RH2INE PROGRAM - SUB-STUDY 1B: SAFETY AND REGULATORY ANALYSIS

SuAc A3 & B3: Guidance for safety distances for bunkering hydrogen in the Netherlands & Germany

RH2INE Consortium

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Objective: this report provides guidance for mandatory (external) safety distances for different land-based bunkering systems and scenarios supplying hydrogen to inland navigational vessels in the Netherlands and Germany.

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DNV

ABREVIATIONS

ATEX	"Appareils destinés à être utilisés en ATmosphères Explosives" (French for Equipment intended for use in Explosive Atmospheres)
Bevi	Dutch decree on external safety of facilities ("Besluit externe veiligheid inrichtingen")
Bkl	Dutch decree quality living environment that will come into force in 2022 ("Besluit kwaliteit leefomgeving")
BauBG	German Federal building code ("Baugesetzbuch")
BlmSchG	German Federal emission protection law ("Bundesemissionschutzgesetz")
Brzo	Dutch decree on risk of major accidents ("Besluit risico's zware ongevallen")
CO2	Carbon Dioxide
EIGA	European Industrial Gases Association
ERPG	Emergency Response Planning Guidelines
H2	Hydrogen
HAZID	Hazard Identification Study
HRS	Hydrogen Refuelling Stations
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISO	International Organization for Standardization
IWT	Inland Waterway Transport
KAS	German commission of plant safety ("Kommission für Anlagensicherheit")
LBW	Life Threatening Concentration ("Levensbedreigende waarde") based on Dutch intervention values
LFL	Lower Flammable Limit
LH2	Liquid hydrogen
LNG	Liquefied natural gas
LoC	Loss of Containment
LSIR	Location-specific individual risk
LUP	Land-use planning
ME	Multi-Energy
NEN	Dutch Standardization Institute ("Nederlands Normalisatie-instituut")
PGS	Dutch guidelines for dangerous goods
QRA	Quantitative Risk Assessment
RH2INE	The Rhine Hydrogen Integration Network of Excellence

RIVM	Dutch National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu)
TTS	Truck-to-Ship
UDM	Unified Dispersion Model
UFL	Upper Flammable Limit
VDI	Association of German Engineers (“Verein Deutscher Ingenieure”)

EXECUTIVE SUMMARY

Introduction

The Rhine Hydrogen Integration Network of Excellence (RH2INE) is an international programme and consists of public and private parties. Its global aim is to implement hydrogen as a fuel in the inland waterway transport (IWT).

This report is the result of sub-activity 3: Guidance for external safety distances and other mandatory safety distances for land-based systems supplying hydrogen to vessels in the Netherlands and Germany of the tender "Sub-study 1b: Safety and Regulatory analysis" issued by the Provence of Zuid-Holland in the Netherlands on behalf of the RH2INE consortium.

Hydrogen facilities and bunkering activities may pose a threat to human health and the environment, due to the possibility of accidents with hazardous consequences. It is therefore important to establish (and get insight in) safety distances to prevent and limit the consequences of possible major accidents. The European legislation for control of major accident hazards, the Seveso III Directive, includes provisions for land-use planning (LUP). Land-use planning aims to prevent and limit the consequences of possible major accidents and deals with the potential conflicts between sources of risk and surrounding land-uses. This is to establish and maintain appropriate external safety distances between sensitive areas and installations where dangerous substances are present. The approach to determine external safety distances differs in the Netherlands and Germany because both countries have made their own implementation of the Seveso III Directive.

In this report, safety distances are calculated for several hydrogen bunkering scenarios based on the applicable LUP methodologies in the Netherlands and Germany. The scenarios are based on the outcomes of RH2INE sub-study 1a: Safety framework conditions, Sub-Activity (SuAc) 1.1b: *Identification of hydrogen bunkering scenarios for inland navigational vessels.* The SuAc 1.1b report contains a short list of the most feasible IWT hydrogen bunkering scenarios as determined in a workshop held with the RH2INE consortium participants and stakeholders.

This report also discusses other (mandatory) safety distances for land-based hydrogen bunkering installations.

Approach

The approach for the study comprises of the following steps:

1. Prepare an overview of the different type of safety distances applicable for hydrogen installations and bunkering;
2. Provide generic guidance to determine these safety distances;
3. Describe the legal framework, methodological approach and criteria for land-use planning (LUP) in the Netherlands and Germany;
4. Determine the safety distances for hydrogen bunkering scenarios based on the specific LUP approach in the Netherlands and Germany.

The study focusses on (mandatory) safety distances applicable for land-based bunkering installations, such as external safety distances.

Results

External safety distances

The approach to determine external safety distances in the Netherlands and Germany differs because both countries have made their own implementation of the Seveso III Directive. The Netherlands uses a risk-based approach (QRA), while Germany has developed a deterministic approach with implicit judgment of risk. For this reason, the distances in

the Netherlands and Germany are not always comparable for the same bunkering scenario and (large) differences are possible.

The bunkering scenarios assessed in this study including the calculated external safety distances are given in Table 1. It must be noted that the distances are highly dependent on the chosen starting points and assumptions (included in Appendix A). The distances should therefore be considered as indicative and are primarily useful to compare the impact on external safety of the different bunkering scenarios. Detailed input and results regarding the calculated distances for bunkering in Germany are included in Appendix B and Appendix D, respectively.

Table 1: Results for external safety distances

Scenario	Description	External safety distance [m]*	
		The Netherlands	Germany
1a	Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack	39	182
1b	Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack	129	230
2a	Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)	37	96
2b	Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)	106	96
3	Truck-to-ship bunkering of liquid hydrogen	82	70
4a	Truck-to-ship bunkering of refrigerated liquid ammonia	175	205
4b	Truck-to-ship bunkering of pressurized liquid ammonia	543	395
5	Truck-to-ship bunkering of methanol	79	67

* Reference is made to Table 4 for an explanation from where these distances should be measured.

The zones resulting from the external safety distances in the Netherlands must be free of vulnerable objects (e.g. housing in residential areas, hospitals). Objects with limited vulnerability (e.g. isolated housing, small office buildings) can only be allowed to be present in the zone if it is sufficiently motivated.

The zones resulting from the external safety distances in Germany should not be understood as areas free of buildings. Within these zones less sensitive areas/usages than those described in article 50 (first sentence) of the Federal Immission Control Act may be planned. Specific guidance is developed (KAS-18), which contains advice on which usages and/or objects are to be considered sensitive (i.e. vulnerable) within the meaning of article 50.

Focus areas

In addition, focus areas are calculated based on new Dutch legislation that is expected to come into force in January 2022. The focus areas provide an insight into the potential hazards in an area and where attention should be paid to extra protection for occupants in buildings. These areas are only relevant for the Netherlands and not Germany. Much is still unknown about the practical implementation of these areas because they are not mandatory yet. For these reasons, the results are not included in this summary. Reference is made to paragraph 7.2 for the results.

Conclusions

The following is concluded from the results for external safety distances:

The Netherlands

The external safety distances for swapping hydrogen containers at container terminals are relatively small (39 m) in the Netherlands when containers are directly loaded from trailer onto the receiving vessel. However, in the future case when demand grows and storage of containers in the stack might be needed (to create a buffer stock), the external safety distance could increase with about a factor 3. This should normally not be a problem for container terminals because of their layout and location, which provides sufficient stand-off distance to vulnerable objects. Bunkering of gaseous hydrogen via hose results in relatively small distances (approx. 40 m) when bunkering takes place directly from a (tube)-trailer. The distance for bunker stations could go up to approximately 100 m.

Germany

The external safety distances for swapping containers at container terminals are about a factor 2 larger than for bunkering gaseous hydrogen with a hose. The reason for this difference is related to the potential for explosions with high overpressures due to the level of confinement present at a container terminal. Typically, this level of confinement (&congestion) is expected to be much less for truck-to-ship bunkering and bunker stations (scenario 2a&2b) as bunkering will typically take place in an open area where the gas cannot accumulate in confined areas. If this is not the case, the safety distances for scenario 1a/1b may be more appropriate.

The Netherlands & Germany

For truck-to-ship (TTS) bunkering of liquid hydrogen and methanol result in safety distances of approximately 70-80 m, which are in line with calculated distances for TTS bunkering of LNG to inland vessels in the LNG Masterplan study of 2015 /12/. For bunkering ammonia, the safety distances are considerably larger and are caused by the high toxicity of ammonia. The distances for pressurized ammonia are about a factor 2-3 larger than for bunkering refrigerated ammonia. It will be challenging to introduce ammonia as a fuel in IWT due to the large safety distances for bunkering ammonia with a hose. This could be showstopper for bunkering ammonia in inland ports and waterways where residential areas and industries etc. could be nearby.

1 INTRODUCTION

The world fleet is large with 115,000 ships and it will grow in the years to come, with more than 30% up to 2030. IMO's goal of halving CO2 emissions from shipping by 2050 will lead to a significant restructuring over the next thirty years. The IMO targets and national decarbonization policies are expected to be fundamental drivers for developing low and zero emission technologies in the shipping industry. Next to IMO's goals, the European Union formulated its goals for all sectors in the European Green Deal. It is necessary to find and integrate low-emission propulsion fuels, such as hydrogen, in every part of the transport sector. Hydrogen could significantly reduce emissions, but implementation in inland shipping is new. Hydrogen is the only available zero emission solution for longer distances and high energy needs, but it will remain expensive, especially in the short term. To bring costs down it is absolutely necessary that authorities push for hydrogen technology to be used in vessels and that safety rules & regulations are standardized, which do not exist today.

The Rhine Hydrogen Integration Network of Excellence (RH2INE) is an international programme and consists of public and private parties. Its global aim is to implement hydrogen as a fuel in the inland waterway transport (IWT). On behalf of the consortium of the RH2INE programme, the province of Zuid-Holland[1] is taking the lead for Sub-study 1b: Safety and Regulatory analysis.

Sub-study 1b specifically focusses on safety and regulations related to land-based systems supplying hydrogen to inland navigational vessels in the Netherlands and Germany. This sub-study comprises of three sub-activities:

1. Identification of land-based regulations and standards for systems supplying hydrogen to vessels in the Netherlands and Germany;
2. Identification of gaps in land-based regulations and standards;
3. Guidance for external safety distances and other mandatory safety distances.

This report covers sub-activity 3: *Guidance for external safety distances and other mandatory safety distances for land-based systems supplying hydrogen to vessels in the Netherlands and Germany*.

Hydrogen facilities and bunkering activities may pose a threat to human health and the environment, due to the possibility of accidents with hazardous consequences. It is therefore important to establish (and get insight in) safety distances to prevent and limit the consequences of possible major accidents. The European legislation for control of major accident hazards, the Seveso III directive, includes provisions for land-use planning (LUP). Land-use planning aims to prevent and limit the consequences of possible major accidents and deals with the potential conflicts between sources of risk and surrounding land-uses. This is to establish and maintain appropriate external safety distances between sensitive areas and installations where dangerous substances are present. The approach to determine external safety distances differs in the Netherlands and Germany because both countries have made their own implementation of the Seveso III directive.

In this report, safety distances are calculated for several hydrogen bunkering scenarios based on the applicable LUP methodologies in the Netherlands and Germany. The scenarios are based on the outcomes of RH2INE sub-study 1a: Safety framework conditions, Sub-Activity (SuAc) 1.1b: *Identification of hydrogen bunkering scenarios for inland navigational vessels* /1/. The SuAc 1.1b report contains a short list of the most feasible IWT hydrogen bunkering scenarios as determined in a workshop held with the RH2INE consortium participants and stakeholders.

This report also provides guidance for other (mandatory) safety distances for land-based hydrogen bunkering installations.

[1] The province of Zuid-Holland is a Dutch organisation that operates on behalf of the community of the province Zuid-Holland in the Netherlands.

2 STUDY APPROACH

The approach for the study comprises of the following steps:

1. Prepare an overview of the different type of safety distances applicable for hydrogen installations and bunkering;
2. Provide generic guidance to determine these safety distances;
3. Describe the legal framework, methodological approach and criteria for land-use planning (LUP) in the Netherlands and Germany;
4. Determine the safety distances for hydrogen bunkering scenarios based on the specific LUP approach in the Netherlands and Germany.

The study focusses on (mandatory) safety distances applicable for land-based bunkering installations, such as external safety distances. Water-based safety distances such as safe passing distances for ships and exclusion[2], monitoring or control zones[3] that may need to be established during hydrogen bunkering are not discussed.

[2] This is the area around the bunkering manifold where water-based uncontrolled ignition sources or activities are not allowed or limited to a minimum to mitigate intrusive ignition risk and intrusions threating the physical integrity of the facility and ships (e.g. due to collision risk).

[3] This is the area around the bunkering facility and ship where ship traffic and other activities are monitored (and controlled) to mitigate harmful effects. For bunkering, these zones are also sometimes referred to as a security zone. However, the term security zone should not be confused with the zones/border described in the International Ship and Port Facility Security (ISPS) code, therefore the term monitoring zone or control zone are more often used in practice.

3 SAFETY DISTANCES

Different types of safety distances can be distinguished. The most relevant for land-based installations are:

- External safety distance;
- Internal safety distances;
- Focus areas;
- Safety zone;
- Hazardous areas.

These concepts are briefly discussed in the paragraphs below.

3.1 External safety distance

The external safety distance is the separation distance between an establishment or activity with hazardous goods (e.g. hydrogen) and surrounding land-uses (e.g. vulnerable objects such as houses, large office buildings, hospitals). There are several methodological approaches to determine external safety distances in the LUP process and many countries have developed their own methodology. These approaches often require the use of specific tools and guidelines. In addition, threshold (or risk) criteria are needed to determine the external safety distance.

The Netherlands has developed a specific risk-based (QRA) methodology, which is described in detail in chapter 4. Germany has adopted a deterministic approach with implicit judgment of risk. The specific methodology and criteria are explained in chapter 5.

The existing methodologies can be divided into the following four main categories:

1. Consequence-based approaches

The consequence-based approach is based on the assessment of consequences of credible (or conceivable) scenarios, without explicitly quantifying the likelihood of these accidents. The consequences of the scenarios are mostly taken into consideration by calculating the distance in which the physical and/or human health impacts (e.g. heat radiation) reach, for a given exposure period and a threshold value (e.g. irreversible health effect/harm or fatality). The external safety zone is thus defined according to which LUP restriction are applied. The method has been generally used in Luxembourg, Spain, and Austria.

2. Deterministic approach with implicit judgment of risk

A simplified form of the consequence-based approach is the use of “generic” safety distances. These distances are usually derived from a selected credible scenario and developed on a conservative basis. In their most simple form, they are derived from expert judgement, including consideration of historical data or experience from operation similar plants. The approach of generic safety distances has been established and used in Germany. A specific consequence calculation to determine the safety distance is also possible, but this is often based on a (standard) credible release scenario. Not all conceivable scenarios have to be considered (e.g. those with low frequencies such as catastrophic failure scenarios), hence there is an implicit judgement of risk. Typically, a representative credible scenario is taken with a relatively high frequency (e.g. in Germany a 25 mm leak scenario would be considered to determine the safety distance).

3. Risk-based (or “probabilistic”) approaches

The risk-based approaches define the risk as a combination of the consequences derived from a range of possible accidents, and the likelihood of the accidents. A Quantitative Risk Assessment (QRA) is required to calculate the risk. The results are represented as location-specific individual risk contours and/or societal risk (reference is made to paragraph 4.1 for definitions). Risk criteria are developed to assess the acceptability of the calculated risk. The external safety distance is based on the location-specific individual risk contours. This approach is followed in e.g. the United Kingdom, Belgium (Flanders), the Netherlands and Switzerland (only societal risk).

4. Hybrid approaches

Hybrid approaches (or semi-quantitative) combining risk and consequence-based approached have been developed and extensively used in France and Italy. Under these methods, one of the elements (usually frequency) is assessed more qualitatively, i.e. using classes rather than continuous figures. The use of a risk matrix is a typical example. For instance, France adopted a hybrid approach that combines a consequence-based approach for the determination of the zones that correspond to damage thresholds and a risk-based approach for the determination of the considered accident scenarios. Respectively, Italy has adopted a hybrid criterion that takes into account the frequencies, as mitigation factor for the damaged zones, identified using a consequence-oriented approach.

3.2 Internal safety distances

An internal safety distance is the minimal separation distance between a potential hazard source (e.g. equipment involving dangerous substances) and an object (e.g. equipment), which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident (also known as domino effect). The provision of adequate internal safety distances is thus a fundamental consideration for safe layout of hydrogen installations.

In general, the approach used to calculate internal safety distances is typically based on EIGA 75/07/E (2007) /2/. The EIGA report describes how a full assessment of the nature of the hazard, the frequency of the event and its potential consequence is essential for understanding which risks can be reasonably mitigated by an internal safety distance. If the resultant safety distance is too large, additional mitigation or prevention measures should be considered and the safety distance re-calculated. Examples of alternatives to implementing the full safety distances include the installation of barriers or protection measures (e.g. firewalls) to reduce escalation, or the alteration of equipment design and/or operating conditions to reduce the severity and/or likelihood of the incident. EIGA uses an individual harm exposure threshold value (or range of values) as the criterion for selecting the incidents to be included in the internal safety distance calculations.

In the Netherlands, the Dutch Standardization Institute (Nederlands Normalisatie-instituut, NEN) develops so-called PGS ("Publicatiereeks Gevaarlijke Stoffen") guidelines, which provide requirements & provisions for the safe design and operation of an installation with hazardous goods. PGS 35 /3/ is a guideline developed for Hydrogen Refuelling Stations (HRS) and contains fixed internal safety distances. The background of the determination of these internal safety distances is given in the report: "Internal Safety Distances for PGS 35" /4/.

A guideline for the design and operation of a hydrogen bunker station to ship is currently not (yet) under development. However, the equivalent PGS guideline for LNG bunker stations (PGS 33-2) was first published in 2014 /5/. Depending on the market developments and the need for regulations for bunker stations, it is expected that a similar guideline will eventually be developed for hydrogen bunker stations ('PGS 35-2'), which should include internal safety distances. In the new environmental legalisation that will come into force in 2022, internal safety distances are mandatory to implement when they are covered in a PGS guideline. Currently, authorities use PGS guidelines in the permitting process and often mandate the provisions and measures given in these guidelines (making them mandatory as well).

Germany has not determined (or developed guidance for) internal safety distances for hydrogen installations.

3.3 Focus areas

Focus areas is a new concept in Dutch law (Environmental and Planning Act) that will come into force in 2022 and are therefore mandatory to establish. Focus areas will replace the societal risk and are determined with means of a consequence-based approach by calculating the maximum effects (to certain thresholds) of all conceivable scenarios that are included in a QRA. Germany does not require the determination of focus areas.

The areas are established around activities with hazardous substances and they visualise where people are possibly 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. There are 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 be paid to extra protection for occupants in buildings against fire, explosion or toxic impact. 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 present (indoors) in focus areas.

3.4 Safety zone

A safety zone is required to be established around the bunkering station to ensure that only essential personnel and activities are allowed in the area that could be exposed to hazards in case of an accidental release during bunkering. The purpose of a safety zone is primarily to control ignition sources in order to reduce the likelihood of igniting a flammable gas cloud due to an accidental release. The size of the safety zone is normally determined by a risk assessment. In general, two different methods can be distinguished to determine a safety zone:

1. A conservative and simple (deterministic) approach based on a qualitative risk assessment (HAZID), or;
2. By a risk based approach (QRA) relating to the overall safety requirements.

The more complex risk based approach may be accepted provided that it can be demonstrated by the QRA that risk acceptance criteria can be met for 1st, 2nd, and 3rd party personnel. If the risk is acceptable in accordance with the acceptance criteria (as agreed with authorities), the safety zone is acceptable. The safety zone should be implemented as a safety distance all around the bunkering area and is complementary to the minimum required external safety distance (to e.g. neighbouring industry, residential or vulnerable areas) as determined based on national criteria for land-use planning. It must be noted that the risk criteria set by (national) authorities must also be evaluated in the risk based approach for safety zone determination (relating to the total risk acceptance).

ISO/TS 18683 provides detailed guidance to determine a safety zone for LNG bunkering /6/. No specific guidance has been developed (e.g. by ISO) to determine safety zones for hydrogen bunkering. Operational safety zones are not mandatory (by law) to establish and implement during bunkering, but are recommended by international bunkering guidelines, checklists and procedures. For these reasons, operational safety zones are not calculated or further discussed in this report (with exception of the external safety zone).

3.5 Hazardous areas

The hazardous area is an area in which an explosive gas atmosphere is or may be expected to be present, in quantities such as to require special precautions for the construction, installation and use of equipment. The purpose of these areas (EX-zones) is to prevent ignition of explosive atmospheres by proper selection of electrical equipment to be used inside the zones. The size of the EX-zones is normally defined by IEC 60079-10-1 /7/ or other relevant (national) regulations and guidelines.

Regulations related to Hazardous Area Classification (ATEX) are generally applicable to all industrial installations, including hydrogen installations. The European ATEX directives 2014/34/EU (ATEX 114) & 99/92/EG (ATEX 153) are commonly applied to onshore installations in the EU. The national implementation of ATEX does not contain specific features that will influence the development of hydrogen land-based installations. A hazardous area does also not fall under the definition of a safety distance, although it is a safety related concept and they are mandatory to establish and implement. Hazardous areas are not further discussed in this report.

4 LAND-USE PLANNING IN THE NETHERLANDS

4.1 Legal framework & risk criteria

The Netherlands uses a risk-based approach (QRA) for the assessment of external risk and to determine external safety distances. Criteria for individual and societal risk for fixed installations (so-called Bevi establishments) are implemented in the Decree External Safety Establishments (*Bevi, Besluit Externe Veiligheid Inrichtingen, 2015*). This decree applies to all establishments falling under the Decree concerning Major Accident Hazards (*Brzo, Besluit risico's zware ongevallen*, 2015), which is the Dutch implementation of Seveso III.

4.1.1 Location-specific individual risk

The location-specific individual risk (LSIR) 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 housing in residential areas, hospitals, schools, large offices etc.) is equal to 10^{-6} per year. This means that vulnerable objects within the 10^{-6} LSIR contour of an establishment are not allowed. For objects with limited vulnerability (such as scattered dwellings, smaller offices, sports complexes etc.) a target value of 10^{-6} per year is defined. The aim should be that these objects do not fall within the 10^{-6} LSIR contour; a higher risk may be permitted, if it is sufficiently motivated.

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

The external safety distance is determined by measuring the distance from the hazardous establishment or activity to the 10^{-6}/year risk contour.

Table 2: Overview of vulnerable objects and objects with limited vulnerability

Vulnerable objects (not allowed to be exposed to a risk level equal or higher than 10^{-6}/year)	Objects with limited vulnerability. Risk level of 10^{-6}/year applies as target value.
Housing; Hospitals, elderly care centers and nursing centers; Schools and day care for minors; Office buildings and hotels with a gross floor area more than 1500 m^2; Shopping malls (with more than five shops and a gross floor area of more than 1000 m^2) and shops with a total floor area of more than 2000 m^2; Camping- and other recreational terrains intended for the stay of more than 50 persons during multiple consecutive days.	Isolated housing (maximum of 2 houses per hectare); Other* office buildings (<1500 m^2); Other* hotels and restaurants; Other* shops; Sporting places, sporting terrains, swimming pools and play grounds; Other* Camping- and other recreational terrains; Company/plant buildings; Equivalent objects; Objects with high infrastructural value

*Other means: other than defined in the first column as vulnerable object

4.1.2 Societal risk

Societal risk is defined as the (cumulative) frequency per year that a particular group of people dies concurrently as a result of accidents. Societal risk is represented in an FN curve, which is a Log-log graph: the X-axis represents the number of deaths and the y-axis the cumulative frequency of the accidents, with the number of deaths equal to N or more.

The societal risk evaluation in the Netherlands is not based on a 'hard' limit value for acceptability for risk. Instead, there is a so-called 'justification' obligation. This implies primarily that the societal risk has to be compared against a target value. This means that the same principle as for individual risk for objects with limited vulnerability is valid: a higher risk could be accepted with proper motivation and under certain conditions. The target value is expressed for fixed installation on an FN curve as 10^{-5} per year for 10 fatalities, with $F=10^{-3}/N^2$ for higher fatalities (see figure below). It does not apply for fewer than 10 fatalities. The societal risk 'cut-off' criterion is 10^{-9}/year, below this value the societal risk is considered negligible for any number of fatalities.

