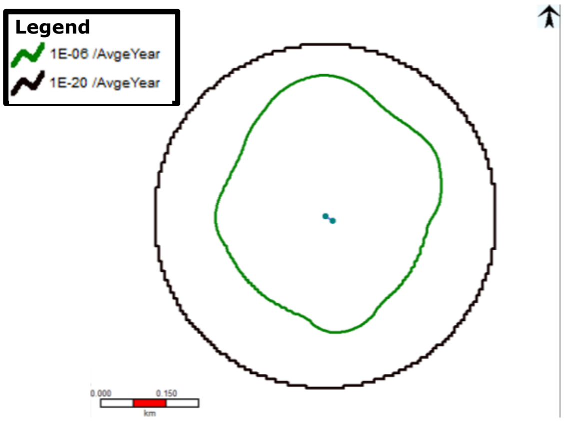
/13/ Memorandum on Comparison Study into bunkering with large and small bunker vessels, Memo No : 116XOT3G-2/ DVDM, date: 31/10/2017

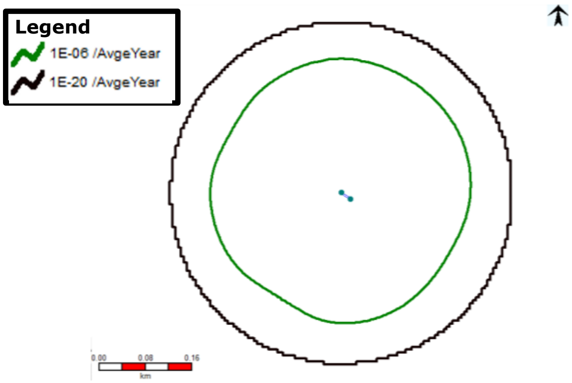
APPENDIX A

Location-specific individual risk contours

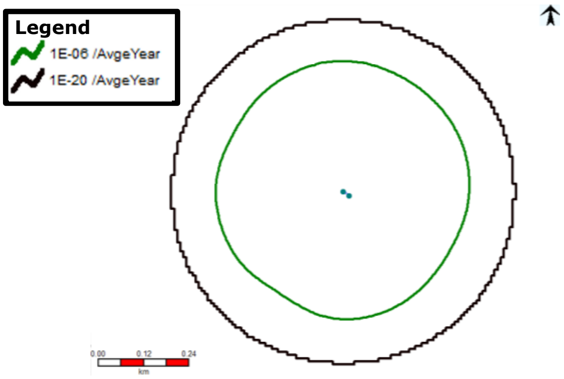
LNG – low flow rate -146 °C



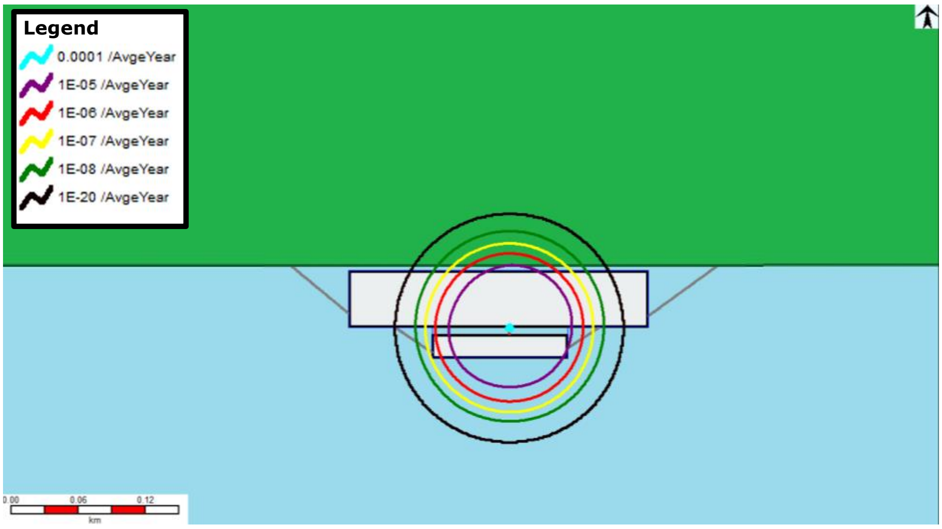
LNG – low flow rate -159 °C



