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RISK ANALYSIS
LNG BUNKERING OF VESSELS WITH PASSENGERS ON BOARD

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1	06/11/2012	Final report without sensitivity analyses
2	07/11/2012	Final report with sensitivity analyses
3	21/08/2013	Final report updated with CFD simulations for selected scenarios, as well as calculation of risk reduction by optimising ESD times. Addition of summary in Norwegian and English.

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CONTENTS

APPENDICES

APPENDIX 1

PHAST parameters

APPENDIX 2

Event Trees in PHAST

APPENDIX 3

Equipment response times and failure probabilities

APPENDIX 4

Sensitivity analysis

APPENDIX 5

CFD method

1. INTRODUCTION

Rambøll was given the task of assessing the risks related to LNG bunkering of vessels, such as ferries and other passenger-carrying vessels, while there are passengers and/or vehicles on board and passengers and/or cars are embarking or disembarking.

1.1 Summary

The present report contains a risk assessment of LNG bunkering of vessels with passengers on board. The risk assessments started with a hazard identification workshop, where undesirable scenarios were identified. The workshop was conducted as a What-If workshop, which is a flexible brainstorming method used for hazard identification and qualitative risk assessment.

From all the identified scenarios a number of scenarios were selected for further impact studies. All serious consequences emerge from a leakage of LNG which then ignites. LNG (liquefied natural gas) is a liquid, which through the supply of heat will evaporate to GNG (gaseous natural gas). GNG is a non-toxic gas, which has an asphyxiating effect by displacing the oxygen in the air when present in high concentrations or in confined spaces where the gas can accumulate.

Only GNG can be ignited and this will cause either a flash fire or an explosion, depending on the confinement around the gas cloud. The flash fire or explosion may be insignificant if only a small gas cloud has developed before ignition. A flash fire or explosion will burn back to its source and ignite the source if GNG is still generated, resulting in a pool fire, a jet fire or both, depending on the source. Flash fires and explosions are the primary causes of harm to passengers during LNG bunkering of vessels.

The consequence modelling software PHAST Risk calculates the severity of a release using Gaussian distribution calculations. The shelter effect provided by the ship and the pier onshore (from releases offshore) can therefore not be modelled. To model the shelter effect some fictitious release points offshore are inserted in the PHAST Risk model to ensure a more accurate gas flow onshore. This means that the model for offshore releases is more correct on the onshore side (where people are located) but incorrect on the offshore side.

Frequencies for the calculated consequences are estimated, including frequencies for ignition, in order to assess the risk. Wind distribution and population groups with different exposure level have also been added to the calculations.

Some of the main results of the risk calculations in PHAST Risk are:

- For tanks on barge it is safer to use hose cranes in preference to unattached hoses.
- For tanks on the ground there is no significant difference in the risks when using hoses, hose cranes or loading arms, and there is also no significant difference in the risks when using hoses or hose cranes for tank trucks.
- The societal risks for using tanks on barge with hose cranes and tanks on the ground are almost identical.
- The societal risks when using tank trucks are slightly higher compared to using tanks on the ground.
- There is no significant difference in the societal risk when having a system pressure of 9 bar instead of 6 bar.
- An open gangway gives significantly higher societal risks compared to a closed gangway.
- A change in the wind distribution does not significantly change the risks.
- Excess flow valves give significantly lower risks when used on tank trucks.

- The location of the bunkering interface relative to the gangway and transit area for cars is important.
- A release time of 5 sec (total reaction and closing time for ESD) gives slightly lower societal risks for tanks on barge relative to a release time of 10/60 sec.
- A release time of 5 sec (total reaction and closing time for ESD) gives significantly lower risks for tanks on the ground relative to a release time of 10/60 sec.
- A release time of 5 sec (total reaction and closing time for ESD) gives almost the same risks for tank trucks with excess flow valves relative to a release time of 10/60 sec.

To clarify the weaknesses of the Gaussian distribution calculations, some additional CFD (computational fluid dynamics) simulations have been made. The CFD simulations showed that the dam effect and shelter effect of the ship, the resulting horizontal and vertical whirlwinds and the low wind speed retains the gas and inhibits dispersion, resulting in a smaller area of impact. The ignition model is essential for the CFD simulations, as an early ignition results in a small area of impact. The resulting place-bound risks follow the ship's shape, and the societal risks are low, as the flash fire hardly reaches the placed waiting area.

The calculated risks with PHAST Risk and CFD simulations differ, as PHAST cannot include contours in the vicinity of the leak. CFD simulations include the possible risk reduction of contours beside the LNG facility itself and can identify any unfortunate contours and thus give rise to a more realistic risk profile. Generally, PHAST Risk specifies only risks associated with an LNG facility on a generic level, whereas CFD simulations can place risks at site.

2. HAZARD WORKSHOP

2.1 Method

As basis for the preparation of a quantitative risk analysis, a Hazard Identification (HAZID) workshop has initially been carried out, with participation from relevant technical groups/experts. The purpose of the workshop was to systematically identify undesirable scenarios (for further impact studies), which could occur in connection with bunkering.

In cooperation with the Norwegian Directorate for Civil Protection (DSB) and the Norwegian Maritime Authority (NMA) it was agreed to use the following basic set-up for the hazard identification, LNG bunkering of ships from:

- fixed tank onshore or tank on barge via hoses
- fixed tank onshore via loading arm
- fixed tank onshore or tank on barge via hose cranes
- tank truck onshore via hoses
- tank truck onshore via hoses to fixed installation with hose crane

As a condition, tanks and facilities are fitted with:

- safety valve on tank
- gas detector
- flame detector
- ESD (activated by detector and emergency shutdown)
- ESD coordinated between shore and ship (not for tank trucks, however)
- drip tray underneath fixed tank for collection of LNG spills
- pull-away/dry-break/break-away/quick release couplings

In addition, the following supplementary safety equipment is assessed:

- excess flow valves and non-return valve
- vapour return

The HAZID is performed as a What-If, which is a general brainstorming method used for hazard identification and qualitative risk assessment. It is a flexible review technique which could be used on any system, work flow or process in order to identify hazards.

The What-If analysis is carried out by a group asking "What-If" questions related to specific aspects of the design (such as blockages, leaks, corrosion, vibration, partial errors and external influences).

2.2 Workshop

The workshop was held on 22 August 2012 from 8:30 to 15:00 in the Rambøll Head Office, Copenhagen, with the following participants:

Workshop leader:

Jan Gramkov, Rambøll Denmark

Workshop secretary:

Sverre Daniel Hanssen, Rambøll Norway

Workshop participants from Rambøll:

Kristina Hoffmann Larsen, Rambøll Denmark
Finn Mølsted Rasmussen, Rambøll Denmark
Henrik Dorn-Jensen, Rambøll Denmark
Ole Frank Jørgensen, Rambøll Denmark
Lars Wahl Andersen, Rambøll Oil & Gas

Workshop participants from the client:

Trond Carlsen, DSB
Arne Dybwad, DSB
Lasse Karlsen, NMA
Øyvind Skog, NMA

2.3 Workshop tables

Workshop date: 22/08/2012

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
1	Hose Disconnection/rupture of fixed connection	The connection has not been connected properly	Procedures Visual detection / quality assurance Slow / step-by-step start-up Internal safety zone on the ship Shipside water curtain Drip trays + foam	Spills on hull, brittle fracture (depending on pump speed, volume) Gas into the ship (crack formation)	LNG detectors onshore (vulnerable to wind) Visual control of system before execution
2	Hose rupture without external influences	Hose weakness, wear and tear, manufacturing defect	Pressure testing Interval replacement Visual detection Double-walled hoses Loss of vacuum Gas detection Internal safety zone on the ship Shipside water curtain Differential pressure measurement and shut-down Drip trays + foam	Spills on hull, brittle fracture (depending on pump speed, volume) Gas into the ship (crack formation in the steel/hull)	Hoses to be tested before initial use

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
3	Hose rupture due to external influences when bunkering from barge	Ship against ship, unintended ship motion (human failure, environmental forces, waves from other ships)	Pull-away/dry-break couplings Speed limitations for ship in port Safety zone onshore and offshore Closing of port for larger ships during bunkering in order to prevent accidents Requirements for mooring and fendering between barge and ship Supervision of ship traffic in the port in order to abort the process if necessary Internal safety zone on the ship Shipside water curtain Differential pressure measurement and shut-down Drip trays + foam	Spills offshore, not onshore Spills on hull Less controllable offshore, gas generation	Assumes that the planned ship motion (due to loading/unloading, tide) will not lead to hose rupture. Safety zone offshore may include the closing of small ports (some ports may not be suitable for LNG bunkering)

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
4	Hose rupture due to external influences when bunkering from shore	Vehicle collision, earthquakes, unintended ship motion (human failure, environmental forces, waves from other ships)	Pull-away/dry-break couplings Speed limitations for ship in port Safety zone onshore and offshore Closing of port for larger ships during bunkering in order to prevent accidents Physical barriers to prevent collision (cones, chains) Road traffic monitoring Restricted loading operations due to danger from falling cargo (safety zone) Internal safety zone on the ship Shipside water curtain Shipside insulating curtain Differential pressure measurement and shut-down Drip trays + foam	Gas generation The spill can accumulate locally on the ground or harm the ship's side	-

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
5	Pipe rupture	External forces, liquid slugs / hammering caused by liquid, manufacturing defect, incorrect installation, incorrect/insufficient maintenance, corrosion (leakage currents from cathodic protection of quay facility)	Design review Inspection and maintenance Double pipes with cryogenic material in both pipes Insulated pipes Monitoring between barriers in double pipes (vacuum, gas detection) Culvert (secondary barrier) Safety zone Speed limitation Road traffic monitoring Differential pressure measurement and shut-down Visual inspection and shut-down Cryogenic drip pan + foam Excess flow valve Bypass / pressure relief	LNG on ground/deck on barge LNG on hull LNG on passenger tunnel (injured passengers/damaged tunnel) LNG on road and parking spaces	-
6	Low pressure in tank	Quick pump-out Design flaw	Pressure measurement/monitoring Pressure build-up Design for vacuum	Implosion	The tank will be designed for a given partial pressure according to Directive (PED)
7	Overfilling of ship's tank	Operator error Safety system failure Design flaw	Overfilling protection Shut-down Return gas pipe with immersion ensuring max. 96% filling. Training/procedures/instructions	Gas in ventilation mast LNG in ventilation mast	-

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
8	LNG in nitrogen system	Operator error Design flaw	Procedures System must be designed to handle methane and nitrogen Design review	LNG/methane release in areas not intended for this	-
9	Premature disconnection	Operator error Design flaw Stress	Training/procedures	Almost as for hose rupture LNG/methane release in areas not intended for this	-
10	External fire	Vehicle fire, building fire, ship fire, lightning stroke	Safety zone Water cannon Local fire-extinguishing equipment and personnel Non-combustible material within safety zone Insulated piping and tanks (temperature build-up takes longer) Shut-down Evacuation Release of ship/hauling line	Shut-down/fire Gas fire	Piping, tanks and hoses must be insulated with non-combustible material
11	Loss of power		Fail safe operation Communication (VHF) not dependent on external power	Shut-down Loss of communication between ship and shore	Emergency power to gas/flame/liquid detection

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
12	Sabotage, terrorism, vandalism, theft		Access control Monitoring Safety zone Inspections Training/vigilance Cooperation with security services and port authorities		-
13	Rupture of loading arm when bunkering from shore	Unintended ship motions (human error, environmental forces incl. bad weather, waves from other ships)	Pull-away coupling Break-away Quick release Dry break See barriers under "hose rupture"		Possibly a higher (m) release point. Assumes that bunkering connecting point is located in relatively the same position on all ship types. Requirement for highest point on loading arm.
14	Incorrect connection	Operator error	Different diameter of couplings		
15	Hose rupture of hose crane on barge	See "hose rupture" High point on hose arm			Possibly a higher (m) release point. Assumes that bunkering connecting point is located in relatively the same position on all ship types. Requirement for highest point on loading arm

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
16	Hose rupture of hose crane onshore	See "hose rupture" High point on hose arm			Possibly a higher (m) release point. Assumes that bunkering connecting point is located in relatively the same position on all ship types. Requirement for highest point on loading arm
Tank truck - hoses					
17	Hose rupture tank truck	Unintended motion of tank truck (human error, insufficient securing of tank truck) Hose too short Collision with other vehicles Parked too far from the ship	Operational lock Level foundation Brake pads Break-away couplings Dry break Procedures/instructions for the ship and tank truck personnel		Break-away and dry break are not standard Normally single hoses For filling with multiple tank trucks it is assumed that this is done in two separate operations
18		Stress Constant turnover of drivers (low continuity) Language issues		Increased likelihood of operator error	

No.	Equipment	Reason	Barriers	Consequences	Remarks/ assumptions
Tank truck -> fixed installation with hose crane					
19	Hose rupture tank truck	Unintended motion of tank truck (human error, insufficient securing of tank truck) Collision with other vehicles	Operational lock Level foundation Brake pads Break-away couplings Dry break Procedures/instructions for the personnel on the ship and tank truck		Break-away and dry break are not standard Normally single hoses In the event of several connected tank trucks it is assumed that these do not fill simultaneously
20		Stress Constant turnover of drivers (low continuity) Language issues		Increased likelihood of operator error	
21	Transfer tank truck to tank truck	Insufficient pressure in one of the tank trucks Unequal pumping capacity in the tank trucks	One-way valves, three-way valves	Overfilling of tank truck	
22	Pump leakage (also applies to fixed installations)	Insufficient cooling Poor maintenance Leakage	Start-up procedure Maintenance procedure Emergency stop Visual inspection /monitoring	Local release of LNG	Only applicable to external pumps

List of scenarios from the hazard identification

No.	Equipment
1	Hose rupture of fixed connection
2	Hose rupture without external influences
3, 4	Hose rupture due to external influences when bunkering from barge and from shore
5	Pipe rupture
6	Low pressure in tank
7	Overfilling of ship's tank
8	LNG in nitrogen system
9	Premature disconnection
10	External fire
11	Loss of power
12	Sabotage, terrorism, vandalism, theft
13	Rupture of loading arm when bunkering from shore
14	Incorrect connection
15, 16	Hose rupture of hose crane on barge and on shore
17, 19	Hose rupture tank truck
18, 20	Stress
21	Transfer tank truck to tank truck
22	Pump leakage

The following points from the HAZID have been modelled indirectly or cannot be modelled in the calculation of local (place-bound) risks and societal risks:

No.	Equipment	Grounds
6	Low pressure in tank	This event is considered not to cause release of LNG, only damage to tank.
8	LNG in nitrogen system	Releases due to LNG in the nitrogen system are only expected to occur in the event of two simultaneous failures (unsuitable material in the nitrogen system and design flaw allowing backflow of LNG to the nitrogen system).
9	Premature disconnection	As pull-away/dry-break/break-away/quick release couplings are listed as a general condition, this event will only cause limited release of LNG.
11	Loss of power	It is assumed that the facility will enter fail-safe mode, where no release of LNG will take place.
12	Sabotage, terrorism, vandalism, theft	These types of accidents are unpredictable with regard to probability and consequence. It will therefore not be practical to prepare event trees for such type of releases.
14	Incorrect connection	This type of event is assumed secured by different diameters and couplings, so that this cannot cause release of LNG.
18, 20	Stress	Stress increases the probability of incorrect use, but is not in itself a cause for release of LNG.
21	Transfer tank truck to tank truck	This event will not cause release of LNG.

3. CONSEQUENCE MATRIX

LNG is a liquefied natural gas, which through the supply of heat will evaporate to GNG (gaseous natural gas). GNG is non-toxic, but it has an asphyxiating effect by displacing the oxygen in the air when present in high concentrations or in confined spaces where the gas can accumulate. There are no Acute Exposure Guideline Levels (AEGLs) for LNG, and Protective Action Criteria (PAC) concentrations are based on the lower flammability limit for methane.

The levels in the consequence matrix and the further calculations are based on gas concentrations of LFL and ½ LFL (LFL: Lower flammability limit) as well as probit for fire (both flash vapour cloud fires and long-lasting pool/jet fires) with indication of 1%, 10% and 50% fatalities (the probit parameters of PHAST are used). The asphyxiating effect of GNG has been included in the consequence matrix, but is not included in the calculations as the effect only occurs at very high concentrations of GNG.

An estimation of the dispersion or risk of explosion in the event of a release on board the ship is generally not carried out, as this is very dependent on the physical conditions on board the ship in question. It is assumed that the LNG piping on board is arranged so that the passengers are not affected by an LNG release of limited volume on board. The risk of gas ingress into the ship (e.g. through the ventilation system) or into the terminal building in the event of an outdoor release is not assessed.

The following groups of people form the basis for the consequence matrix:

- Passengers on board the ship, indoors
- Passengers on board the ship, outdoors
- Passengers on board the ship, in vehicles
- Passengers in (open) transit to or from the ship
- Passengers in (closed) transit to or from the ship
- Passengers in terminal building
- Passengers in vehicles in transit to or from the ship
- Passengers in vehicles in vehicle holding lanes
- 3rd part of quay area (for smaller ferry landings)

The effects of a concentration of LFL (4.4%) or ½ LFL (2.2%) on humans in the event of a release, are not sufficient to cause poisoning.

Three conditions have to be met in order for a flammable liquid (a flammable substance in its condensed state) to be ignited:

1. A sufficient amount of flammable vapour must be released when preheating the liquid.
2. The vapour must be mixed in a suitable ratio with air (a gas phase oxidant).
3. The mixture must either have high enough temperature to self-ignite or there must be a source of ignition that can heat the gas mixture locally to a temperature near the adiabatic flame temperature, where an ignition may occur and spread throughout the gas mixture.

<u>Vapour cloud fire:</u>
A vapour cloud fire (VCF) may arise when a cloud of flammable vapour is released e.g. through pressure relief valves on a tank or by evaporation of a flammable liquid that escapes the primary container (tanks, pipes, pumps, etc.), e.g. by overfilling of tank, pipe leakage, pump leakage or other defects.

A smaller, seeping release will not cause a high evaporation rate, whereas a streaming or pouring release could cause relatively quick evaporation. Releases within a drip tray or culvert with high walls will normally collect (i.e. accumulate) the vapour far better than in unconfined spaces outdoors. The released vapour is flammable, and it could ignite immediately if there is a source of ignition present nearby, if not the vapour will be dispersed in a fan shape. If the vapour cloud encounters a source of ignition, a (delayed) ignition may occur, resulting in a VCF or an explosion in the vapour cloud (unconfined vapour cloud explosion, UVCE). It is expected that an explosion in the vapour cloud could occur if the vapour is completely or partially enclosed by equipment or constructions, or if there is an explosion inside a building which propagates to the larger external cloud.

A VCF creates a powerful and acute heat generation which could cause direct damage to sensitive equipment, such as cables and similar. Combustion in open areas (without obstructions or screening) will happen relatively slowly (up to 20 seconds is normal), and will only create a slight, if any, overpressure. Damage to other equipment directly exposed to the fire may also occur.

If the vapour cloud disperses amongst walls, between tanks and pipes, or into buildings before ignition occurs, a UVCE may occur, where, in addition to an intense heat generation, a localised overpressure will be generated which could cause significant damage (cf. the Buncefield fire, ref. /5/). An aspect of large volume gas explosion, compared to explosives such as TNT, is that the overpressure does not spread out from one emission point, but occurs over a large area where the combustion takes place. The damaged area may therefore be significant.

The extent of the damage will depend on the overpressure and on the exposed equipment. At the worst, a total failure of the primary containers (pipes, tanks, etc.) could occur, so that flammable liquid or gas is released.

It is known (and has been observed at e.g. the Buncefield fire, ref. /5/) that an explosion that arises in a confined volume (a semi-open building or similar) will be capable of spreading to a volume of flammable gas outside the confinement. In such cases, an explosion will occur in the vapour cloud instead of a vapour cloud fire. This effect is called a "bang-box" ignition.

Pool fire:
A pool fire may arise when vapour from flammable liquid is ignited, which expands to the terrain from tanks or pipes (i.e. failure of the primary container). Depending on the size and degree of the release, the fire may escalate to a scale where it could cause intense heating of exposed equipment. Tanks and pipes near the pool fire are typically the most vulnerable to heat exposure in the form of direct flame exposure or radiant heat exposure. In the event of large pool fires, even more distant equipment could be affected.

If there are pipes with enclosed volumes (between closed valves or similar) that are exposed to intense fires, the heating could cause the pipes to burst if there is no other possibility for sufficient pressure release. Heat transmission occurs through thermal conduction through connected metal pipes exposed to the fire, or through radiation from the fire directly onto the pipes.

Thermal radiation from pool fires could cause personal injuries. In the risk assessment the possible harmful effect from thermal radiation on people is taken into consideration when estimating lethal dose.

Iso-probability curves, corresponding to lethal dose are shown in Figure 3-1.