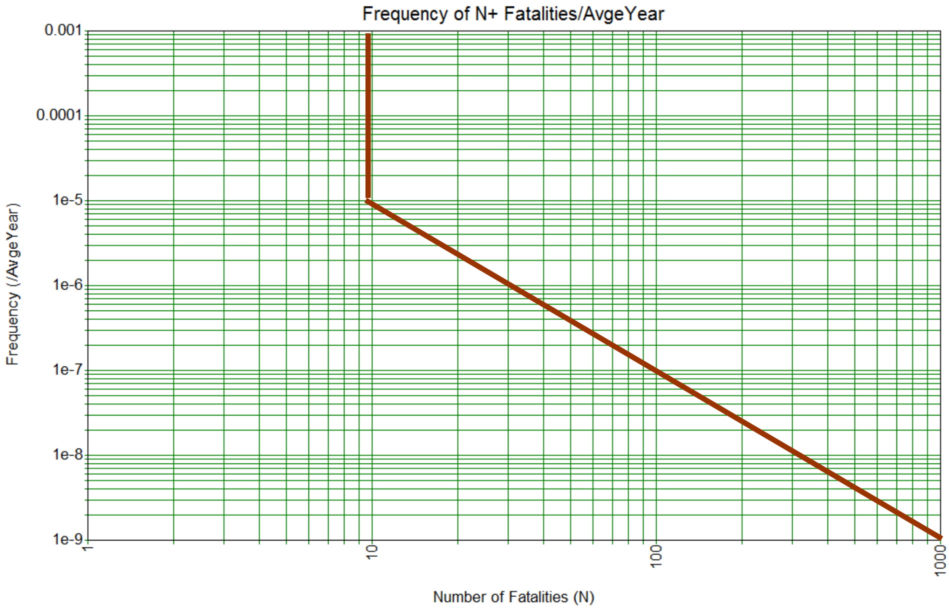

Figure 1: Criteria for societal risk in the Netherlands (target value)

Because societal risk does not directly result in a required external safety distance and because it depends heavily on the population present the vicinity of the bunkering activity, it is not further addressed in this study. Moreover, in the new Environmental and Planning Act (expected to come into force in January 2022), societal risk will be replaced by focus areas.

4.1.3 Focus areas

A distinction is made between three types of focus areas:

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

The methodology to determine these areas is explained in the subsequent paragraphs.

4.1.3.1 Fire focus area

For the calculation of the fire focus area, the fire effect areas calculated in a QRA are used. 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.

4.1.3.2 Explosion focus area

The explosion focus area is determined as the area in which 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 of 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. In addition, the explosion focus area may also be determined by the 35 kW/m^2 radiation contour from the fireball.

4.1.3.3 Toxic cloud focus area

The toxic cloud focus area is defined as the area in which a toxic concentration of 2.54 times the LBW (for 1-hour exposure) of a substance can occur. The LBW-1h 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. The National Institute for Public Health and the Environment ("Rijksinstituut voor Volksgezondheid en Milieu"), the RIVM, has determined that if the toxic concentration in a cloud outside is equal to 2.54 x LBW (corresponds approximately to the ERPG-3 concentration[4]), concentrations equal to LBW can occur indoors. Within the toxic focus area, people who are indoors can therefore be exposed to life-threatening toxic concentrations.

4.2 Guidelines

Bevi specifies that a QRA must be developed based on the Reference Manual Risk Assessments Bevi /8/ written by the RIVM and making use of DNV's software program Safeti-NL 8.x (current version is 8.3). This manual provides information about possible failure scenario's, failure frequencies and how to model the consequences & risk. The manual is based on and is the successor of the most well-known and world-wide accepted guideline for the execution of quantitative risk assessment: the 'Purple Book' /9/. Together with the other 'coloured books' (yellow, green and red) the guideline forms valuable reference material for safety studies. The coloured books have become obsolete and are not kept up-to-date anymore since 2005.

The Reference Manual Risk Assessments Bevi /8/ is not specifically written for hydrogen, it has generic applicability. For instance, the manual does not specify hydrogen-specific failure frequencies for e.g. storage in tube-containers, but rather specifies generic failure frequencies for pressurized onshore storage or pressurized vessels on trailers, which could be derived based on failure data of storage vessels that are very different in design compared to (compressed or liquid) hydrogen containment systems.

The RIVM has developed calculation guidelines for specific installations, e.g. container terminals, LNG refuelling stations and LNG bunker stations. These guidelines also contain case studies. Similar guidelines for hydrogen installations (e.g. bunker stations) do not exist. However, the RIVM has written a memo on risk and effect distances of HRS /10/. Based on these results the Ministry of Infrastructure and Environment has decided to include fixed external safety distances for HRS (30 m or 35 m depending on the supply of hydrogen via pipeline or trailer, respectively) in the new 2022 legislation (Bkl) and not to develop a specific QRA calculation guideline for HRS. However, there is still a need to develop a QRA calculation guideline for hydrogen bunker stations supplying hydrogen as a fuel to (inland)

[4] EPRG: Emergency Response Planning Guidelines. Three concentrations are specified for each substance (EPRG-1 to EPRG-3). The EPRG-3 value for a substance is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odour.

vessels, because the way of calculating the risk of hydrogen releases differs compared to other substances (e.g. related to ignition probability[5], definition of failure cases and outflow modelling).

The QRA calculation guideline for container terminals is included in the Reference Manual /8/, module C, chapter 5. This guideline does not specify failure scenarios for hydrogen containers in particular. The scenarios are related to hoisting and storage of tank-containers, either with gas or liquid. The assumptions related to gas tank-containers are actually based on liquified gas (inventory 20 m^3 and a liquid head of 2 m is assumed) and specific assumptions for e.g. pressurized (hydrogen) gas in e.g. tube-containers are not given. In addition, the design and strength (e.g. wall thickness of the tube/cylinder) of such containers is very different to a liquefied gas tank-container and therefore the failure scenarios & frequencies may not be appropriate. More research would be required to investigate the failure modes and derive failure frequencies from e.g. incident databases or fault trees.

4.3 QRA methodology

A QRA gives insight into the risks to human life of a certain activity by calculating the potential hazardous effects of a variety of scenarios as well as considering the probability of occurrence of these scenarios. The QRA methodology is visualized in the figure underneath.

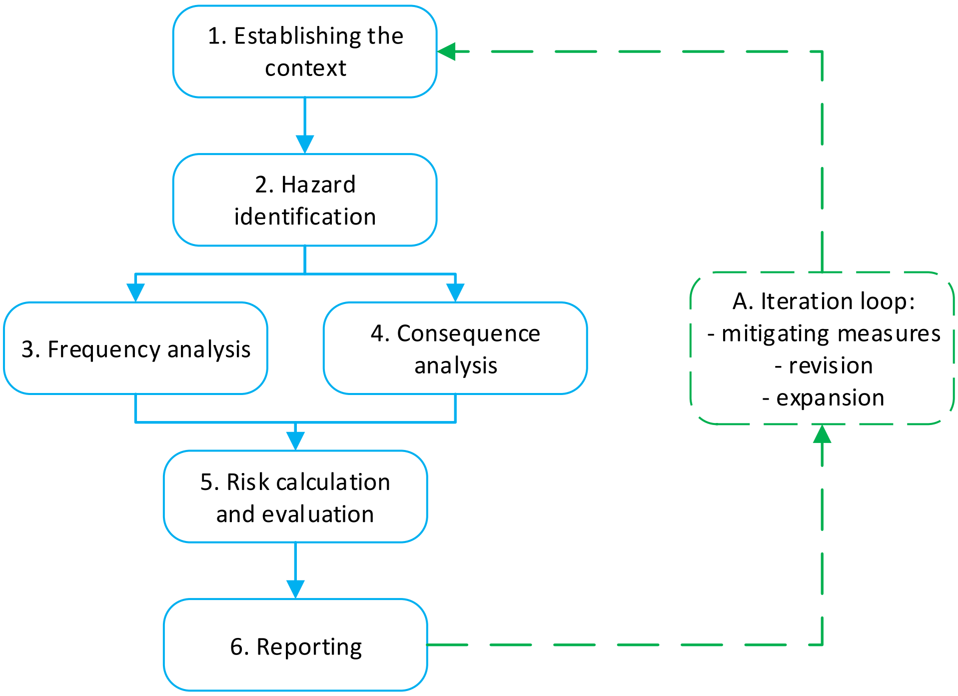

Figure 2: QRA methodology

In general, a QRA tries to answer six simple questions. Beside each question, the technical term is listed for that activity in the QRA:

1. What can go wrong? Hazard identification
2. How bad? Consequence analysis
3. How often? Frequency analysis
4. What is the risk? Risk calculation

[5] For instance, the RIVM memo /10/ assumes an immediate ignition probability of 1 for gaseous hydrogen and 0.9 for liquid hydrogen. These specific parameters should be captured in a QRA calculation methodology for hydrogen installations, such as bunker stations.

5. So What? Risk assessment (or evaluation)

6. What do I do? Risk management (risk mitigation measures)

These activities are further explained below.

What can go wrong? Hazard identification

Potential hazards to people can arise if Loss of Containment (LoC) of hazardous substances occurs. Several LoC-scenarios associated with failure of equipment are defined for the QRA. The failure cases (scenarios) for the selected equipment items must be taken from the Dutch Reference Manual Bevi Risk Assessments /8/.

How bad? Consequence analysis

In parallel with the frequency analysis, consequence analysis (modelling) evaluates the resulting effects if the accidents occur, and their impact on people. Ignited flammable releases can result in various consequences such as jet-, pool-, or flash fire or vapour cloud explosions depending on the type of scenario and time and place of ignition. The consequence assessment must be carried out using recognized and validated consequence modelling tools that can determine the resulting effects and their impact on people. The consequences for the scenarios in a Dutch QRA are calculated by Phast 8.3 (incorporated in Safeti-NL 8.3).

How often? Frequency analysis

After the hazards of a system or activity have been identified, the next step in performing the QRA is to estimate the frequency at which the hazardous events (scenarios) may occur. Default failure frequencies for the scenarios must be taken from the Reference Manual /8/ and are adjusted for the annual bunkering time.

What is the risk? Risk calculation

Once the potential physical damage zones are estimated by a consequence analysis, the probability of actual damage realization (i.e. safety risk) is calculated by taking various event probabilities into account. For example, frequent occurrence of an undesirable event by itself may not cause damage. Actual damage realization depends on several event probabilities like:

- Weather stability class;
- Wind direction probability;
- Wind velocity and stability probability;
- Ignition probability (immediate and delayed);
- Presence of people (population) in the effect zone (only relevant for societal risk).

The likelihood of the damage realization is determined by an event tree analysis taking the above event probabilities into account. Another important factor that determines the actual damage caused is the vulnerability of people/property in the effected zone and the time of exposure using e.g. probit functions or other vulnerability criteria.

The software program used to calculate the risk in the Netherlands is Safeti-NL 8.3. Fixed model parameters are incorporated in Safeti-NL, which cannot be modified.

So What? Risk assessment

The next stage is to introduce criteria which are yardsticks to indicate whether the risks are “acceptable”, “tolerable” or “negligible” or to make some other value-judgment about their significance. This step begins to introduce non-technical issues of risk acceptability and decision making, and the process is then known as risk assessment.

What do I do? Risk management

In order to make the risks acceptable or the safety distances smaller, risk reduction measures may be necessary. The benefits from these mitigating measures can be evaluated by recalculating the risk. Detailed investigation of risk mitigation measures and their impact on the calculated risk is normally only performed when the calculated risks are evaluated as unacceptable based on the risk criteria applied.

5 LAND-USE PLANNING IN GERMANY

5.1 Legal background

The German 'Störfallkommission' (now called "Kommission für Anlagensicherheit" (KAS)) prepared guidelines in 2005 (2nd revised edition 2010) /11/ for implementing article 13 of the Seveso III Directive on land-use planning and ensuring the necessary distances between major hazard establishments and vulnerable objects. The requirements of Seveso were transposed into German law primarily through Article 50 of the Federal Immission Control Act (BlmSchG) and by amending Article 9 of the Federal building code (Baugesetzbuch, BauBG).

5.2 Approach & consequence-based thresholds

Germany has adopted a simplified version of a consequence-based approach (the deterministic approach with implicit judgment of risk, see paragraph 3.1) to determine generic external safety distances. Distinction in the approach depends on two situations:

1. Recommendation for safety distances for the land-use-planning without detailed information about the establishment ('greenfield sites')

   The relevant authority in Germany has to decide which industrial activities can be projected for different areas based on the distances provided in appendix 1 of KAS-18 /11/. These are generic safety distances (so called "Achtungsabstände") based on the declared substances stored or used by the establishment. The distance requirements are divided into four classes, with distances of: 200, 500, 900 and 1500 m. The latter distances are based on a consequence calculation of a release scenario with the following parameters:

   - Leakage of the dangerous substance from a 490 mm^2 hole (corresponds to a rupture of a pipe with a nominal diameter of 25 mm)
   - Flammable substances ignite immediately
   - Atmospheric parameters and the dispersion model are based on the VDI[6] guideline 3783 Blatt 1 for low density gases and Blatt 2 for heavy gas dispersion.
   - Effect distances are calculated for the following end-point (threshold) values and the maximum value is taken:
     - 1.6 kW/m^2 for thermal radiation
     - 0.1 bar for overpressure
     - For toxic substances the EPRG-2 value[7] is calculated

2. Planning in the surrounding of industrial activities with information.

   This is often the case when an operator/company plans to extend/change an operation or a new development is planned in the surrounding of an existing industrial activity. In this both cases, the hazardous potential of the handled material is usually well-known, so the required safety distances can be calculated based on a more detailed approach. If the so called "Achtungsabstand" (distance of respect or safety distance) will be underrun in an individual case, a systematic determination of the appropriate safety distance has to be performed based on the precise location and the nature of the industrial activity. Consequence calculations can be performed for specific release scenarios and under consideration of the actual safety measures in place to prevent and/or to mitigate the consequence of the specific accident scenario. In variation of the approach described under point 1 (or chapter 3.1 in KAS-18) some freedom is permitted in selecting the scenario parameters (e.g. a specific

[6] Association of German Engineers ("Verein Deutscher Ingenieure"). See http://www.vdi.eu/guidelines/

[7] The EPRG-2 value for a substance is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action.

hole size can be chosen), but the calculation is limited to the assumptions provided in chapter 3.2 of KAS-18 (page 12-14). The conventions given in KAS-18 must be respected in each concrete determination of appropriate safety distances in order to ensure the comparability and reproducibility of the results. It is, however, allowed to use other (than VDI) validated software tools if the tools are calibrated against the KAS-18 guideline[9] (e.g. Phast 8.4, which has implemented state of the art dispersion (UDM[10]) and consequence models implemented). For the individual determination of appropriate safety distances the approach, calculation methods and (model) assumptions should be properly documented in a detailed report. If the individual case calculation is not done by the authority itself, it is recommended that the consequence calculation and the determination of the safety distances is performed by a nominated expert according § 29 a BImSchG. The selected approach should then be communicated to the authority in an early stage.

Table 3: Recommended external safety distances* to be used in Germany when no detailed information is available, adopted from KAS-18 /11/.

Class I, required distance: 200m	Class II, required distance: 500m	Class III, required distance: 900m	Class IV, required distance: 1500m
Ethylene oxide	Oleum 65% (Sulphur trioxide)	Sulphur dioxide	Phosgene
Acrylnitrile	Bromine	Hydrogen sulphide	Acrolein
Hydrogen chloride	**Ammonia**	Formaldehyde (>90%)	Chlorine
Methanol	Hydrogen fluoride	Hydrogen cyanide	
Propane (F-gas)	Fluorine		
Benzene			

*Note: **Hydrogen** is currently not yet categorized.

5.3 Application of external safety distances

The external safety distances are to be understood as consultation distances (i.e. not as a hard criterion). The safety distance apply for the following land-use planning scenarios:

- Identification of new building zones for establishments
- Identification of site for extensions to existing establishments
- Sensitive land use (i.e. vulnerable objects) moving closer to existing establishments

The safety distance only apply to human risk receptors and not to other risk receptors under article 50 of the Federal Immission Control Act. Furthermore, the distances do not apply to: permitting individual projects inside the establishment, existing developments and external emergency planning.

The recommended safety distance can be exceeded under certain conditions according § 31 paragraph 1 BauGB. In that case it can be assumed that prevention at the planning level has been sufficient in order to limit as much as possible the effects of major accidents, and that the planning-related protection objective stipulated in Article 50 of the Federal Immission Control Act is met.

The zones resulting from the safety distance should not be understood as areas free of buildings. Within these zones less sensitive areas/usages than those described in article 50 (first sentence) of the Federal Immission Control Act may be planned. Specific guidance is developed (KAS-18, see below), which contains advice on which usages and/or objects are to be considered sensitive (i.e. vulnerable) within the meaning of article 50.

According article 12 of the Seveso-III Directive the member states shall ensure during the LUP process that appropriate safety distances are preserved between:

[9] "Fachtagung Anlagensicherheit", Köthen, 07.-08.11.2013, Dipl.-Ing. Jürgen Farsbotter & Dipl.-Ing. Sibylle Mayer, „Land-Use-Planing", Practical Experiences with the application of the KAS-18 guideline" (deutsch: Praktische Erfahrungen bei der Anwendung des Leitfadens KAS-18).

[10] Unified Dispersion Model

- Industrial activities (falling under the Störfall-Verordnung) on the one hand and
- Residential areas, buildings and areas of public use, major transport routes as far as possible, recreational areas and areas of particular natural sensitivity

Typical sensitive objects for each category are given below:

- Residential areas (e.g. apartments, houses, block of flats etc.)
- Buildings and areas of public use (e.g. stores, shops, educational establishments, child care, etc.)
- Major transport routes (as far as possible) – (e.g. public roads and streets)
- Recreational area and areas of particular sensitivity (e.g. park areas, protected nature, etc.)

All other objects would normally be allowed within the calculated safety distance.

5.4 Guidelines

The guidance document KAS-18 /11/ offers guidance, assessment methods and recommendations with respect to the consequence-based safety distance. Key principles of this guideline are stipulated in this paragraph and also given/summarized underneath:

- The KAS-18 is a “guideline” that helps especially authorities responsible for the LUP to determine safety distances and to comply with § 50 BImSchG.
- The intention of the KAS-18 guideline is not to predict, describe and evaluate a real accident scenario (also if you have detailed information this is not the intention of the guideline).
- The frequency of an accident scenario will not be considered at all and it is also not important whether a bunkering activity takes place day and night all the week or only for some hours 1-2 times per week.
- The condition/maintenance of an operation will be also not considered, e.g. the safety distance is the same for poorly maintained operations and operations with good maintenance practices.
- The number of vessels does not have an influence on the safety distance. If you have an operation A with 2 pressure vessels and an operation B with one pressure vessel (same as in operation A) the safety distances would be the same. That means the risk potential will be completely taken out of the consideration in KAS-18.
- The different steps described in KAS-18 (source term, dispersion, evaluation) are defined as (simple) requirements in order to assure comparability and reproducibility for all cases.

6 HYDROGEN BUNKERING SCENARIOS

Safety distances are calculated for several hydrogen bunkering scenarios based on the applicable LUP methodologies in the Netherlands and Germany as described in the previous two chapters. The bunkering scenarios are based on the outcomes of RH2INE sub-study 1a: Safety framework conditions, SuAc 1.1b: *Identification of hydrogen bunkering scenarios for inland navigational vessels* /1/. The SuAc 1.1b report contains a short list of the most feasible IWT hydrogen bunkering scenarios as determined in a workshop held with the RH2INE consortium participants and stakeholders.

The following bunkering scenarios are considered in this study:

1. Swapping containers with pressurized hydrogen at container terminals
    a. Start-up case: swapping 300 bar containers (no storage in stack)
    b. Future case: swapping 500 bar containers (with storage in stack)
2. Bunkering of gaseous hydrogen via hose to fixed tanks on board
    a. Start-up case: truck-to-ship bunkering with tube-trailer (300 bar) and compressor pressurize hydrogen to 500 bar and slow fill with 60 g/s to storage on board
    b. Future case: bunker station to ship with onshore storage (380 bar) and bunkering based on pressure balancing and cascade filling at low pressure storage on board (250 bar), achieving a fast filling rate (3.000 kg/h)
3. Truck-to-ship bunkering of liquid hydrogen
4. Truck-to-ship bunkering of liquid ammonia
    a. Bunkering of refrigerated liquid ammonia (-34 °C)
    b. Bunkering of pressurized liquid ammonia (9 barg)
5. Truck-to-ship bunkering of methanol

The bunkering scenarios are further detailed below. Relevant starting points, parameters & assumptions for each scenario that are needed for safety distance calculations are provided in Appendix A.

Scenario 1A: swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case)

At a container terminal, tube-containers or containers with vertical cylinders with a volume inventory of 44 m^3 gaseous hydrogen at 300 bar (900 kg) are hoisted directly from a trailer onto a hydrogen propelled vessel by a crane. Three hydrogen containers are swapped per week (low demand case).

Scenario 1B: swapping containers with pressurized hydrogen (500 bar) at container terminals (Future case)

At a container terminal, containers with an inventory of 44 m^3 gaseous hydrogen at 500 bar (1370 kg) are hoisted directly from the stack onto a vessel. The stack contains on average 10 gaseous hydrogen containers. Two hydrogen containers are hoisted onto a vessel per day (high demand case). The supply of containers to the container terminal can take place via road (trailers), rail (train wagons) or water (e.g. container barges).

Scenario 2A: Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)

A vessel is bunkered with gaseous hydrogen from a tube-trailer (300 bar). The tube-trailer is connected via hoses to a compressor which compresses the gas to 500 bar that is in turn supplied to the receiving vessel. The bunker rate is controlled at 60 g/s to prevent excessive heating caused by adiabatic compression. A vessel (e.g. ferry) is bunkered once per day at a fixed location during nighttime (365 bunkering operations per year). The bunker volume equals the inventory of one tube-trailer (900 kg). The bunker duration is 4 hours and 10 minutes.

Scenario 2B: Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)

Gaseous hydrogen is supplied to the bunker station via an incoming hydrogen pipeline (20 bar). A compressor pressurizes the gas to 380 bar for storage into 10 (onshore) tube-containers. From the tube-containers, hydrogen is transferred through a pipeline with flexible joints to a bunker pontoon at which a receiving vessel is moored. The vessel is bunkered via two hose connections. Using pressure balancing (at relatively low pressures) and cascade filling and thereby avoiding problems of excessive adiabatic heating, a bunker rate of 3.000 kg/h is achieved. The onboard storage pressure is 250 bar. The fuel storage capacity is 2 x 800 kg (1600 kg). With a bunker rate of 3.000 kg/h this results in a bunker duration just over half an hour, conservatively assuming that the bunker volume is the same as the onboard fuel storage capacity. 1500 bunker operations are carried out per year (a little over 4 bunkering operations per day), which is assumed to be a feasible business case for a bunker station.

Scenario 3: Truck-to-ship bunkering of liquid hydrogen

Vessels are bunkered with liquid hydrogen from a trailer using a cryogenic pump and with a bunker rate of 65 m^3/h. The trailer is connected to a filling point with means of a short hose. An insulated pipeline runs from the filling point into a bunker boom. The outboard side of the bunker boom is a short 2 inch bunker hose that is connected to the bunker manifold of the receiving vessel. The vessel has a fuel tank capacity of 100 m^3. One vessel is bunkered per day at the same location (365 bunker operations per year), requiring 2 trailers per bunker operation to meet the bunker demand (50 m^3 per trailer).

Scenario 4A: Truck-to-ship bunkering of refrigerated liquid ammonia

Vessels are bunkered with refrigerated liquid ammonia from a trailer using a pump with a bunker rate of 65 m^3/h. The temperature of refrigerated liquid ammonia is -34 °C at atmospheric pressure. The trailer is connected directly to the vessel's bunker manifold using a hose. The fuel tank capacity is 75 m^3, which is scaled based on the difference in energy density using the liquid hydrogen scenario (scenario 3, with 100 m^3 fuel tank) as a reference. The bunker volume is 50 m^3 (inventory of one trailer) per operation, because it is assumed that a second trailer will not deliver only half of its capacity. The number of bunker operations is determined based on the assumption that the vessel has the same yearly energy demand as assumed in scenario 3 to allow for a meaningful comparison of bunkering the different liquid fuels and associated risk profiles (and safety distances). Based on the difference in energy density between liquid ammonia and liquid hydrogen, the required number of bunkering operations is determined at 549 per year to meet the same demand.

Scenario 4B: Truck-to-ship bunkering of pressurized liquid ammonia

Vessels are bunkered with liquid ammonia from a trailer using a pump with a bunker rate of 65 m^3/h. The pressure of liquid ammonia is 9 barg at atmospheric temperature. The trailer is connected to the vessel's manifold using a hose and is bunkered at 12 barg. A vessel has a fuel tank capacity of 67 m^3, scaled using the same approach as for scenario 4A. The bunker volume is 50 m^3 per operation. A total of 489 bunker operations per year are needed to meet the same annual demand as for scenario 4A. Pressurized liquid ammonia has a slightly higher energy density than refrigerated liquid ammonia therefore fewer bunkering operations are needed.

Scenario 5: Truck-to-ship bunkering of methanol

Vessels are bunkered with methanol from a trailer using a pump with a bunker rate of 65 m^3/h. The trailer is connected to the vessel's manifold using a hose. The fuel tank capacity is 54 m^3 based on differences in energy density (see explanation under scenario 4A). 398 bunker operations are required to meet the same annual energy demand as in the other truck-to-ship bunkering scenarios (3&4).