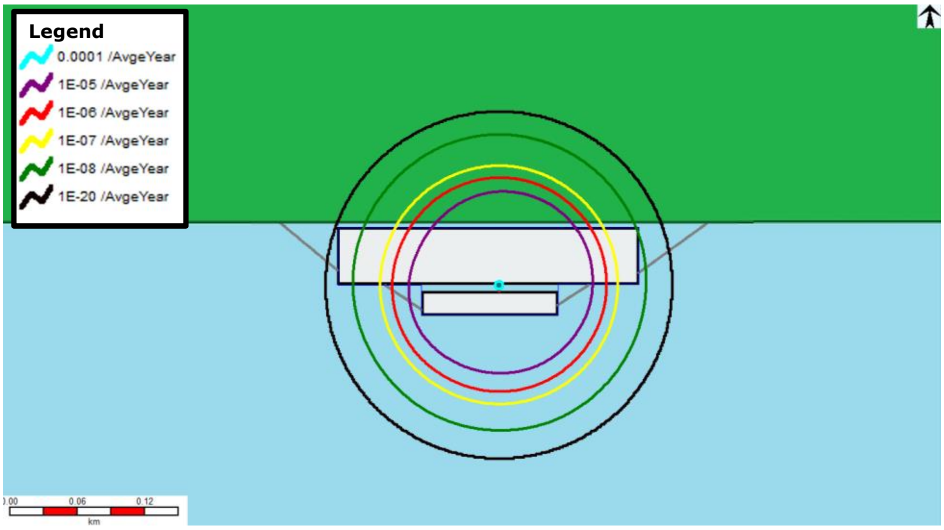
LNG – high flow rate



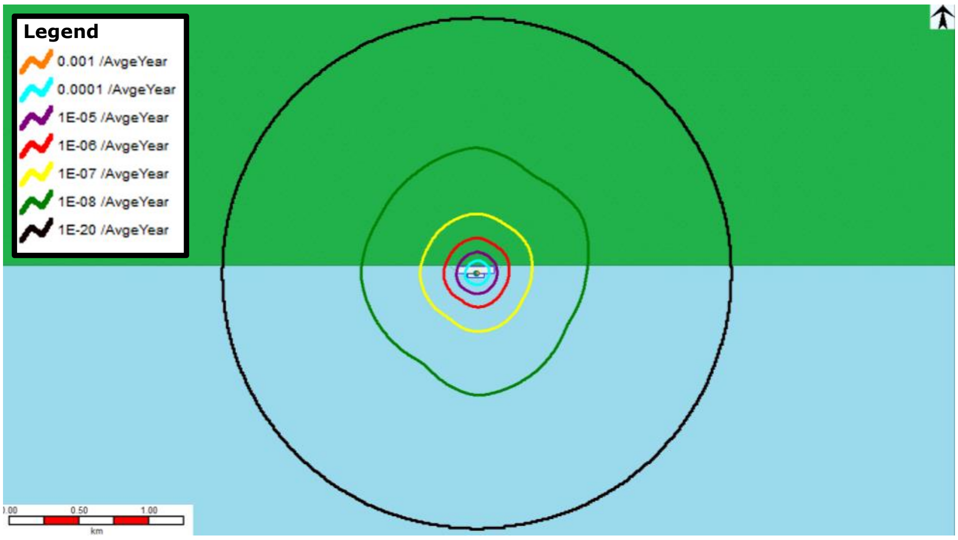
Methanol – Low flow rate



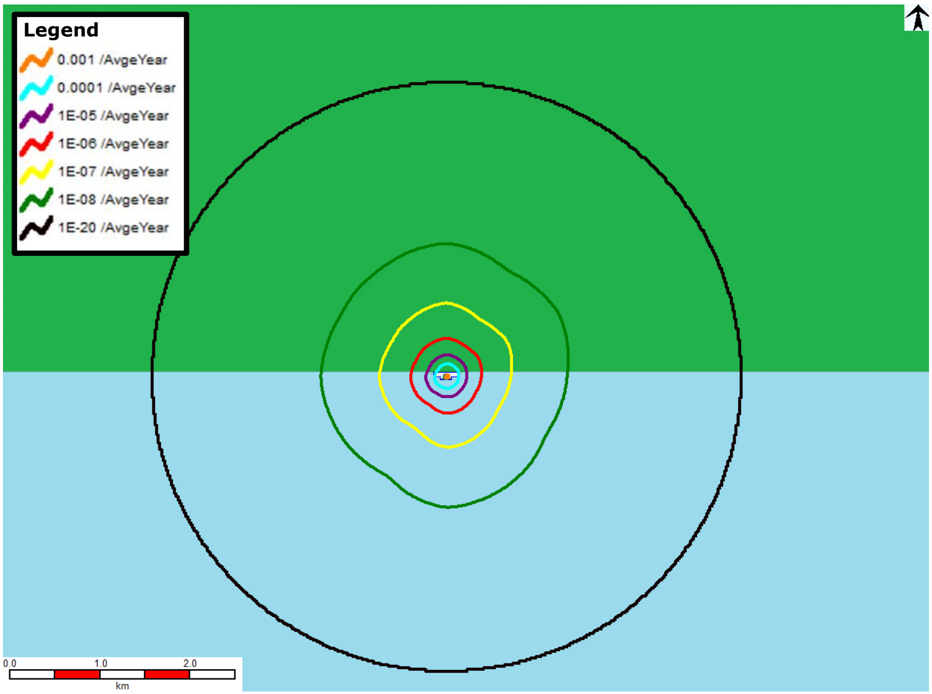
Methanol – high flow rate



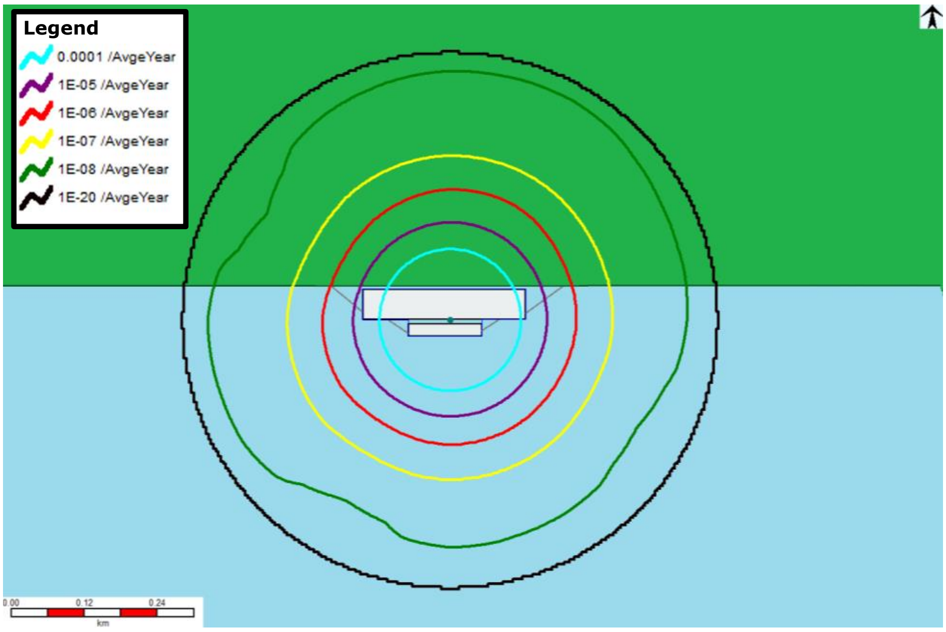
NH3 (T) – low flow rate



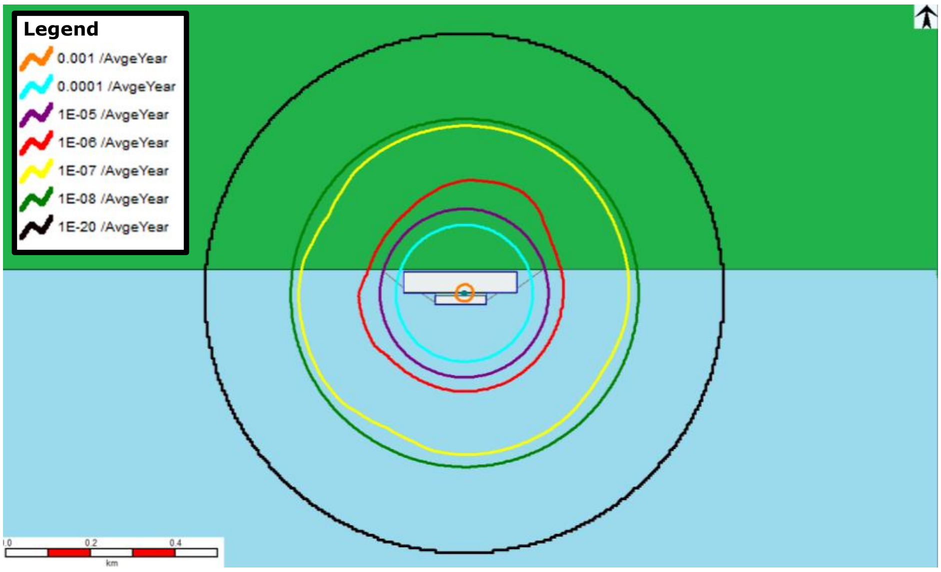
NH3 (T) – High flow rate



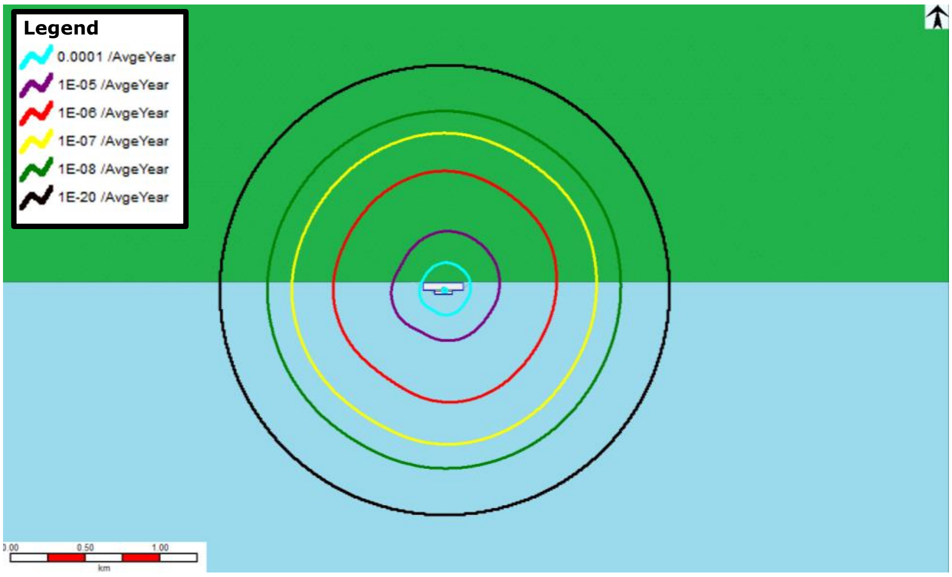
Hydrogen (L) – low flow rate