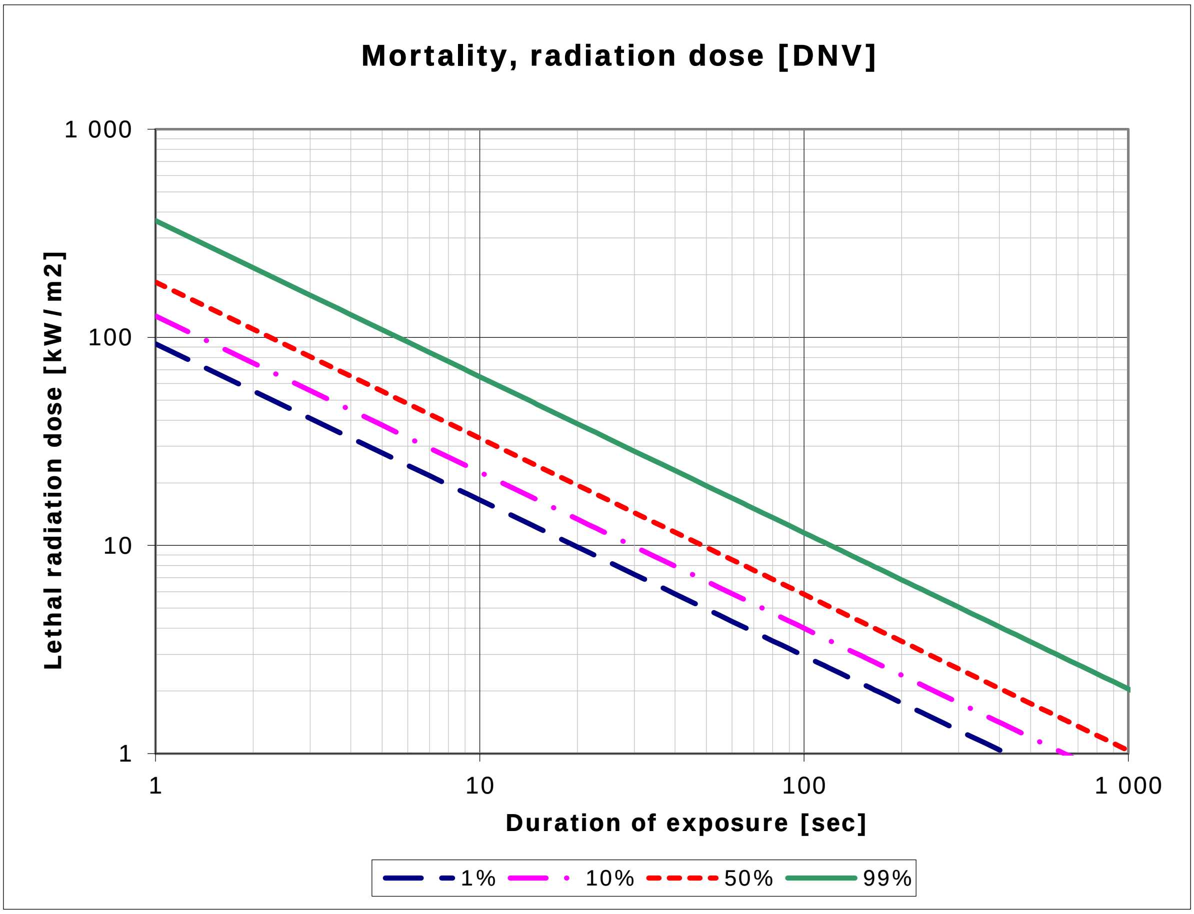


Figure 3-1 Iso-probability curves for fatality, for variation in exposure time and thermal radiation intensity.

Duration of radiation exposure from fire depends on factors such as:

- Duration of fire
- Whether it is possible to escape or hide from the radiation (evacuation)

The thermal radiation, to which people could be exposed in Norwegian ports, stems from long-lasting fires such as pool fires. It is, however, for the most part possible for people to escape the thermal radiation on their own, as long as they are not severely exposed when the ignition occurs.

The above evaluations give, when using figure 3-1, the damage criteria shown in the table below, which are used for the consequence calculations in the risk assessments.

Probability of fatalities	Exposure time (min)	Thermal radiation (kW/m^2)
1%	1.1	4
10%	1.7	4
50%	2.8	4
99%	6.8	4
1%	0.24	12.5
10%	0.36	12.5
50%	0.60	12.5
99%	1.5	12.5
1%	0.06	35
10%	0.09	35
50%	0.15	35
99%	0.38	35

Table 3-1 Fatal radiation intensity under various conditions.

A radiation level from a fire of 35 kW/m^2 (or more) impacting cars or other equipment, could cause damage if the exposure lasts for more than a few minutes, cf. /7/.

Jet fire:
If a release sprays out of a smaller hole or a pressure relief valve, and this spill is immediately ignited, a jet fire could occur. A jet fire will be extinguished only when the source of the fire has been removed (exhausted or closed).
A jet fire consists of a very intense directional flame which could cause immediate damage to sensitive equipment, such as cables and similar. Moreover, heating of exposed equipment and tanks located close to the jet fire or directly hit by the jet flame could occur. The thermal radiation from a jet fire decreases quickly with increasing distance.

The damage criteria for jet fires are identical to the damage criteria for pool fires.

Explosion:
If burning of a gas mixed with an oxidant (oxygen) occurs in an accumulated volume where the increase of pressure is faster than the pressure relief (e.g. a closed container, a building, a ship's hull), then the increase of pressure will speed up the combustion rate of the mixture, which will in turn increase the pressure. Pressure relief from an explosion within a piece of equipment or building, could take place via dedicated openings (normally in process plants) and through doors, windows and other openings. If the pressure relief can only be performed at a distance from the ignition point, it is not certain that the pressure relief could prevent a significant pressure build-up. The process of pressure increase and increased combustion rate will continue until the fire fuel is consumed, the cabinet is broken or the maximum exposure pressure is achieved (normally 6-10 bar, but it could be higher under special conditions).

In Table 3-2 an extract from ref. /8/ is shown, describing the damage criteria in the event of explosions.

Overpressure (bar)	Harmful effect
0.01-0.03	Glass failure
0.03	Minor structural damage to buildings
0.07	Partial demolition of houses
0.12	Failure of windows with steel wire
0.2	Some broken pipes, sprinkler pipes broken
0.3	Many broken pipes
0.5	Loaded vehicles and trucks are overturned
0.5	Shattered masonry walls in concrete frames
0.7	Complete destruction of buildings
0.1	Damage to human organs
0.03	Hearing damage

Table 3-2 Explosion damage criteria

The values above show that a person could be injured or, at the worst, die if the person is in an area where the overpressure is 0.1 bar or more, and that a person's hearing could be damaged at an overpressure of 0.03 bar.

Consequence matrix:

Group of people	**½ LFL (2.2%) Effects of concentration for outdoor releases**	**LFL (4.4%) Effects of concentration and explosion for outdoor releases and explosion**	**Vapour cloud fire Effects of radiation for outdoor flash fires**	**Pool/jet fire Effects of radiation for outdoor long-lasting fires**	**Asphyxiation (>25%) Effects of concentration for outdoor releases**
Passengers on board the ship, indoors	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the ship.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the ship. In the event of an explosion outdoors, people indoors could be injured by glass splinters from the ship windows if the increase in pressure causes the windows to shatter.	No effect on humans as the ship will provide a sheltering effect	No effect on humans as the ship will provide a sheltering effect	No effect on humans from the LNG itself, as the LNG would first have to enter the ship. If the LNG enters the ship, people could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.

Group of people	**½ LFL (2.2%) Effects of concentration for outdoor releases**	**LFL (4.4%) Effects of concentration and explosion for outdoor releases and explosion**	**Vapour cloud fire Effects of radiation for outdoor flash fires**	**Pool/jet fire Effects of radiation for outdoor long-lasting fires**	**Asphyxiation (>25%) Effects of concentration for outdoor releases**
Passengers on board the ship, outdoors	No effect on humans from the LNG itself, as the concentration would need to be considerably higher.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. In the event of an explosion outdoors, humans could be affected by pressure if a sufficient increase of pressure occurs.	People could be burned, but would need to be close to the spill or the centre of the fire before there is a risk of fatality.	People could be burned, and there is risk of fatality.	People could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentration could lead to fatalities.
Passengers on board the ship, in vehicles	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. In addition, the LNG would need to enter the ship and then the vehicles.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. In addition, the LNG would need to enter the ship and then the vehicles. In the event of an explosion outdoors, people in their vehicles on board the ship would not be affected by the resulting pressure.	No effect on humans as the ship (and the vehicles) will provide a sheltering effect.	No effect on humans as the ship (and the vehicles) will provide a sheltering effect.	No effect on humans from the LNG itself, as the LNG would first have to enter the ship and then the vehicles. If the LNG enters the ship, people could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.

Group of people	½ LFL (2.2%) Effects of concentration for outdoor releases	LFL (4.4%) Effects of concentration and explosion for outdoor releases and explosion	Vapour cloud fire Effects of radiation for outdoor flash fires	Pool/jet fire Effects of radiation for outdoor long-lasting fires	Asphyxiation (>25%) Effects of concentration for outdoor releases
Passengers in (open) transit to or from the ship	No effect on humans from the LNG itself, as the concentration would need to be considerably higher.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. In the event of an explosion outdoors, humans could be affected by pressure if a sufficient increase of pressure occurs.	People could be burned, but would need to be close to the spill or the centre of the fire before there is a risk of fatality.	People could be burned, and there is a risk of fatality.	People could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.
Passengers in (closed) transit to or from the ship	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the transit gangway.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the transit gangway. In the event of an explosion outdoors, people on the gangway could be injured by glass splinters from the gangway windows if the increase in pressure causes the windows to shatter. In the event of a strong increase in pressure, the structure of the gangway could be damaged.	No effect on humans as the transit gangway will provide a sheltering effect.	No effect on humans as the transit gangway will provide a sheltering effect.	No effect on humans from the LNG itself, as the LNG would first have to enter the transit gangway. If the LNG enters the gangway, people could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.

Group of people	**½ LFL (2.2%) Effects of concentration for outdoor releases**	**LFL (4.4%) Effects of concentration and explosion for outdoor releases and explosion**	**Vapour cloud fire Effects of radiation for outdoor flash fires**	**Pool/jet fire Effects of radiation for outdoor long-lasting fires**	**Asphyxiation (>25%) Effects of concentration for outdoor releases**
Passengers in terminal building	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the terminal building.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the terminal building. In the event of an explosion outdoors, people indoors could be injured by glass splinters from the terminal building's windows if the increase in pressure causes the windows to shatter.	No effect on humans as the terminal building will provide a sheltering effect.	No effect on humans as the terminal building will provide a sheltering effect.	No effect on humans from the LNG itself, as the LNG would first have to enter the terminal building. If the LNG enters the terminal building, people could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.

Group of people	½ LFL (2.2%) Effects of concentration for outdoor releases	LFL (4.4%) Effects of concentration and explosion for outdoor releases and explosion	Vapour cloud fire Effects of radiation for outdoor flash fires	Pool/jet fire Effects of radiation for outdoor long-lasting fires	Asphyxiation (>25%) Effects of concentration for outdoor releases
Passengers in vehicles in transit to or from the ship	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the vehicles.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the vehicles. In the event of an explosion outdoors, people in the vehicles could be injured by glass splinters from the vehicle's windows if the increase in pressure causes the windows to shatter.	No effect on humans as the vehicles will provide a sheltering effect.	A vehicle would be quickly heated up by radiation from the fire, and people could be affected.	No effect on humans from the LNG itself, as the LNG would first have to enter the vehicles. If the LNG enters the vehicles, people could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.
Passengers in vehicles in vehicle holding lanes	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the vehicles.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. LNG would also need to enter the vehicles. In the event of an explosion outdoors, people in the vehicles could be injured by glass splinters from the vehicle's windows if the increase in pressure causes the windows to shatter.	No effect on humans as the vehicles will provide a sheltering effect.	A vehicle would be quickly heated up by radiation from the fire, and people could be affected.	No effect on humans from the LNG itself, as the LNG would first have to enter the vehicles. If the LNG enters the vehicles, people could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.

Group of people	½ LFL (2.2%) Effects of concentration for outdoor releases	LFL (4.4%) Effects of concentration and explosion for outdoor releases and explosion	Vapour cloud fire Effects of radiation for outdoor flash fires	Pool/jet fire Effects of radiation for outdoor long-lasting fires	Asphyxiation (>25%) Effects of concentration for outdoor releases
3rd part of quay area (for smaller ferry landings)	No effect on humans from the LNG itself, as the concentration would need to be considerably higher.	No effect on humans from the LNG itself, as the concentration would need to be considerably higher. In the event of an explosion outdoors, humans could be affected by pressure if a sufficient increase of pressure occurs.	People could be burned, but would need to be close to the spill or the centre of the fire before there is a risk of fatality.	People could be burned, and there is a risk of fatality.	People could experience increased heart rate and pulse, and impaired coordination, perception and power of judgement. Higher concentrations could lead to fatalities.

4. IMPACT STUDIES WITH PHAST RISK

4.1 General assumptions

It is assumed that a procedure is developed for when bunkering should be aborted due to poor weather conditions.

4.2 Calculations

Based on experience from the modelling of releases from other similar projects as well as on the results from the HAZID, it was decided to take into account the following variations:

Contents:
a) Pipes, hoses and loading arms carrying liquid
b) Pipes, hoses and loading arms carrying gas

Material parameters:
a) 100% methane, -182°C, vapour pressure -0.1 bar
b) 100% methane, -161°C, vapour pressure 0.1 bar
c) 100% methane, -142°C, vapour pressure 3 bar
d) 100% methane, -140°C, gaseous state

System pressure (after pumps and in the ferry tank):
a) 6 bar
b) 9 bar

Release height:
a) For releases onshore: 0.5 meters above ground
b) For releases offshore: 3 metres above the water level

The release height has not been adjusted for use of loading arms.

Release variations:
a) Catastrophic tank failure
b) Pipe, hose or loading arm failure
c) Large perforation of pipe, hose or loading arm (25 mm Ø hole - 1")
d) Small perforation of pipe, hose or loading arm (1.784 mm Ø hole - ATEX; 2.5 mm^2 leak from flange with gasket)
e) Activation of safety valve at 16 bar.

A catastrophic tank failure due to heating from an external fire has not been included in the release variations, as third parties and crew are expected to be vacated from the exposed area in such situations.

Release rate for failure:
a) Corresponding to a pump rate of 413 m^3/hr that corresponds to the maximum fluid velocity through a centrifugal pump with an inner diameter of 150 mm (see section 4.3.2)
b) Corresponding to a pump rate of 320 m^3/hr
c) Corresponding to failure of a 80 mm gas-carrying pipe (vapour return) (only -140°C, 3 bar)

Release rate for perforation:

The release rate for leakage from a perforation is calculated based on the hole size with a standard discharge coefficient of 0.6. The value 0.6 represents a clean-cut pipe failure. If the perforation is not considered clean-cut, the discharge coefficient will be lower, resulting in a lower release rate. A discharge coefficient of 0.6 is conservative.

Release duration:

a) 10 seconds (until stopped by ESD or similar safety device)
b) 30 seconds (until stopped by ESD or similar safety device)
c) 60 seconds (until stopped by ESD or similar safety device)
d) Until tank is empty:
   I. Tank truck volume: 50 m^3
   II. Fixed tank or tank on barge: 250 m^3
   III. Fixed tank or tank on barge: 1,000 m^3

4.3 Results

In the event of LNG releases where the temperature is higher than the boiling point for LNG at atmospheric pressure, sufficient flashing will occur in the escaping liquid to cool down the remaining LNG to below the boiling point.

Material	Temperature	Flash fraction
100% methane	-182°C	0.00
100% methane	-160°C	0.01
100% methane	-140°C	0.14

Vaporisation will occur from LNG with a temperature lower than the boiling point for LNG at atmospheric pressure. This vaporisation occurs from the escaping liquid as well as from the accumulated pool of LNG. In order to avoid confusion, vaporisation from the accumulated pool is in the following referred to as evaporation.

Gas developed from flashing, vaporisation and from evaporation will be carried along by the wind and slowly mixed with air due to atmospheric turbulence and diffusion.

4.3.1 Catastrophic tank failure

In the event of a catastrophic tank failure with an overpressure (LNG at a temperature higher than the boiling point), the contents will be ejected (the force and velocity is determined by the pressure in the tank) in the direction where the failure originated. In the first phase of such a failure, flashing occurs in the air, vaporisation (due to the large available surface area) occurs as well as a mixing of gas/vapour and air. Liquid will then fall to the ground, gas/vapour heavier than air will sink to the ground, and gas/vapour lighter than air will remain in the air and start to rise and to mix.

In the event of a catastrophic tank failure with an underpressure (LNG at a temperature lower than the boiling point), air is sucked into the tank. If the hole is above the fluid level, a slow evaporation of LNG will take place through the hole. If the hole is below the fluid level, the contents will leak out and accumulate in a pool and the dispersion is determined by the terrain and/or the evaporation rate (as determined by the LNG temperature and energy supply from the ground, air and sun).

In the event of failure of a tank containing LNG at a temperature higher than the boiling point, significant flashing will occur along with significant vaporisation. The remaining liquid will be cooled to below the boiling point for LNG at atmospheric pressure. This will results in 2 types of consequences: a) A heavy gas cloud from the failure itself migrating with the wind; b) A pool of LNG from which gas continuously evaporates.

In the event of failure of tank containing LNG at a temperature lower than the boiling point, vaporisation will occur (small amount compared to the evaporation from the pool) during the first phase. The remaining liquid will be cooled to below the starting temperature. This will result in 2 types of consequences: a) A heavy (smaller) gas cloud from the failure itself migrating with the wind; b) A pool of LNG from which gas continuously evaporates.

In the event of a tank failure, a drip tray or culvert will help retain the remaining liquid that ends up therein. This amount is determined by the ejection length and direction of the liquid during the failure, compared to the size of the drip tray or culvert. Drip trays or culverts are normally not constructed for tank failure, since it is not known where the contents of the tank will end up (distance from tank) in the event of a tank failure.

4.3.2 Failure of pipe, hose or loading arm carrying liquid

In the event of LNG releases where the temperature is higher than the boiling point, flashing will initially occur until the temperature is lower than the boiling point (see the start of this section).

In the event of a pipe, hose or loading arm failure, a minor vaporisation will occur while the jet of LNG is in the air. The LNG release will form a pool which will extend until the pool meets a boundary (e.g. a drip tray or culvert), or until equilibrium is achieved between the inlet of LNG and the evaporation of LNG.

For tank trucks it is assumed that a centrifugal pump with a pump rate of 100 m^3/hr is used. For fixed tanks and tanks on barge it is assumed that positive displacement pumps are used with a pump rate of 320 m^3/hr (ref. /4/).

It is necessary to create manual release sources in PHAST in order to model that the pumps give sufficient resistance to avoid escalation of the release velocity. The release velocity in the event of failure is not dependent of the system pressure.

For centrifugal pumps the resistance of the pump is determined by the liquid's velocity through the pump, and it is assumed that the liquid can achieve a velocity of maximum 6.5 m/s. Positive displacement pumps deliver the same flow regardless of back pressure, where the flow is unchanged in the event of a failure. The release rate in kg/s can thus be calculated using the form below:

Temperature	Pump rate	Release rate	Flash fraction	Liquid density (at release point)	Release rate	Release rate	Pipe diameter	Release velocity
°C	m^3/hr	m^3/hr		kg/m^3	kg/hr	kg/s	mm	m/s
-160	100	413	0.01	420.9	173.844	48.29	150	6.5
-140			0.14					
-160	320	320	0.01		134.698	37.42		5.0
-140			0.14					

The dispersion scenarios for pipe failures onshore are stabilised after 60-120 sec for low wind forces (0.5-2 m/s) and unstable atmospheric classes, see figure 4-1, and after 150-825 sec for stable atmospheric classes, and already after 20-45 sec for stronger wind forces (7-10 m/s)), see figure 4-2. The dispersion scenarios for pipe failures offshore for low wind forces (0.5-2 m/s) show longer stabilisation periods, up to 640 sec.

Stabilisation of the dispersion scenarios means that the maximum dispersion distance of ½LFL is achieved. During the stabilisation phase the ignition probability is the only variable that increases with the length of the release and dispersion scenario. When the scenarios end (e.g. by ESD) the dispersion scenarios also end just as quickly.

In event of failure, the major onshore consequences are jet flames and flash fires, both having a range of impact (to 4 kW/m^2) of around 200 m, or 205 m and 188 m respectively. In the event of releases offshore, an almost complete vaporisation of the LNG will take place due to the heat transfer from the water, resulting in a range of impact of up to 506 m for flash fires. The condition for the nearly complete vaporisation of the LNG during offshore releases is that the LNG comes into contact with water. This means that the discharge must be released into open waters, and not to e.g. the small strip of water between the ship and the quay or between ship and bunker vessel.

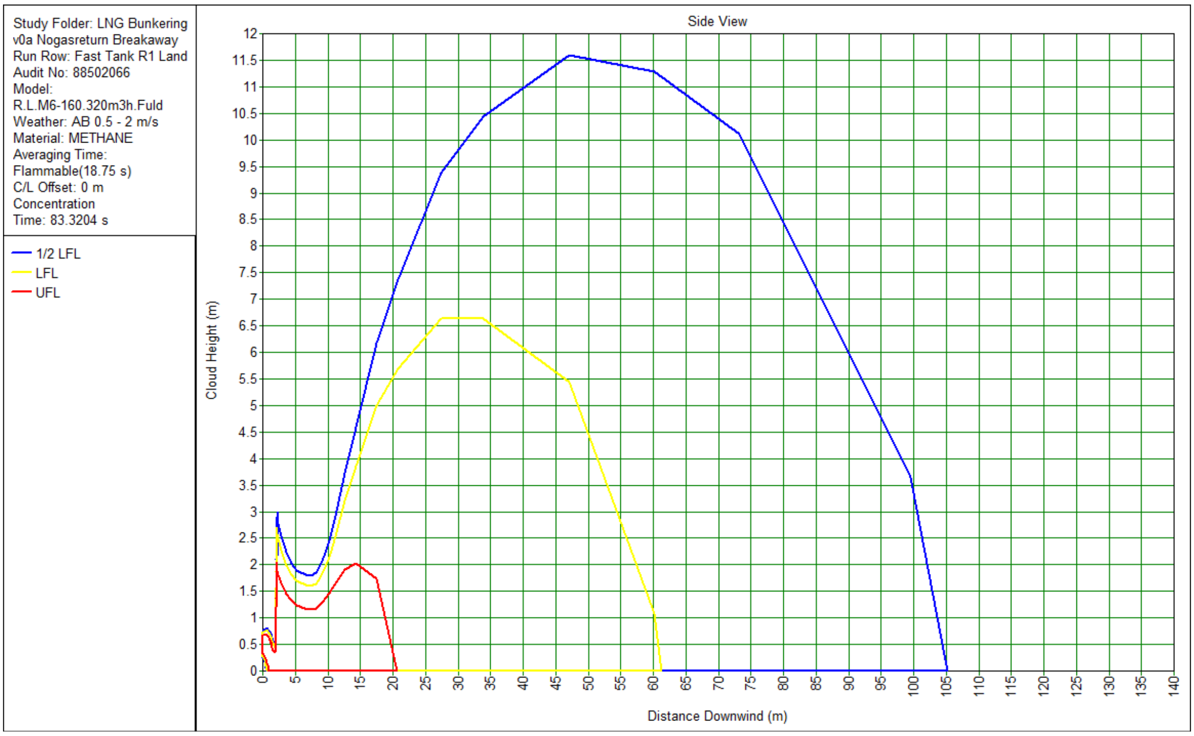


Figure 4-1 Vapour dispersion from (mainly) flashing from a failure with a release rate of 320 m^3/hr over land at -160°C and 6 bar system pressure at a low wind force of 0.5-2 m/s, stability class A/B. The dispersion is seen from the side and indicates the dispersion distance after 83 sec.