7 RESULTS

7.1 External safety distances

The calculated external safety distances per hydrogen bunkering scenario as determined in accordance with the applicable LUP approach in the Netherlands and Germany are given in Table 4. Reference is made to Appendix C for a more accurate size and location of the calculated external safety zone (10^{-6}/year risk contours) for bunkering in the Netherlands. Detailed input and results regarding the calculated distances for bunkering in Germany are included in Appendix B and Appendix D, respectively.

Table 4: Results for external safety distances

Scenario	Description	External safety distance [m]	
		The Netherlands*	Germany**
1a	Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack	39	182
1b	Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack	129	230
2a	Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)	37	96
2b	Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)	106	96
3	Truck-to-ship bunkering of liquid hydrogen	82	70
4a	Truck-to-ship bunkering of refrigerated liquid ammonia	175	205
4b	Truck-to-ship bunkering of pressurized liquid ammonia	543	395
5	Truck-to-ship bunkering of methanol	79	67

*Measured from the receiving vessel's bunker manifold to the boundary of the 10^{-6}/year location-specific risk contour (see Appendix C). For swapping containers, the distance is measured from the location of the containers on the vessel in the direction land inwards.
**Measured from possible leak locations, typically the distance is measured from the site boundary

The zones resulting from the external safety distances in the Netherlands must be free of vulnerable objects (e.g. residential areas, hospitals). Objects with limited vulnerability (e.g. isolated housing, small office buildings) can only be allowed to be present in the zone if it is sufficiently motivated.

The zones resulting from the external safety distances in Germany should not be understood as areas free of buildings. Within these zones less sensitive areas/usages than those described in article 50 (first sentence) of the Federal Immission Control Act may be planned. Specific guidance is developed (KAS-18), which contains advice on which usages and/or objects are to be considered sensitive (i.e. vulnerable) within the meaning of article 50.

The following is concluded from the results in Table 4:

The Netherlands

The external safety distances for swapping hydrogen containers at container terminals are relatively small (39 m) in the Netherlands when containers are directly loaded from trailer onto the receiving vessel. However, in the future case when demand grows and storage of containers in the stack might be needed (to create a buffer stock), the external safety distance could increase with about a factor 3. This should normally not be a problem for container terminals because of their layout and location, which provides sufficient stand-off distance to vulnerable objects. Bunkering of gaseous hydrogen via hose results in relatively small distances (approx. 40 m) when bunkering takes place directly from a (tube)-trailer. The distance for bunker stations could go up to approximately 100 m.

Germany

The external safety distances for swapping containers at container terminals are about a factor 2 larger than for bunkering gaseous hydrogen with a hose. The reason for this difference is related to the potential for explosions with high overpressures due to the level of confinement present at a container terminal. Typically, this level of confinement (&congestion) is expected to be much less for truck-to-ship bunkering and bunker stations (scenario 2a&2b) as bunkering will typically take place in an open area where the gas cannot accumulate in confined areas. If this is not the case, the safety distances for scenario 1a/1b may be more appropriate.

The Netherlands & Germany

For truck-to-ship (TTS) bunkering of liquid hydrogen and methanol result in safety distances of approximately 70-80 m, which are in line with calculated distances for TTS bunkering of LNG to inland vessels in the LNG Masterplan study of 2015 /12/. For bunkering ammonia, the safety distances are considerably larger and are caused by the high toxicity of ammonia. The distances for pressurized ammonia are about a factor 2-3 larger than for bunkering refrigerated ammonia. It will be challenging to introduce ammonia as a fuel in IWT due to the large safety distances for bunkering ammonia with a hose. This could be showstopper for bunkering ammonia in inland ports and waterways where residential areas and industries etc. could be nearby.

7.2 Focus areas

The distances for the calculated focus areas are provided in Table 5. These areas are only applicable in the Netherlands and are based on new legislation that is expected to come into force in January 2022. Germany does not require the determination of focus areas.

Table 5: Focus area distances

Scenario	Description	Fire area distance* [m]	Explosion area distance* [m]	Toxic area distance* [m]
1a	Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack	110	128	-
1b	Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack	150	223	-
2a	Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)	60	132	-
2b	Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)	105	195	-
3	Truck-to-ship bunkering of liquid hydrogen	150	185	-
4a	Truck-to-ship bunkering of refrigerated liquid ammonia	-	-	777
4b	Truck-to-ship bunkering of pressurized liquid ammonia	-	-	1203
5	Truck-to-ship bunkering of methanol	122	-	-

*Measured from the receiving vessel's bunker manifold to the boundary of the contours given in Appendix C. For swapping containers, the distance is measured from the location of the containers on the vessel in the direction land inwards.

The following is observed from the above results:

- The explosion focus areas are all in the range of approximately 130 m – 220 m for bunkering hydrogen in gaseous (via hose or container swapping) or liquid form.
- The fire focus areas are between 60 m – 150 m.
- The focus areas for bunkering ammonia are very large (in the range of 1 km) due to the high toxicity of ammonia.

Within the areas, specific construction requirements may be enforced for buildings to offer protection against fire, explosion or toxic impact to the occupants inside.

8 CONCLUSIONS

This study provides guidance for safety distances for land-based systems supplying hydrogen to vessels in the Netherlands and Germany. Different types of safety distances applicable for hydrogen installations and bunkering are discussed: external & internal safety distances, focus areas, safety zone distances and hazardous areas. External safety distances that need to be considered in the permitting and land-use planning (LUP) process are calculated. These are determined in accordance with the applicable LUP approach as mandated by national legislation.

In addition, focus areas are calculated based on new Dutch legislation that is expected to come into force in January 2022. The focus areas provide an insight into the potential hazards in an area and where attention should be paid to extra protection for occupants in buildings. These areas are only relevant for the Netherlands and not Germany. Much is still unknown about the practical implementation of these areas because they are not mandatory yet. For these reasons, the results are not further discussed in the conclusion. Reference is made to paragraph 7.2 for the results.

The bunkering scenarios assessed in this study are based on the outcomes of RH2INE sub-study 1a: Safety framework conditions, Sub-Activity (SuAc) 1.1b: *Identification of hydrogen bunkering scenarios for inland navigational vessels* /1/. The SuAc 1.1b report contains a short list of the most feasible IWT hydrogen bunkering scenarios as determined in a workshop held with the RH2INE consortium participants and stakeholders.

The approach to determine external safety distances in the Netherlands and Germany differs because both countries have made their own implementation of the Seveso III Directive. The Netherlands uses a risk-based approach (QRA), while Germany has developed a deterministic approach with implicit judgment of risk. For this reason, the distances in the Netherlands and Germany are not always comparable for the same bunkering scenario and (large) differences are possible.

The bunkering scenarios assessed in this study including the calculated external safety distances are given in the table below. It must be noted that the distances are highly dependent on the chosen starting points and assumptions (included in Appendix A). The distances should therefore be considered as indicative and are primarily useful to compare the impact on external safety of the different bunkering scenarios.

Table 6: Results for external safety distances

Scenario	Description	External safety distance [m]*	
		The Netherlands	Germany
1a	Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack	39	182
1b	Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack	129	230
2a	Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)	37	96
2b	Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)	106	96
3	Truck-to-ship bunkering of liquid hydrogen	82	70
4a	Truck-to-ship bunkering of refrigerated liquid ammonia	175	205
4b	Truck-to-ship bunkering of pressurized liquid ammonia	543	395
5	Truck-to-ship bunkering of methanol	79	67

* Reference is made to Table 4 for an explanation from where these distances should be measured.

The zones resulting from the external safety distances in the Netherlands must be free of vulnerable objects (e.g. housing in residential areas, hospitals). Objects with limited vulnerability (e.g. isolated housing, small office buildings) can only be allowed to be present in the zone if it is sufficiently motivated.

The zones resulting from the external safety distances in Germany should not be understood as areas free of buildings. Within these zones less sensitive areas/usages than those described in article 50 (first sentence) of the Federal Immission Control Act may be planned. Specific guidance is developed (KAS-18), which contains advice on which usages and/or objects are to be considered sensitive (i.e. vulnerable) within the meaning of article 50.

The following is concluded from the results for external safety distances:

The Netherlands

The external safety distances for swapping hydrogen containers at container terminals are relatively small (39 m) in the Netherlands when containers are directly loaded from trailer onto the receiving vessel. However, in the future case when demand grows and storage of containers in the stack might be needed (to create a buffer stock), the external safety distance could increase with about a factor 3. This should normally not be a problem for container terminals because of their layout and location, which provides sufficient stand-off distance to vulnerable objects. Bunkering of gaseous hydrogen via hose results in relatively small distances (approx. 40 m) when bunkering takes place directly from a (tube)-trailer. The distance for bunker stations could go up to approximately 100 m.

Germany

The external safety distances for swapping containers at container terminals are about a factor 2 larger than for bunkering gaseous hydrogen with a hose. The reason for this difference is related to the potential for explosions with high overpressures due to the level of confinement present at a container terminal. Typically, this level of confinement (&congestion) is expected to be much less for truck-to-ship bunkering and bunker stations (scenario 2a&2b) as bunkering will typically take place in an open area where the gas cannot accumulate in confined areas. If this is not the case, the safety distances for scenario 1a/1b may be more appropriate.

The Netherlands & Germany

For truck-to-ship (TTS) bunkering of liquid hydrogen and methanol result in safety distances of approximately 70-80 m, which are in line with calculated distances for TTS bunkering of LNG to inland vessels in the LNG Masterplan study of 2015 /12/. For bunkering ammonia, the safety distances are considerably larger and are caused by the high toxicity of ammonia. The distances for pressurized ammonia are about a factor 2-3 larger than for bunkering refrigerated ammonia. It will be challenging to introduce ammonia as a fuel in IWT due to the large safety distances for bunkering ammonia with a hose. This could be showstopper for bunkering ammonia in inland ports and waterways where residential areas and industries etc. could be nearby.

9 REFERENCES

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/5/ Dutch Standardization Institute (Nederlands Normalisatie-instituut, NEN) - PGS 33-2 (“Publicatiereeks Gevaarlijke Stoffen”), Guideline for LNG bunker stations (shore to ship), April 2020.

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/7/ IEC 60079-10-1, Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres, 2020

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/11/ KAS – Commission on Process Safety. KAS-18: Recommendations for separation distances between establishments covered by the Major Accidents Ordinance (Störfall-Verordnung) and areas worthy of protection within the framework of land-use planning – implementation of article 50 of the Federal Immission Control Act (BlmSchG); 2nd revised edition, Nov. 2010. Supplemented by KAS-32: Scenario specific questions related to KAS-18; 2nd revised edition, Nov. 2015.

/12/ DNV, Safety Study LNG Masterplan for Rhine Port Group, Suac D 2.4.2, Part C: Comparison of risk assessment tools, 2015

APPENDIX A
Starting points and assumptions for bunkering scenarios

Scenario 1A: Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack

Parameter	Value	Unit	Remarks
Material	Hydrogen		
Temperature	9.8	°C	Average ambient temperature in the Netherlands
Pressure	300	barg	300 bar systems are currently the most used and are readily available (start-up case).
Volume inventory per container (at pressure)	44	m^3	Reference point is a tube-container containing 900 kg @ 20 °C and 300 bar = 44 m^3 H_2 gas
Container transfers (full containers)	156	$Year^{-1}$	The base assumption is 3 container swaps per week (low demand case). Containers taken from the vessel are assumed to be empty and not taken into account.

Scenario 1B: Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack

Parameter	Value	Unit	Remarks
Material	Hydrogen		
Temperature	9.8	°C	Average ambient temperature in the Netherlands
Pressure	500	barg	500 bar is assumed to be most optimal for inland shipping in terms of energy density and weight of the containment system
Design pressure of cylinders/tubes in container	750	barg	Assumption (not based on design data). This assumption is needed for definition of the failure case when containers are stored in stack and exposed to a fire resulting in a catastrophic failure at design pressure.
Inventory container	44	m^3	Reference point is a tube-container containing 900 kg @ 20 °C and 300 bar = 44 m^3 H_2 gas
Container transfers (full containers)	730	$Year^{-1}$	Base assumption is 2 container swaps per day. Containers taken from the vessel are assumed to be empty and not taken into account.
Full containers in stack	10	containers	It is assumed that there is an average of 10 containers in the stack present throughout the year.

Scenario 2A: Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)

Parameter	Value	Unit	Remarks
Material	Hydrogen		
Temperature	9.8	°C	Average ambient temperature in the Netherlands
Pressure trailer	300	barg	
Bunker pressure	500	barg	Using a compressor
Hose diameter	1	inch	
Number of hoses	1	-	
Maximum onboard storage capacity	900	kg	
Bunker volume (mass)	900	Kg	Inventory one trailer
Bunker rate	60	g/s	
Number of bunker operations per year	365	$Year^{-1}$	1 bunkering operation per day
Bunker hours	1522	h/year	Based on bunker rate

Scenario 2B: Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)

Parameter	Value	Unit	Remarks
Material	Hydrogen		
Temperature	9.8	°C	Average ambient temperature in the Netherlands
Pressure storage onshore	380	barg	
Pressure storage fuel tanks on board	250	barg	
Hose diameter	2	inch	
Number of hoses	2	-	Two 2-inch hoses are used simultaneously
Inventory onboard storage	2x800	Kg	2 tube-containers of each 800 kg at 250 bar (e.g. 44 m3 inventory per tube-container)
Number of bunker operations per year	1500	$Year^{-1}$	Assumed to be a feasible business case for a bunker station (based on previous studies)
Bunker hours	800	h/year	Based on 3000 kg/h, 1600 kg onboard storage and 1500 operations per year
Hydrogen throughput	2.400.000	Kg/year	Based on 1600 kg onboard storage and 1500 operations per year
Onshore storage capacity	10 x 44	m^3	Assumption based on ~1.5x daily demand to account for supply interruptions. 10 tube-containers.

Scenario 3: Truck-to-ship bunkering of liquid hydrogen

Parameter	Value	Unit	Remarks
Material	Hydrogen		
Temperature	-246	°C	Due to heat intake (trailer/hoses), temperature will be a few degrees higher than normal boiling point (-253 °C)
Bunker pressure	7	barg	7 barg bunker pressure, 5 barg onboard storage pressure
Hose diameter	2	inch	
Number of hoses	1	-	
Inventory fuel tank	100	m^3	Based on energy density LNG vs LH2 assuming equivalent to typical 40 m^3 LNG fuel tank for inland vessels based on previous studies. Rounded to 100 m^3
Bunker rate	65	m^3/h	Assumed 4000 kg/h bunker rate (@ -246 °C and 7 barg)
Bunker volume (per operation)	100	m^3	Two trailers unload during one operation
Number of bunker operations per year	365	$Year^{-1}$	Assumed 1 bunkering operation per day
Bunker hours	562	h/year	Based on 100 m^3 onboard storage, 65 m^3/h bunker rate and 365 operations per year
Hydrogen throughput	2.248.000	Kg/year	Based on bunker rate of 4000 kg/h and 562 hours per year

Scenario 4A: Truck-to-ship bunkering of refrigerated liquid ammonia

Parameter	Value	Unit	Remarks
Material	Ammonia		
Temperature	-34	°C	
Bunker pressure	5	barg	
Hose diameter	2	inch	
Number of hoses	1	-	
Inventory fuel tank	75	m^3	Scaled based on the difference in energy density using the liquid hydrogen scenario (scenario 3, with 100 m^3 fuel tank) as a reference
Bunker rate	65	m^3/h	Same rate as scenario 3. A two inch hose results in acceptable flow velocity in the range of 7-12 m/s.
Bunker volume (per operation)	50	m^3	One trailer per bunker operation
Number of bunker operations per year	549	$Year^{-1}$	Assumed same energy demand as for LH2 (scenario 3). See detailed scenario explanation in section 1.
Bunker hours	422	h/year	Based on 75 m^3 onboard storage, 65 m^3/h bunker rate and 549 operations per year
Annual ammonia throughput	27.430	m^3/year	422 bunker hours per year with 65 m^3/h

Scenario 4B: Truck-to-ship bunkering of pressurized liquid ammonia

Parameter	Value	Unit	Remarks
Material	Ammonia		
Temperature	9.8	°C	
Bunker pressure	12	barg	
Hose diameter	2	inch	
Number of hoses	1	-	
Inventory fuel tank	67	m^3	Scaled based on the difference in energy density using the liquid hydrogen scenario (scenario 3, with 100 m^3 fuel tank) as a reference.
Bunker rate	65	m^3/h	See scenario 4A
Bunker volume (per operation)	50	m^3	One trailer per bunker operation
Number of bunker operations per year	489	$Year^{-1}$	Assumed same energy demand as for LH2 (scenario 3). See detailed scenario explanation in section 1.
Bunker hours	376	h/year	Based on 67 m^3 onboard storage, 65 m^3/h bunker rate and 489 operations per year
Annual ammonia throughput	24.440	m^3/year	376 bunker hours per year and a bunker rate of 65 m^3/h

Scenario 5: Truck-to-ship bunkering of methanol

Parameter	Value	Unit	Remarks
Material	Ammonia		
Temperature	9.8	°C	
Bunker pressure	5	barg	
Hose diameter	2	inch	
Number of hoses	1	-	
Inventory fuel tank	54	m^3	Scaled based on the difference in energy density using the liquid hydrogen scenario (scenario 3, with 100 m^3 fuel tank) as a reference.
Bunker rate	65	m^3/h	See explanation under scenario 4A
Bunker volume (per operation)	50	m^3	One trailer per bunker operation
Number of bunker operations per year	398	$Year^{-1}$	Assumed same energy demand as for LH2 (scenario 3). See detailed scenario explanation in section 1.
Bunker hours	306	h/year	Based on 54 m^3 onboard storage, 65 m^3/h bunker rate and 398 operations per year
Annual ammonia throughput	19 890	m^3/year	306 bunker hours per year with 65 m^3/h

APPENDIX B

Scenario-specific input parameters for KAS-18 calculations

Scenario 1a: Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack

Hazardous substance:	Hydrogen
Maximum volume in trailer:	V = 44 m³
Temperature:	T = 20 °C
Pressure:	P = 300 barg
Hole size:	A = 490 mm² ➔ D = 25 mm
Discharge coefficient:	0.62 (sharp)
Roughness length:	1000 mm; regular large obstacle coverage
Release duration (calculated):	164 s
Discharge rate (Phast):	5.5 kg/s
Released amount:	899 kg
Multi Energy (ME) strength curve:	10 (due to high reactivity)[11]

Scenario 1b: Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack

Hazardous substance:	Hydrogen
Maximum volume in trailer:	V = 44 m³
Temperature:	T = 20 °C
Pressure:	P = 500 barg
Hole size:	A = 490 mm² ➔ D = 25 mm
Design pressure container:	750 barg
Discharge coefficient:	0.62 (sharp)
Roughness length:	1000 mm; regular large obstacle coverage
Release duration (calculated):	151 s
Discharge rate (Phast):	8.9 kg/s
Released amount:	1334 kg
Multi Energy (ME) strength curve:	10 (due to high reactivity)[11]

Scenario 2a: Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)

Hazardous substance:	Hydrogen
Maximum volume in vessel:	V = 44 m³
Temperature:	T = 20 °C
Pressure:	P = 500 barg
Hole size:	A = 490 mm² ➔ D = 25 mm (= hose diameter)
Pipe length:	5 m
Roughness length:	300 mm; relatively flat area with small buildings
Release duration:	120 s; truck-to-ship bunkering operation is supervised, operator intervention is assumed that stops the release after latest 120 s
Discharge rate (Phast):	7.4 kg/s

[11] Hydrogen is a high reactive material and there are expected to be congested areas on a container terminal, therefore a ME strength curve of 10 (highest) is used for the explosion calculations.

Released amount (calculated):	889 kg
Multi Energy (ME) strength curve:	2 (default unconfined explosion strength)[12]

Scenario 2b: Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)

Hazardous substance:	Hydrogen
Maximum volume in container:	V = 88 m^3 (assumed two tube containers in open connection)
Temperature:	T = 20 °C
Pressure:	P = 380 barg
Hole size:	A = 490 mm^2 ➔ D = 25 mm
Discharge coefficient:	0.62 (sharp)
Roughness length:	300 mm; relatively flat area with small buildings
Release duration:	120 s; bunkering operation is supervised, operator intervention is assumed that stops the release after latest 120 s
Discharge rate (Phast):	6.8 kg/s
Released amount (calculated):	822 kg
Multi Energy (ME) strength curve:	2 (default unconfined explosion strength)[13]

Scenario 3: Truck-to-ship bunkering of liquid hydrogen

Hazardous substance:	Hydrogen
Maximum volume (fuel tank vessel)[14]:	V = 100 m^3
Temperature:	T = -246 °C
Pressure:	P = 7 barg
Hole size:	A = 490 mm^2 ➔ D = 25 mm
Discharge coefficient:	0.62 (sharp)
Roughness length:	300 mm; relatively flat area with small buildings
Release duration:	120 s; truck-to-ship bunkering operation is supervised, operator intervention is assumed that stops the release after latest 120 s
Discharge rate (Phast):	2.8 kg/s
Released amount (calculated):	335 kg
Multi Energy (ME) strength curve:	2 (default unconfined explosion strength)[15]

[12] During truck-to-ship bunkering, it is not expected that flammable gas clouds (due to leakage scenarios) can reach congested areas. Typically, truck-to-ship bunkering will take place in an open area. In an open space, outdoors situation, there is no or limited confinement. Additionally, since hydrogen is lighter than air it will lift off, reducing the probability of gas accumulating in a congested area. For the explosion analysis, however, it is assumed that a typical strength factor would be 2 applicable (slight confinement, e.g. fences, bunds, or hedges).

[13] During truck-to-ship bunkering, it is not expected that flammable gas clouds (due to leakage scenarios) can reach congested areas. Typically, truck-to-ship bunkering will take place in an open area. In an open space, outdoors situation, there is no or limited confinement. Additionally, since hydrogen is lighter than air it will lift off, reducing the probability of gas accumulating in a congested area. For the explosion analysis, however, it is assumed that a typical strength factor would be 2 applicable (slight confinement, e.g. fences, bunds, or hedges).

[14] It is assumed that the vessel will only bunker if it can accept the load of a full truck. The maximum amount of material in the truck + vessel is equal to the maximum storage capacity of the vessel. For the LH2 vessel a storage tank of 100 m^3 is assumed, this is based on previous studies with inland LNG vessels with a typical storage capacity of 40 m^3 LNG. Using the energy density of LNG and LH2 the storage capacity for LH2 is calculated so that it carries a similar amount of energy to a typical LNG inland vessel.

[15] During truck-to-ship bunkering, it is not expected that flammable gas clouds (due to leakage scenarios) can reach congested areas. Typically, truck-to-ship bunkering will take place in an open area. In an open space, outdoors situation, there is no or limited confinement. Additionally, since hydrogen is lighter than air it will lift off, reducing the probability of gas accumulating in a congested area. For the explosion analysis, however, it is assumed that a typical strength factor would be 2 applicable (slight confinement, e.g. fences, bunds, or hedges).

Scenario 4a: Truck-to-ship bunkering of refrigerated liquid ammonia

Hazardous substance:	Ammonia
Maximum volume (fuel tank vessel)[16]:	V = 75 m³
Temperature:	T = -34 °C
Pressure:	P = 5 barg
Hole size:	A = 490 mm² ➔ D = 25 mm
Discharge coefficient:	0.62 (sharp)
Roughness length:	300 mm; relatively flat area with small buildings
Release duration:	120 s; truck-to-ship bunkering operation is supervised, operator intervention is assumed that stops the release after latest 120 s
Discharge rate (Phast):	9.0 kg/s
Released amount (calculated):	1076 kg
Multi Energy (ME) strength curve:	2 (default unconfined explosion strength)[17]

Scenario 4b: Truck-to-ship bunkering of pressurized liquid ammonia

Hazardous substance:	Ammonia
Maximum volume (fuel tank vessel)[18]:	V = 67 m³
Temperature:	T = 20 °C
Pressure:	P = 12 barg
Hole size:	A = 490 mm² ➔ D = 25 mm
Discharge coefficient:	0.62 (sharp)
Roughness length:	300 mm; relatively flat area with small buildings
Release duration:	120 s; truck-to-ship bunkering operation is supervised, operator intervention is assumed that stops the release after latest 120 s
Discharge rate (Phast):	13 kg/s
Released amount (calculated):	1576 kg
Multi Energy (ME) strength curve:	2 (default unconfined explosion strength)[19]

[16] It is assumed that the vessel will only bunker if it can accept the load of a full truck. The maximum amount of material in the truck + vessel is equal to the maximum storage capacity of the vessel. Based on the energy density of ammonia and LH2, the storage capacity for ammonia is calculated so that the vessel carries a similar amount of energy as the LH2 vessel (scenario 3).

[17] During truck-to-ship bunkering, it is not expected that flammable gas clouds (due to leakage scenarios) can reach congested areas. Typically, truck-to-ship bunkering will take place in an open area. In an open space, outdoors situation, there is no or limited confinement. For the explosion analysis, however, it is assumed that a typical strength factor would be 2 applicable (slight confinement, e.g. fences, bunds, or hedges).

[18] It is assumed that the vessel will only bunker if it can accept the load of a full truck. The maximum amount of material in the truck + vessel is equal to the maximum storage capacity of the vessel. Based on the energy density of ammonia and LH2, the storage capacity for ammonia is calculated so that the vessel carries a similar amount of energy as the LH2 vessel (scenario 3).