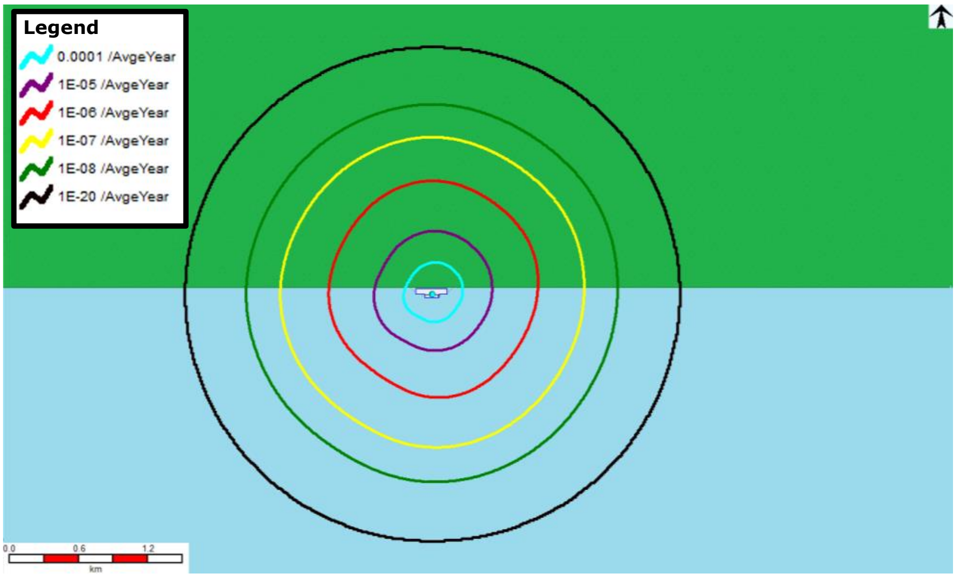
Hydrogen (L) – high flow rate



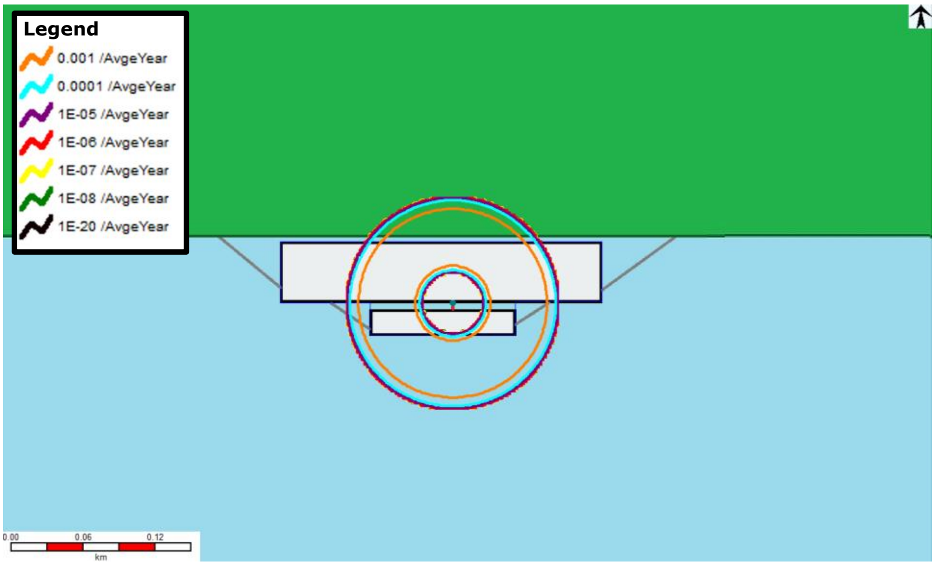
NH3 (P) – low flow rate



NH3 (P) – high flow rate



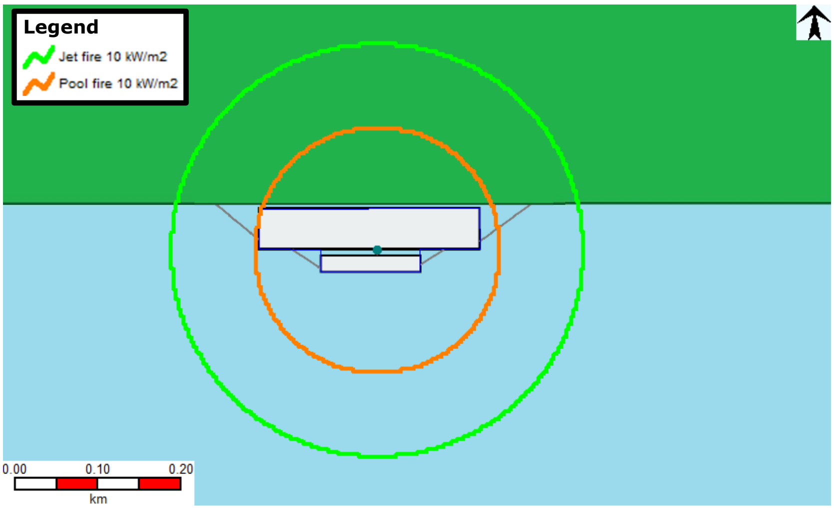
Hydrogen (G) – high flow rate



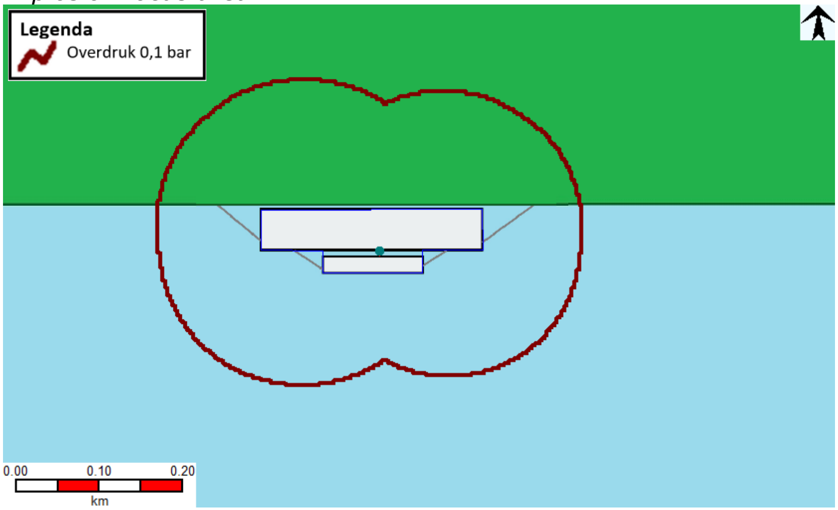
APPENDIX B
Focus areas

LNG – low flow rate -146 °C

Fire focus area

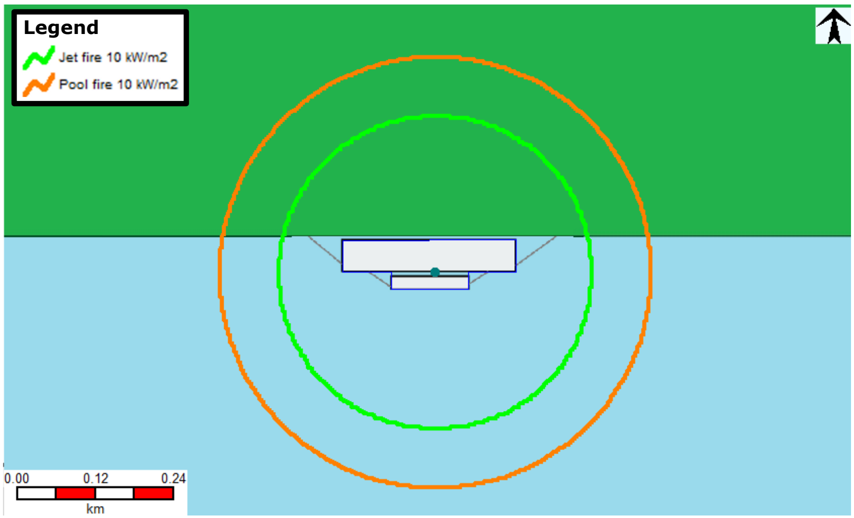


Explosion focus area