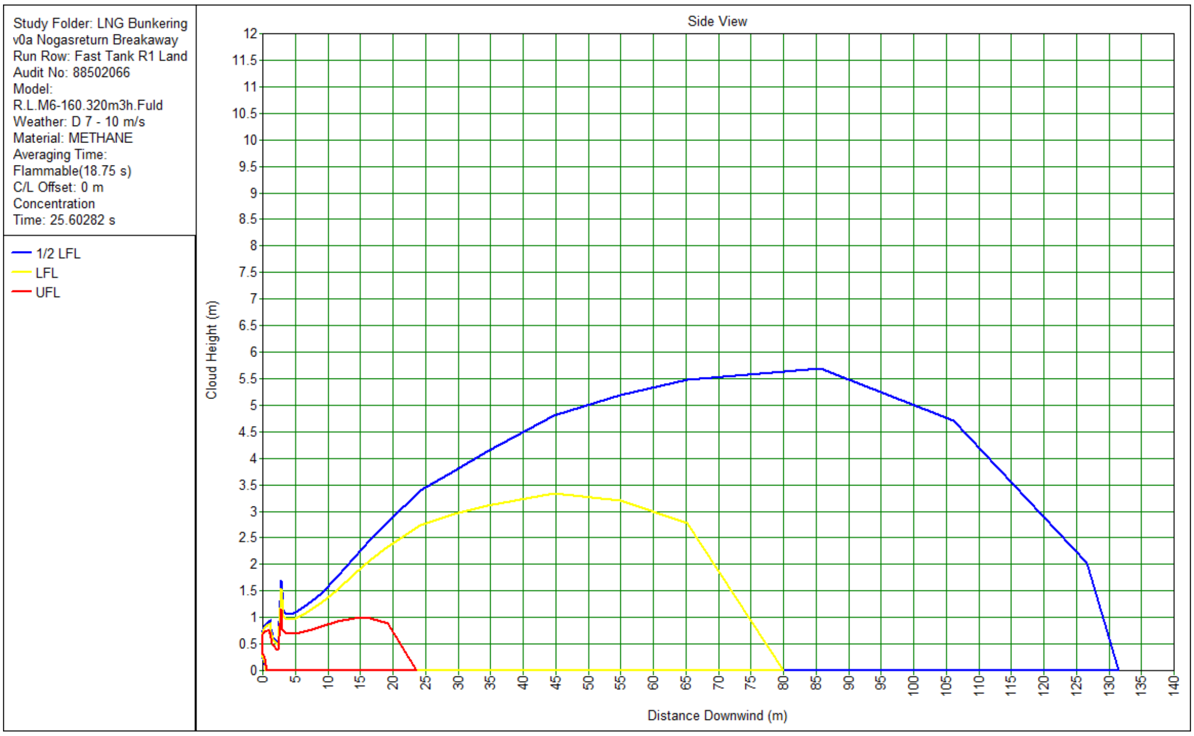
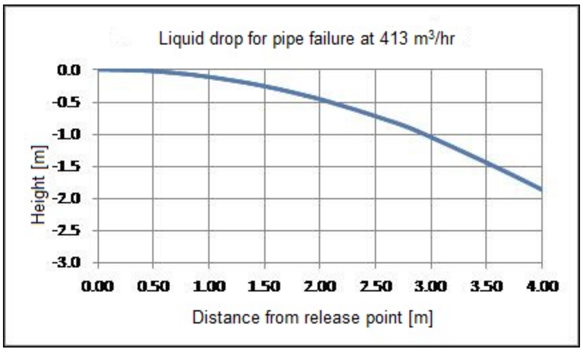
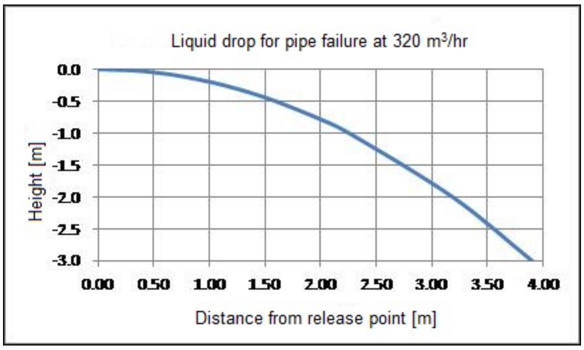


Figure 4-2 Vapour dispersion from (mainly) flashing from a failure with a release rate of 413 m^3/hr over land at -160°C and 6 bar system pressure at a wind force of 7-10 m/s. The dispersion is seen from the side and indicates the dispersion distance after 17 sec.

Impending flow

The drop curve for the LNG jet will be expressed as follows for a release rate of 413 m^3/hr (fluid drift velocity of 6.5 m/s) and 320 m^3/hr (fluid drift velocity of 5.0 m/s), respectively:





If the release, from a pipe failure, hose failure or failure of a loading arm, is close to the ship's side, the ship will be hit by the jet with concomitant effects on the steel and on the gas dispersion.

The following is a result of a hypothetical experiment with release on the hull of the ship:
If the release occurs between the ship and the quay or between the ship and bunker vessel, the ship's hull (and the bunker vessel's hull) will most likely be directly exposed to liquid LNG at a temperature of -140°C, leading to crack formation in the steel (unless the steel is of a special type). Together with ice formation in the small strip of water (0.5-1.0 m) between the ship and quay/ bunker vessel, this can easily result in LNG leaking into the ship with appurtenant risks, including explosions within the ship.

4.3.3 Failure of pipe, hose or loading arm carrying gas

In the event of failure of pipe, hose or loading arm carrying gas, the escaping gas will migrate with the wind and be mixed slowly with air due to atmospheric turbulence and diffusion.

The escaping gas may be ignited, resulting in a jet flame. The jet flame could have a range of up to 48 m (4 kW/m^2). Unignited, it is estimated that the gas can form a gas cloud of up to 84 m with a concentration of ½LFL. Upon subsequent ignition, this could cause severe burns.

Impending flow

If the gas jet hits the side of the ship or tank, the energy absorption of gaseous LNG is not sufficient to cause destruction without long-lasting impact.

4.3.4 Medium or small hole in pipes, hoses or loading arm

In the event of LNG releases where the temperature is higher than the boiling point, flashing will initially occur until the temperature is lower than the boiling point, see section 4.3.

In the event of a pipe, hose or loading arm failure, a minor vaporisation will occur while the LNG jet is in the air. The LNG will form a pool which will extend until the pool meets a boundary (e.g. a drip tray or culvert), or until equilibrium is achieved between the inlet and the evaporation of LNG.

Escaping liquid from a flange leak (1.784 mm Ø hole - ATEX; 2.5 mm^2 leak from flange with gasket) has a small area of impact. It is estimated to be maximum 7.6 m (calculated as a concentration of ½ LFL at a wind force of 7-10 m/s).

The dispersion scenarios for medium releases (25 mm Ø hole – 1") are stabilised after less than 60 sec for low wind forces (0.5-2 m/s) and already after less than 15 sec for stronger wind forces (7-10 m/s). Stabilisation of the dispersion scenarios means that the maximum dispersion distance of ½LFL is achieved. During the stable phase the ignition probability is the only variable that increases with the length of the release and dispersion scenario. When the scenarios end (e.g. by ESD) the dispersion scenarios also end just as quickly. The major consequence of medium releases is flash fires, which have a range of up to 125 m and jet flames with a range of up to 70 m.

4.3.5 Ship and quay front as dikes

In the event of offshore releases, the gas cloud will migrate with the wind along the surface of the water. If the gas cloud is carried towards the ship or the quay, these will work as dikes and divert parts of the cloud to drift along the ship/quay.

It has been measured how far the gas clouds will drift along the hull of the ferry and then hit the quay. The gas cloud will drift 110 m north toward the bow of the ferry or 80 m south toward the stern of the ferry.

It is assumed that the upper edge of the quay front is 2.85 above the water level, and that the effective height is 0.5 m less than the difference in height. Reduction of the height shall compensate for the gas that the wind forces over the quay front. The intersection between retained and not retained gas is shown in figure 4-3. A cross section of the gas cloud after having drifted 110 m is rendered in figure 4-4 and figure 4-5, with indication of quay height and effective height. The amount of gas being retained for the indicated wind forces has been calculated, see table 4-1. It is not possible to verify the effective height in PHAST, as this requires CFD calculations.

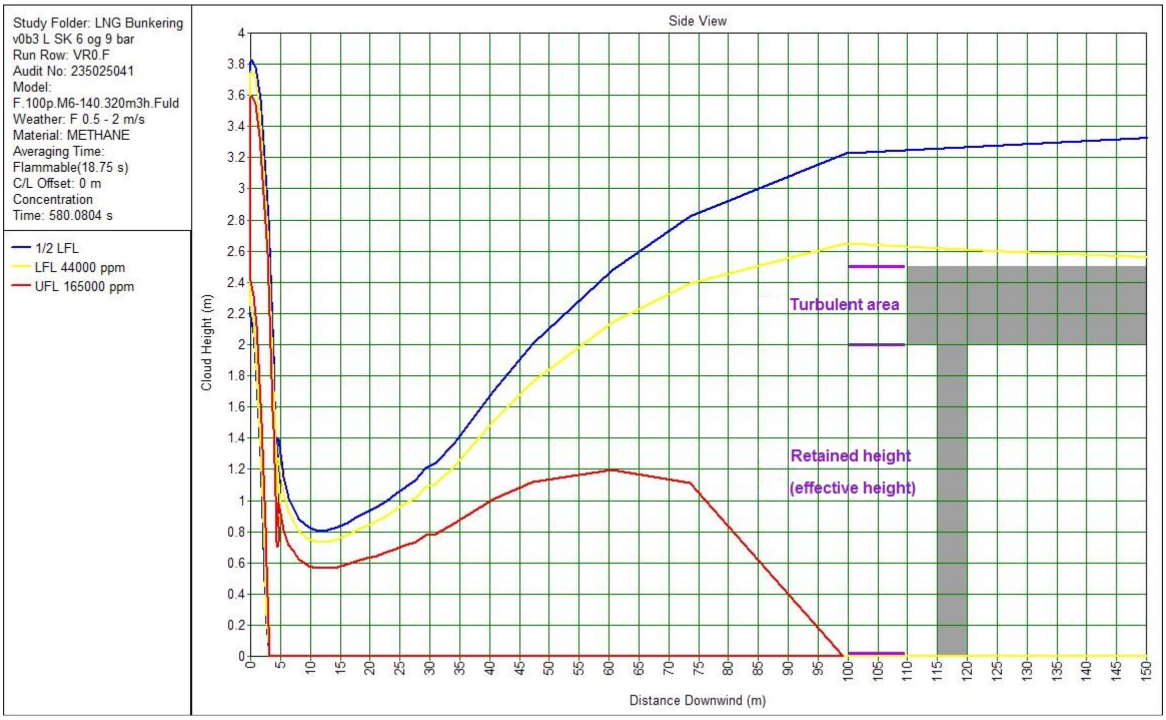


Figure 4-3 Vapour dispersion from a failure with a release rate of 320 m^3/hr over water at -140°C and 6 bar system pressure at a wind force of 0.5-2 m/s, stability class F. The dispersion is seen from the side, with indication of a quay at a distance of 110 m. On the curve, a quay with a height of 2.5 m has been drawn, which is an assumed effective height of 2.0 m where the gas cloud is retained and a turbulent area where the gas cloud is forced over the quay front.

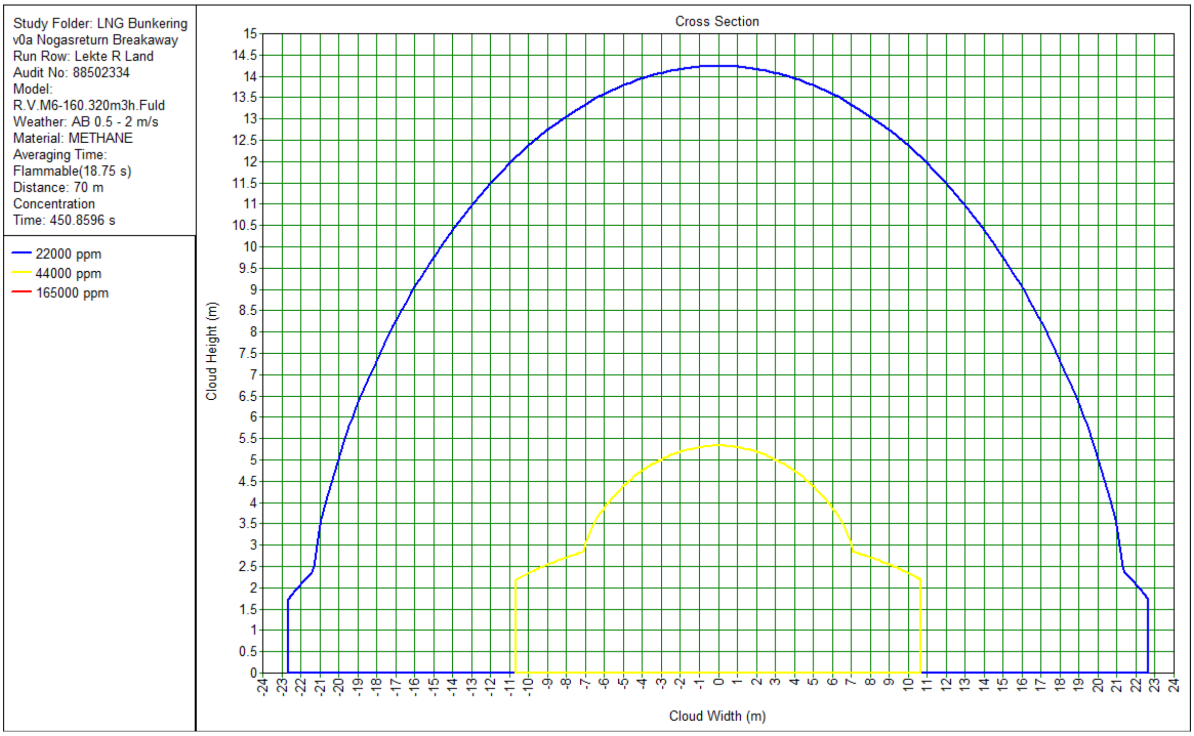


Figure 4-4 Vapour dispersion from a failure with a release rate of 320 m^3/hr over water at -160°C and 6 bar system pressure at a wind force of 0.5-2 m/s. The dispersion is seen in a cross section 70 m from the source.

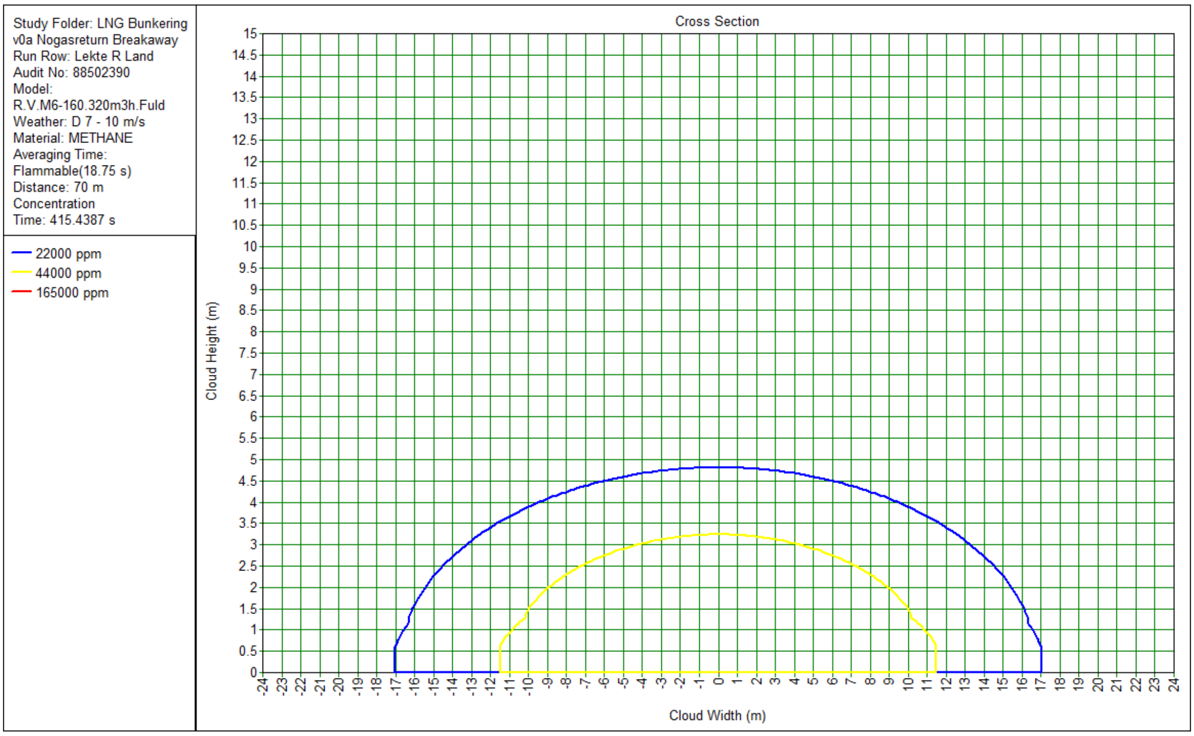


Figure 4-5 Vapour dispersion from a failure with a release rate of 320 m^3/hr over water at -160°C and 6 bar system pressure at a wind force of 7-10 m/s. The dispersion is seen in a cross section 70 m from the source.

	0.5-2 m/s		2-4 m/s		4-7 m/s		7+
	A/B	**F**	**B/C**	**E**	**C/D**	**D**	**D**
80 m	11%	34%	-	7%	-	-	-
110 m	20%	45%	-	14%	14%	7%	-

Table 4-1 Retained gas at the quay when the gas cloud has drifted 80 m and 110 m, respectively, along the ship's hull. The calculation is based on the assumption that the effective height is 0.5 m lower than the actual difference in height between the water level and the quay front (2.5 m).

In the order to model the retention of gas by the quay, the percentage indicated in table 4-1 has been used to reduce the release rate at the release point. It is also necessary to indicate some fictitious release points resulting in the correct migration of the gas cloud onshore. These fictitious release points are shown in figure 4-6. As a result of the described method of modelling the retention by the quay, the risk evaluation for the barge side of the ferry is incorrect, as the risks are underestimated along the ferry's side and overestimated further out (closer to the fictitious release points). Concurrently, it is not possible for Gaussian distribution calculations to take into account that the cloud cannot disperse infinitely horizontally due to e.g. the ferry's boundaries. Gas clouds will therefore be calculated in areas which are in reality protected by the ferry.

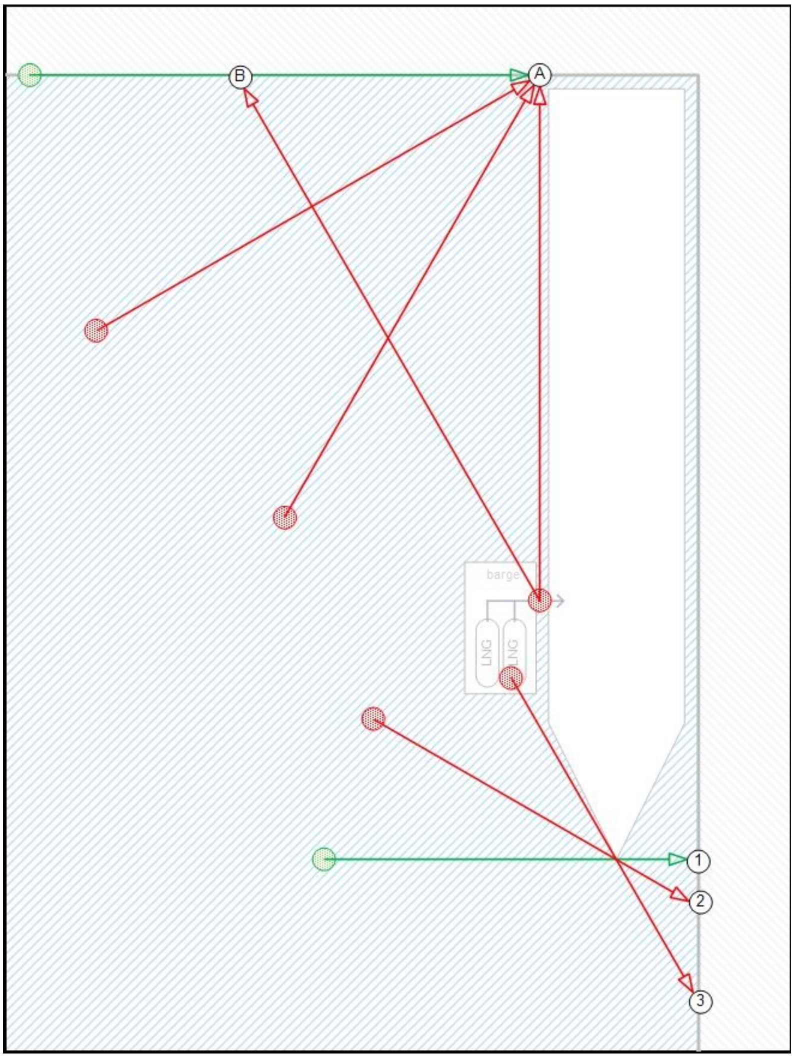


Figure 4-6 Fictitious release points indicated in Outline 1. The figure shows how it is ensured that gas clouds migrate in the correct directions after being slowed down by the quay. The basis for the placement of the fictitious points are the landing points (1, 2, 3, A and B), the release points are then calculated based on angle and distance.