[19] During truck-to-ship bunkering, it is not expected that flammable gas clouds (due to leakage scenarios) can reach congested areas. Typically, truck-to-ship bunkering will take place in an open area. In an open space, outdoors situation, there is no or limited confinement. For the explosion analysis, however, it is assumed that a typical strength factor would be 2 applicable (slight confinement, e.g. fences, bunds, or hedges).

Scenario 5: Truck-to-ship bunkering of methanol

Hazardous substance:	Methanol
Maximum volume (fuel tank vessel)[20]:	V = 54 m^3
Temperature:	T = 20 °C
Pressure:	P = 5 barg
Hole size:	A = 490 mm^2 ➔ D = 25 mm
Discharge coefficient:	0.62 (sharp)
Roughness length:	300 mm; relatively flat area with small buildings
Release duration:	120 s; truck-to-ship bunkering operation is supervised, operator intervention is assumed that stops the release after latest 120 s
Discharge rate (Phast):	9.9 kg/s
Released amount (calculated):	1184 kg
Multi Energy (ME) strength curve:	2 (default unconfined explosion strength)[21]

[20] It is assumed that the vessel will only bunker if it can accept the load of a full truck. The maximum amount of material in the truck + vessel is equal to the maximum storage capacity of the vessel. Based on the energy density of methanol and LH2, the storage capacity for methanol is calculated so that the vessel carries a similar amount of energy as the LH2 vessel (scenario 3).

[21] During truck-to-ship bunkering, it is not expected that flammable gas clouds (due to leakage scenarios) can reach congested areas. Typically, truck-to-ship bunkering will take place in an open area. In an open space, outdoors situation, there is no or limited confinement. For the explosion analysis, however, it is assumed that a typical strength factor would be 2 applicable (slight confinement, e.g. fences, bunds, or hedges).

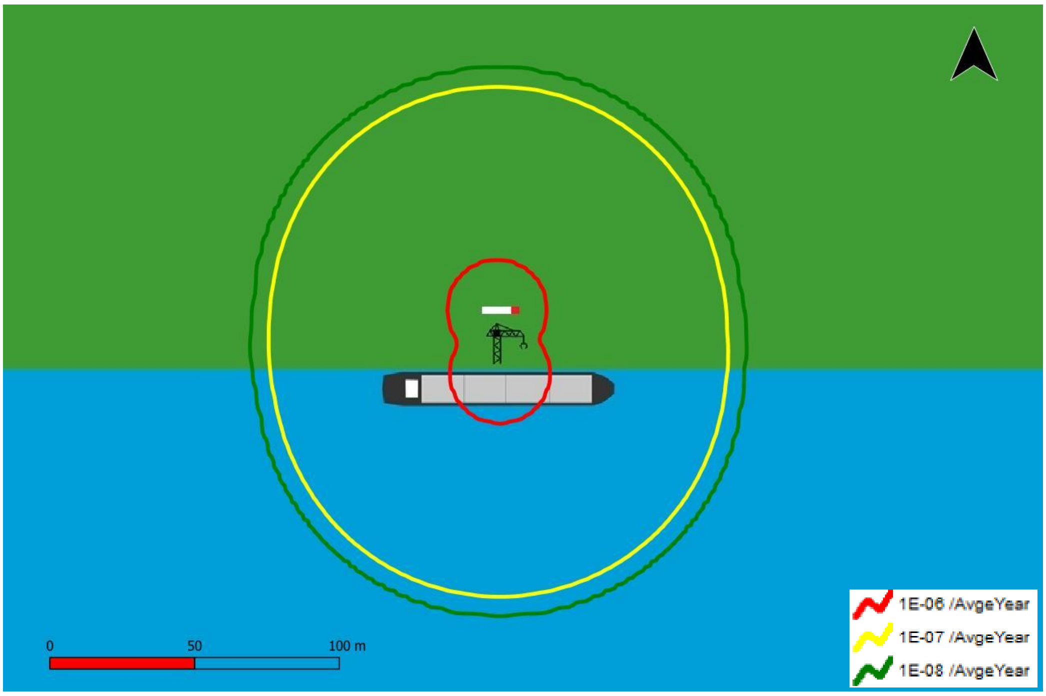
APPENDIX C

Detailed QRA results (risk contours & focus areas)

Location-specific individual risk contours

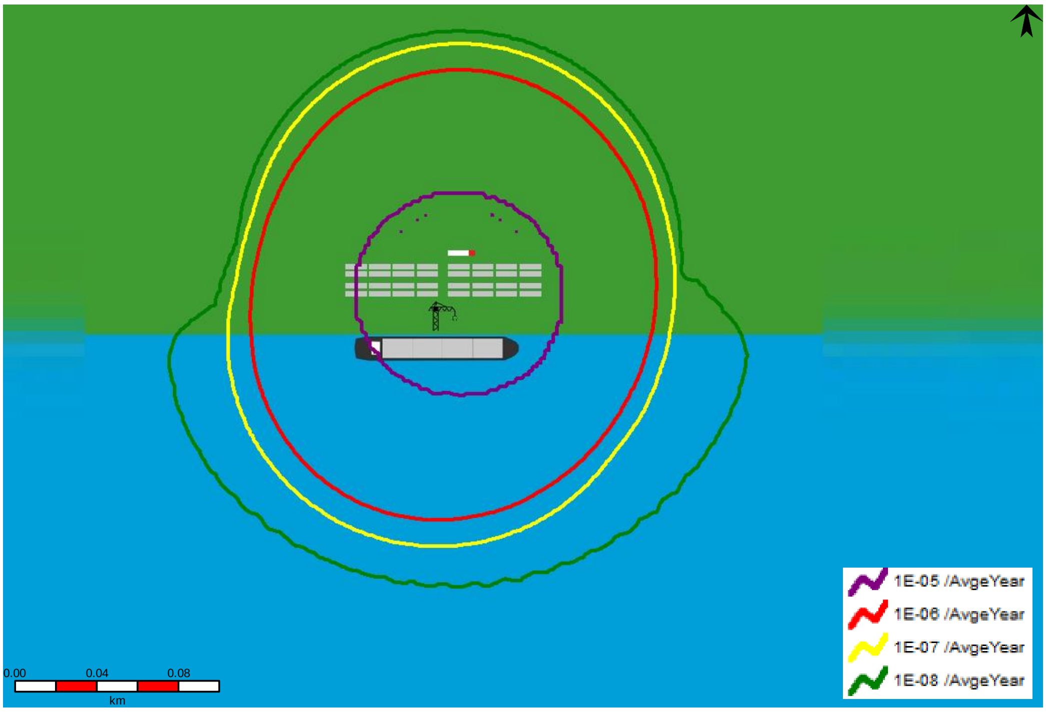
The external safety distances below are based on the size of the 10^{-6}/year risk contour. The distance is measured from the receiving vessel's bunker manifold to the boundary of the 10^{-6}/year contour. For swapping containers, the distance is measured from the location of the containers on the vessel in the direction land inwards.

Scenario 1A: Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack



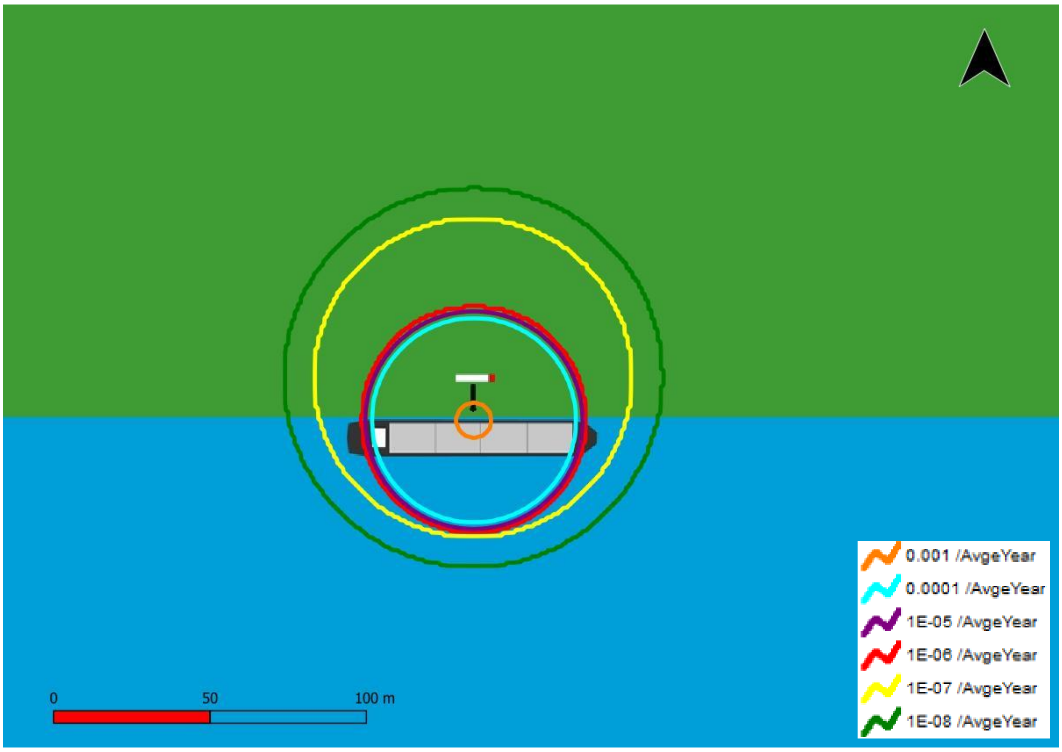
External safety distance: 39 m

Scenario 1B: Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack



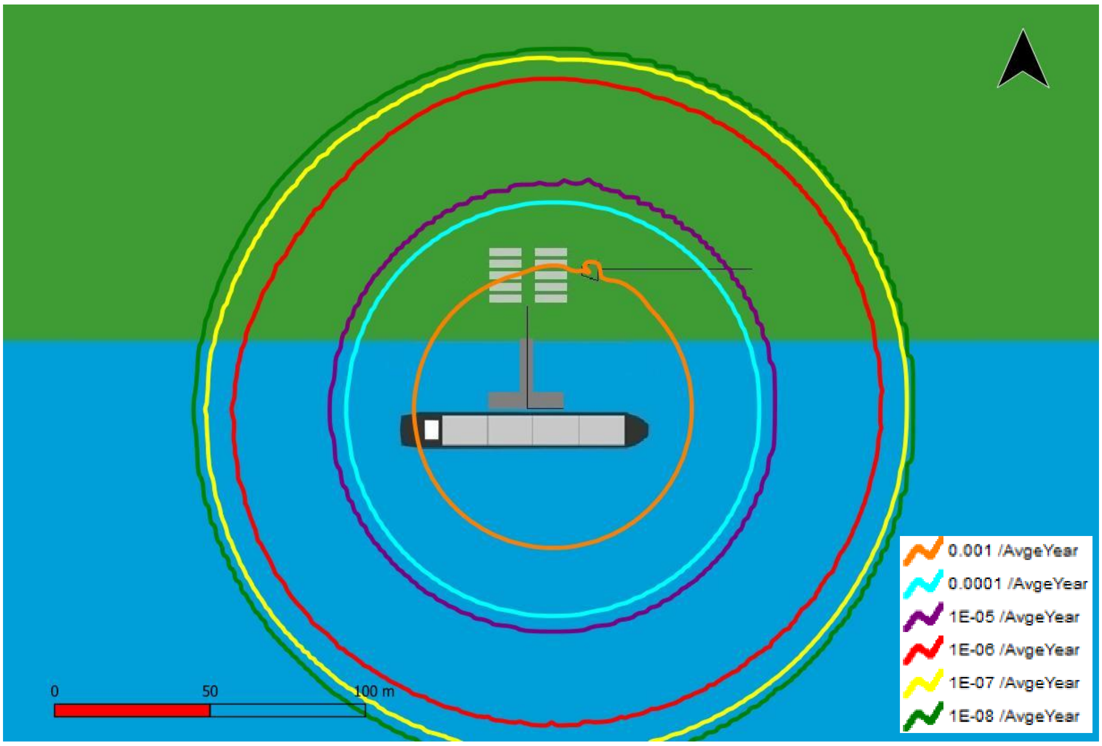
External safety distance: 129 m

Scenario 2A: Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)



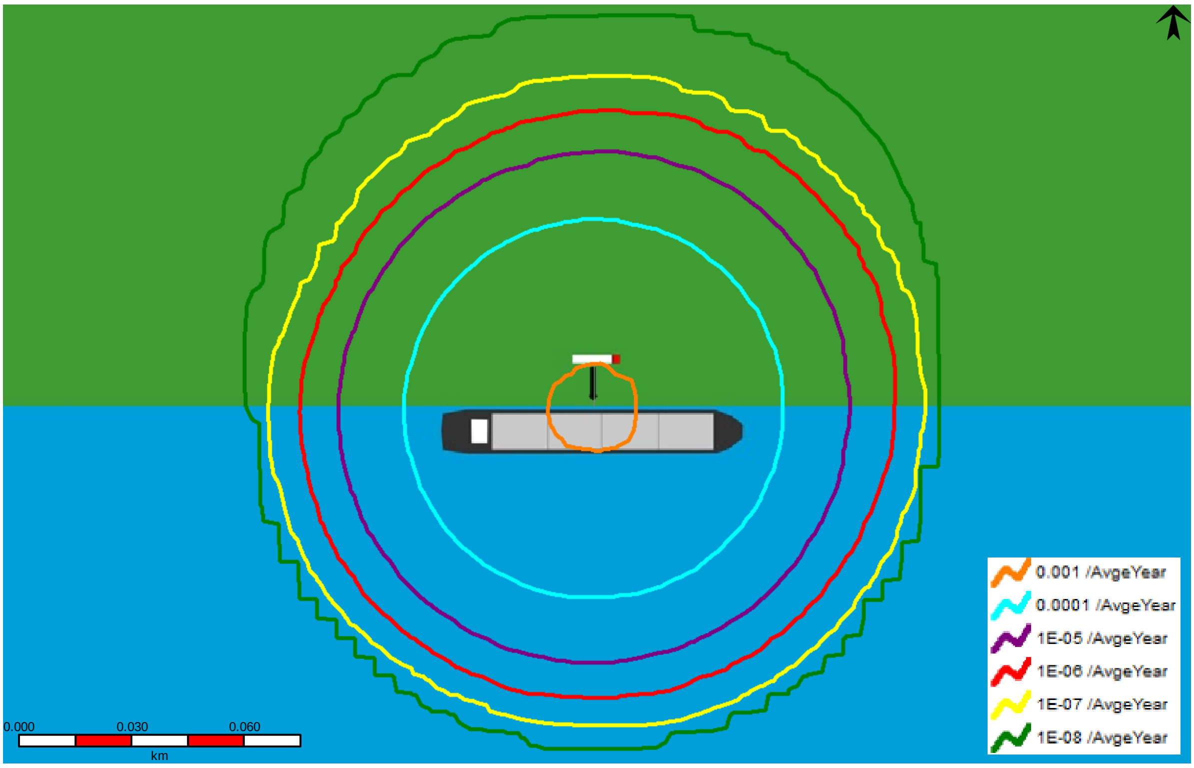
External safety distance: 37 m

Scenario 2B: Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)



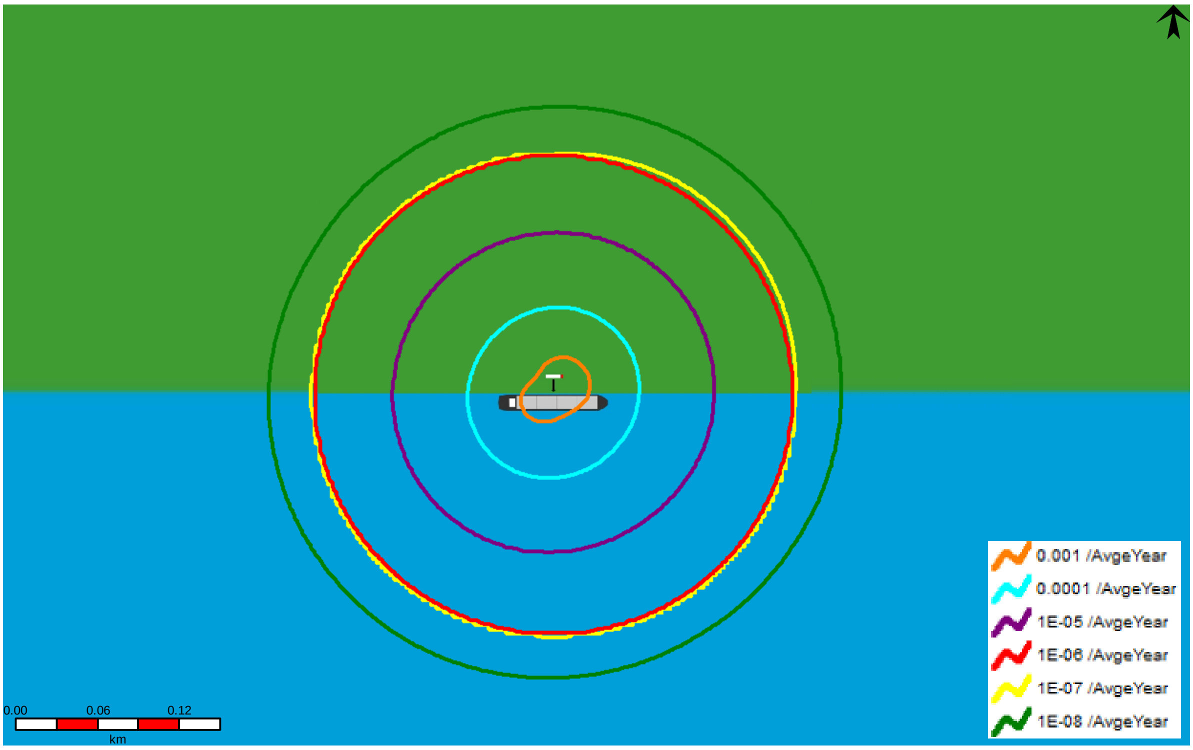
External safety distance: 106 m

Scenario 3: Truck-to-ship bunkering of liquid hydrogen



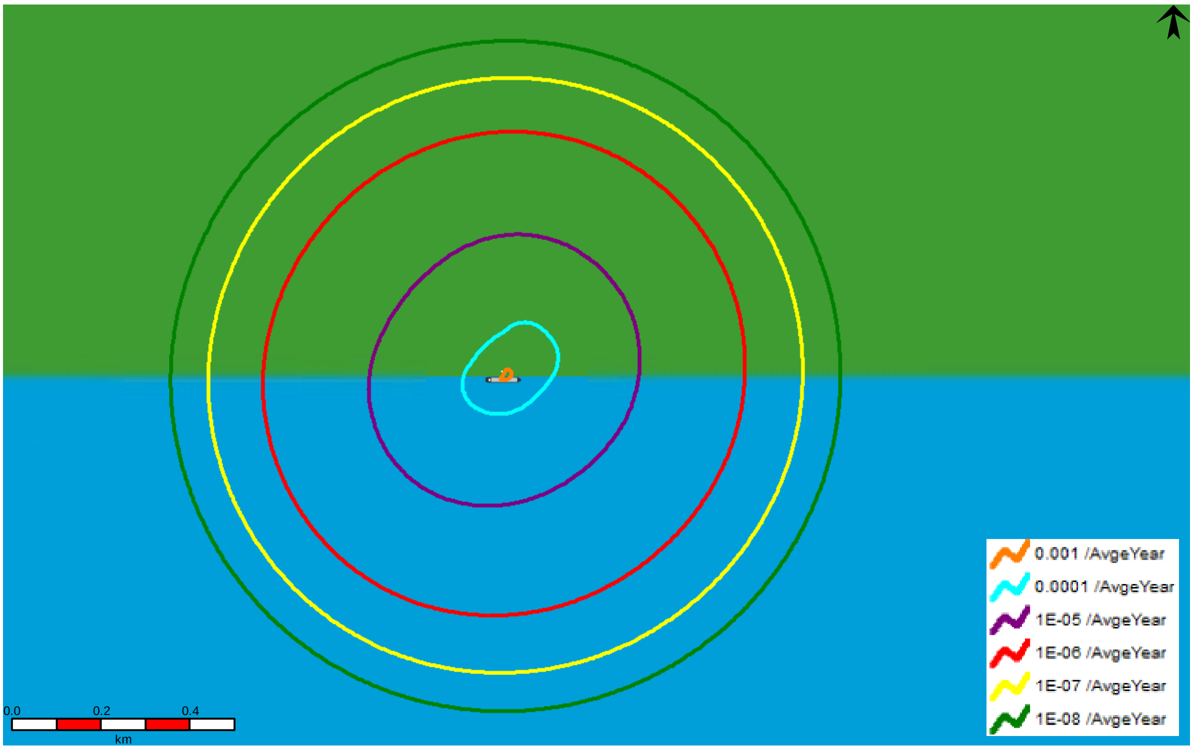
External safety distance: 82 m

Scenario 4A: Truck-to-ship bunkering of refrigerated liquid ammonia



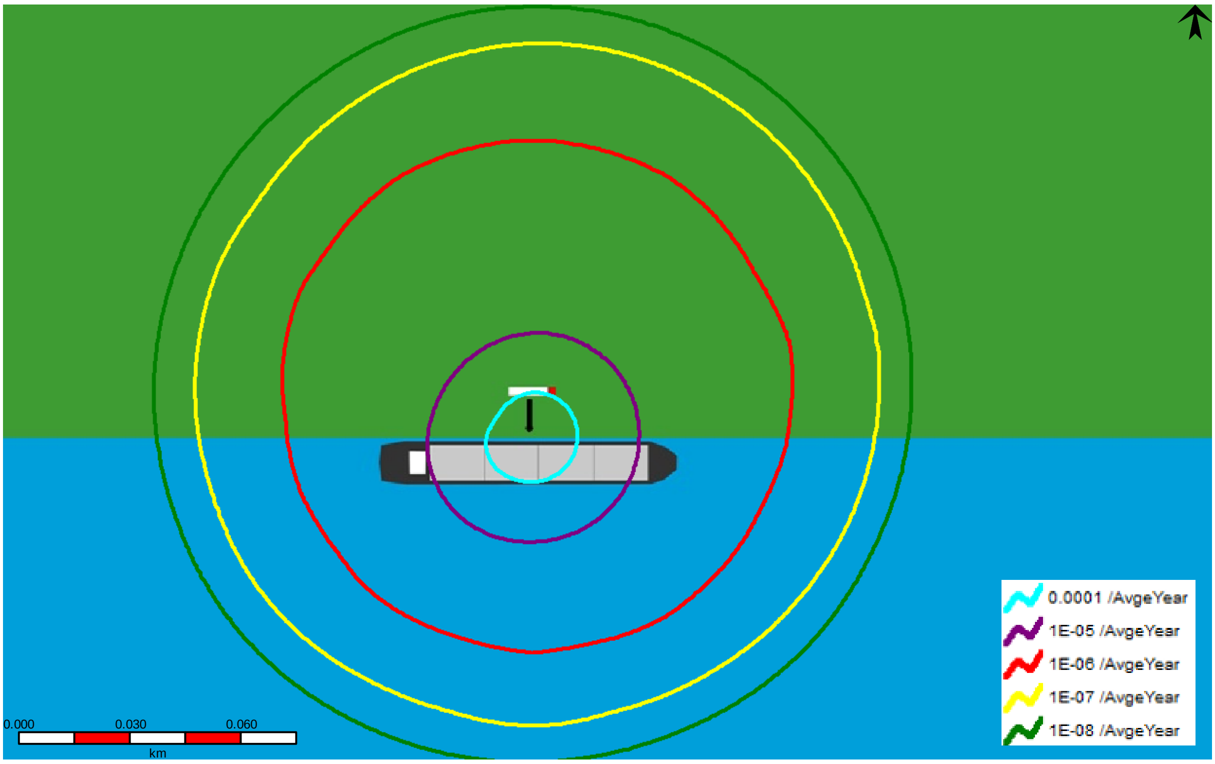
External safety distance: 175 m

Scenario 4B: Truck-to-ship bunkering of pressurized liquid ammonia



External safety distance: 543 m

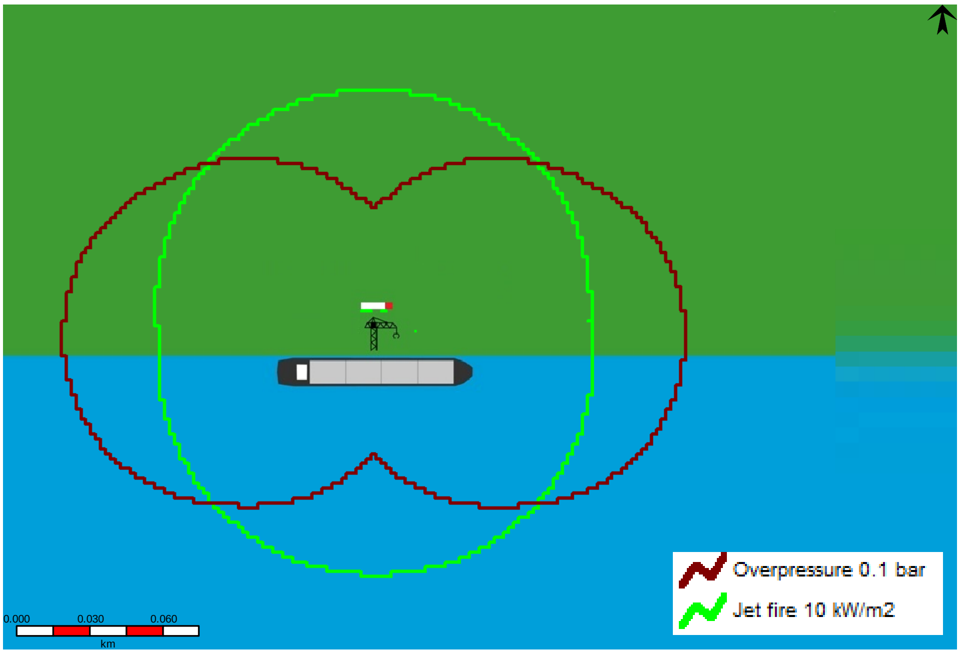
Scenario 5: Truck-to-ship bunkering of methanol