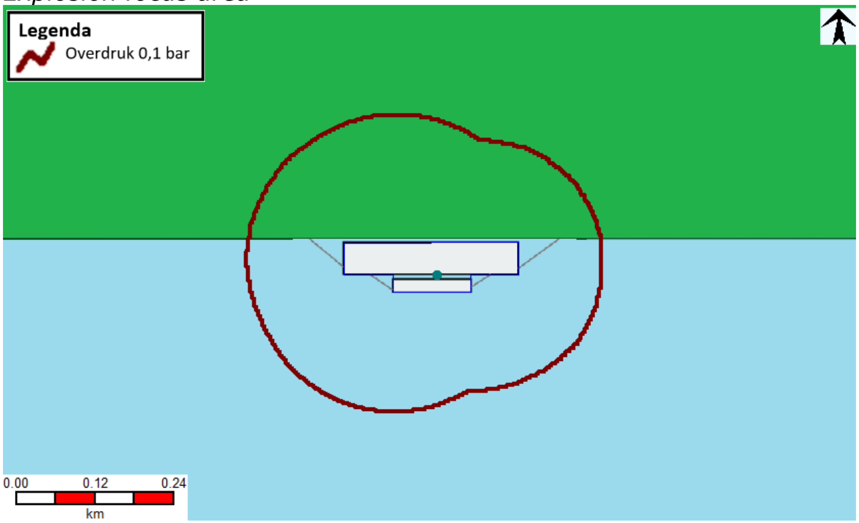


LNG – low flow rate -159 °C

Fire focus area

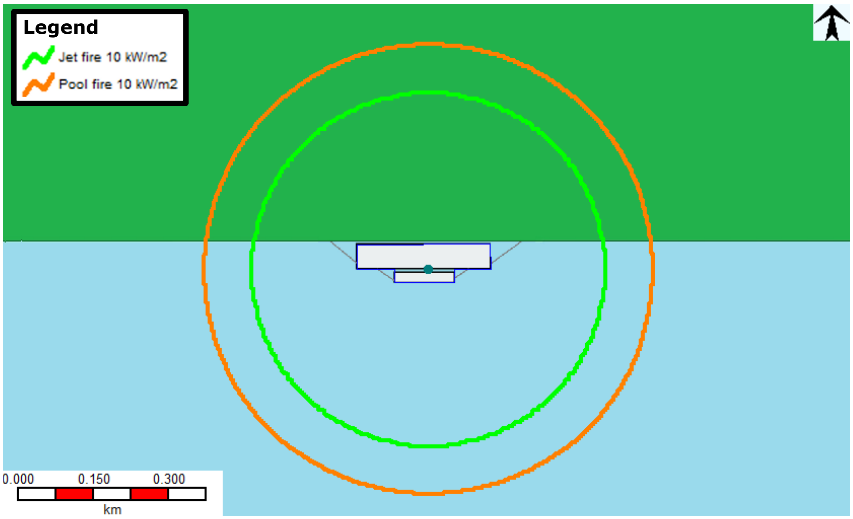


Explosion focus area

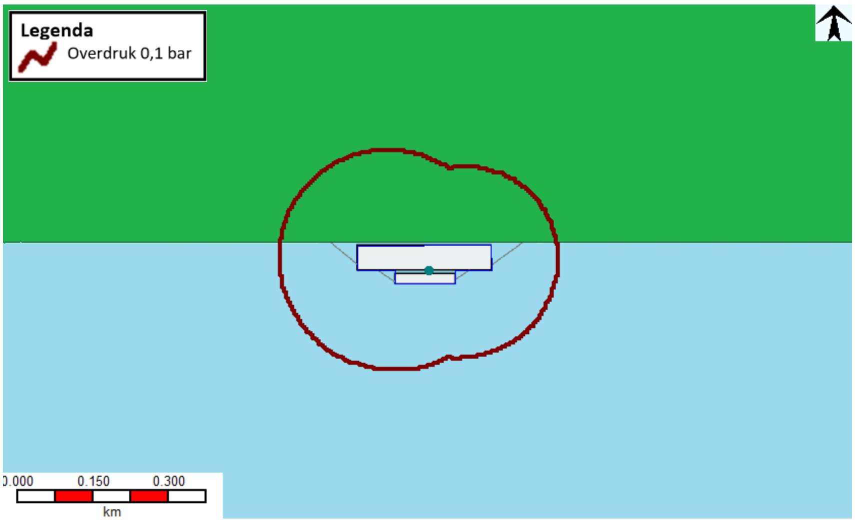


LNG – high flow rate

Fire focus area

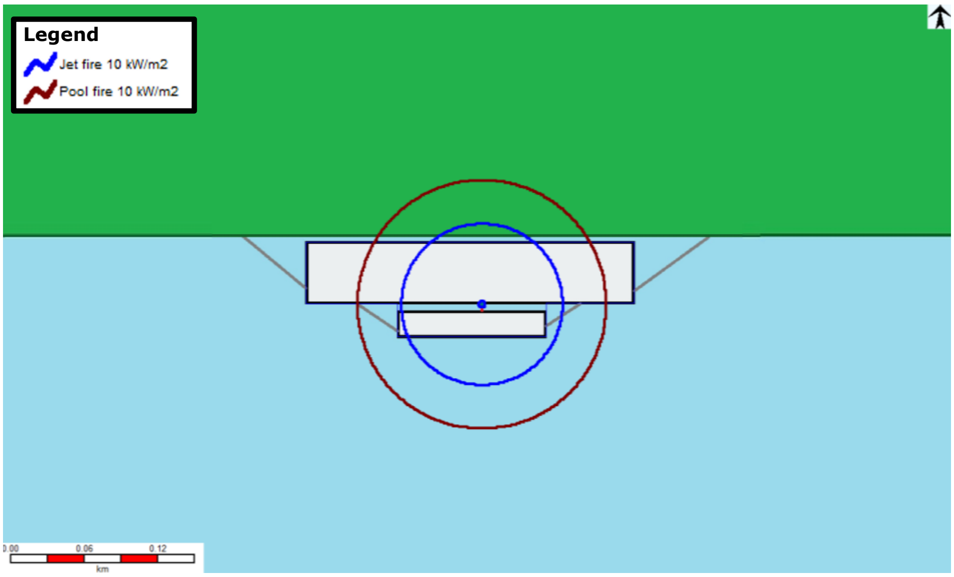


Explosion focus area

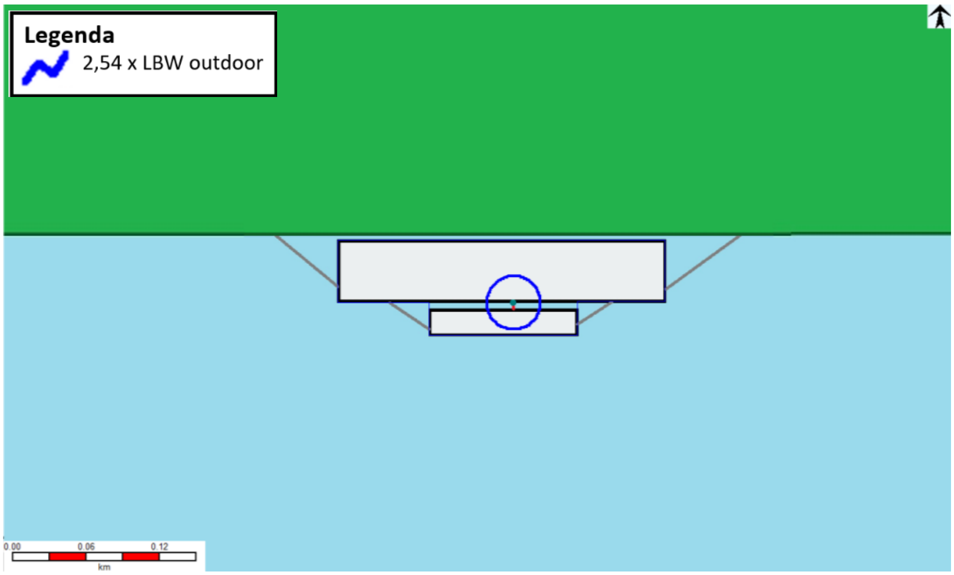


Methanol – low flow rate

Fire focus area

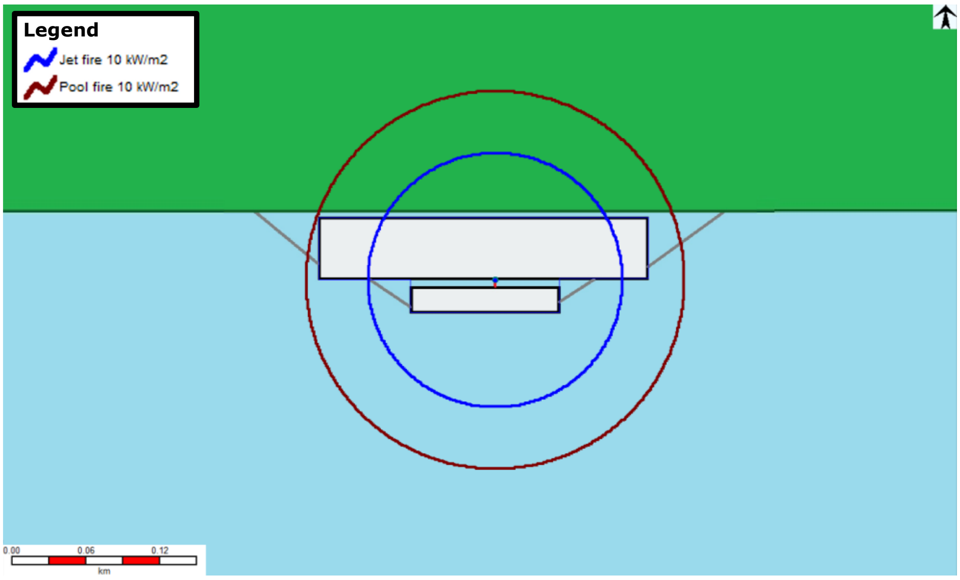