4.3.6 Pool fire

The impact studies for pool fires have been carried out for 6 bar and -160°C, as this will be a conservative estimate compared to 6 bar and -140°C. For pipe failures there is no difference between the released amount at 6 bar and 9 bar. The pressure is therefore not important for the calculations of pool fires.

Calculations of radiation levels for pool fires (fully developed) arising after pipe failures, show that the radiation levels achieve the longest distances at high wind speeds. All figures illustrating the radiation levels are therefore shown for wind category 16+ m/s D.

Figure 4-7 depicts radiation levels of 4 kW/m^2, 12 kW/m^2 and 35 kW/m^2 from pool fires (fully developed) for a pipe failure when the tank is being emptied.

Figure 4-8 depicts radiation levels of 4 kW/m^2, 12 kW/m^2 and 35 kW/m^2 from pool fires (fully developed) for a pipe failure when the release is stopped after 60 seconds.

Figure 4-9 depicts radiation levels of 4 kW/m^2, 12 kW/m^2 and 35 kW/m^2 from pool fires (fully developed) for a pipe failure when the release is stopped after 10 seconds.

Figure 4-10 depicts radiation levels of 4 kW/m^2, 12 kW/m^2 and 35 kW/m^2 from pool fires (fully developed) for a pipe failure when the pipe is being emptied.

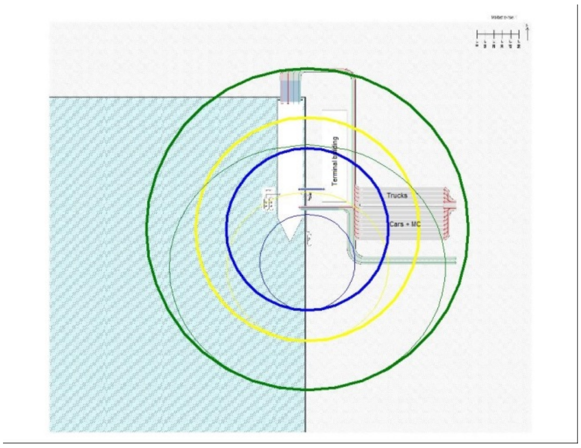


Figure 4-7 Radiation level of 4 kW/m^2, 12,5 kW/m^2 and 35 kW/m^2 for pool fires for pipe failure releases, where the tank is being emptied at wind category 16+ m/s D.

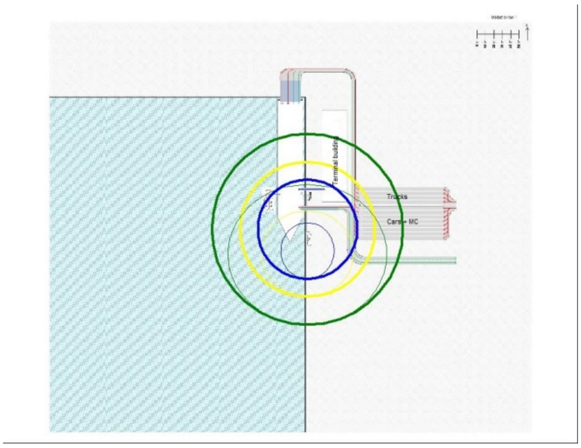


Figure 4-8 Radiation level of 4 kW/m^2, 12,5 kW/m^2 and 35 kW/m^2 for pool fires for pipe failure releases, where the release is stopped after 60 seconds at wind category 16+ m/s D.

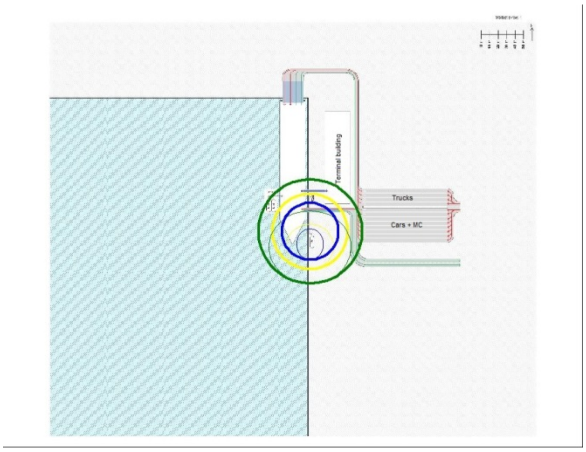


Figure 4-9 Radiation level of 4 kW/m^2, 12,5 kW/m^2 and 35 kW/m^2 for pool fires for pipe failure releases, where the release is stopped after 10 seconds at wind category 16+ m/s D.

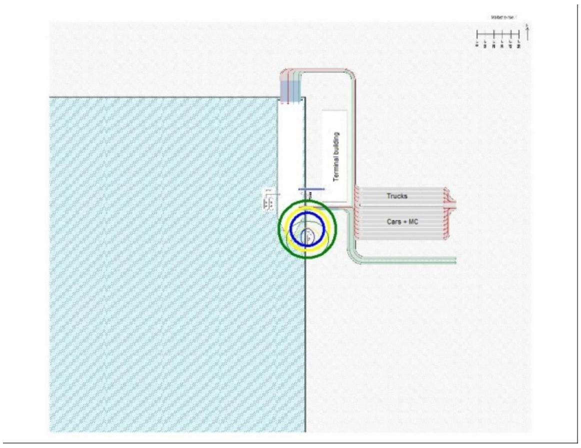


Figure 4-10 Radiation level of 4 kW/m^2, 12,5 kW/m^2 and 35 kW/m^2 for pool fires for pipe failure releases, where the pipe is being emptied at wind category 16+ m/s D.

Radiation levels

4 kW/m^2 Ellipsis — 12.5 kW/m^2 Ellipsis — 35 kW/m^2 Ellipsis

4 kW/m^2 Effect zone — 12.5 kW/m^2 Effect zone — 35 kW/m^2 Effect zone

Risks related to pool fires have been included in the risk assessment.

4.3.7 Confined explosion

At low wind speed there is a possibility that gas can accumulate between the terminal building and the ship. This could in the event of an ignition result in a confined explosion.

The impact studies for this explosion are based on an enclosed area with a length of 115 m (the length of the terminal building), a width of 23 m (the distance between the terminal building and the ship) and a height of 5 m (the height of the terminal building). The area is open upwards and at the ends.

Table 4-2 shows the distance to overpressures of 0.1 bar and 0.03 bar, as well as flame speed for explosions with various amounts of gas.

Gas amount / concentration	Distance to 1.1 bar (m)	Distance to 1.03 bar (m)	Max. flame speed (m/s)
UEL	200	640	6.76
1000 kg	180	540	18.3
500 kg	160	460	44

Table 4-2 Distances to overpressure of 0.1 bar and 0.03 bar, as well as flame speed for confined explosions between the terminal building and the ship.

A confined explosion could also occur below the quay if the gas accumulates there.

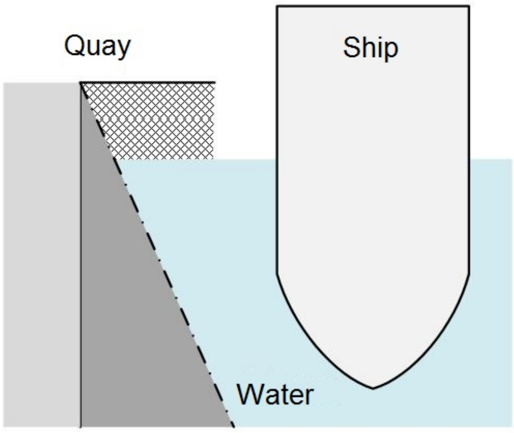


Figure 4-11 Outline of possible confined explosion under quay.

The impact studies for this explosion are based on the shaded area in Figure 4-11.

The area is 3 m high (from the water to the underside of the quay), 6 m wide on top of the quay, 4 m wide at the water level and 140 m long (along the ship). The area is open at the ends and upwards between the quay and the ship.

Table 4-2 shows the distance to overpressures of 0.1 bar and 0.03 bar, as well as flame speed for explosions with various amounts of gas.

Gas amount / concentration	Distance to 1.1 bar (m)	Distance to 1.03 bar (m)	Max. flame speed (m/s)
UEL	60	240	0.47
250 kg	60	220	0.75
100 kg	40	180	1.6

Table 4-3 Distances to overpressure of 0.1 bar and 0.03 bar, as well as flame speed for confined explosions below the quay.

Risks from confined explosions are not included in the risk assessments.

4.3.8 Processing of results

The PHAST models cannot fully calculate releases hitting the ship's side or other obstruction, and which then migrate with the wind along this surface. PHAST can, however, model a user defined release, in which a release point is assumed where the surface comes to an end, and where a gas-air ratio is applied (based on the concentration at a corresponding distance from the source). Test calculations thereof show that the models cannot handle this. The model transitions are too rough to result in usable results. The consequence is furthermore significantly underestimated in the test calculations. The fact that this cannot be modelled will not have a large influence on the calculation of the risks related to releases on the shore-side of the ship, but the ship's shadow effect for releases on the water-side of the ship cannot be modelled.

It is not possible to model the effect in the small strip of water between ship and quay and between ship and bunker vessel.

As the majority of an offshore release is below the quay front, the harbour will function as a drip tray or culvert for the LNG gas. PHAST can only model terrain as coefficient of roughness, where the quay front, ship and terminal building represent obstructions that change the direction of flow of heavy gases. At long distances, where the fan-shaped gas clouds are wide, it is an acceptable approach to model "walls" as roughness. Near the release source, however, these "walls" are very significant for the consequence, which cannot be modelled. This flaw is one of the major weaknesses of Gaussian distribution calculations in general.

The calculations of confined explosions show that in the event of a worst case explosion between the ship and terminal building, windows at a distance of up to 640 m from the centre of the explosion could shatter, and people (outdoors) could be affected up to 200 m from the centre of the explosion, with fatalities as result in the worst case.

4.4 Conclusion

PHAST can calculate the risks related to releases onshore. Releases offshore will be overestimated in the PHAST calculations, as neither the shelter effect from the ship nor the basin effect (on the dispersed gas) from the harbour can be included in the model.

4.4.1 Selection and delimitation

Tank failure of modern tanks, constructed according to the Pressure Directive (PED), is not expected to occur spontaneously or as a result of material defects or incorrect maintenance. Tank failures are only expected to occur as a result of external forces; collision, loss of objects from e.g. a crane, plane crash, rockslide, etc. It has been assumed in this report that all possible measures have been taken in order to avoid these external influences. Tank failures are therefore not included in the calculation of local (place-bound) risks and societal risks.

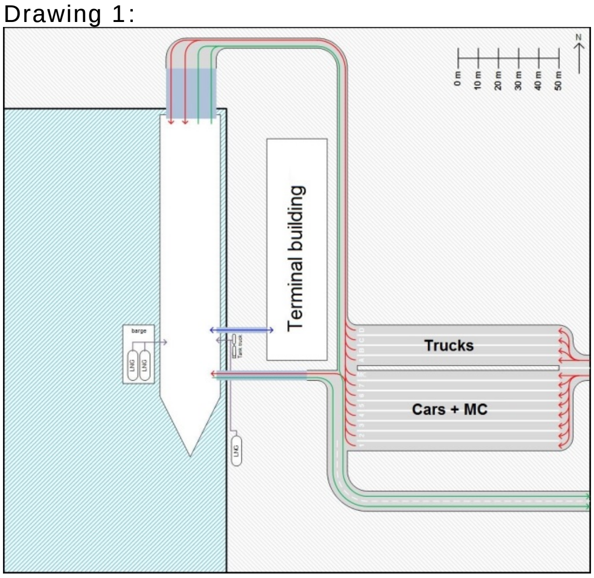
In order to minimise the number and complexity of the calculations, releases from flange leaks have not been included in the calculation of local (place-bound) and societal risk, since the area of impact (consequence range) is very limited, and is thus considered not visible in the calculations.

A release from a tank or tank truck can fall into a drip tray or culvert, if any, but since the outcome of such releases is unclear and since many pipes will be located directly above such collectors, drip trays or culverts have not been included in the calculation of local (place-bound) and societal risks.

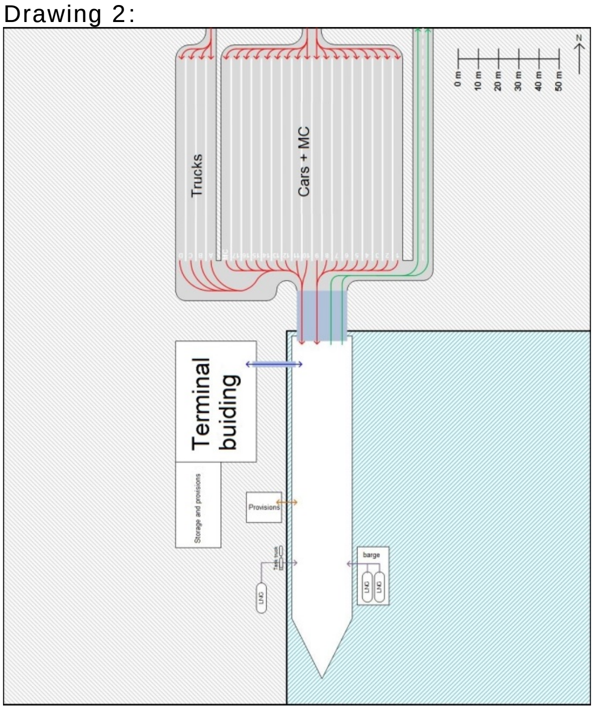
5. SCALE DRAWINGS

In order to draw up a map of iso risk curves for the local risks as well as the for calculation of the societal risks, 3 principle drawings have been made of possible port areas where the variations of placement and orientation of ship, terminal building and vehicle holding lanes have been included.

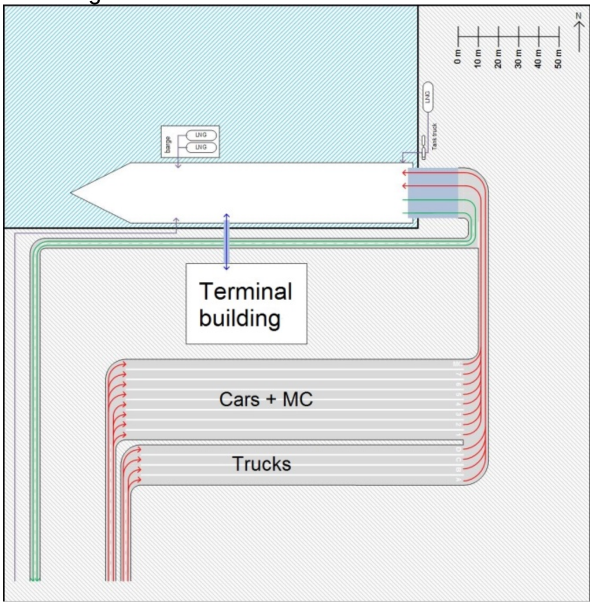
Drawing 1:



Drawing 2:



Drawing 3:



5.1 Sources of ignition

A car is assumed to occupy 3 m breadthwise and 6 m lengthwise (18 m^2) in the vehicle holding lane and 3 m breadthwise and 10 m lengthwise during transit (30 m^2).

A truck is assumed to occupy 3.3 m breadthways and 20 m lengthwise (66 m^2) in the vehicle holding lane and 3.3 m breadthwise and 30 m lengthwise during transit (99 m^2).

It is assumed that vehicles are disembarking 50% of the time, and that vehicles are embarking 50% of the time.

The transit to the ship is assumed to be occupied by passenger cars 90% of the time and of trucks 10% of the time.

In the vehicle holding lanes it is assumed that 25% of the passenger cars and the trucks have their engines running, and 75% have the engine turned off.

The ignition probability of 40% per 60 seconds for a motorised vehicle is taken from ref. /1/. It is assumed that a passenger car with the engine turned off has an ignition probability of 1% per 60 seconds, and a truck with the engine turned off has an ignition probability of 5% per 60 seconds.

The ignition probability of 50% per 60 seconds for a ship and the terminal building is taken from ref. /1/.

The ignition probability of 30% per 60 seconds for a ship during LNG bunkering is taken from ref. /1/.

At the request of the British Health and Safety Executive (HSE) a detailed study has been conducted, ref. /2/, containing statistical data of oil and gas releases from installations in the British section of the North Sea. On average, an ignition probability of 2.1% was registered for oil releases. In the study, releases were divided into categories based on size and whether the release took place in a classified area (zone 1 or zone 2) or in a non-classified area. The following average ignition probabilities can be derived from the report data: Zone 1: ~1.4%, zone 2: ~2.1%, non-classified: ~6.4%.

Based on these data, and on the expectation that fixed tank installations with LNG will be classified to zone 2, the ignition probability has therefore been set to 2.1% per 60 seconds. In addition the ignition probability for tank trucks with LNG is specified as the same as for non-classified = 6.4% per 60 seconds.

Source of ignition	**Active**	**Likely in active form**	**Likely in passive form**
Passenger cars in transit from the ship	45%	40% per 60 sec per passenger car (30 m^2)	0%
Trucks in transit from the ship	5%	40% per 60 sec per truck (99 m^2)	0%
Passenger cars in transit to the ship	45%	40% per 60 sec per passenger car (30 m^2)	0%
Trucks in transit to the ship	5%	40% per 60 sec per truck (99 m^2)	0%
Passenger cars in vehicle holding lanes	25%	40% per 60 sec per passenger car (18 m^2)	1% per 60 sec per passenger car (18 m^2)
Trucks in vehicle holding lanes	25%	40% per 60 sec per truck (66 m^2)	5% per 60 sec per truck (66 m^2)
Ferry	100%	50% per 60 sec	-
Bunker vessel	100% *)	30% per 60 sec	-
Terminal building	100%	50% per 60 sec	-
Fixed bunker tank incl. pumps and steering	100% *)	2.1% per 60 sec	-
Tank truck with LNG	100% *)	6.4% per 60 sec	-
Open areas with street lighting	50%	6.4% per 60 sec per 400 m^2	-
Areas with signals	100%	6.4% per 60 sec per 10 m^2	-

*) If this type of bunkering is used

Human activity (smoking, use of non-explosion-proof electronic equipment etc.) is not included as source of ignition as this would give a very small increase in the probability in areas where vehicles are present since these areas already have a high ignition probability. A minor increase is assumed not to affect the overall risk scenario.

Set-up, sources of ignition:

No.	Bunkering from	Cars (in transit and in vehicle holding lanes)	Trucks (in transit and in vehicle holding lanes)	Ferry	Bunker vessel	Terminal building	Fixed bunker tank	Tank truck with LNG	Open areas with street lighting	Areas with signals
1	Barge with cars	X	X	X	X	X			X	X
2	Barge without cars			X	X	X			X	X
3	Fixed tank onshore with cars	X	X	X		X	X		X	X
4	Fixed tank offshore with cars			X		X	X		X	X
5	Tank truck with cars	X	X	X		X		X	X	X
6	Tank truck without cars			X		X		X	X	X

5.2 Population groups

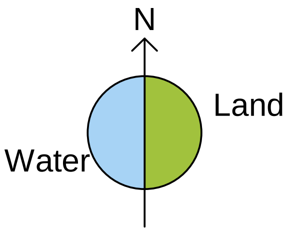
Group of people	Density	Fraction indoors
Ferry	1,050 people in 170x30 m^2 (0.2059 persons per m^2)	80%
Transit route to and from ship	2 persons per passenger car (30 m^2) (0.0667 persons per m^2)	100%
Vehicle holding lanes for passenger cars	2 persons per passenger car (18 m^2) (0.1111 persons per m^2)	75%
Vehicle holding lanes for trucks	1 person per truck (66 m^2) (0.0152 persons per m^2)	75%
Terminal building	450 people in 30x30 m^2 (0.5000 persons per m^2)	100%
Terminal bridge (closed)	1 person per m^2	100%
Terminal bridge (open)	1 person per m^2	0%
Bunker interface	4 persons	0%

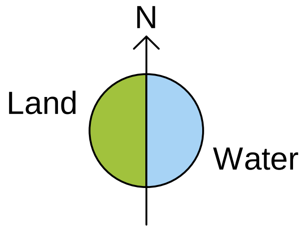
Set-up, group of people:

No.	Description	Ferry	Transit route, cars	Vehicle holding lanes for passenger cars	Vehicle holding lanes for trucks	Terminal building	Terminal bridge (closed)	Terminal bridge (open) + access road	Bunker interface
1	Large ferry with cars and passengers	1050	65	130	30	150	75	-	4
2	Large ferry with passengers	1050	-	-	-	300	150	-	4
3	Large ferry with passengers (open)	1050	-	-	-	150	-	300	4
4	Small ferry with cars and passengers	350	25	50	-	50	25	-	4

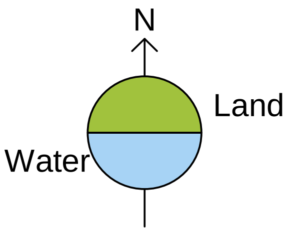
5.3 Surface roughness

Since LNG releases in general could occur next to the ship (either shore-side or water-side), the ship can be used as a division line between shore and water. This means that for the drawings 1 and 2 there is a division line between shore and water running north-south:





and for drawing 3 there is a division line running east-west:



At the water side, the surface within the first 100-200 m is primarily level water. An "Open water" surface roughness can therefore be used (Surface Roughness Length = 0.2 mm; Surface Roughness Parameter = 0.037).

On the shore-side, the surface within the first 100-200 m is primarily flat terrain with objects such as road blocks and cars. A "High-crops; Scattered large obstacles" surface roughness can therefore be used (Surface Roughness Length = 25 cm; Surface Roughness Parameter = 0.108).

6. LOCAL (PLACE-BOUND) AND SOCIETAL RISKS IN PHAST RISK

6.1 Risk results

The basic calculations of the local (place-bound) and societal risks are indicated in this section. These calculations have been carried out for a facility without gas return and fitted with break-away valves, for a large ferry transporting both cars and passengers and exposed to a wind-rose corresponding to the West coast of Norway.