External safety distance: 79 m

Focus areas

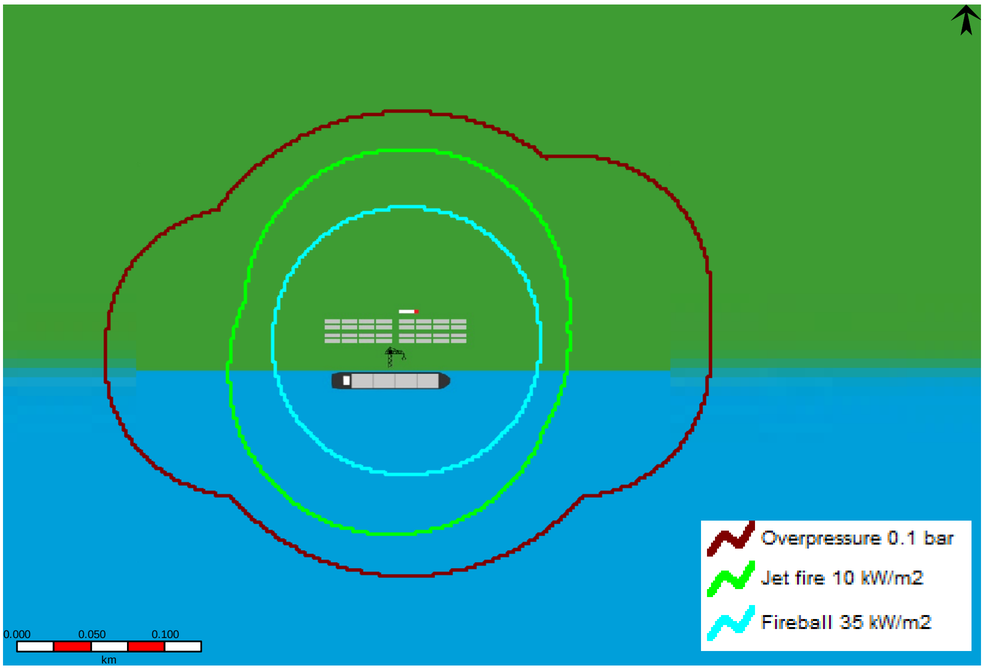
Scenario 1A: Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack



Fire area distance: 110 m

Explosion area distance: 128 m

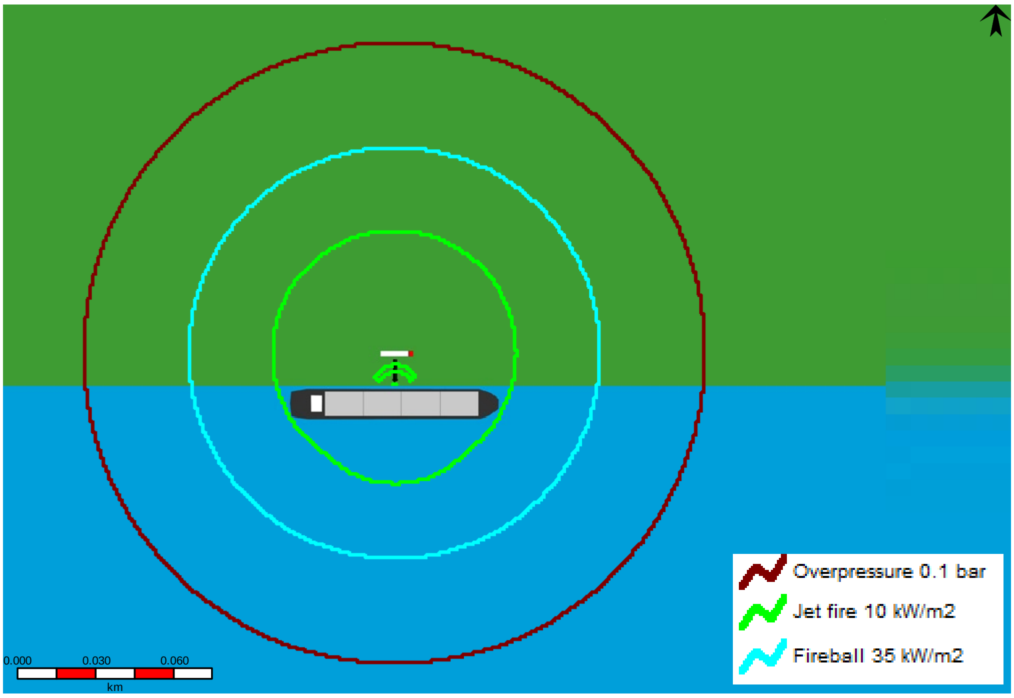
Scenario 1B: Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack



Fire area distance: 150 m

Explosion area distance: 223 m

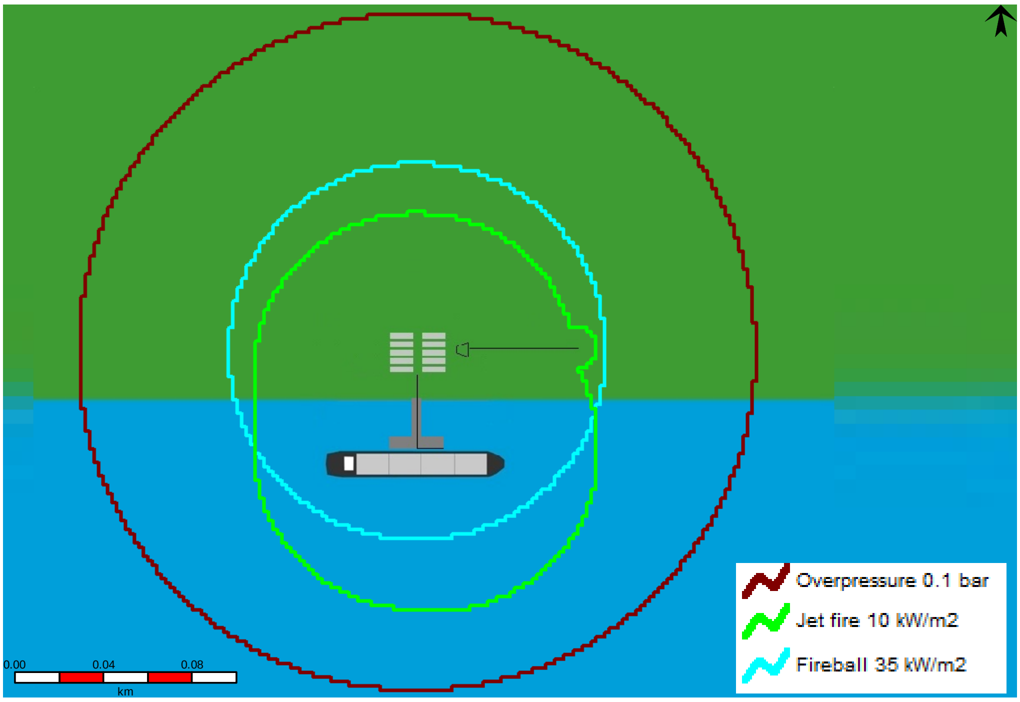
Scenario 2A: Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)



Fire area distance: 60 m

Explosion area distance: 132 m

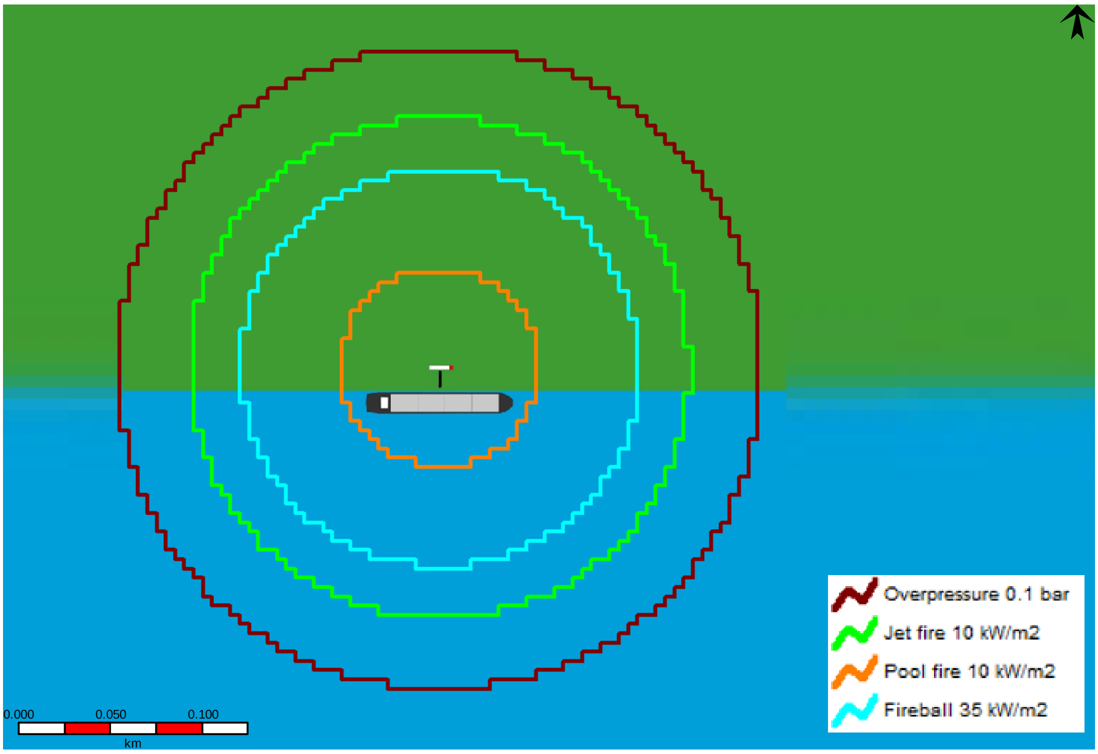
Scenario 2B: Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)



Fire area distance: 105 m

Explosion area distance: 195 m

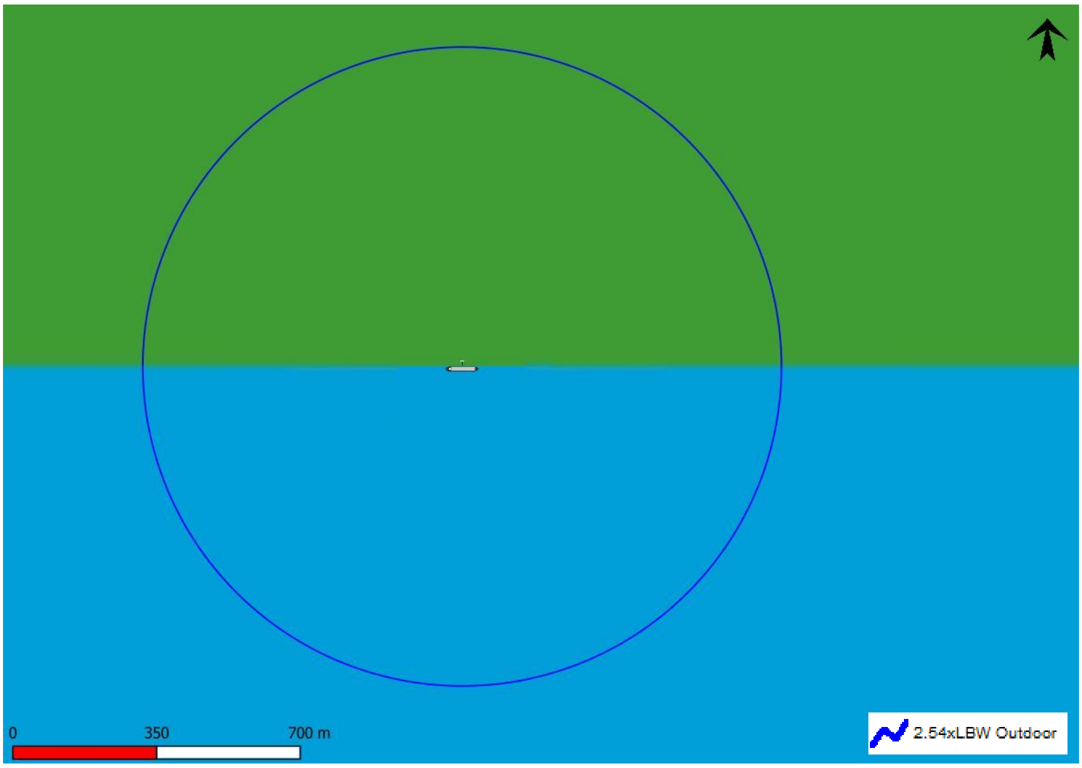
Scenario 3: Truck-to-ship bunkering of liquid hydrogen



Fire area distance: 150 m

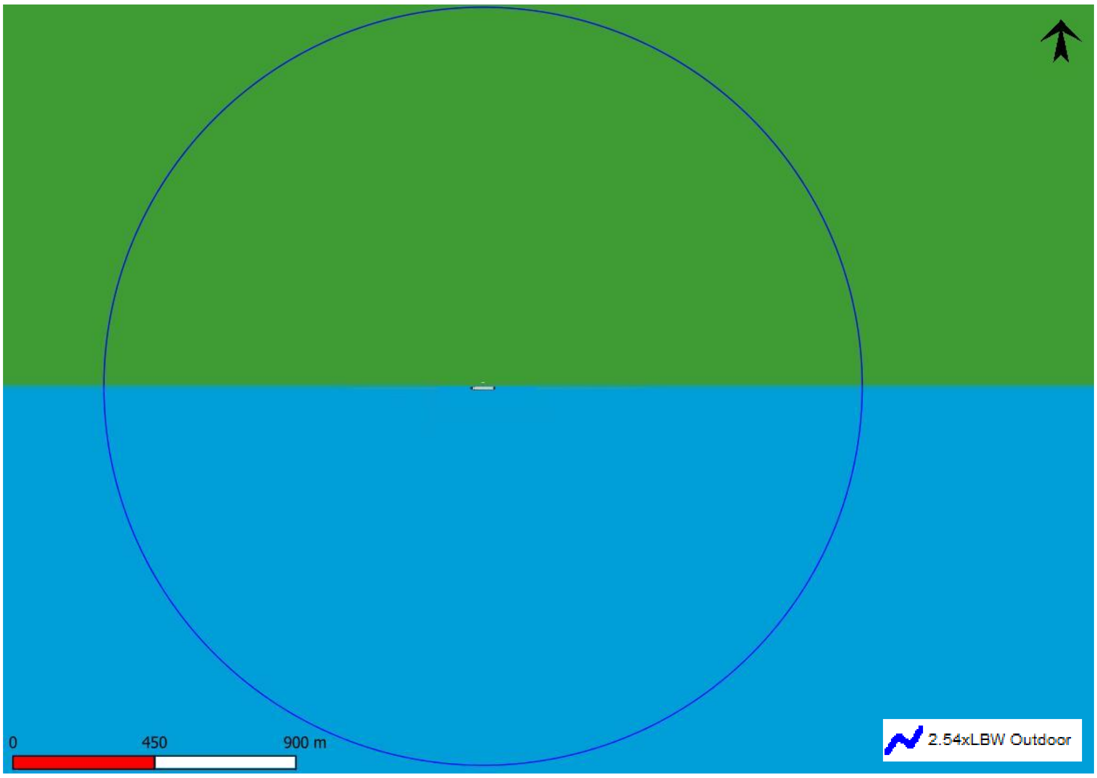
Explosion area distance: 185 m

Scenario 4A: Truck-to-ship bunkering of refrigerated liquid ammonia



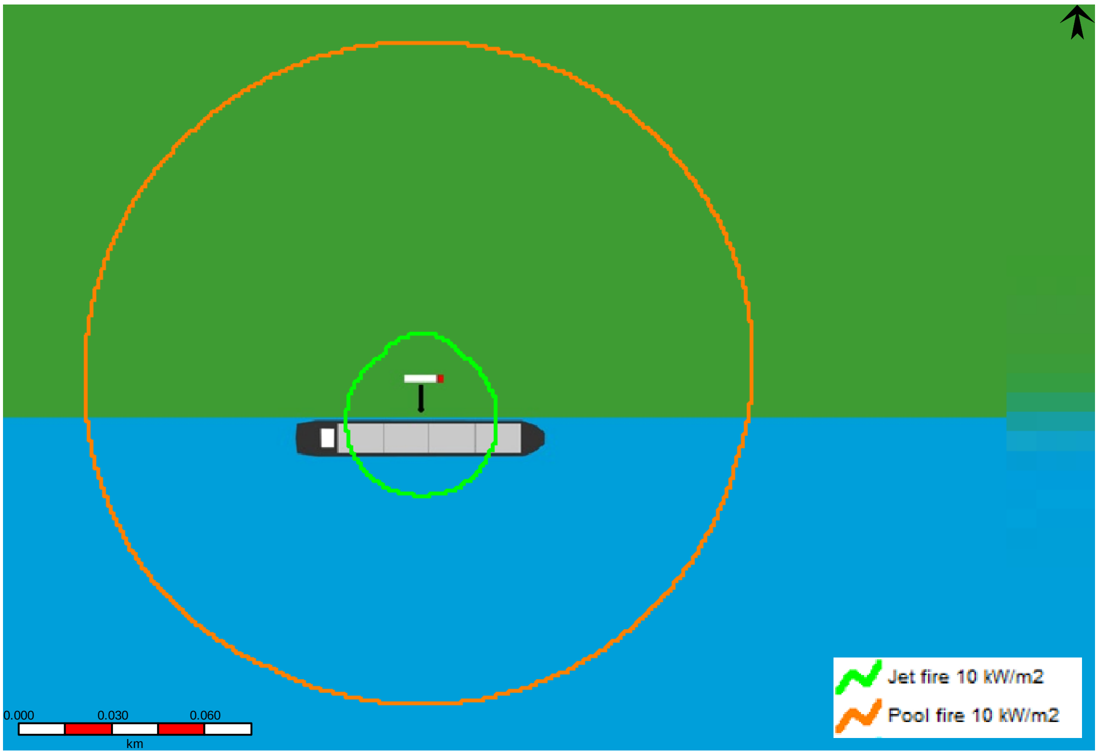
Toxic area distance: 777 m

Scenario 4B: Truck-to-ship bunkering of pressurized liquid ammonia



Toxic area distance: 1203 m

Scenario 5: Truck-to-ship bunkering of methanol



Fire area distance: 122 m

APPENDIX D

Detailed results KAS-18 calculations

Effect distances are calculated for the following end-point (threshold) values and the maximum value is taken for the external safety distance:

- **1.6 kW/m²** for thermal radiation, in case of direct ignition (resulting in jet fire).
- **0.1 bar** for max. side-on overpressure

The toxic criterion of KAS-18 is the **ERPG-2** value.

PHAST 8.4 is used for the calculation of the effect distances, which has implemented state of the art dispersion (UDM[22]) and consequence models.

The consequences of the bunkering scenarios are partially purely flammable (scenarios 1 a/b, 2a/b and 3 with hydrogen releases) or both flammable and toxic (scenarios 4a/b (ammonia releases) and 5 (methanol release)).

Scenario 1a: Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack

The maximum distances to LFL (64 m) and 0.5 LFL (88 m) are shown in the maximum concentration footprint in the figure below.

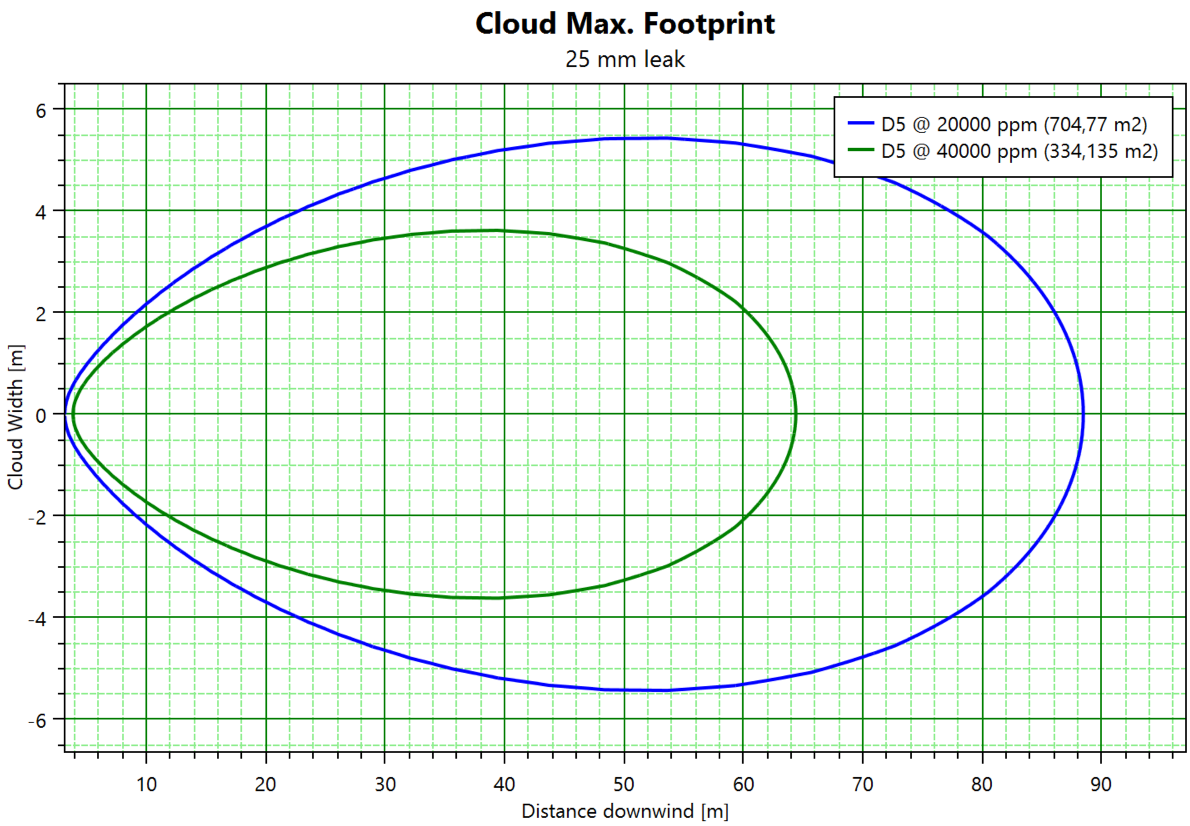


Figure 3: Maximum concentration footprint for 50 % LFL (20000 ppm) and LFL (40000 ppm) of cloud at 0 m height for scenario 1a

The gas cloud is per definition only ignitable between the UFL and the LFL, potentially causing a flash fire or an explosion when ignited. For this assessment a safety factor 2 is applied to determine the end-point criterion for a flammable gas cloud, i.e. *the range of the flash fire extends to the 50 % LFL contour*.

[22] Unified Dispersion Model

The heat radiation contours for the jet fire are shown in the figure below.