Toxic cloud focus area

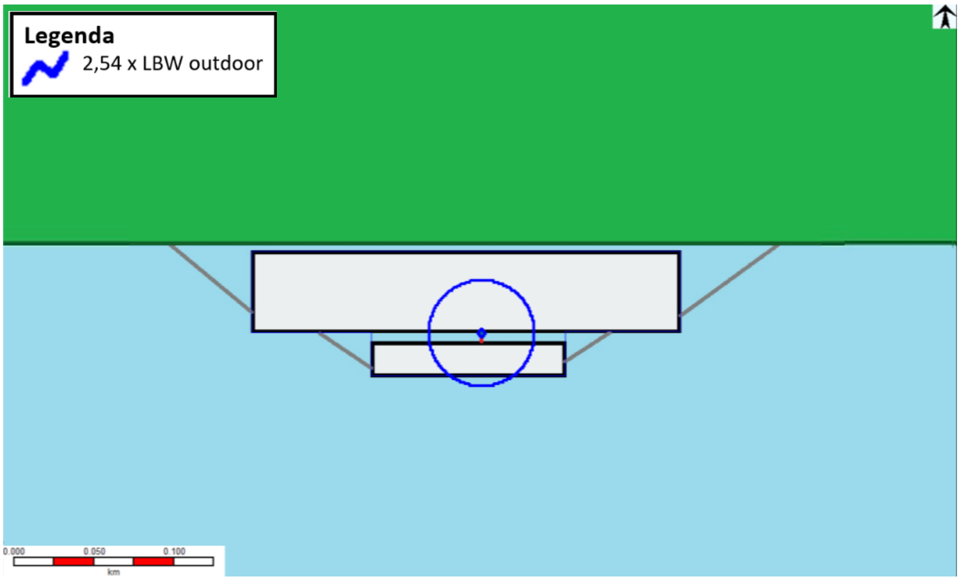


Methanol – high flow rate

Fire focus area

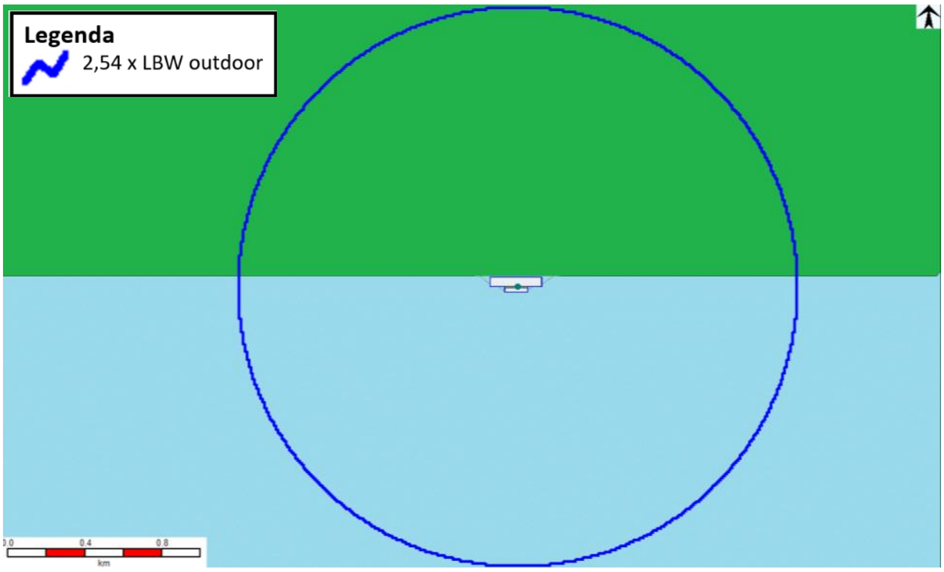


Toxic cloud focus area



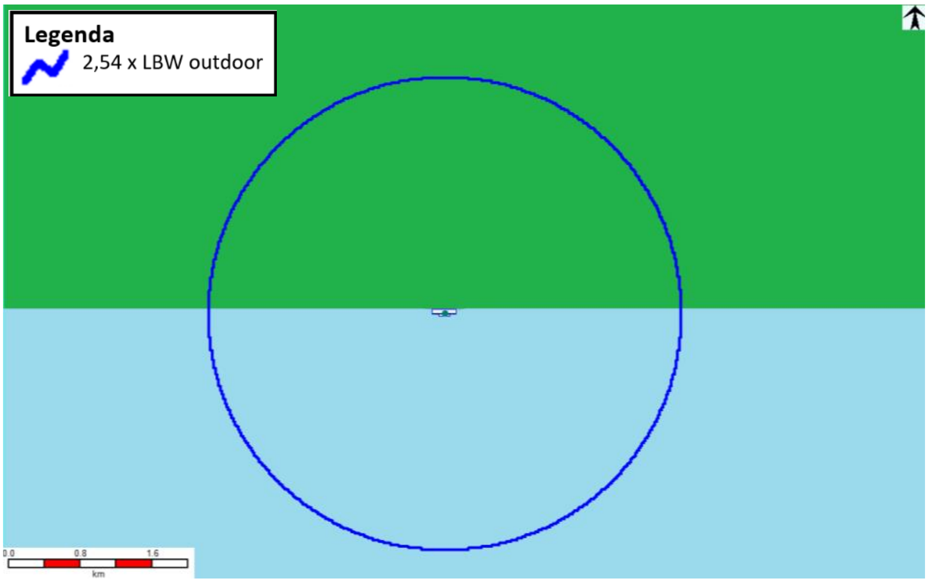
NH3 (T) – low flow rate

Toxic cloud focus area



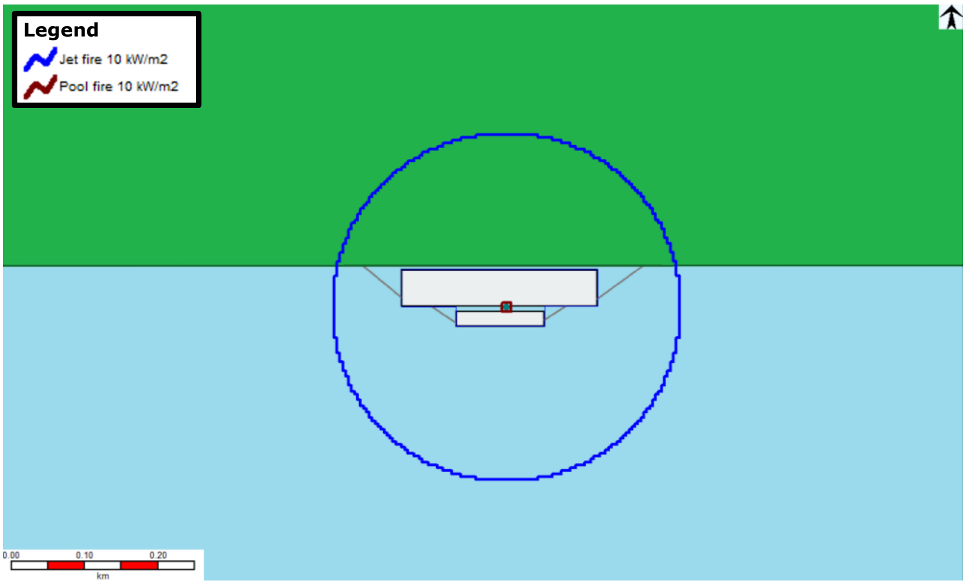
NH3 (T) – high flow rate

Toxic cloud focus area

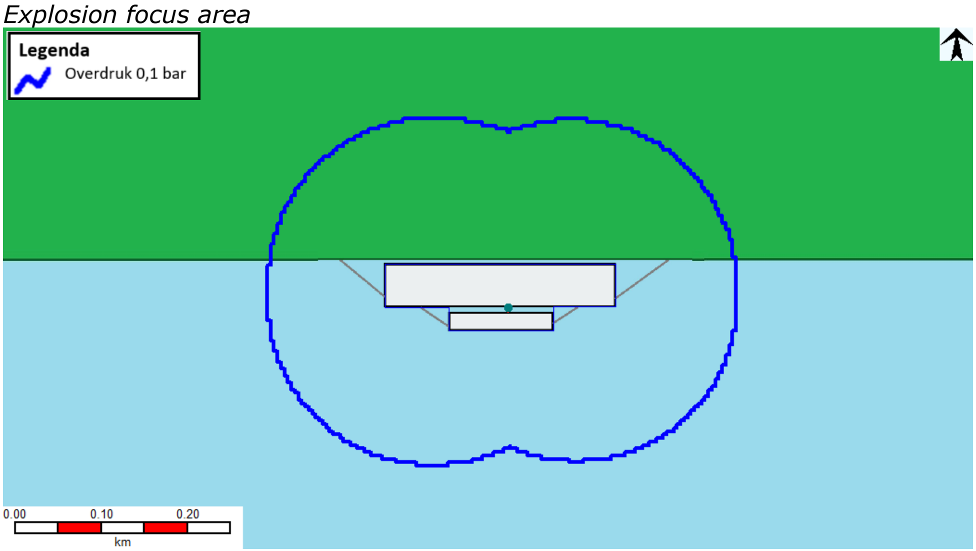


Hydrogen (L) – low flow rate