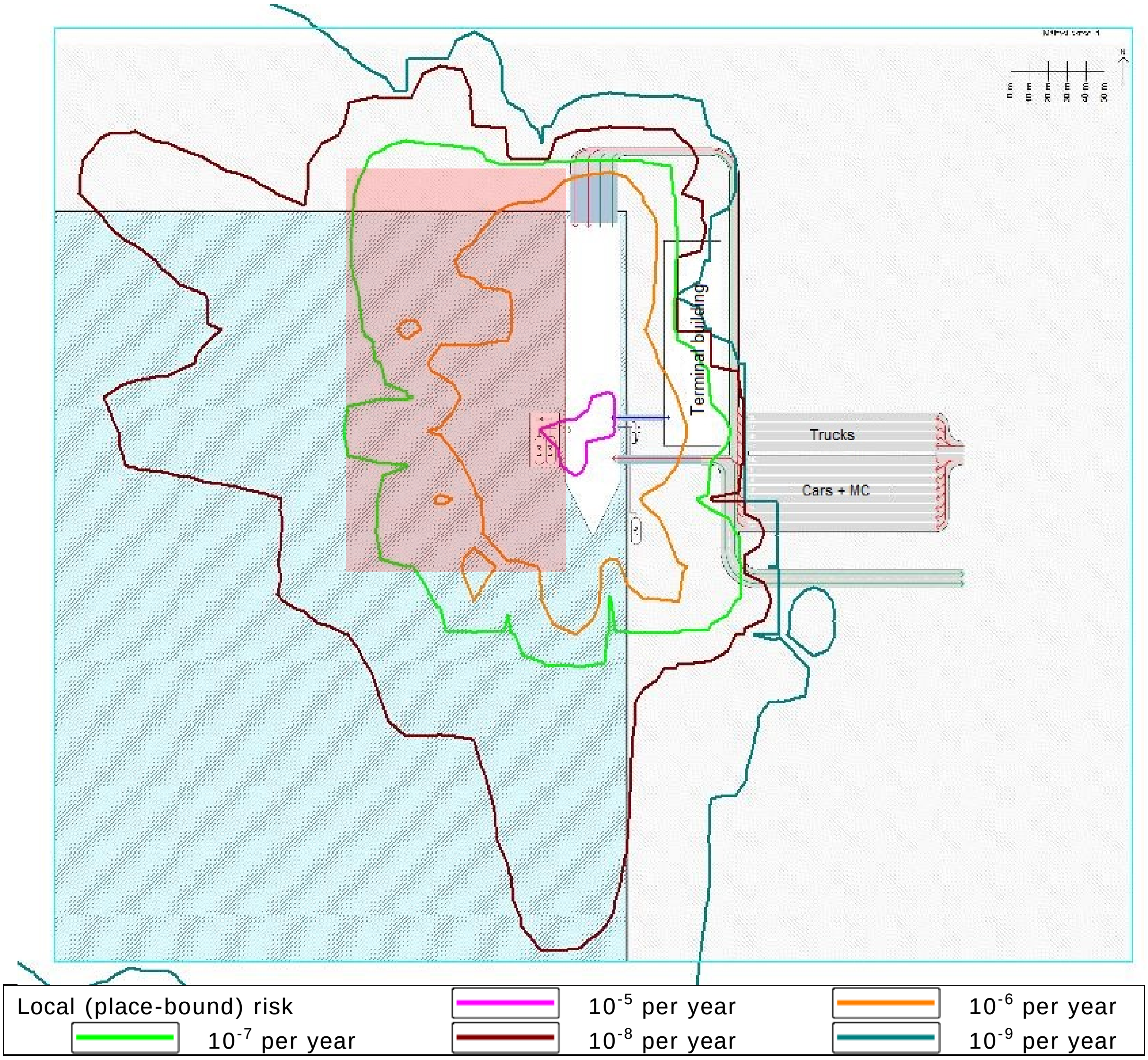
All calculations are indicated for drawing 1 with a map of iso risk curves and an FN curve. Some of the scenarios were then repeated for barge with hose crane and fixed tank with hose crane.

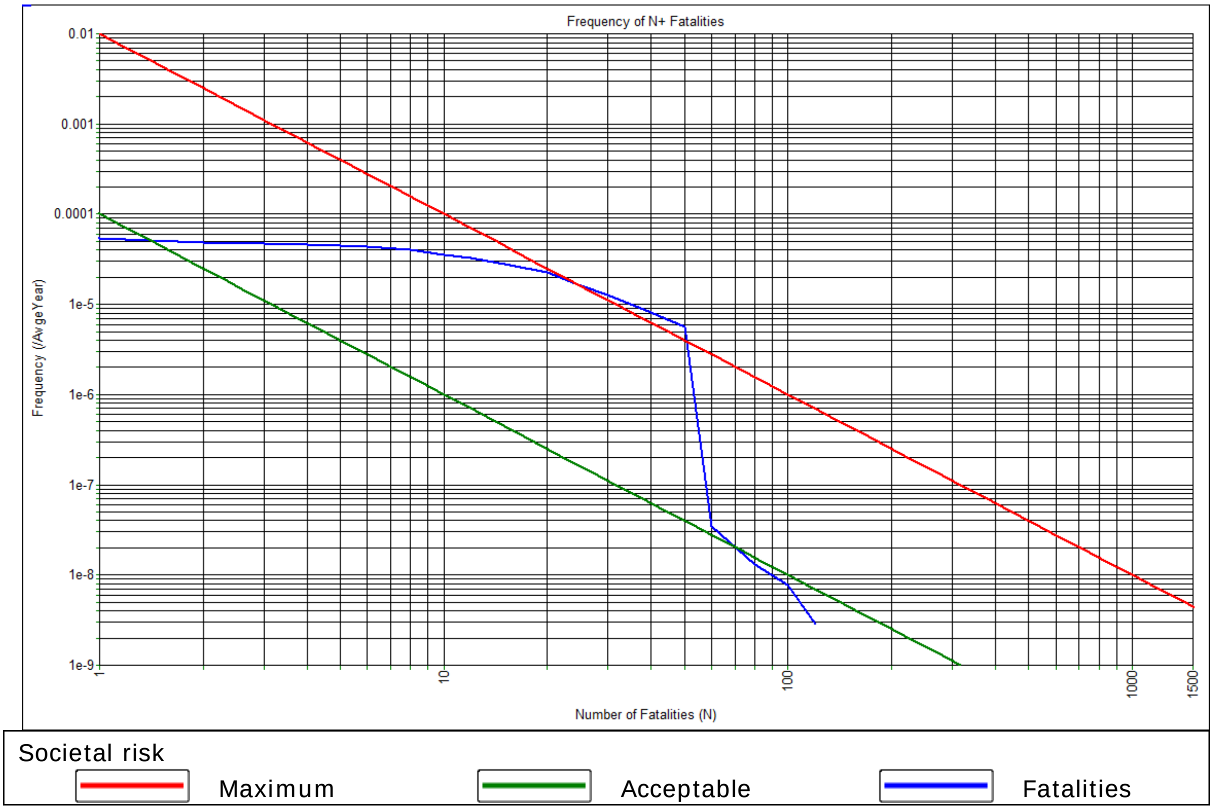
6.1.1 Drawing 1 – West coast winds - Large ferry with cars and passengers – 6 bar

Barge, hoses

Calculation of bunkering from barge with hoses to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.

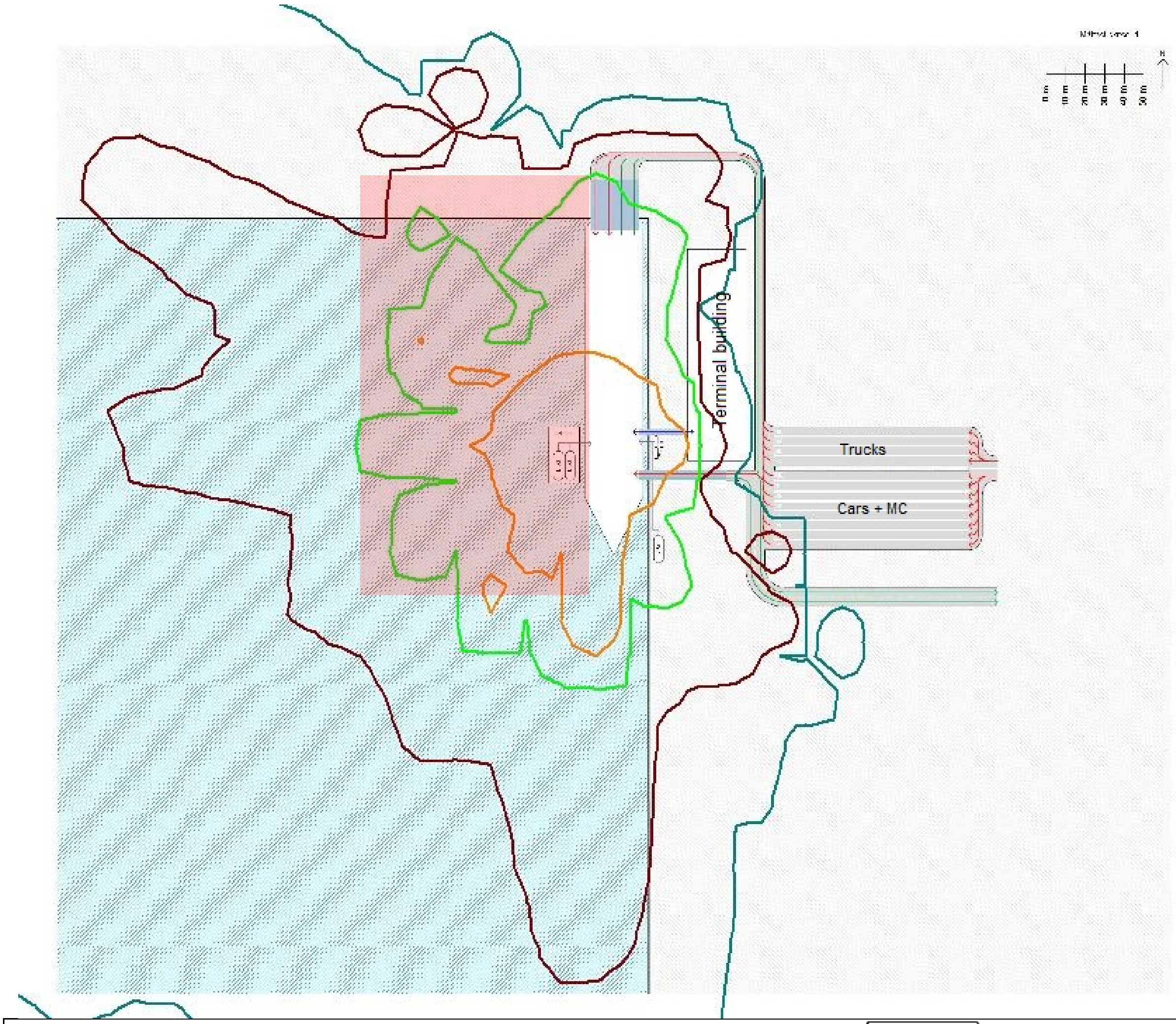



Frequency of N+ Fatalities
Frequency (/AvgeYear)
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Barge, hose crane

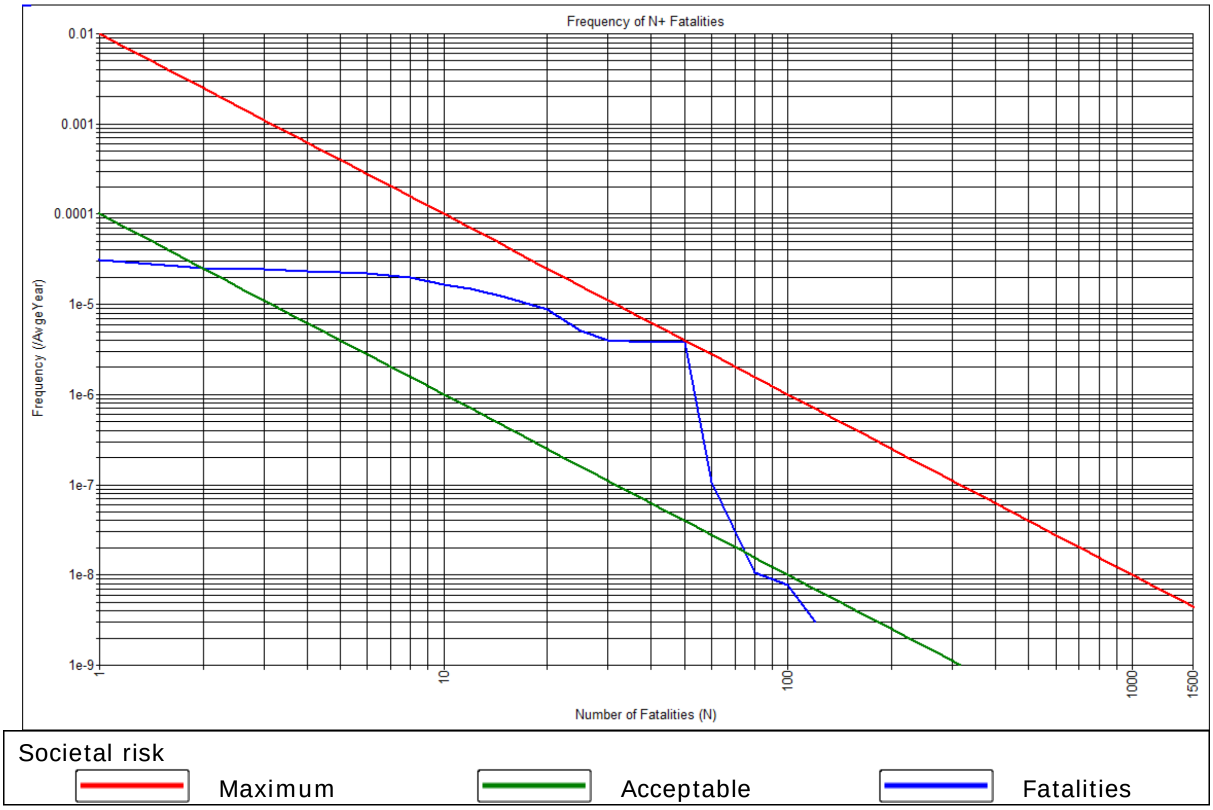
Calculation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.



Local (place-bound) risk

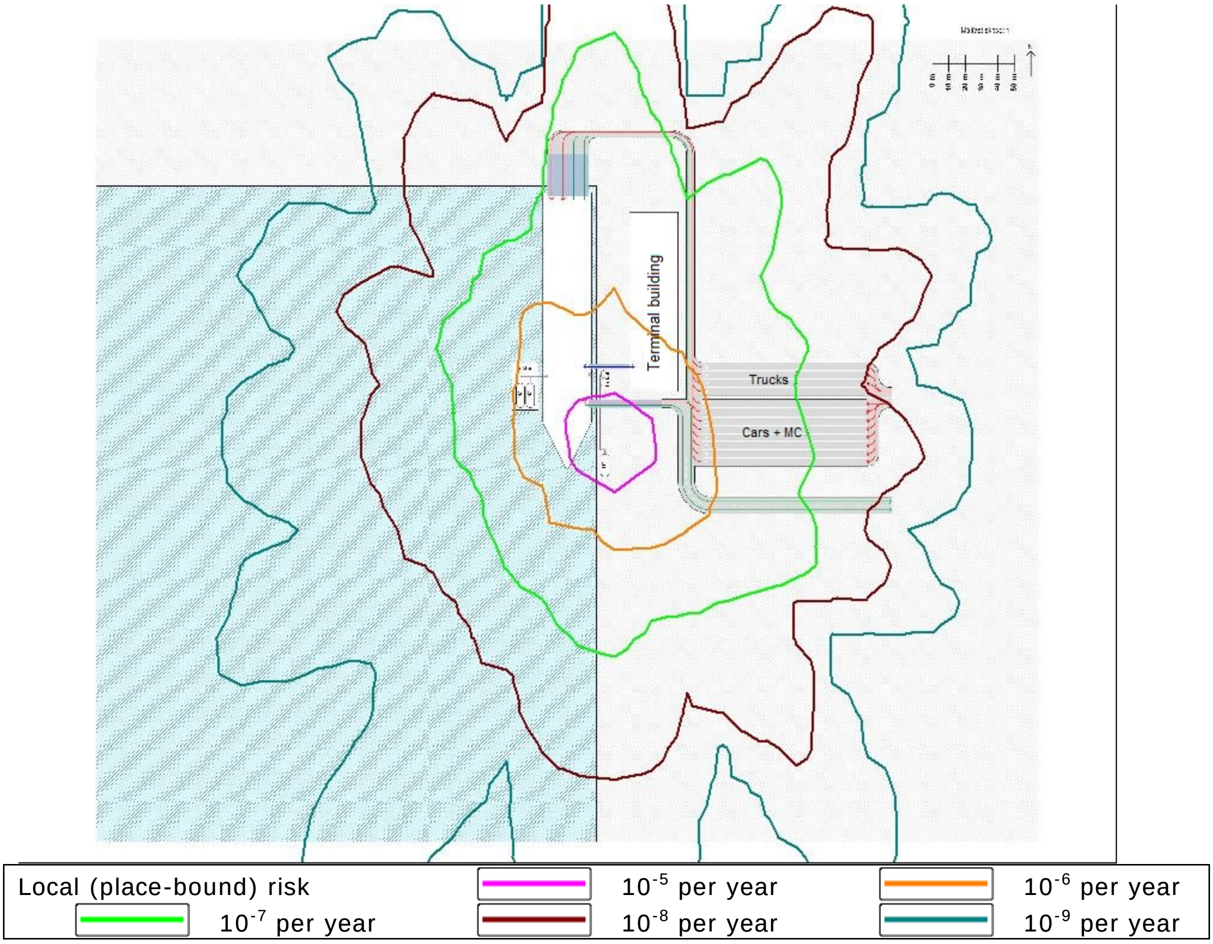
10^{-7} per year	10^{-8} per year	10^{-6} per year
		10^{-9} per year

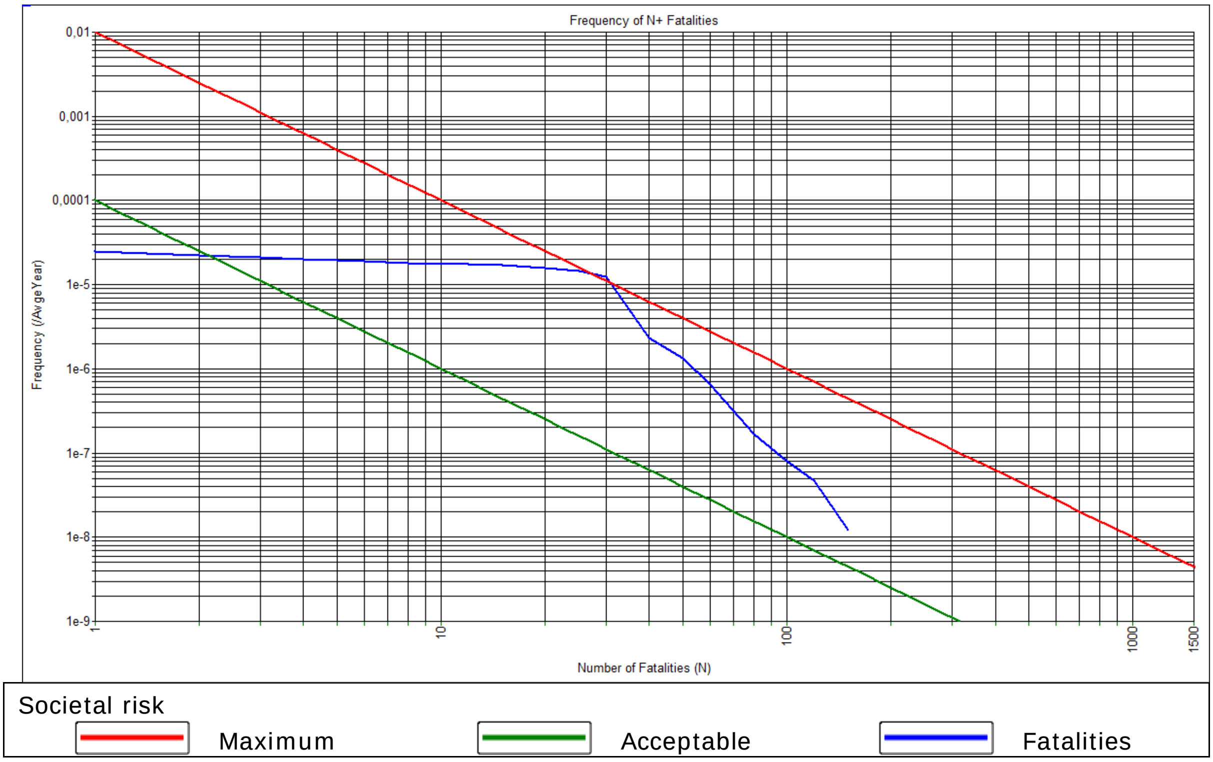


The calculations for barge show that hose cranes are safer than loose hoses.

Fixed tank, hoses

Calculation of bunkering from a fixed tank onshore with hoses to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.