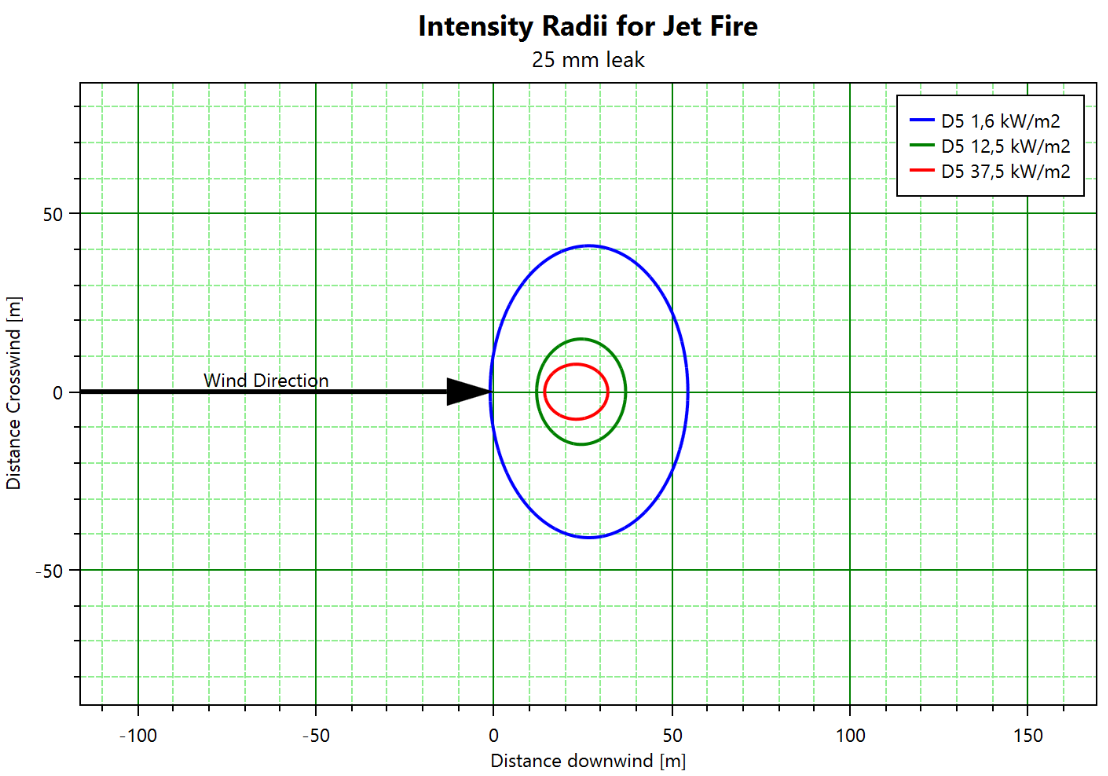


Figure 4: Heat radiation contours for the jet fire for scenario 1a

The range of the 1.6 kW/m^2 safety distance extends up to 55 m.

The results overpressure contours are shown in Figure 5.

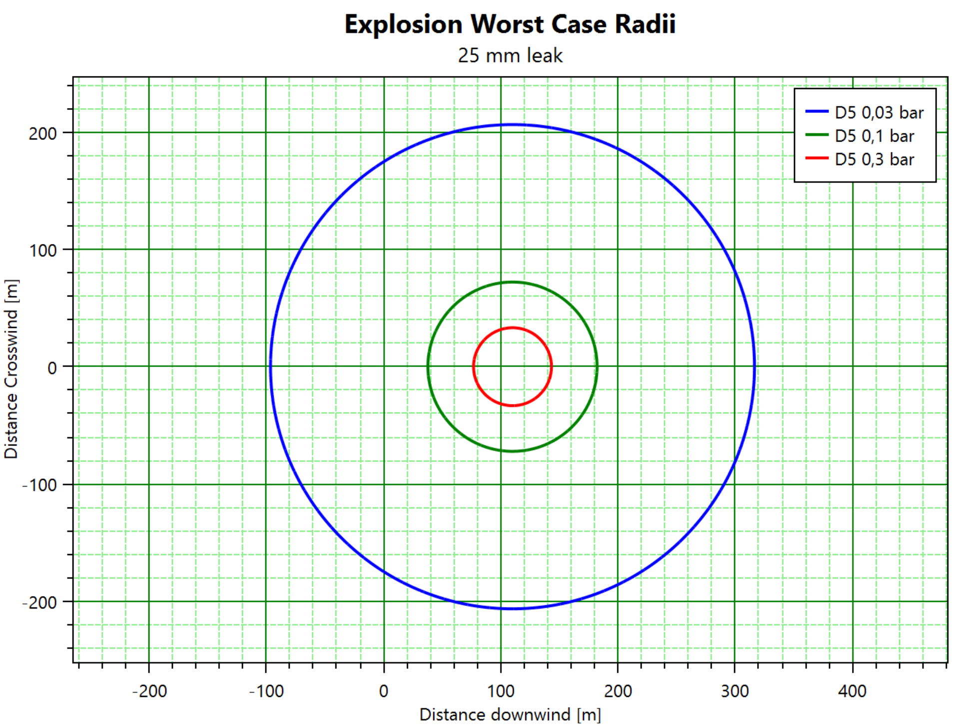


Figure 5: Overpressure contours for scenario 1a

The range of the 100 mbar contour is 182 m.

Generally, in case of a unconfined ignition, instead of an explosion accompanied by a flash fire (confined situation), just the flash fire may occur. The resulting range of the flash fire is shown in the figure below. The 50 % LFL zone in which hot combustion gases may cause lethal consequences extends to 88 m.

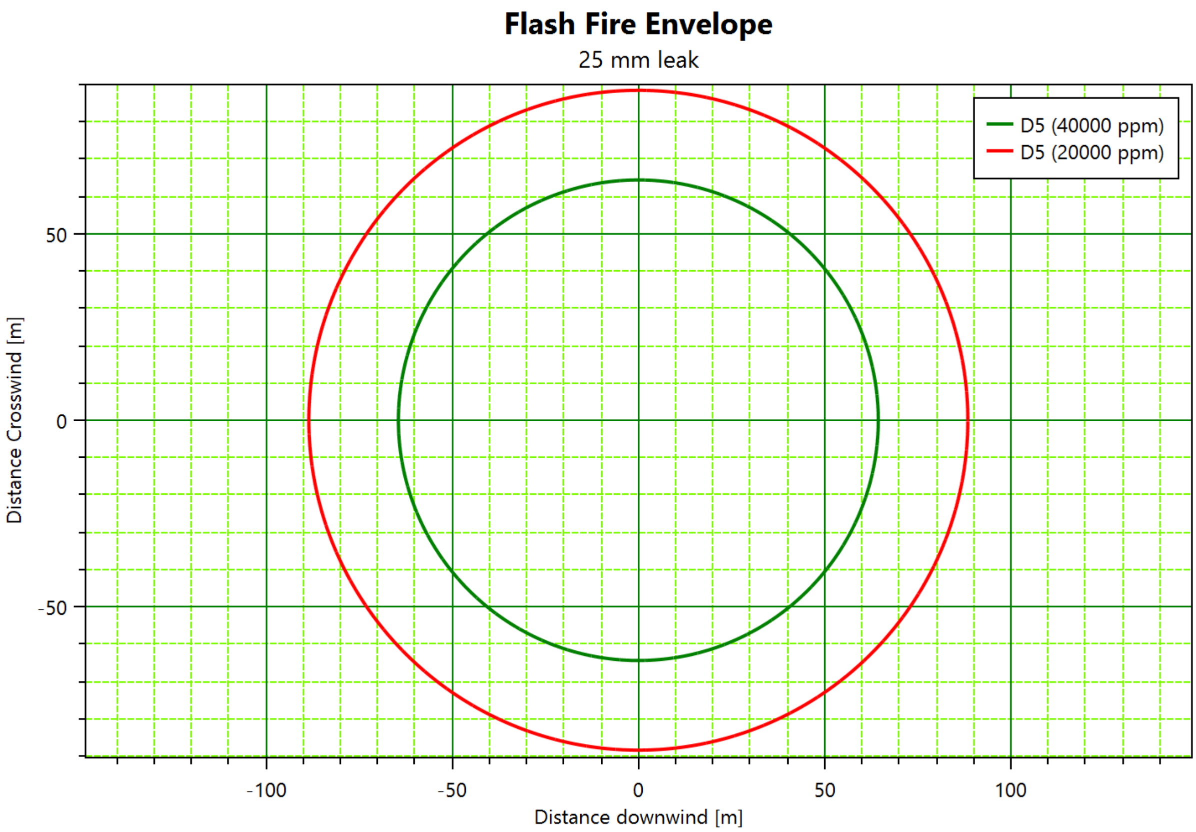


Figure 6: Flash fire envelope at ground level for scenario 1a

Scenario 1b: Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack

The maximum distances to LFL (78 m) and 0.5 LFL (104 m) are shown in the maximum concentration footprint in the figure underneath.

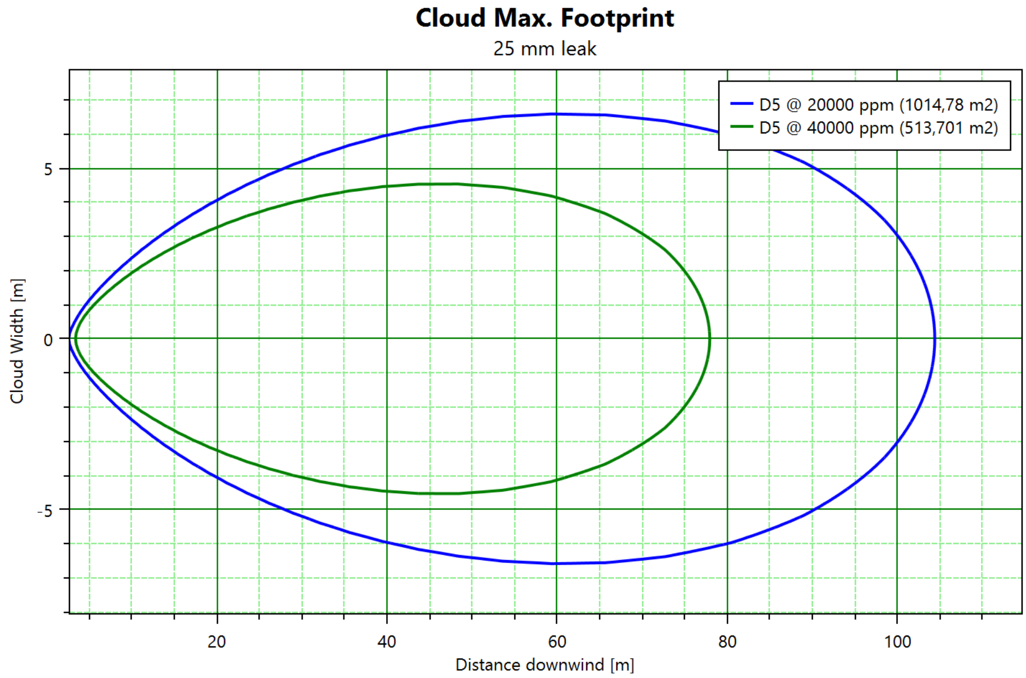


Figure 7: Maximum concentration footprint for 50 % LFL (20000 ppm) and LFL (40000 ppm) of cloud at 0 m height for scenario 1b

The heat radiation contours for the jet fire are shown in Figure 8.

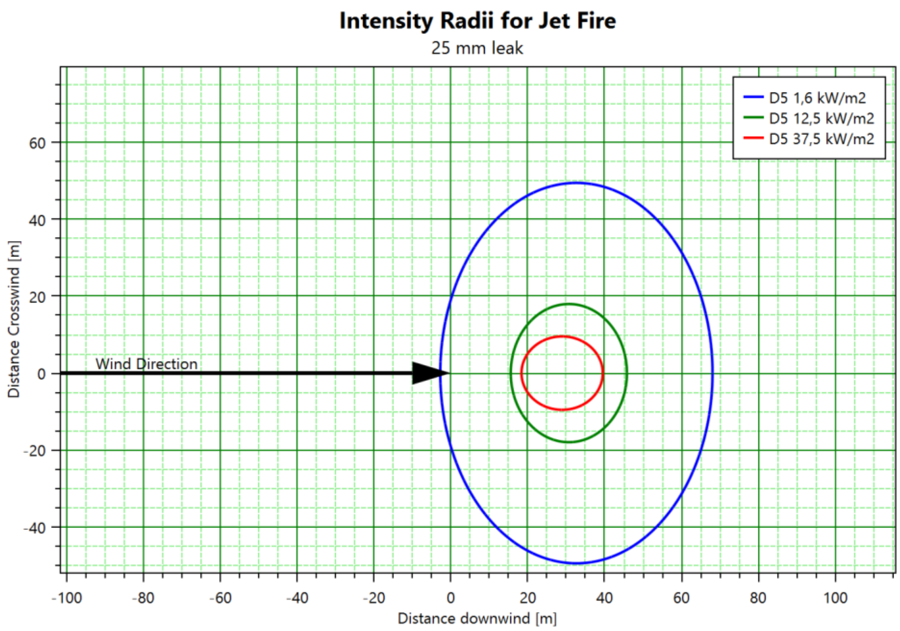


Figure 8: Heat radiation contours for the jet fire for scenario 1b

The range of the 1.6 kW/m^2 safety distance extends up to 68 m.

The results for the overpressure contours are shown the figure below.

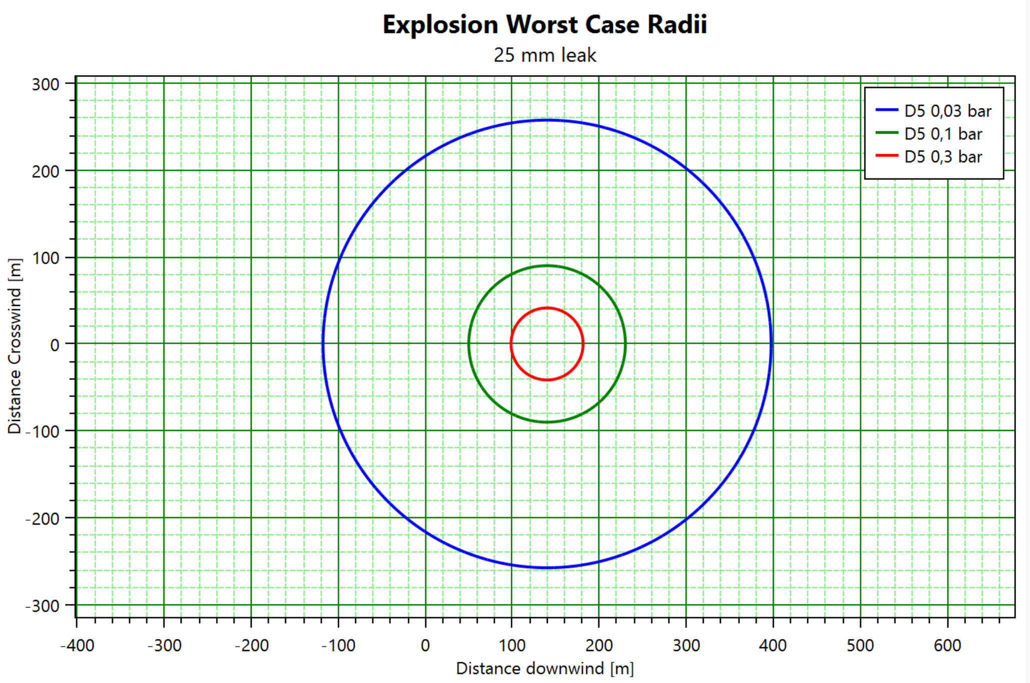


Figure 9: Overpressure contours for scenario 1b

The range of the 0,1 bar zone is 230 m.

Further to the jet fire and the explosion, a flash fire is possible following the late ignition of hydrogen. The resulting range of the flash fire is shown in the figure underneath. The 50 % LFL zone in which hot combustion gases may cause lethal consequences extends to 104 m.

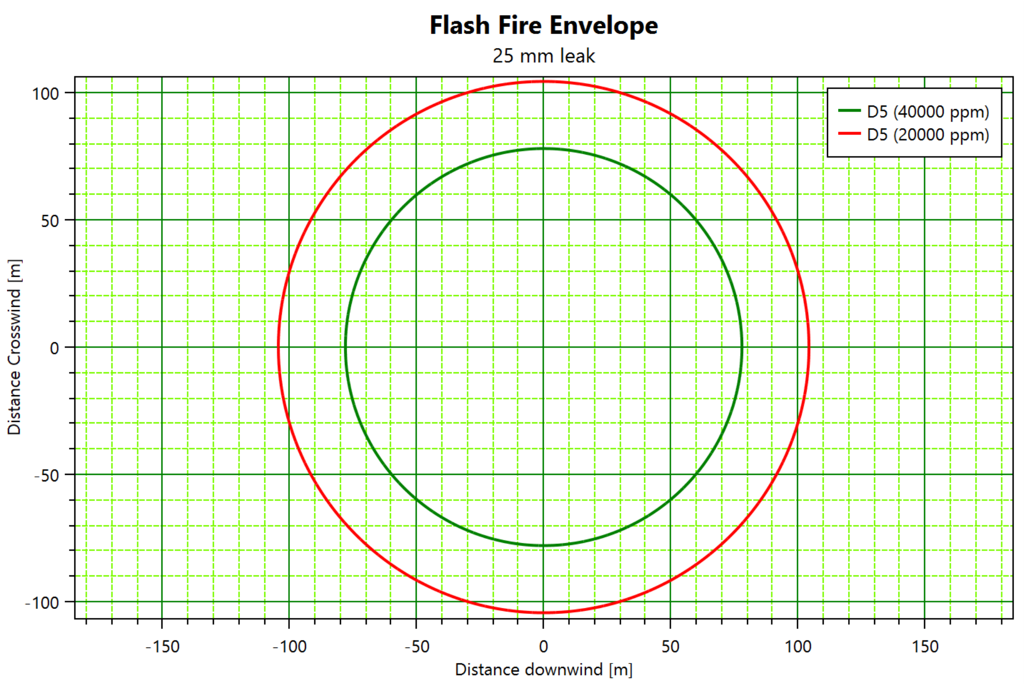


Figure 10: Flash fire envelope for scenario 1b at ground level

Scenario 2a: Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)

The maximum distances to LFL (72 m) and 0.5 LFL (96 m) are shown in the maximum concentration footprint in the figure below.

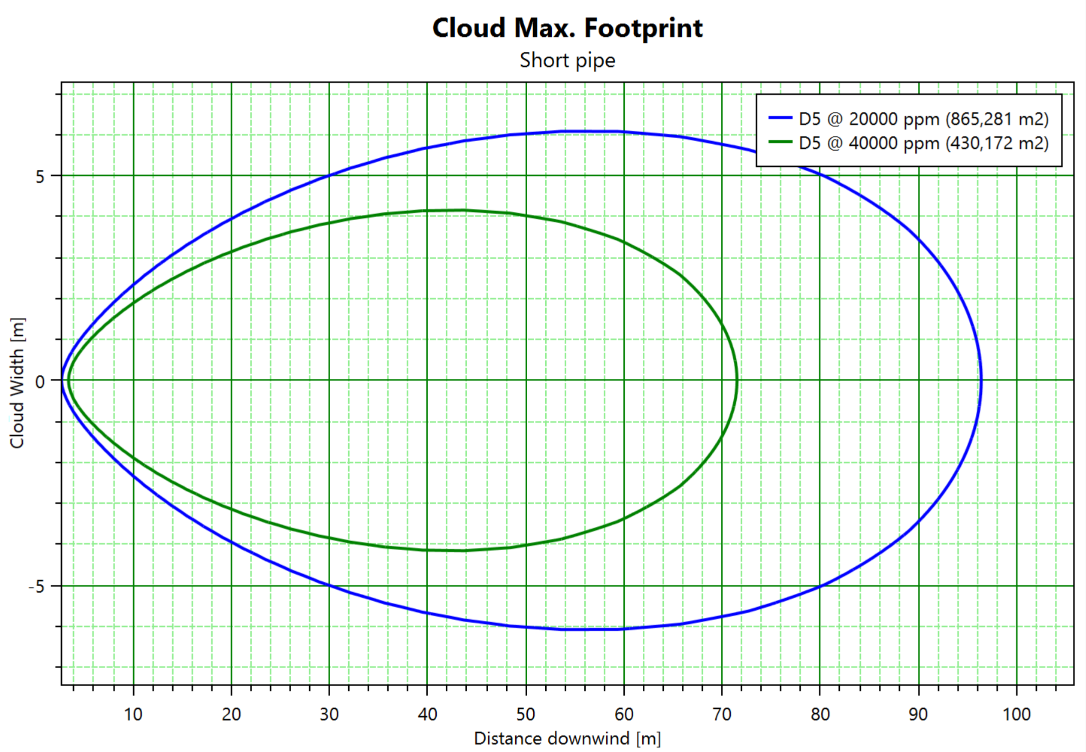


Figure 11: Maximum concentration footprint for 50 % LFL (20000 ppm) and LFL (40000 ppm) of cloud at 0 m height for scenario 2a

The heat radiation contours for the jet fire are shown in Figure 12.

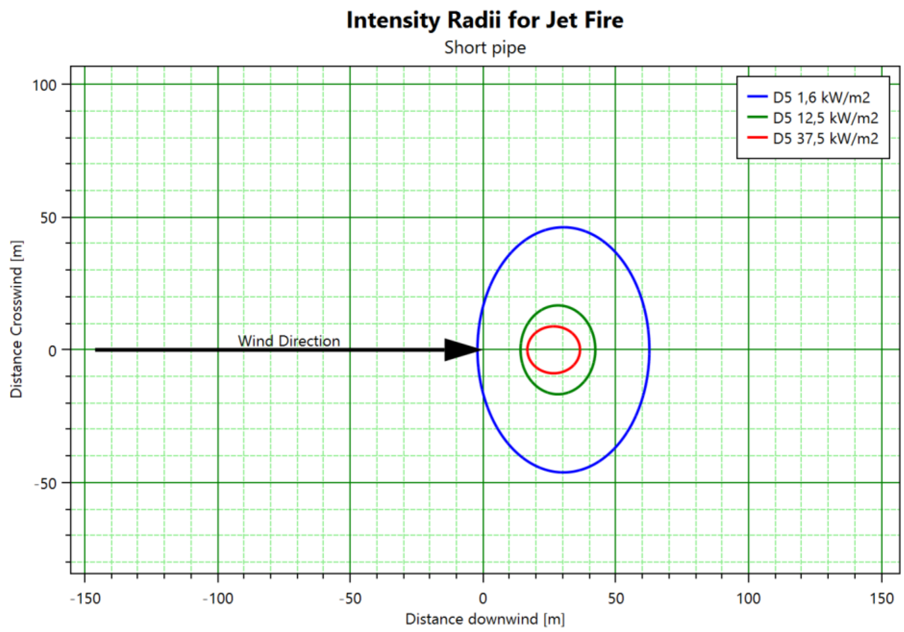


Figure 12: Heat radiation contours for the jet fire of scenario 2a

The range of the 1.6 kW/m^2 safety distance extends up to 63 m.

Due to the scenario-specific assumption of an unconfined explosion, the calculations show that the 0.1 bar contour is not reached in this scenario. This may have to be revised when details on the actual confinement situation are known.

Further to the jet fire, a flash fire is possible after a delayed ignition of hydrogen. The resulting range of the flash fire is shown in Figure 13. The 50 % LFL zone in which hot combustion gases may cause lethal consequences extends to 96 m.

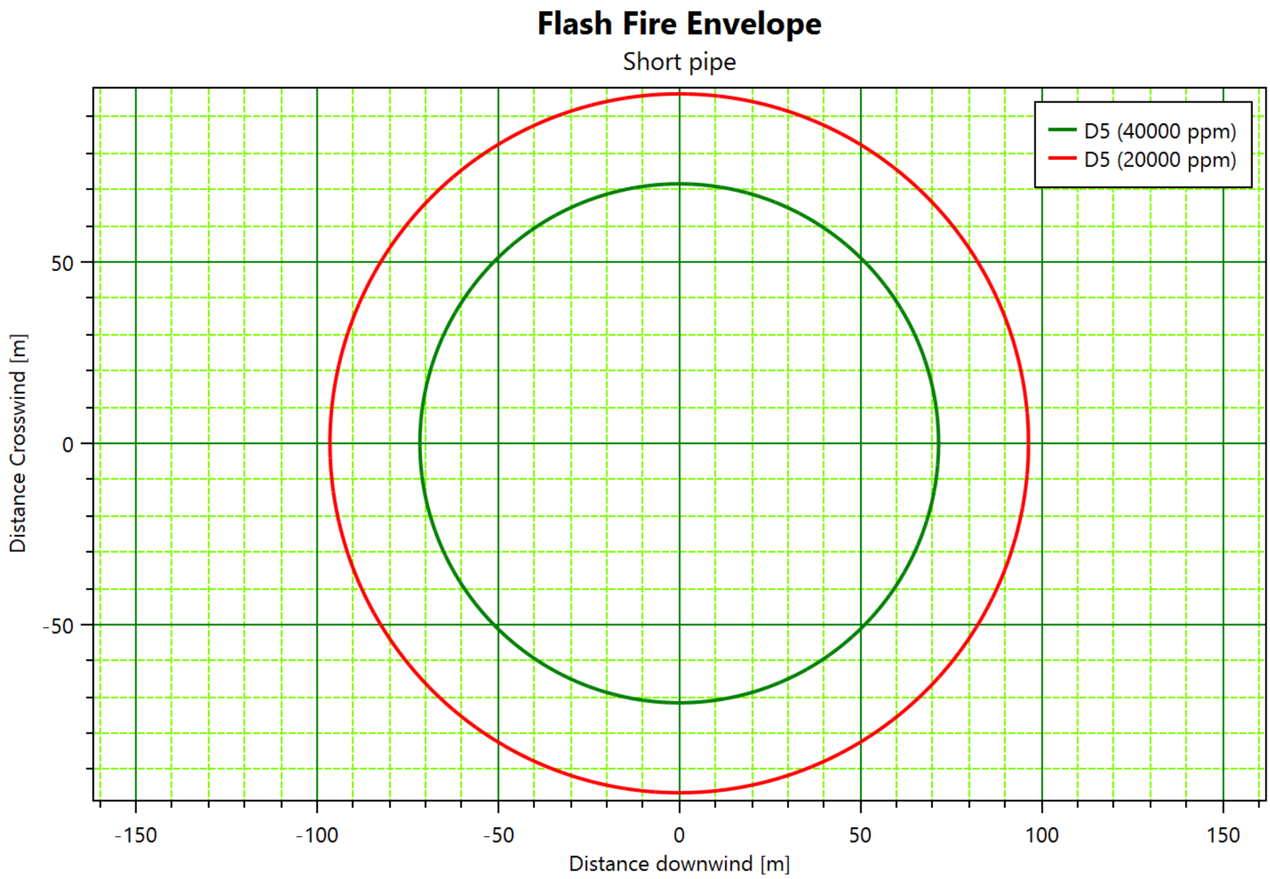


Figure 13: Flash fire envelope for scenario 2a at ground level

Scenario 2b: Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)

The maximum distances to LFL (72 m) and 0.5 LFL (96 m) are shown in the maximum concentration footprint in the figure underneath.