Fire focus area

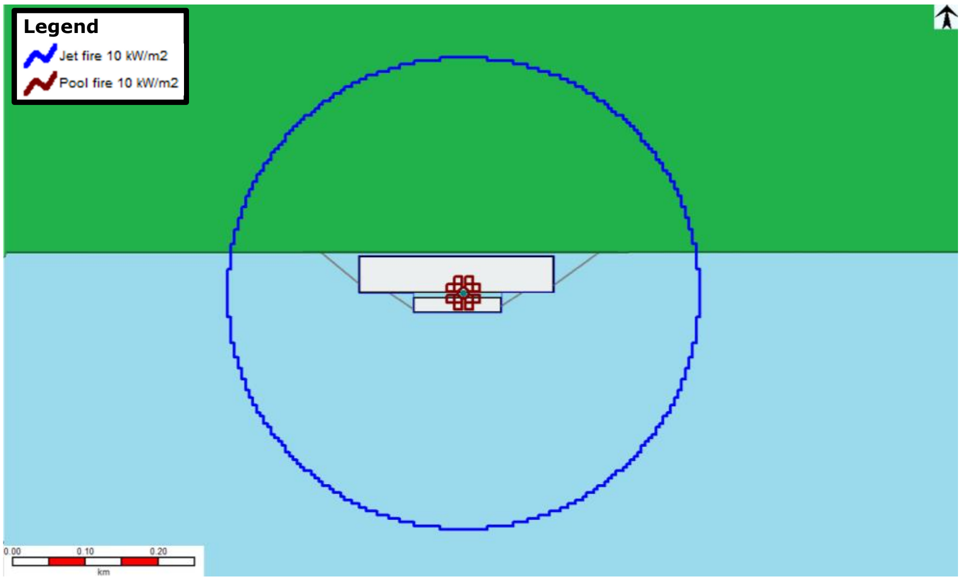


Explosion focus area

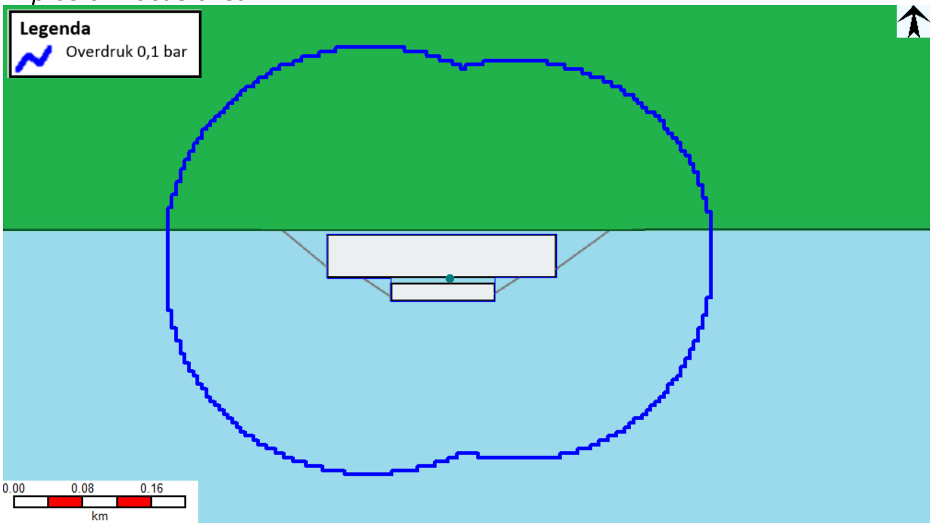


Hydrogen (L) – high flow rate

Fire focus area

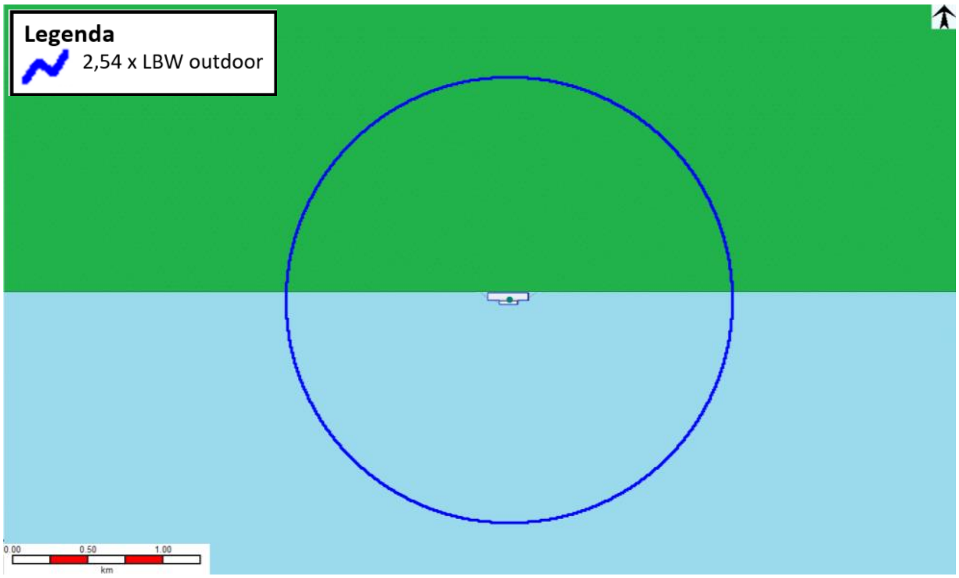


Explosion focus area



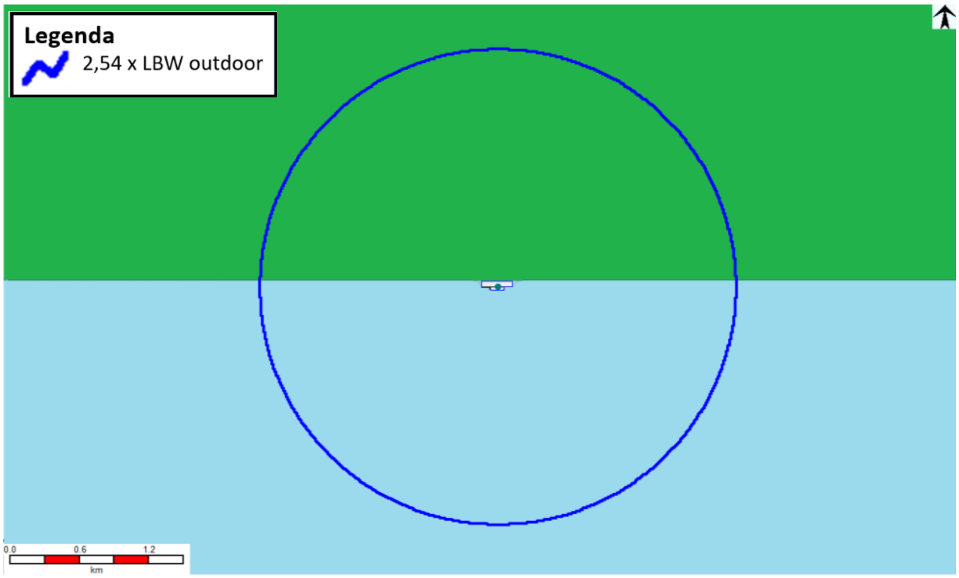
NH3 (P) – low flow rate

Toxic cloud focus area



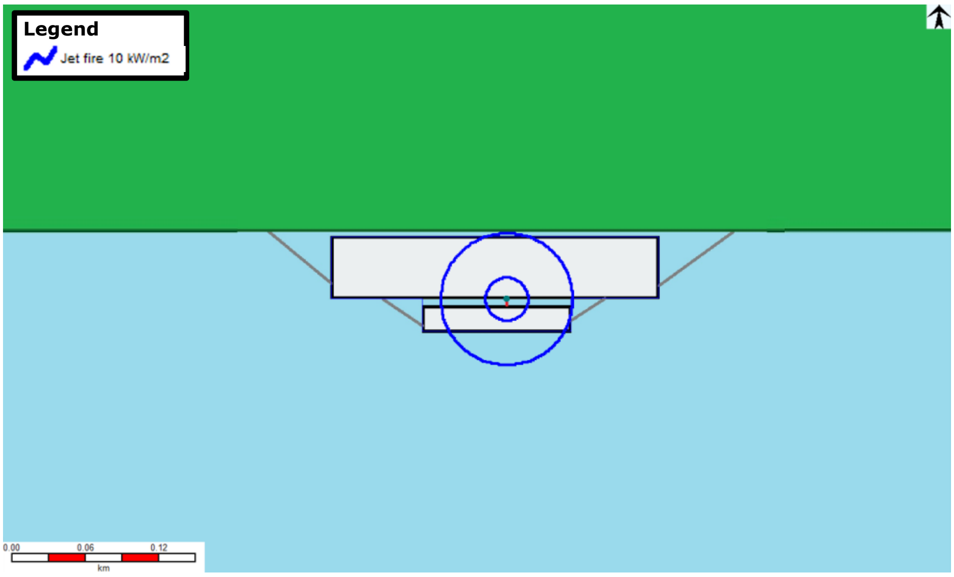
NH3 (P) – High flow rate

Toxic cloud focus area