Frequency of N+ Fatalities
Frequency (/AvgeYear)
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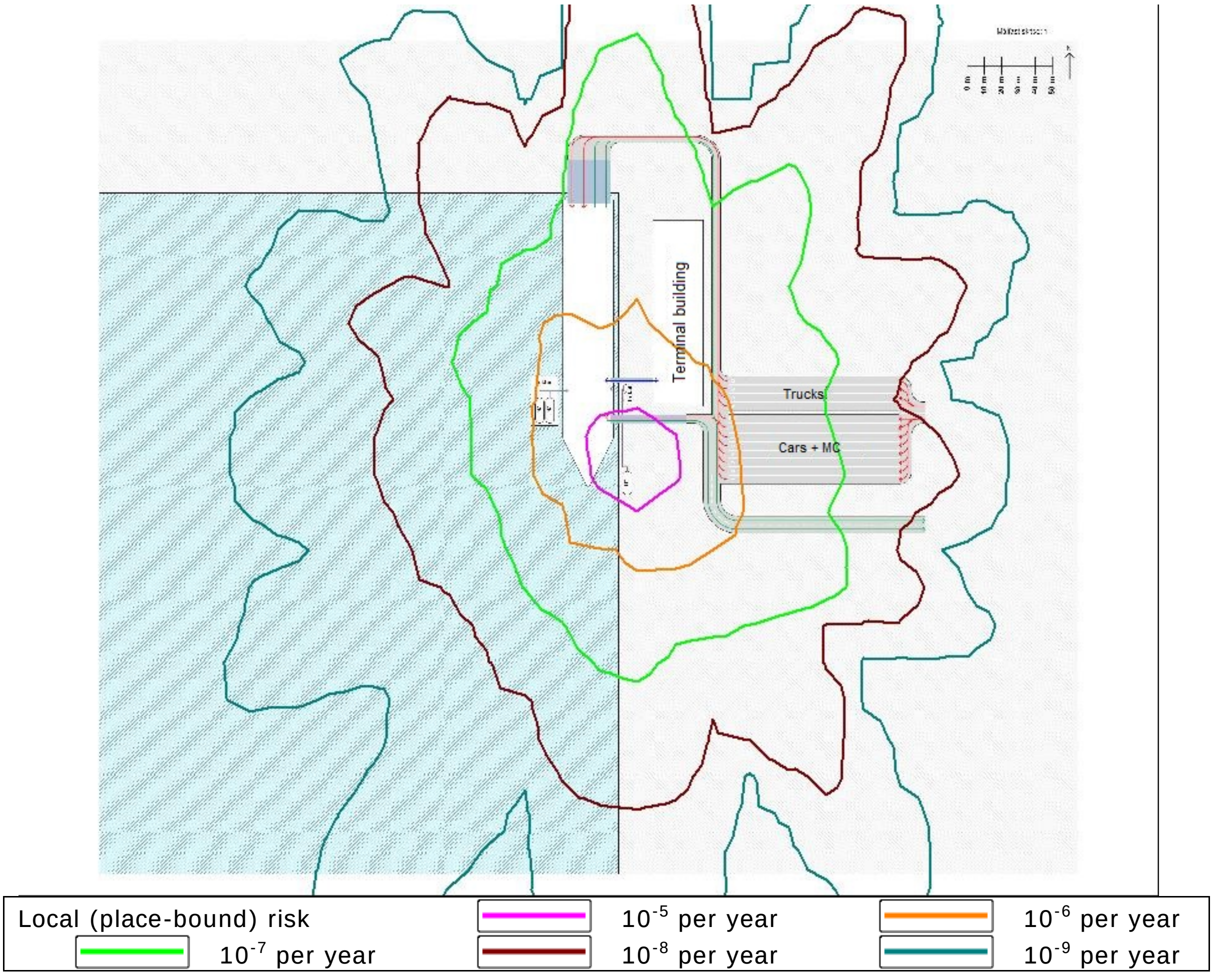
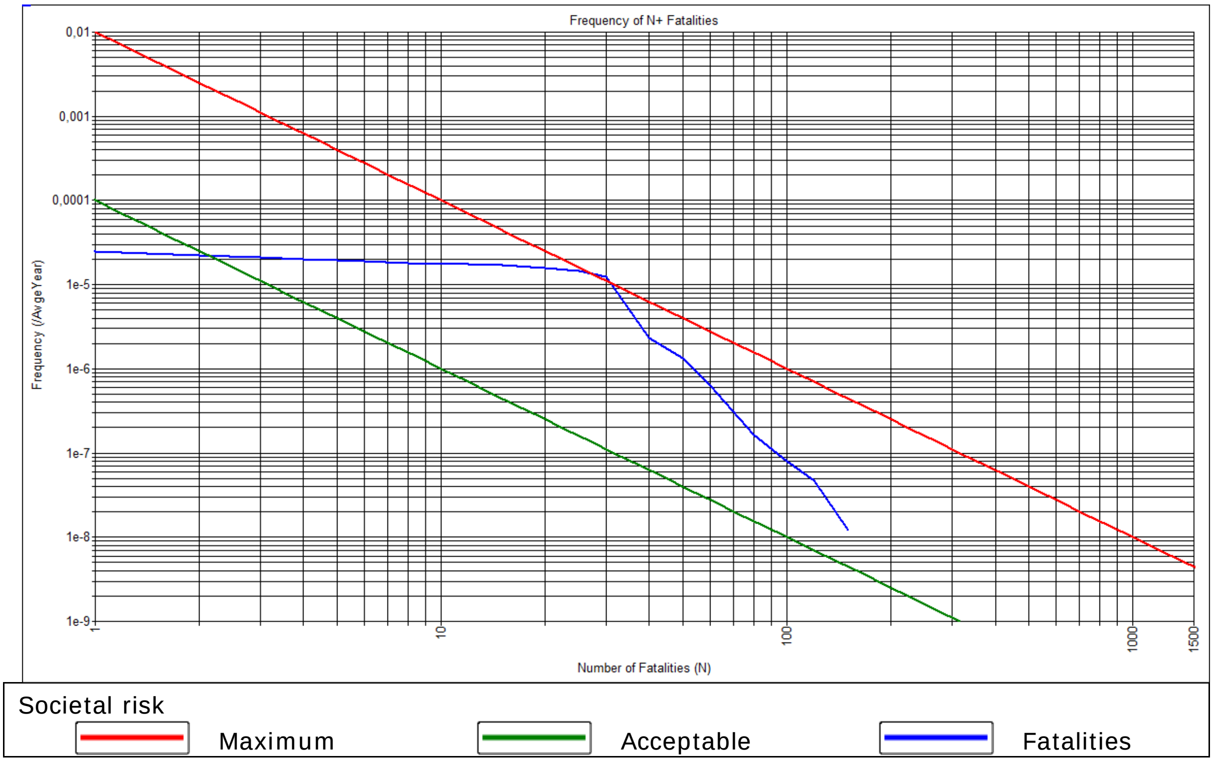
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.




Frequency of N+ Fatalities
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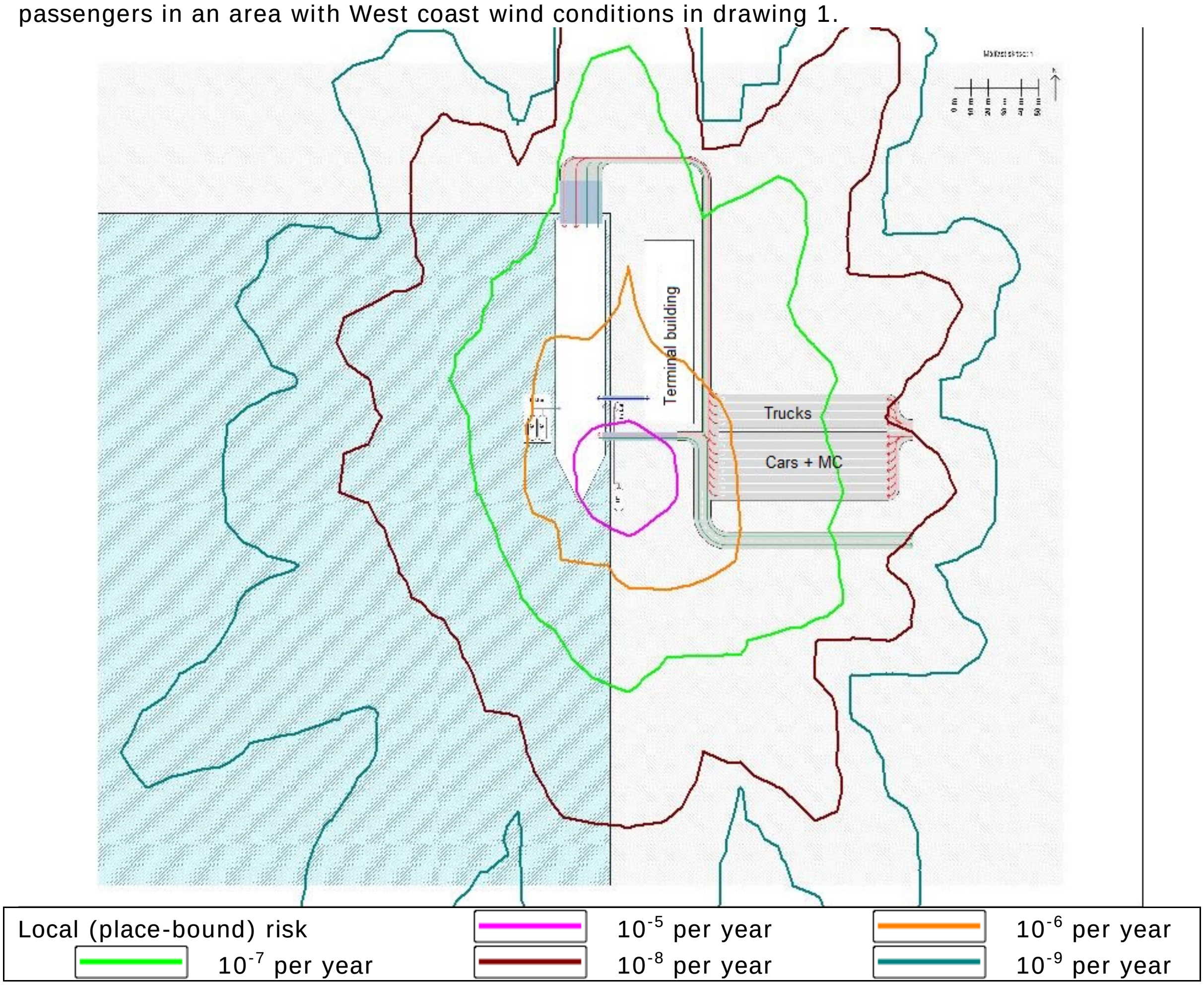
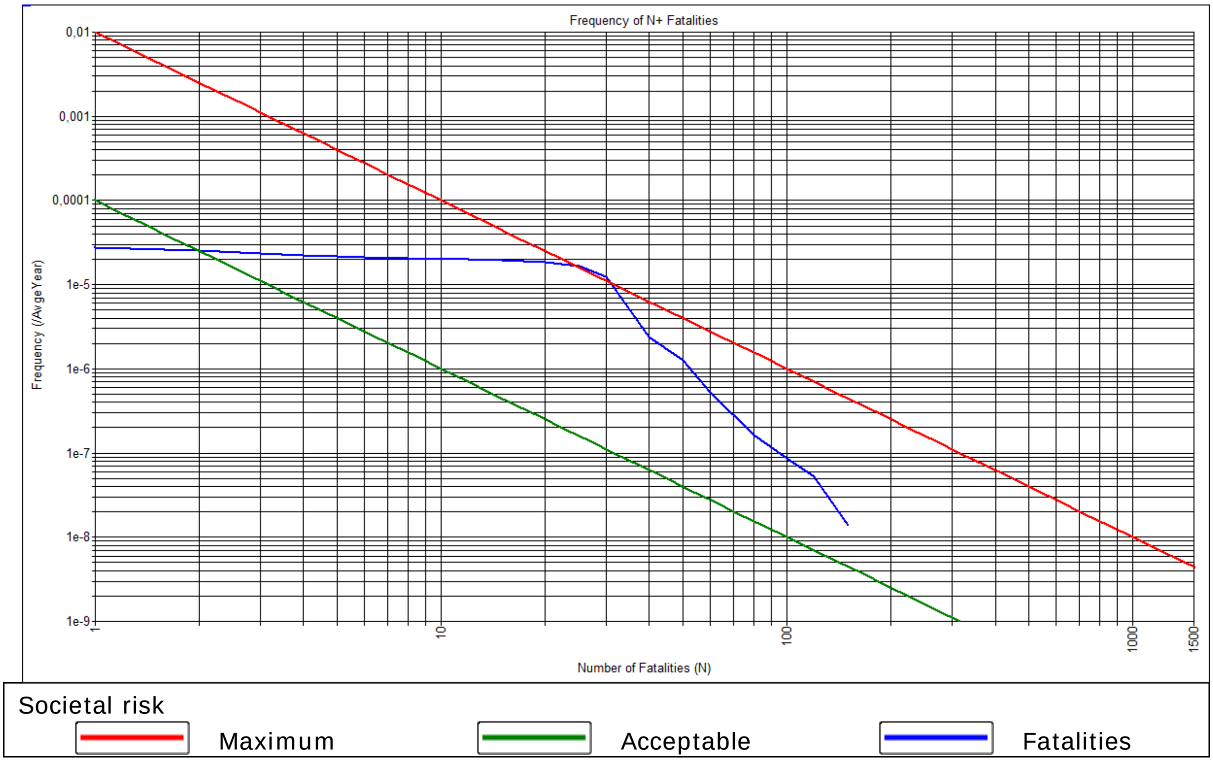
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, loading arm

Calculation of bunkering from a fixed tank onshore with loading arm to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.




Frequency of N+ Fatalities
Frequency (/AvgeYear)
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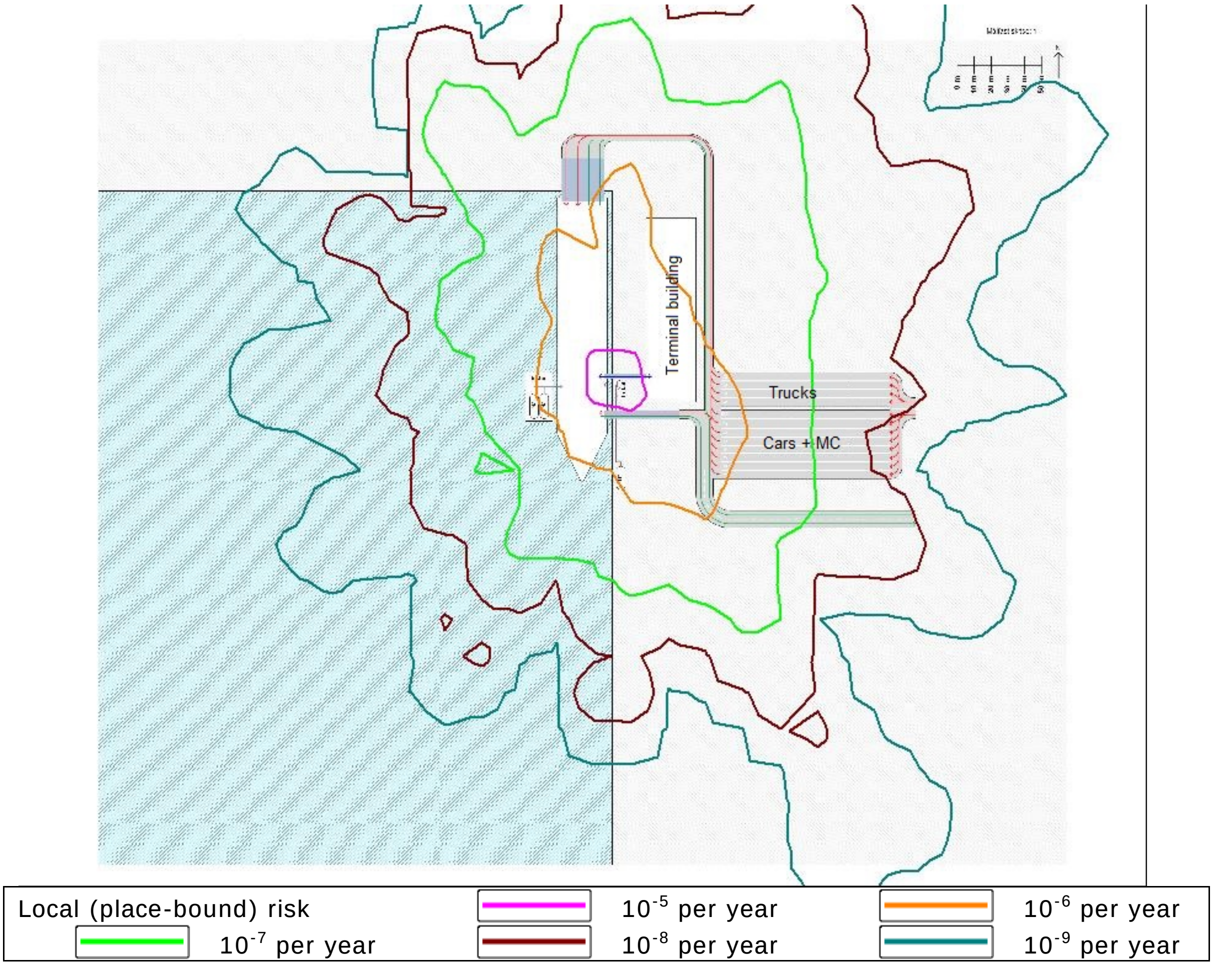
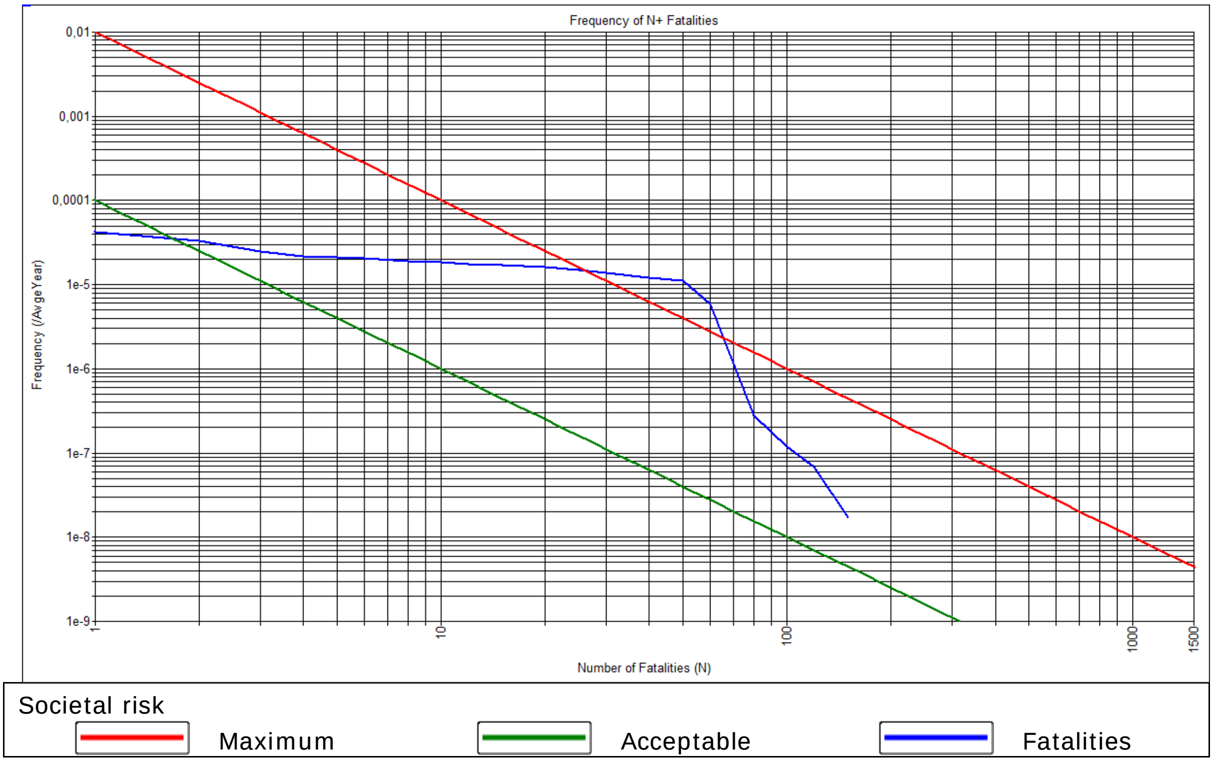
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Tank truck, hoses

Calculation of bunkering from a tank truck onshore with hoses to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.