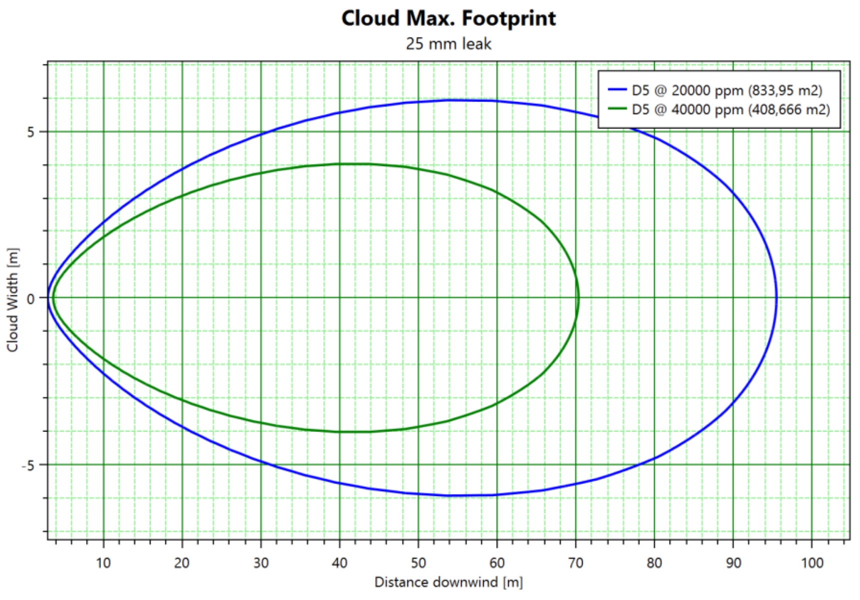


Figure 14: Maximum concentration footprint for 50 % LFL (20000 ppm) and LFL (40000 ppm) of cloud at 0 m height for scenario 2b

The heat radiation contours for the jet fire are shown in Figure 15.

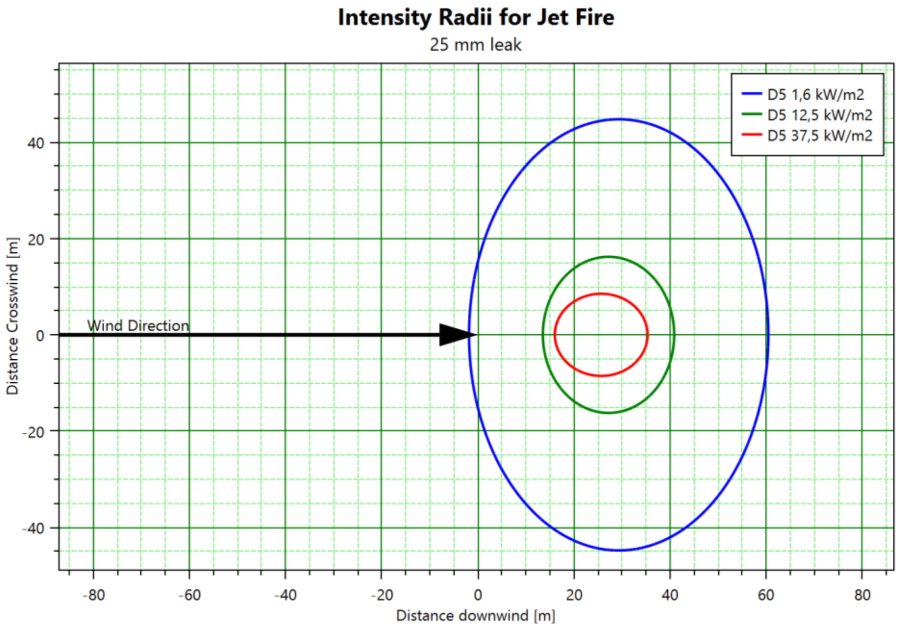


Figure 15: Heat radiation profile for the jet fire for scenario 2b

The range of the 1.6 kW/m^2 safety distance extends up to 61 m.

Due to the scenario-specific assumption of an unconfined explosion, the calculations show that the 0.1 bar contour is not reached in this scenario. This may have to be revised when details on the actual confinement situation are known.

The consequences of the potential flash fire are shown in Figure 16. The 50 % LFL zone in which hot combustion gases may cause lethal consequences extends to 96 m.

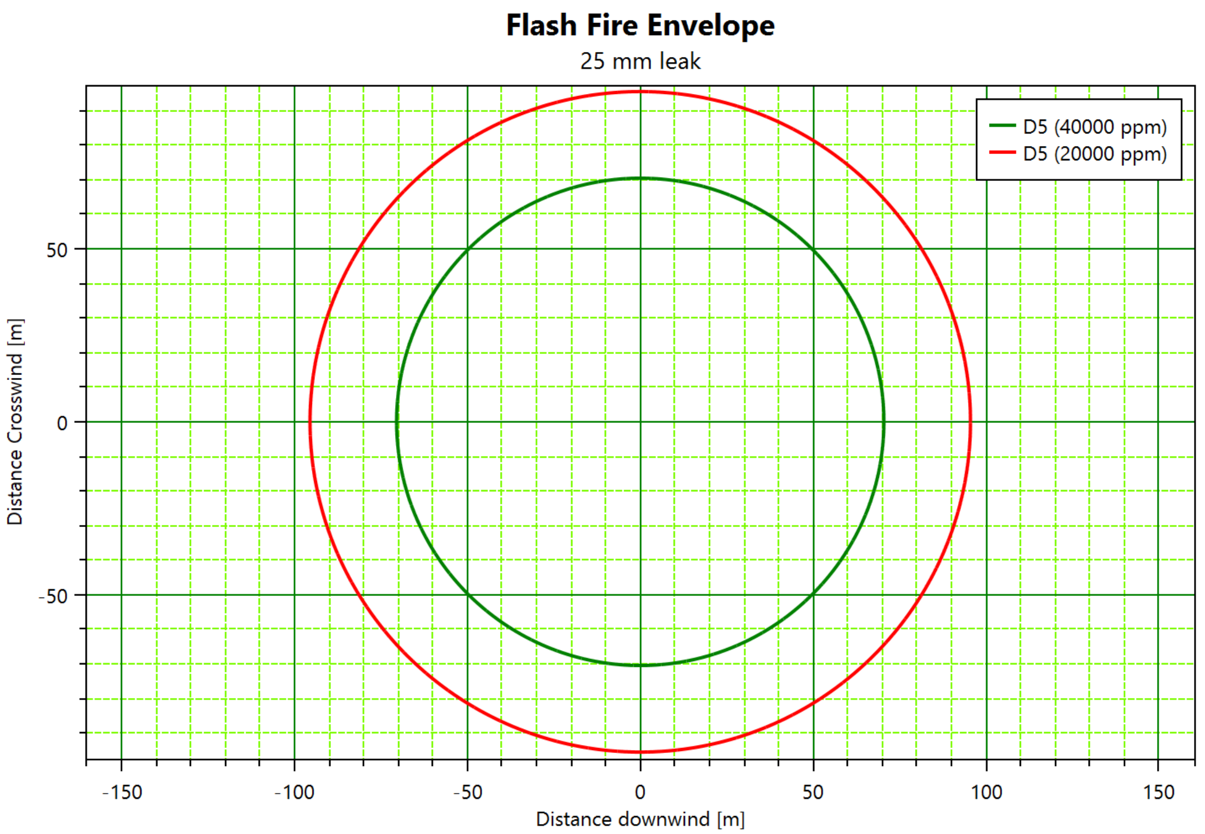


Figure 16: Flash fire envelope for scenario 2b at ground level

Scenario 3: Truck-to-ship bunkering of liquid hydrogen

The maximum distances to LFL (41 m) and 0.5 LFL (52 m) are shown in the maximum concentration footprint in Figure 17.

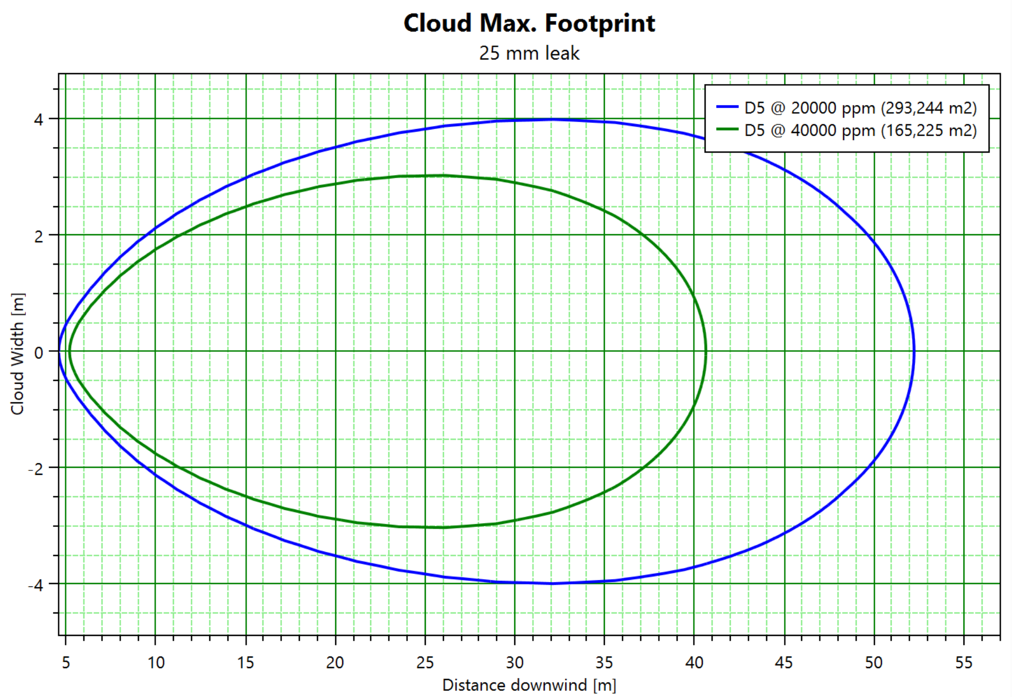


Figure 17: Maximum concentration footprint for 50 % LFL (20000 ppm) and LFL (40000 ppm) of cloud at 0 m height for scenario 3

The heat radiation contours for the jet fire are shown in Figure 18.

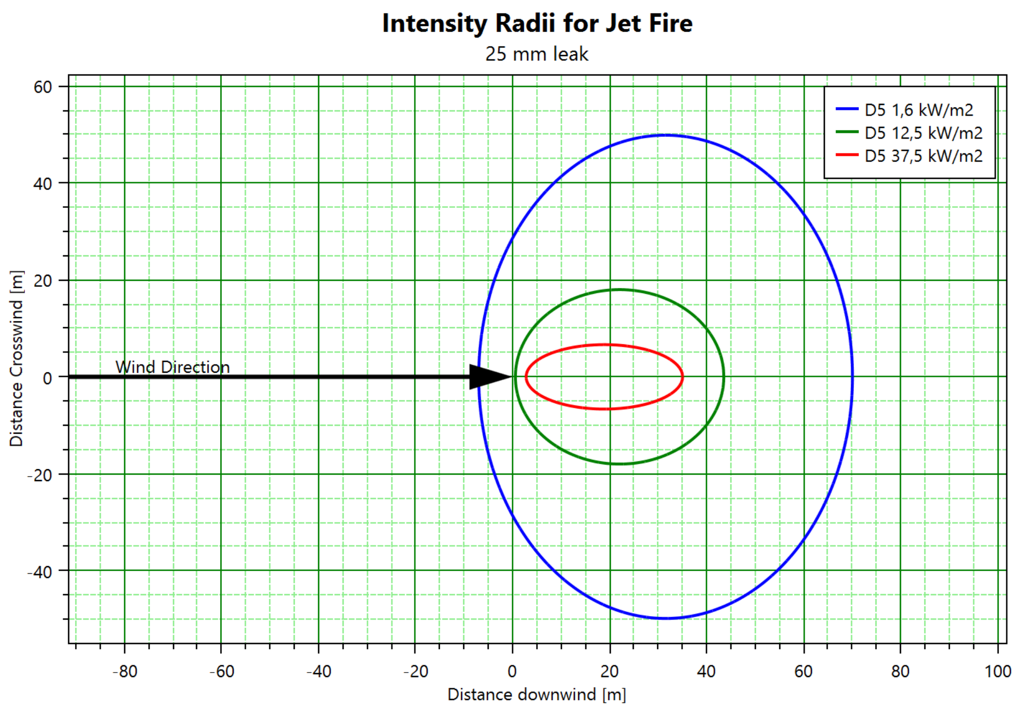


Figure 18: Heat radiation contours for the jet fire for scenario 3

The range of the 1.6 kW/m^2 safety distance extends up to 70 m.

Due to the scenario-specific assumption of an unconfined explosion, the calculations show that the 0.1 bar contour is not reached in this scenario. This may have to be revised when details on the actual confinement situation are known.

Further to the jet fire, a flash fire is possible following the late ignition of hydrogen. The resulting range of the flash fire is shown in Figure 19. The 50 % LFL zone in which hot combustion gases may cause lethal consequences extends to 52 m.

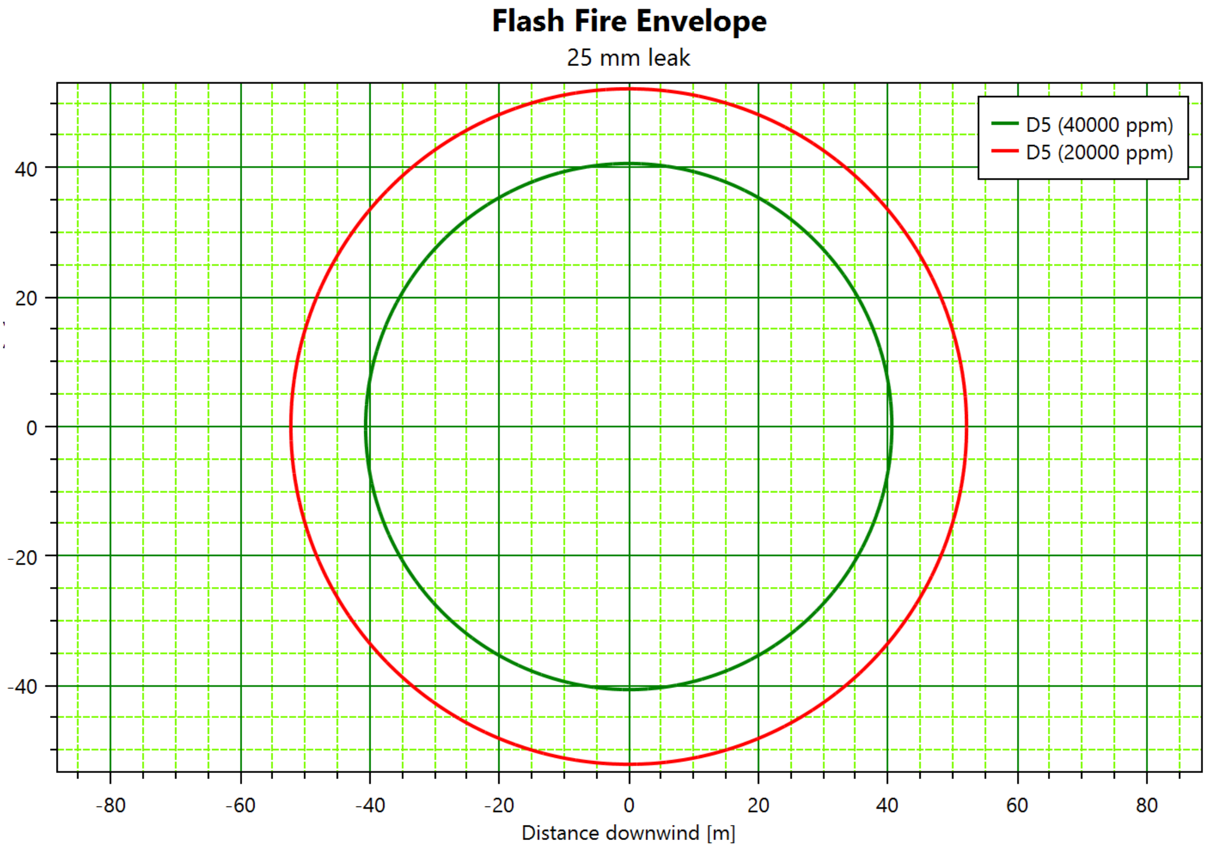


Figure 19: Flash fire envelope for scenario 3 at ground level

Scenario 4a: Truck-to-ship bunkering of refrigerated liquid ammonia

This scenario as well as the subsequent scenario 4b cover the potential release of ammonia which is both flammable and toxic. But ammonia is difficult to ignite. Nevertheless, the calculations of flammable consequences have been included here for sake of completeness regardless that they are unlikely. As the flammable consequences are similar to those of the previous scenarios, only the toxic consequences are discussed here (safety distances for flammable consequences are provided in Table 7).

The KAS-18 assessment for toxic consequences is based on the ERPG-2 value which is the toxic concentration to which a person may be exposed up to 1 hour without suffering from irreversible consequences. For ammonia, the 1 hour ERPG-2 value is 150 ppm.

Figure 20 shows the maximum ERPG-2 (1 h; 150 ppm) contour for scenario 4a which extends to approx. 1093 m. This result appears extreme, but it has to be taken into account that this is a maximum value not taking into account the duration of the exposure. Figure 21 shows the time dependence at a distance of 1090 m in wind direction. Obviously, the ERPG-2 is exceeded only for a few seconds, i.e. the one hour ERPG-2 value should not be applied in this way.

Therefore we look onto the toxic dose D which according to Haber's rule is given for a person exposed to a constant concentration C by

$$D = C^n \times t_E,$$

where t_E is the time of exposure and n is the substance specific toxic exponent being n = 2 for ammonia. The toxic dose corresponding to the 1 h ERPG-2 hence is $D_{1h} = 150^2$ ppm x 60 min. = 1.35 x 10^6 ppm min.

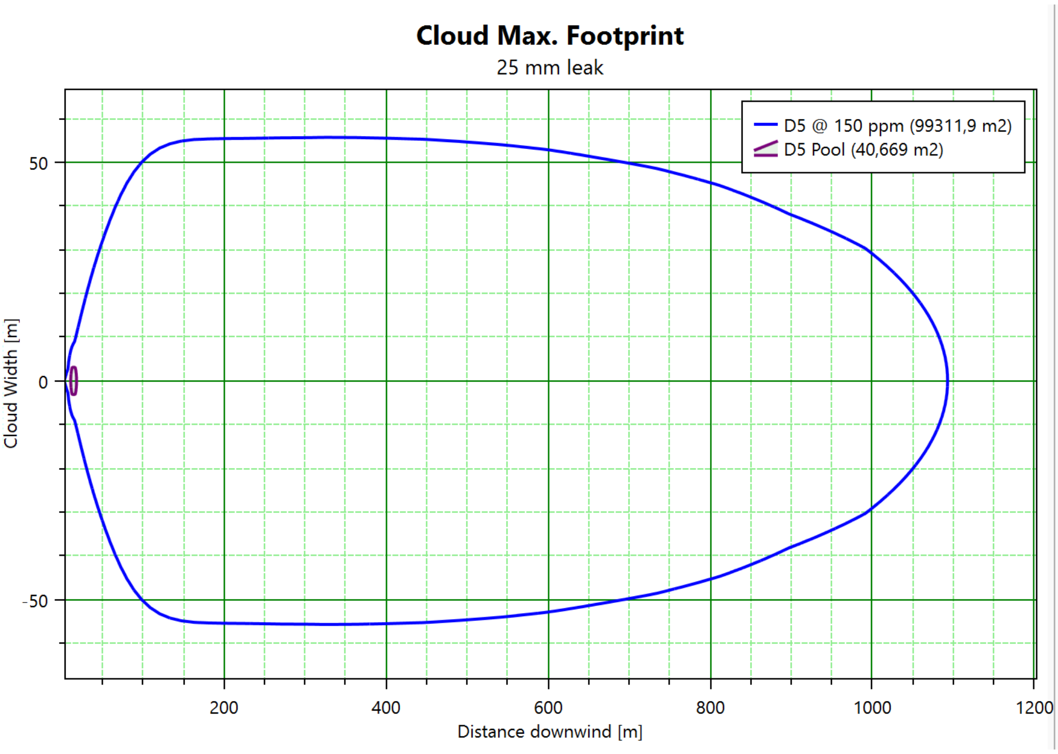


Figure 20: Maximum ERPG-2 contour for scenario 4a

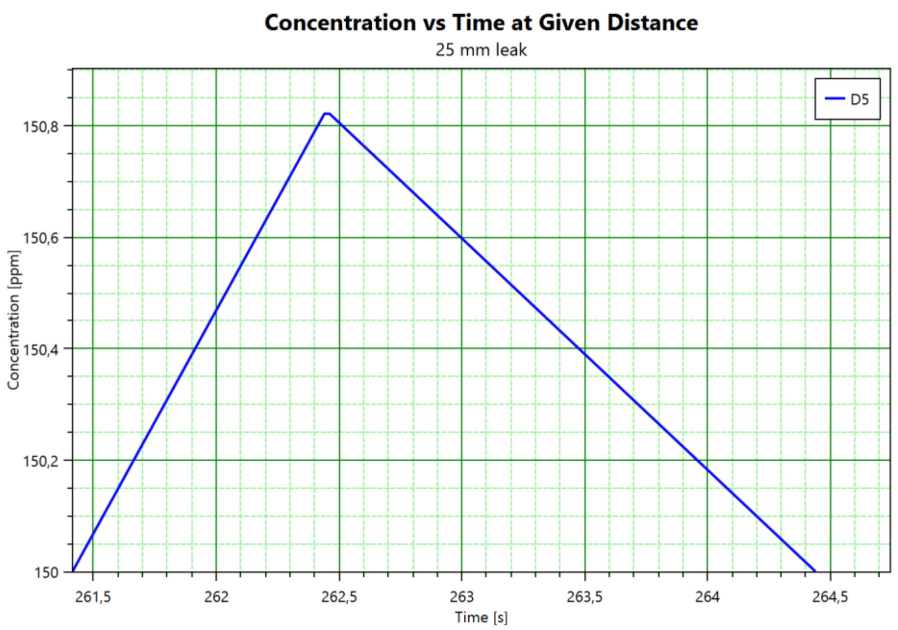


Figure 21: Time dependence of the local concentration at 1090 m in wind direction

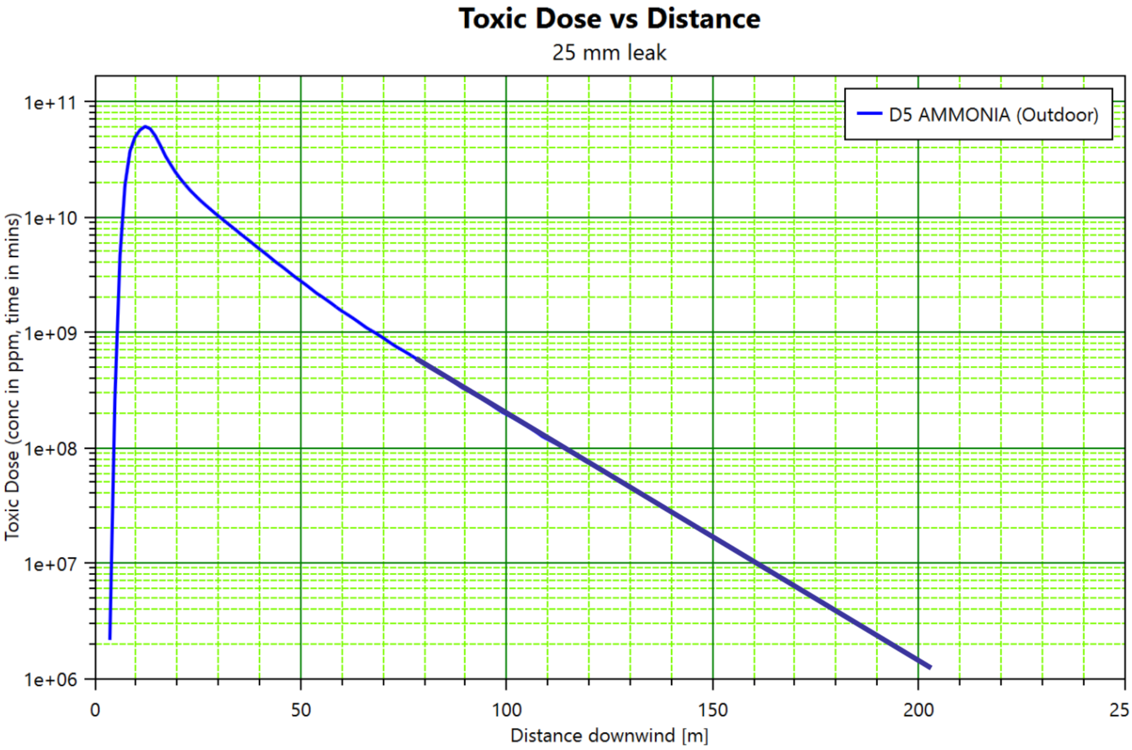


Figure 22: Toxic dose for scenario 4a

Figure 22 shows the toxic dose for scenario 4a. If extrapolated to higher distances, it is obvious that the dose corresponding to the 1 h ERPG is achieved at a distance of 205 m. This is the toxic safety distance for scenario 4a.