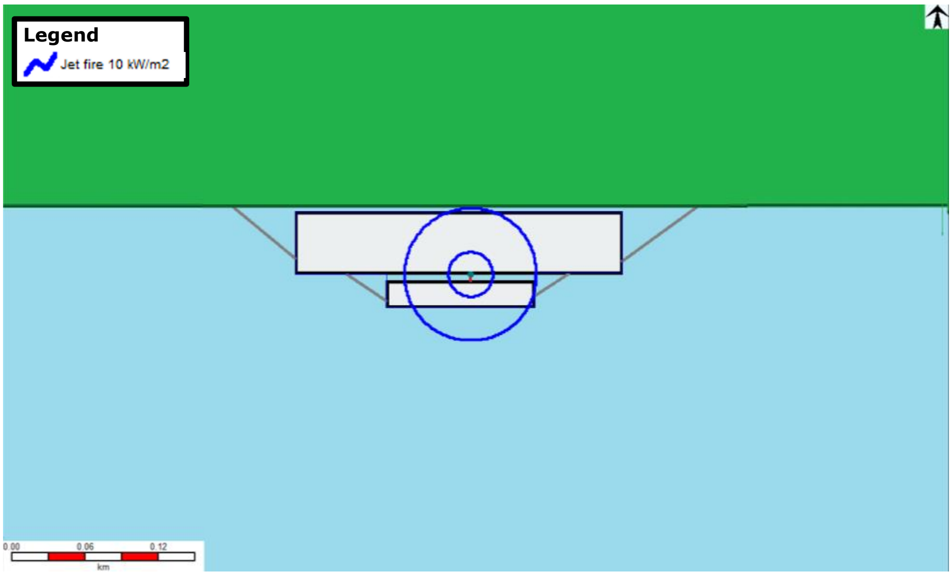
Hydrogen (G) – 700 bar

Fire focus area



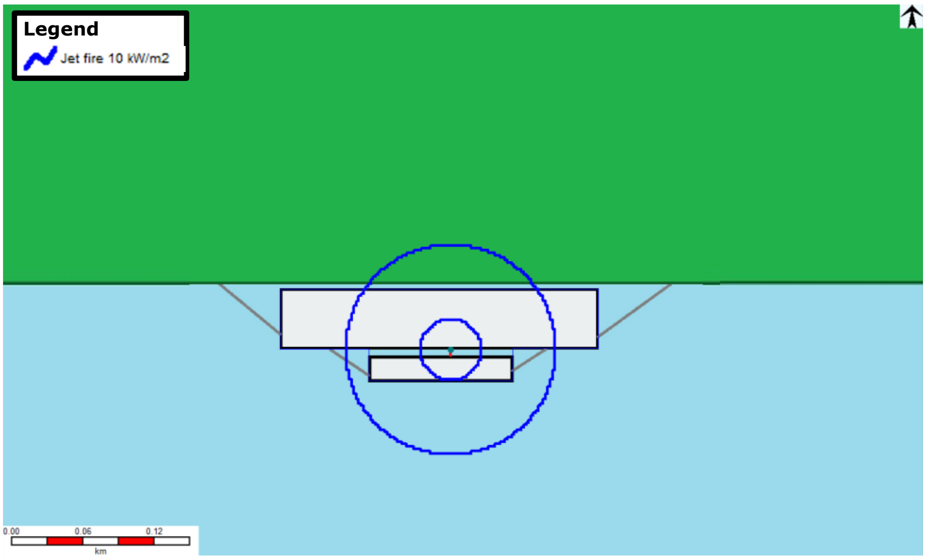
Hydrogen (G) – 1000 bar

Fire focus area



Hydrogen (G) – High flow rate

Fire focus area



* The fire focus area is virtually the same as the risk contours because the scenario only results a jet fire, the event probability of an explosion is set to 0 in the event tree, immediate ignition probability = 1 for gaseous hydrogen so no pool fire/flash fire, and hydrogen is not toxic. The only effect that remains is a jet fire.

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Driven by our purpose of safeguarding life, property and the environment, DNV enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our professionals are dedicated to helping our customers make the world safer, smarter and greener.