Frequency of N+ Fatalities
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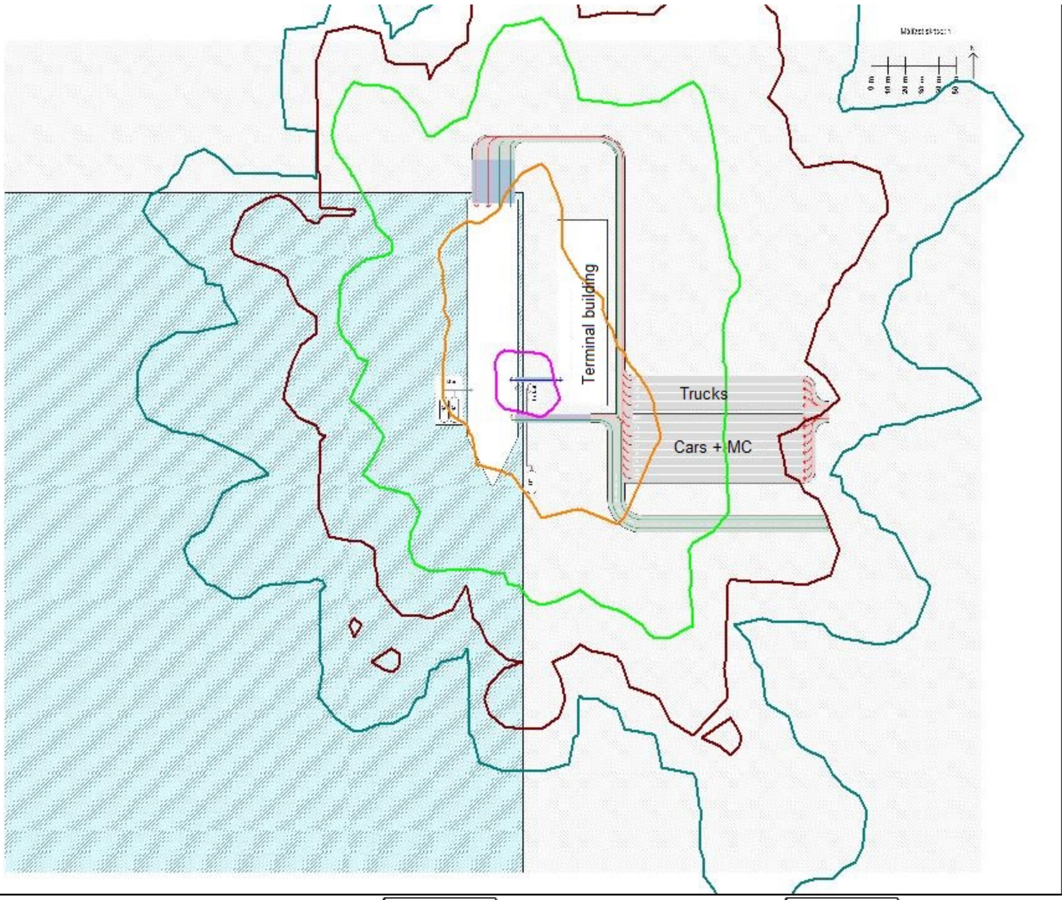
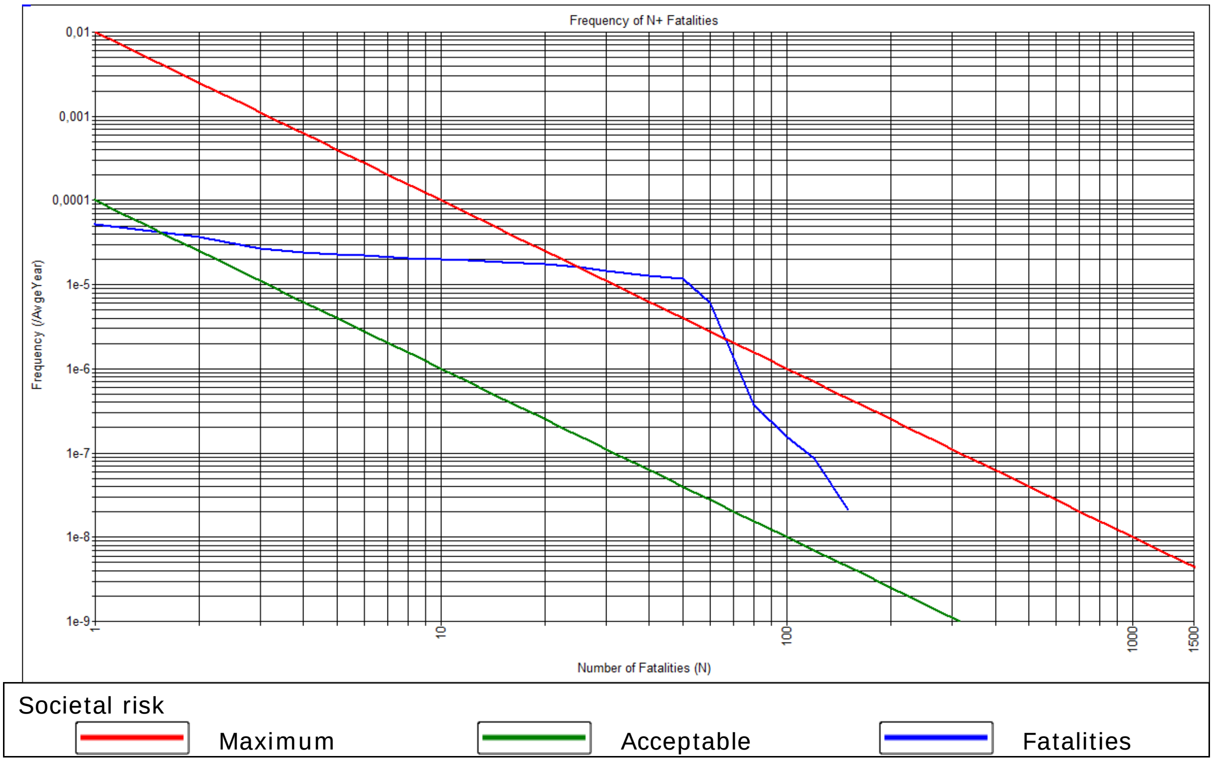
0,001
0,0001
1e-5
1e-6
1e-7
1e-8
1e-9
Frequency (/AvgeYear)
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Tank truck, hoses to rig to hose crane

Calculation of bunkering from a tank truck onshore with hoses to a rig and onwards with a hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.



Local (place-bound) risk: 10^{-5} per year; 10^{-6} per year; 10^{-7} per year; 10^{-8} per year; 10^{-9} per year



The calculations show that the placement of the bunkering interface on the same side as the passenger access and the car traffic results in higher risks compared to keeping the bunkering on the other side of the ship.

For the 7 scenarios the distance to the iso risk curves for fatalities with probabilities of 10^{-5} per year, 10^{-6} per year and 10^{-7} per year have been collected from the figure. The distances are presented in Table 6-1.

Scenario	**Distance (m) to**			
	terminal building / assembly area	**10^{-5} per year**	**10^{-6} per year**	**10^{-7} per year**
Barge, hoses	50 / 95	25	121	155
Barge, hose crane	50 / 95	-	81	118
Fixed tank, hoses	15-40 / 55	34	74	140
Fixed tank, hose crane	15-40 / 55	34	74	140
Fixed tank, loading arm	15-40 / 55	37	76	147
Tank truck, hoses	15 / 60	24	93	170
Tank truck, hoses to rig to hose crane	15 / 60	24	94	170

Table 6-1 Distance to iso risk curves for fatalities with probabilities of 10^{-5} per year, 10^{-6} per year and 10^{-7} per year.

The calculations show that it is safer to use a crane hose than loose hoses on barge. There is basically no difference between using hoses, hose cranes or loading arms for installations with a fixed tank, and there is basically no difference between using hoses or hoses to rig to crane hose for installations with tank trucks.

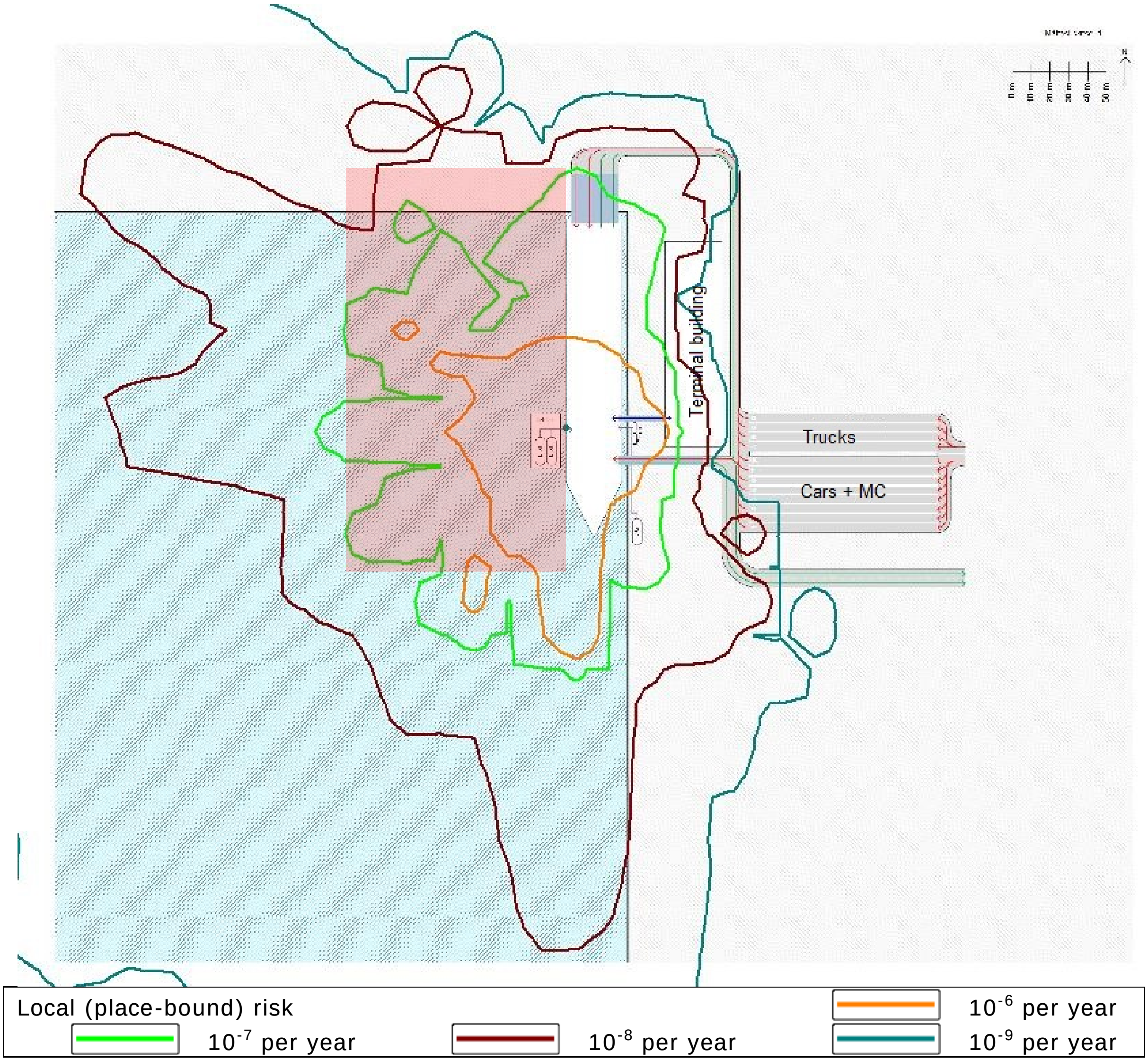
The societal risks when using barge with hose crane are in most cases identical to the risks when using fixed tank. The societal risks when using tank truck are slightly higher than the risks when using fixed tank.

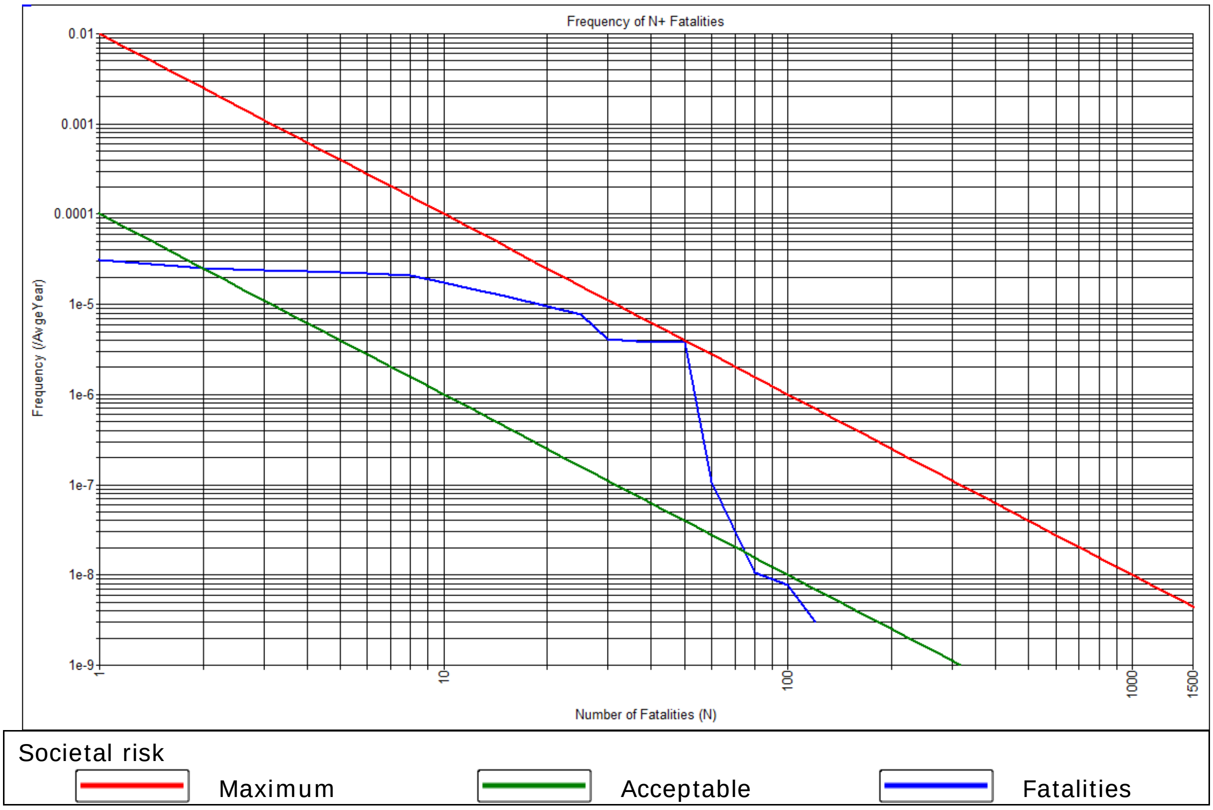
6.1.2 Drawing 1 – West coast winds - Large ferry with cars and passengers – 9 bar

Barge, hose crane

Calculation of bunkering with a system pressure of 9 bar from barge with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

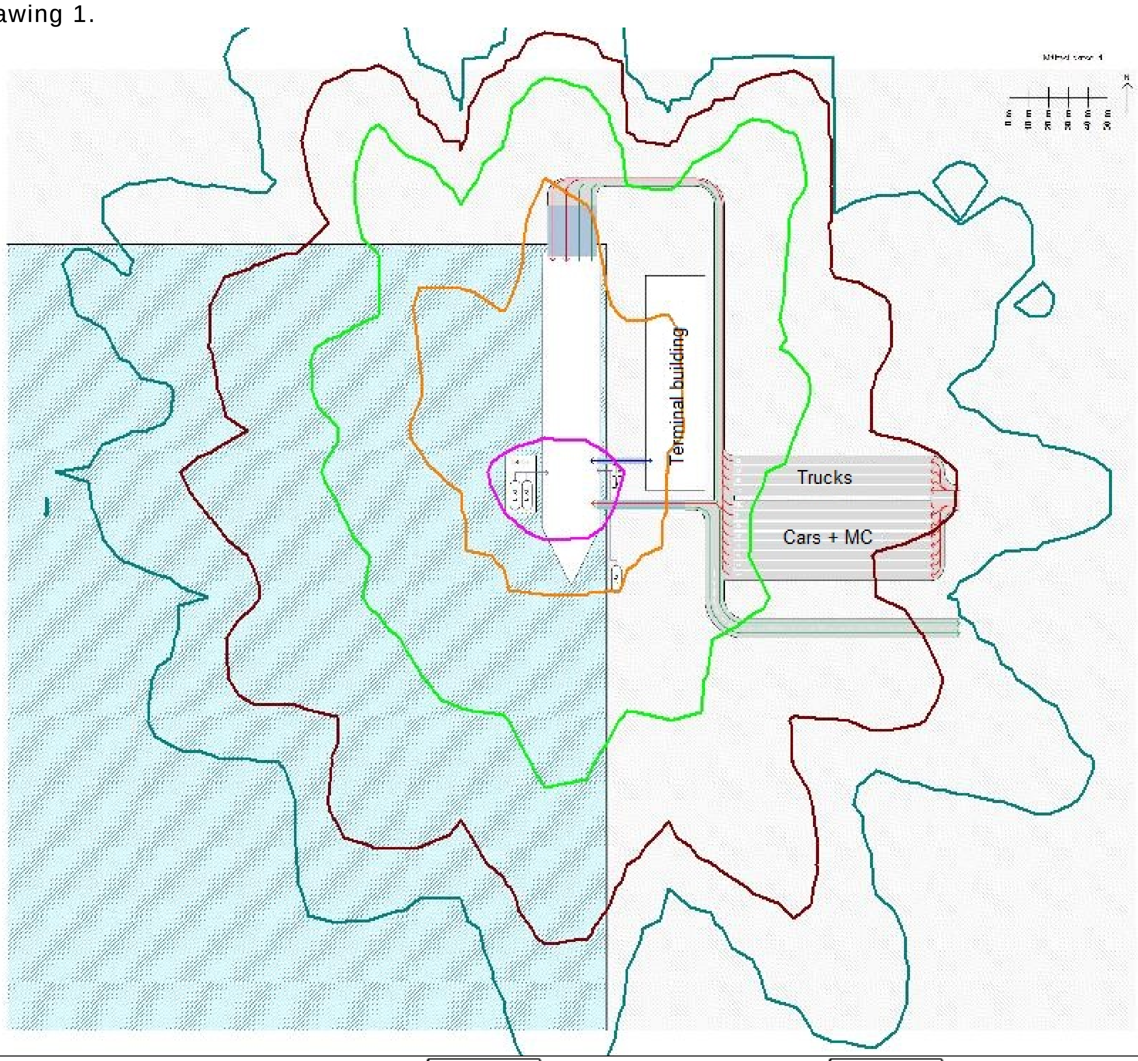
In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.



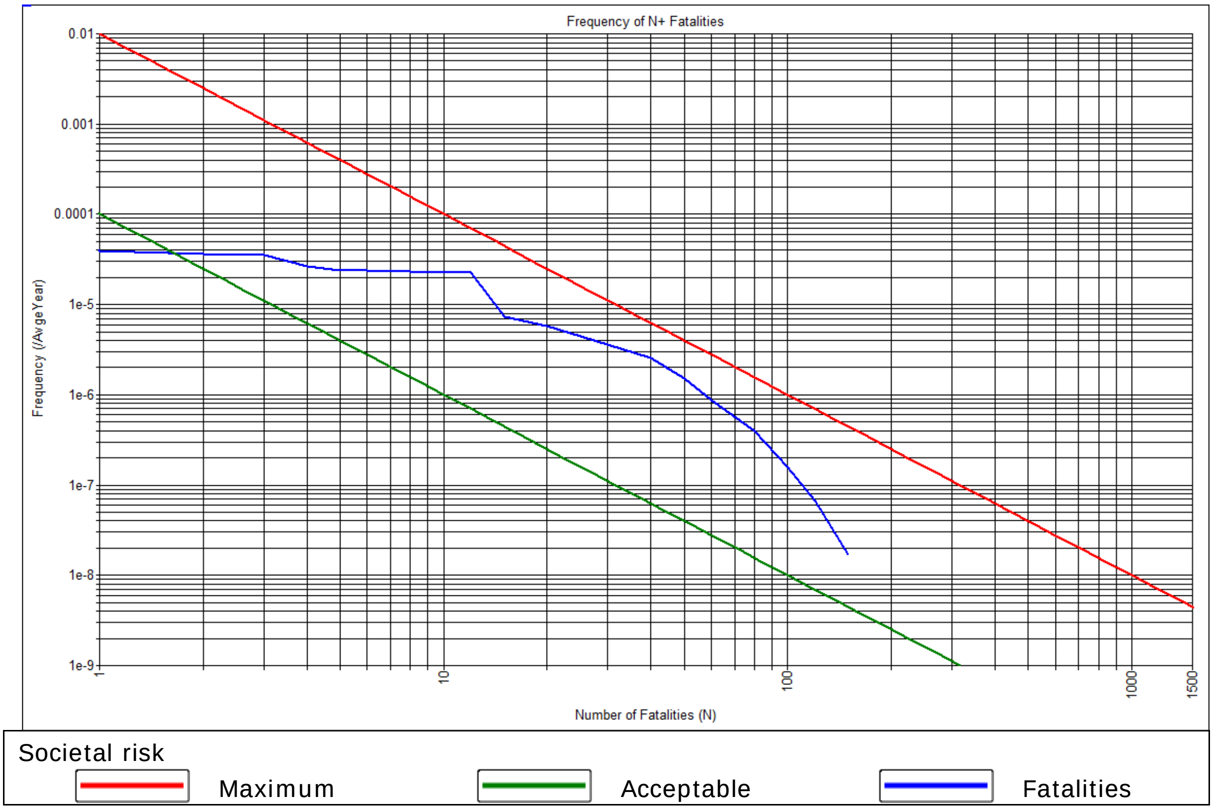

Frequency of N+ Fatalities
Frequency (/AvgeYear)
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, hose crane

Calculation of bunkering with a system pressure of 9 bar from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.



Local (place-bound) risk — 10^{-5} per year — 10^{-6} per year — 10^{-7} per year — 10^{-8} per year — 10^{-9} per year



The risk calculations are compared to the same calculation basis (drawing 1 West coast winds) but with a system pressure of 6 bar (see section 6.1.1).

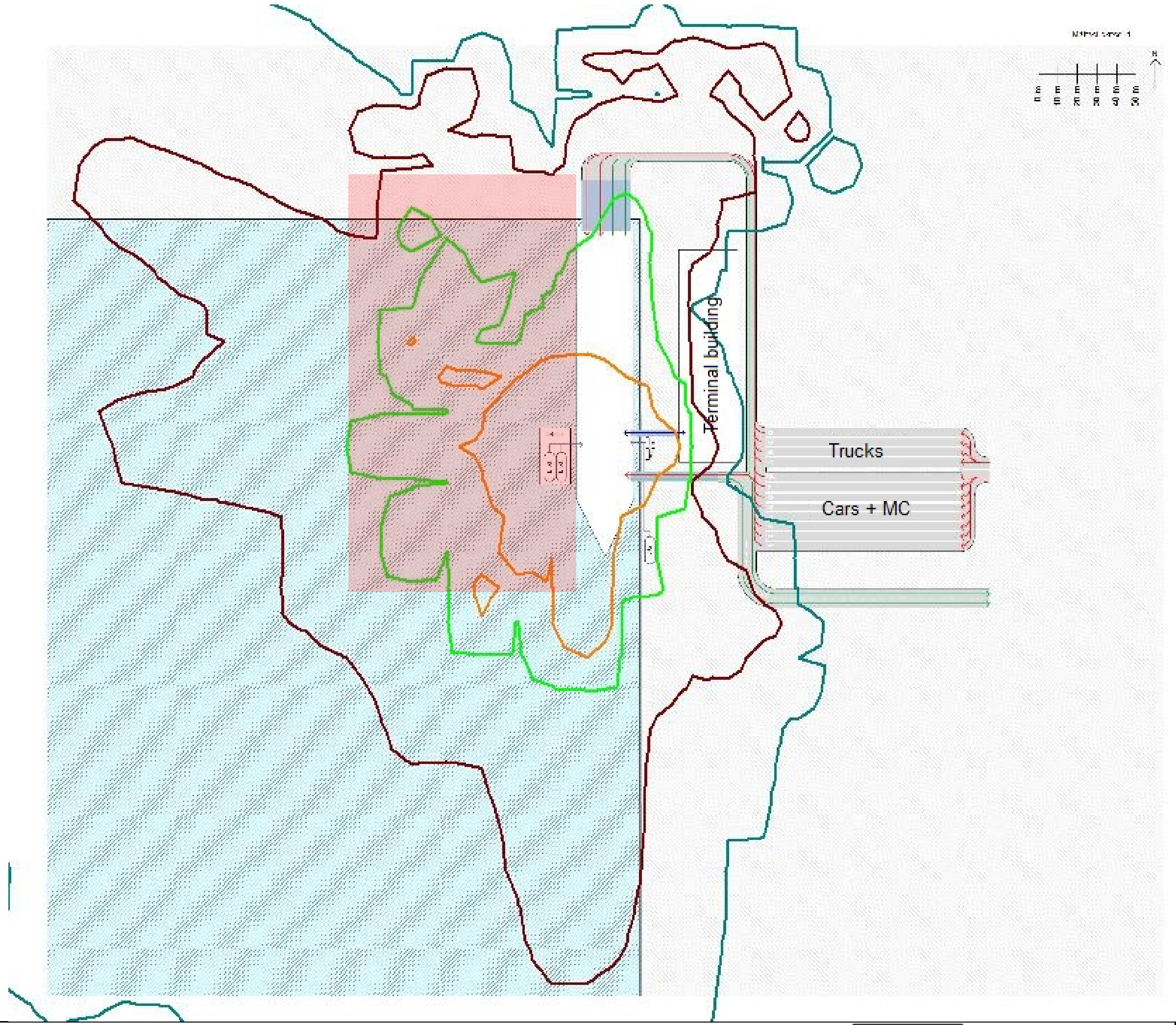
Based on the calculations, there are no noticeable differences between the societal risks of a pressure of 9 bar and the societal risks of a pressure of 6 bar, neither for barges with hose crane nor for fixed tank with hose crane.