Scenario 4b: Truck-to-ship bunkering of pressurized liquid ammonia

For the second scenario describing an ammonia release, Figure 23 shows the maximum ERPG-2 (1 h; 150 ppm) contour which extends to approx. 1895 m. This result appears extreme, but here again, it has to be taken into account that this is a maximum value not taking into account the duration of the exposure. Figure 24 shows the time dependence at a distance of 1860 m in wind direction. Obviously, the ERPG-2 is exceeded only for about 30 s. Therefore, the toxic dose D has to considered again, i.e. the toxic dose corresponding to the 1 h ERPG-2 which is 1.35 x 10^6 ppm x min. The toxic does is shown in Figure 25.

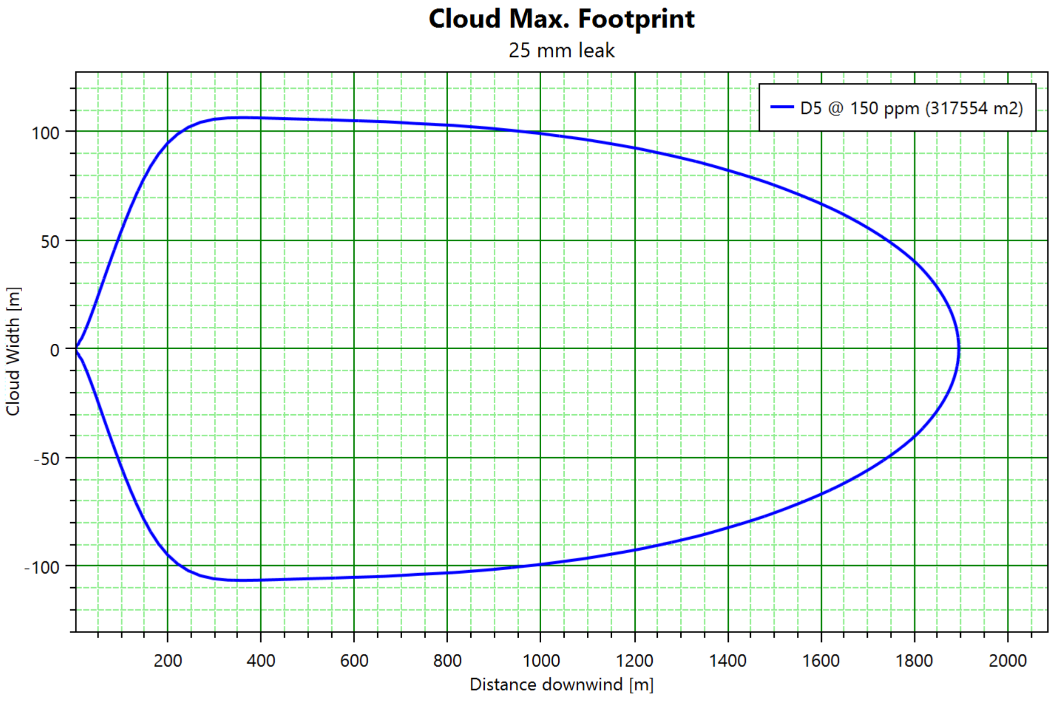


Figure 23: Maximum ERPG-2 contour for scenario 4b

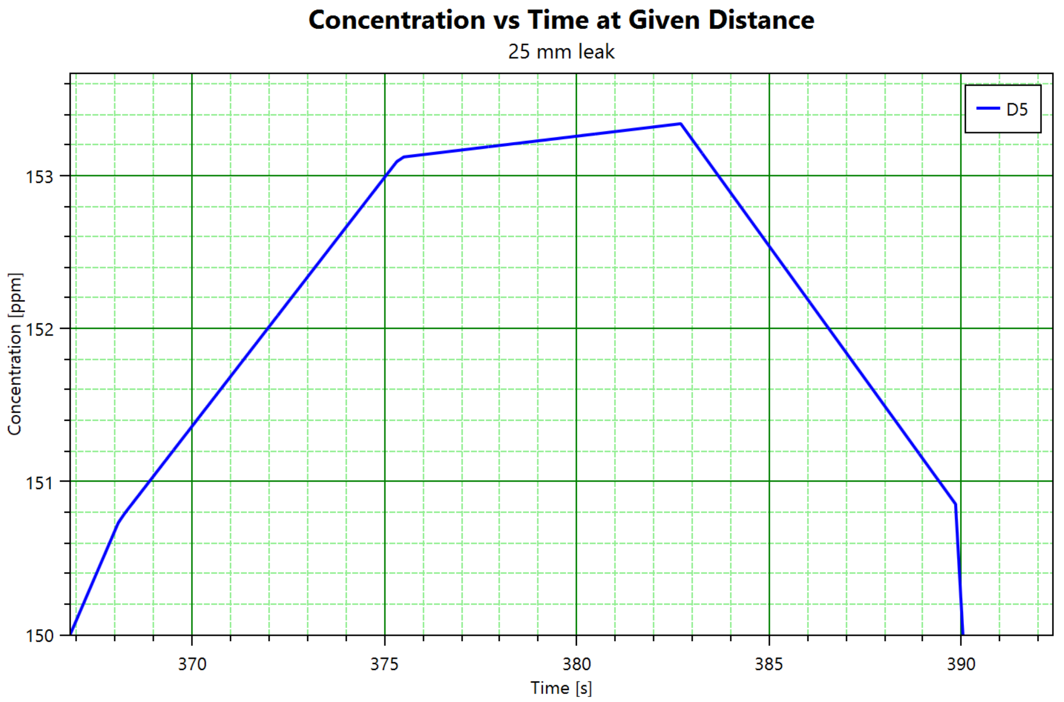


Figure 24: Time dependence of the local concentration at 1860 m in wind direction for scenario 4b

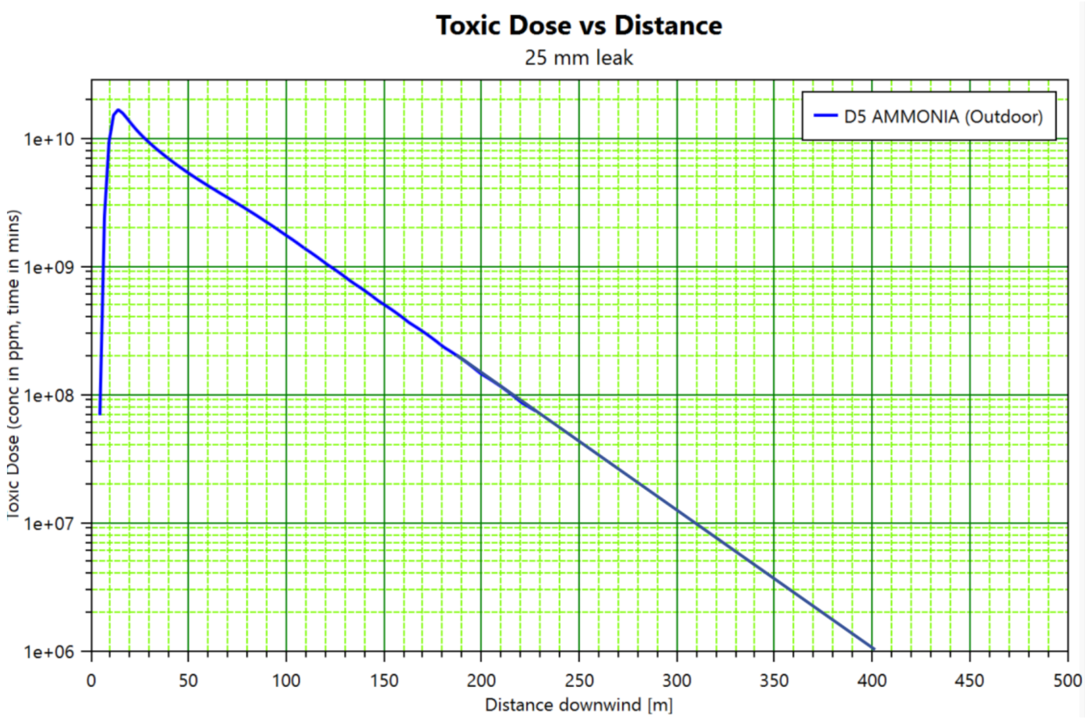


Figure 25: Toxic dose for scenario 4b

When the toxic dose is extrapolated to higher distances, it is obvious that the dose corresponding to the 1 h ERPG is achieved at a distance of 395 m which is very close to the value given in KAS-18 for ammonia (398 m).

Scenario 5: Truck-to-ship bunkering of methanol

This scenario covers the potential release of methanol which is both flammable and toxic. Safety distances for flammable consequences are contained in Table 7.

For methanol, the 1 hour ERPG-2 value is 1000 ppm. The substance specific toxic exponent for methanol is n = 1. The toxic dose corresponding to the 1 h ERPG-2 hence is D_{1h} = 1000 ppm x 60 min. = 60,000 ppm min.

The PHAST calculations show that the toxic dose of 60,000 ppm min is not reached.

The maximum concentration footprint is shown in the figure underneath.

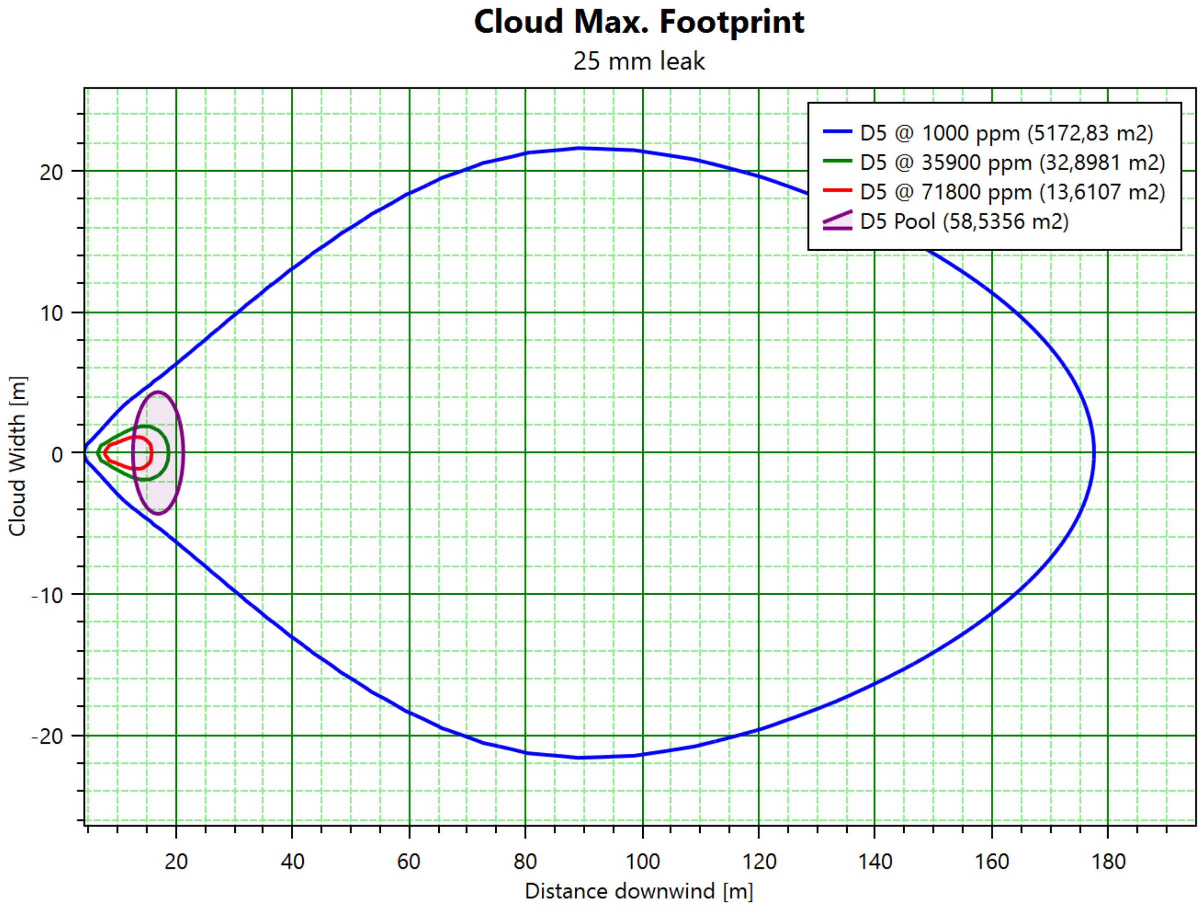


Figure 26: Maximum concentration footprint of methanol for scenario 5 (ERPG-2 = 1000 ppm; 50 % LFL = 35,900 ppm and LFL =71800 ppm)

In summary, the toxic consequences are not of relevance for the determination of the safety distance for this methanol release.

It is obvious that a substantial fraction of the methanol release accumulates in a pool, which shows a rather small evaporation rate. Hence the distance to the LFL is 16 m only. If the jet is ignited it will develop into a jet fire. The heat radiation contours are shown in Figure 27.

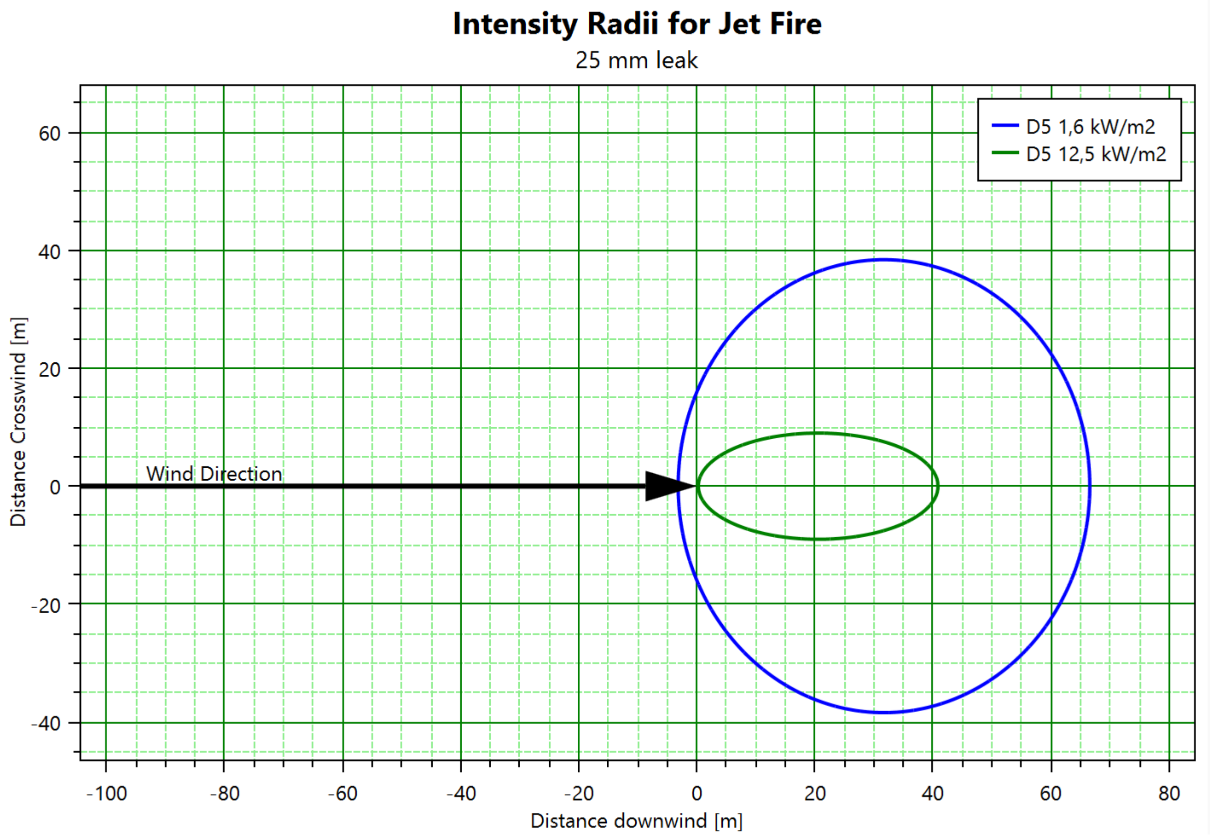


Figure 27: Jet fire heat radiation contours for scenario 5

The range of the 1.6 kW/m^2 zone is 67 m.

If the methanol in the pool catches fire, the pool fire develops. The respective radiation contours are shown in Figure 28.

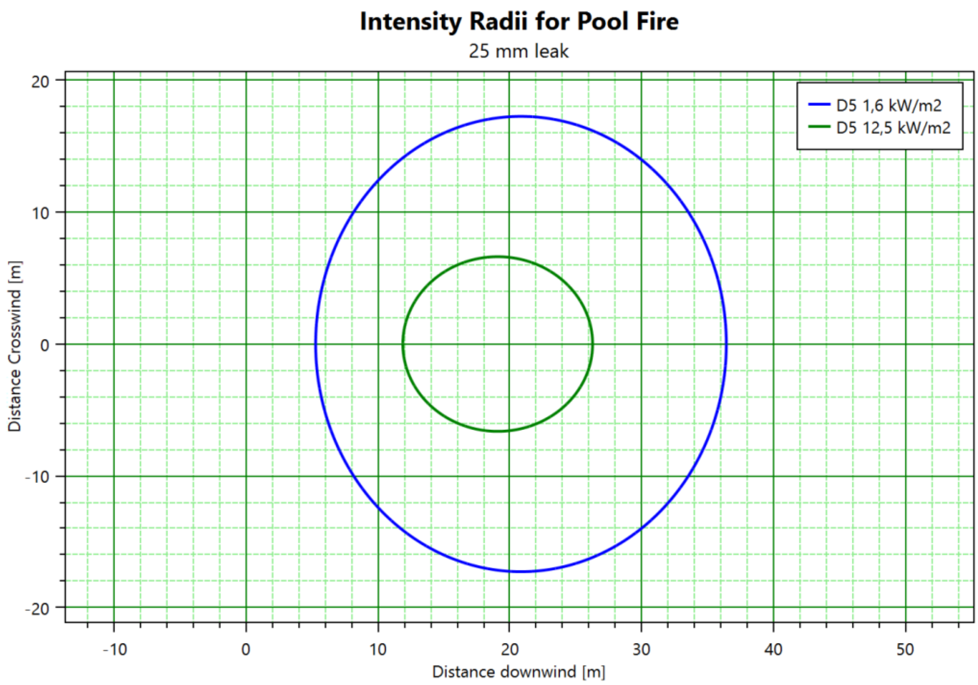


Figure 28: Heat radiation from the pool fire developing in scenario 5

The range of the 1.6 kW/m^2 contour for the pool fire is 36 m.

Figure 29 shows the extent of the flash fire (50 % LFL) which is 19 m.

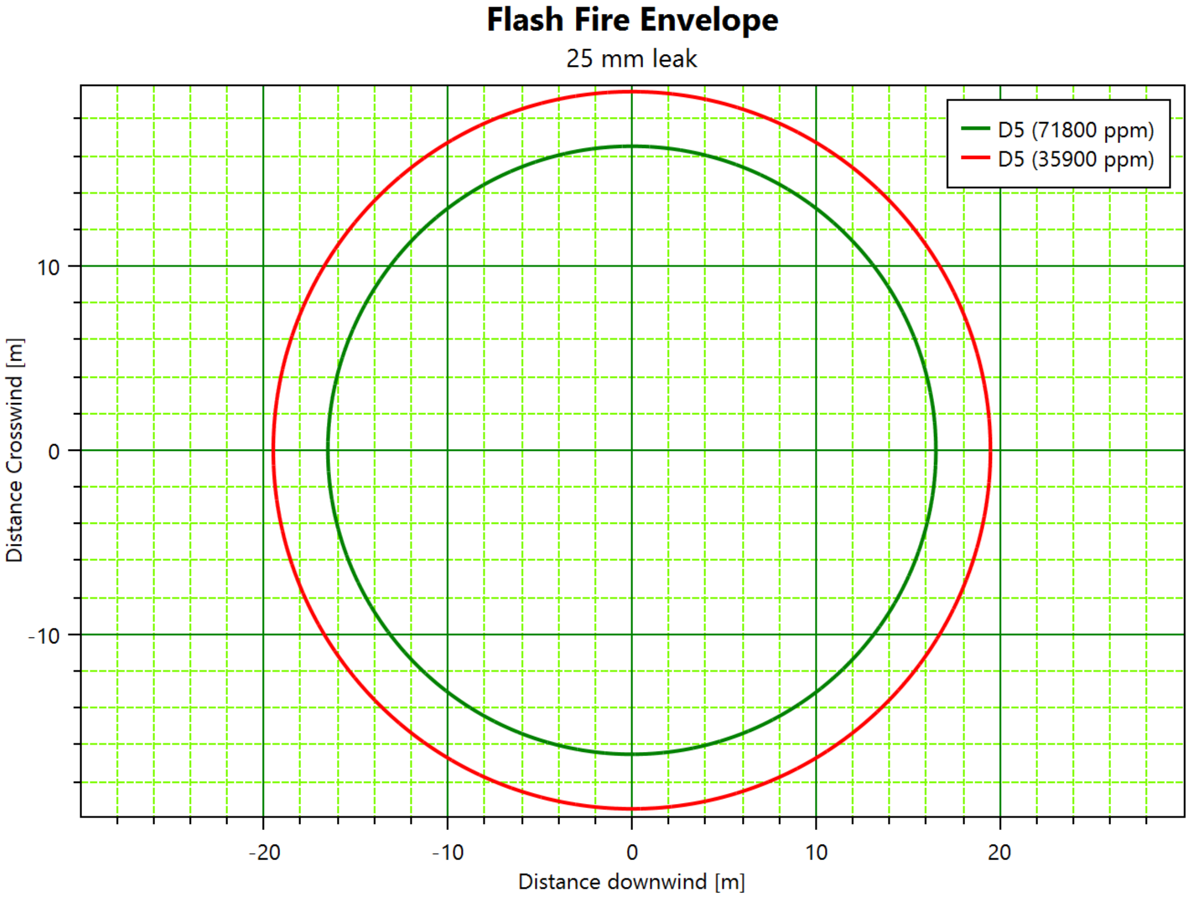


Figure 29: Flash fire envelope for scenario 5

Due to the small amount of gaseous methanol present in the flammable cloud, an explosion is not possible.

Summary of Consequence Calculations

The subsequent table summarizes the results for all scenarios.

Table 7: KAS-18 safety distances for all scenarios

Scenario	Material released	Distance to max jet / pool fire radiation of 1.6 kW/m2 [m]	Distance to flash fire (50 % LFL) [m]	Distance to 0.1 bar overpressure [m]	Distance to ERPG-2 [1 h] [m]
1a	Hydrogen	55	88	182	n/a*
1b	Hydrogen	68	104	230	n/a
2a	Hydrogen	63	96	n/r	n/a
2b	Hydrogen	61	96	n/r	n/a
3	Hydrogen	70	52	n/r	n/a
4a	Ammonia	81	28	n/r	205
4b	Ammonia	81	24	n/r	395
5	Methanol	67	19	n/r	n/r

* n/r = not reached; n/a = not applicable

The table below shows the maximum external safety distances per scenario:

Table 8: Maximum external safety distance per scenario

Scenario	Description	External safety distance [m]
1a	Swapping containers with pressurized hydrogen (300 bar) at container terminals (start-up case) – no storage in stack	182
1b	Swapping containers with pressurized hydrogen (500 bar) at container terminals (future case) – storage in stack	230
2a	Truck-to-ship bunkering of gaseous hydrogen via hose to fixed tanks on board (start-up case)	96
2b	Bunker station to ship, bunkering of gaseous hydrogen via hose to fixed tanks on board (future case)	96
3	Truck-to-ship bunkering of liquid hydrogen	70
4a	Truck-to-ship bunkering of refrigerated liquid ammonia	205
4b	Truck-to-ship bunkering of pressurized liquid ammonia	395
5	Truck-to-ship bunkering of methanol	67

DNV

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