6.1.3 Drawing 1 – West coast winds - Large ferry with passengers (without cars) – 6 bar

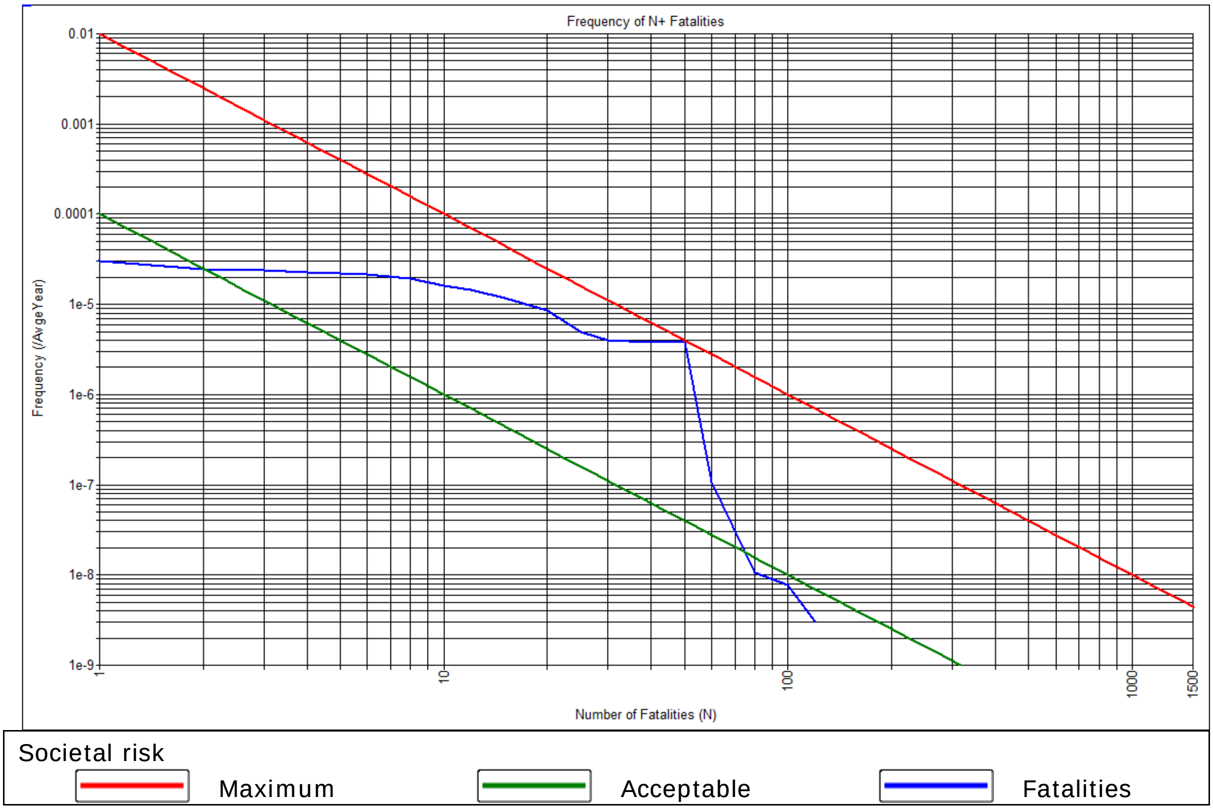
Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with passengers (without cars) in an area with West coast wind conditions in drawing 1.

In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.

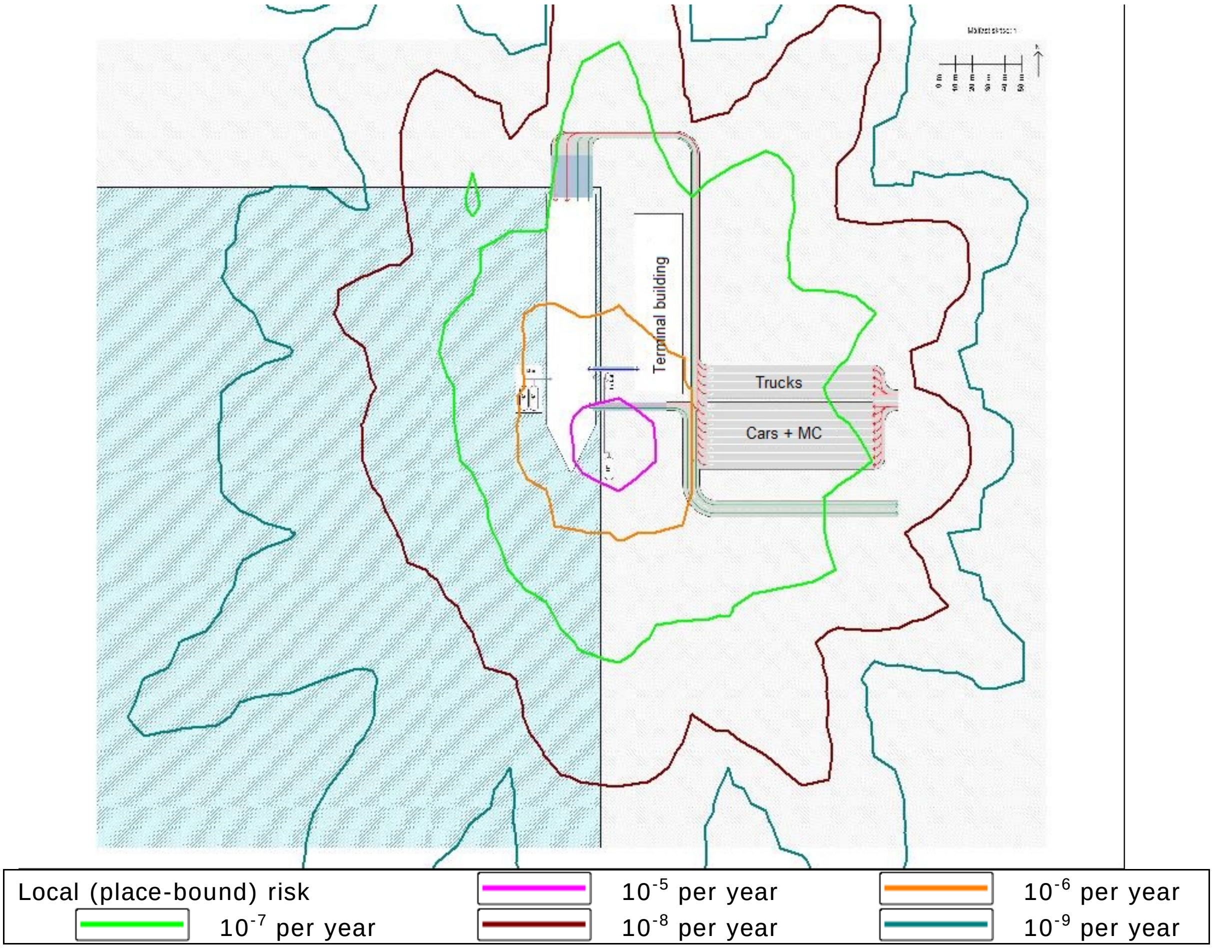


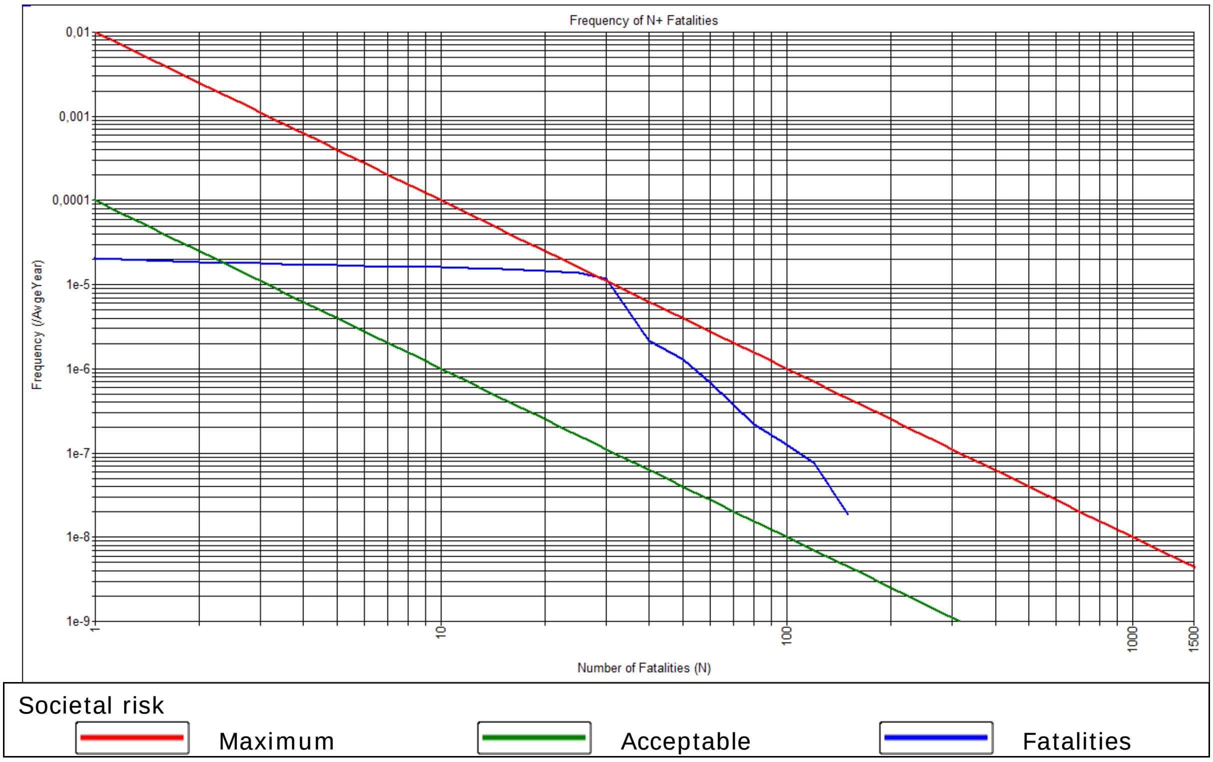
Local (place-bound) risk: green line = 10^{-7} per year; dark red line = 10^{-8} per year; orange line = 10^{-6} per year; teal line = 10^{-9} per year


Frequency of N+ Fatalities
Frequency (/AvgeYear)
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with passengers (without cars) in an area with West coast wind conditions in drawing 1.





The risk calculations are compared to the same calculation basis (drawing 1 West coast winds) for a ferry with cars (see section 6.1.1).

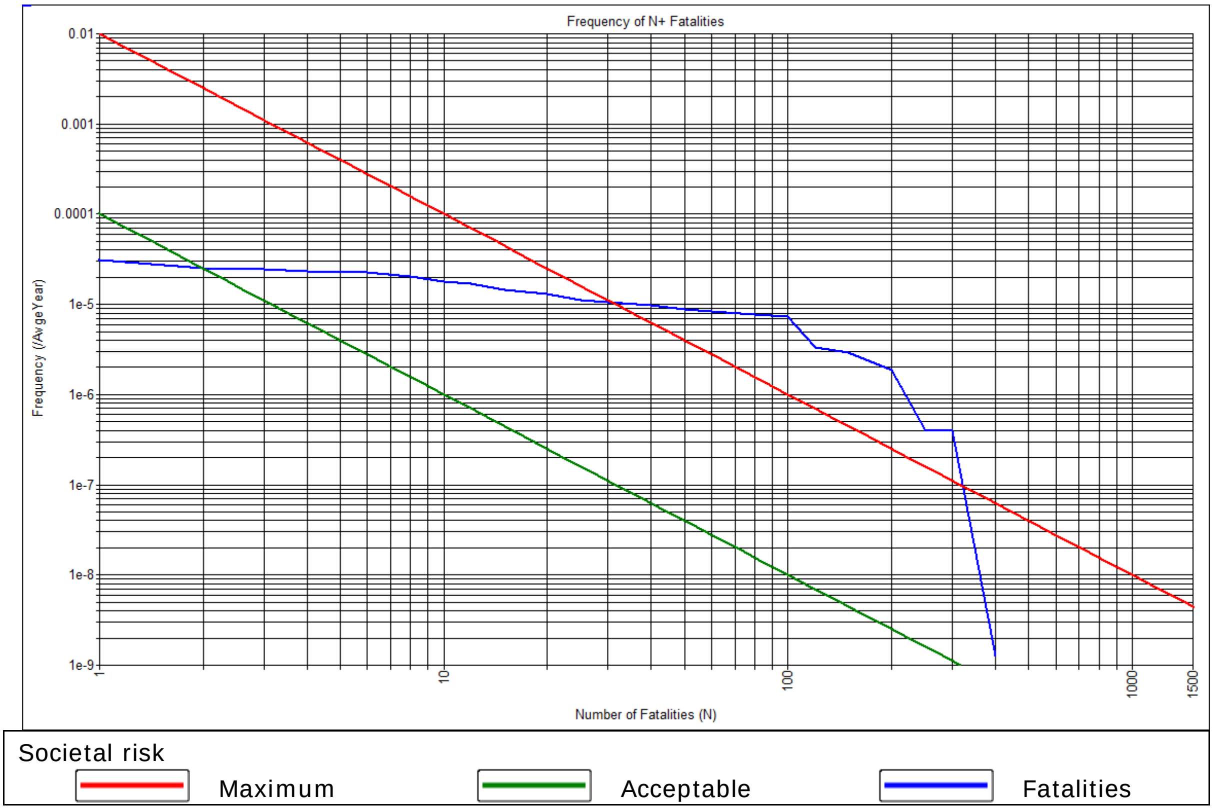
There are no noticeable differences between the societal risks for a ferry with cares compared to the societal risks for a ferry without cars, neither for barges with hose crane nor for fixed tank with hose crane.

6.1.4 Drawing 1 – West coast winds - Large ferry with passengers and open terminal bridge – 6 bar

Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with passengers (without cars) and open terminal bridge in an area with West coast wind conditions in drawing 1.

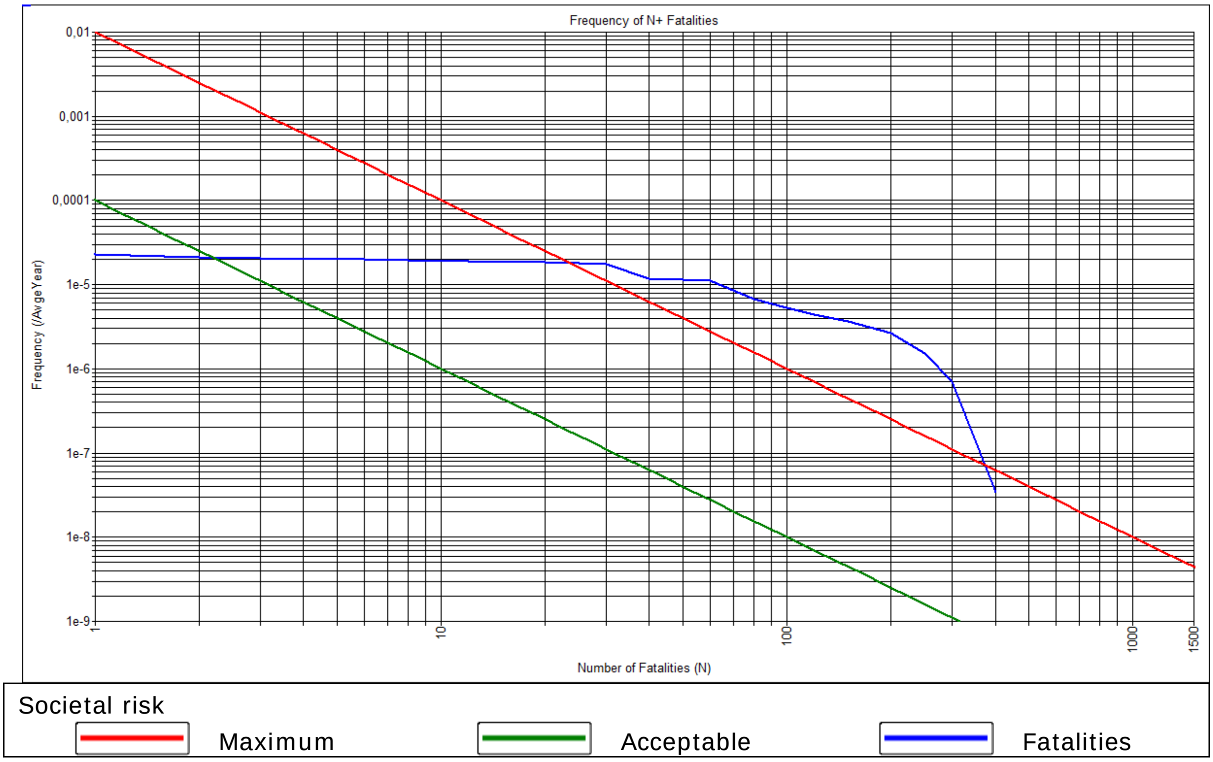
The iso risk curves are identical to the calculation of "Large ferry with passengers".



Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with passengers (without cars) and open terminal bridge in an area with West coast wind conditions in drawing 1.

The iso risk curves are identical to the calculation of "Large ferry with passengers (without cars)".



The risk calculations are compared to the same calculation basis (drawing 1 West coast winds) but with a closed terminal bridge (see section 6.1.3).

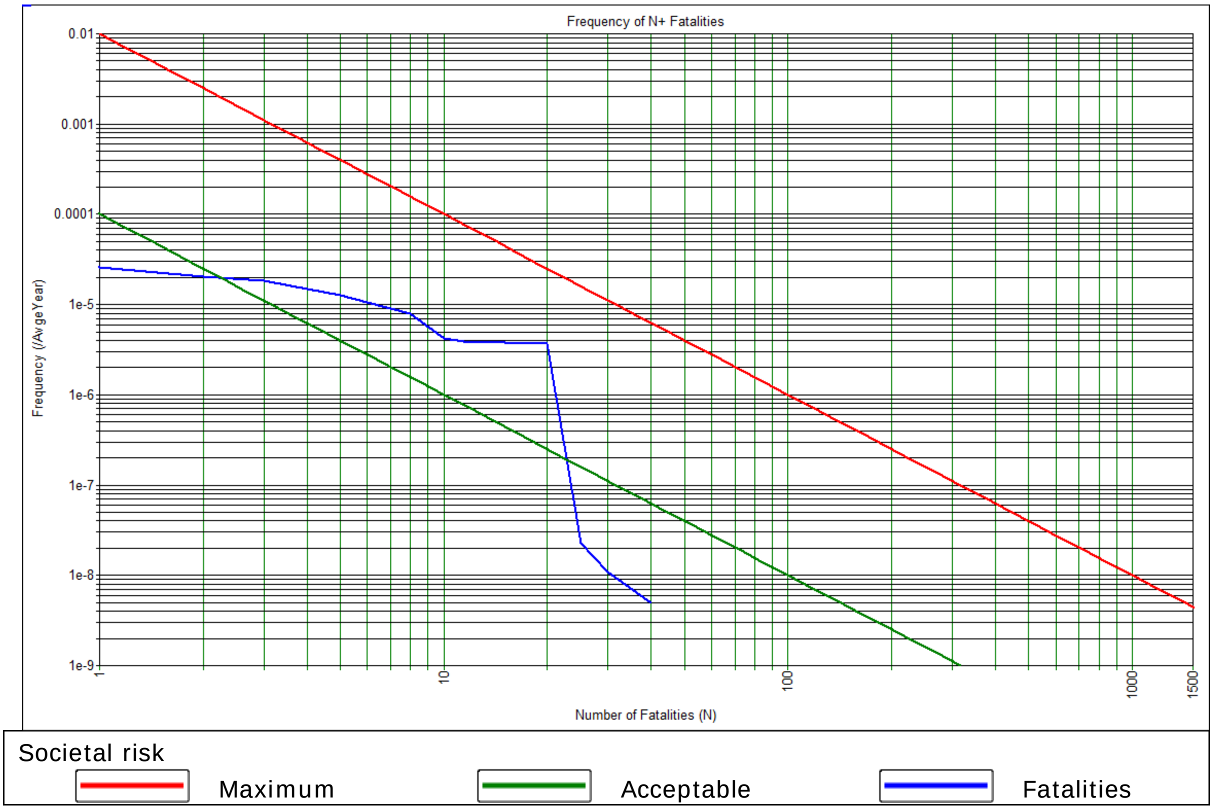
An open terminal bridge gives a significant aggravation of the societal risks compared to a closed terminal bridge.

6.1.5 Drawing 1 – West coast winds - Small ferry with cars and passengers – 6 bar

Barge, hose crane

Calculation of bunkering from barge with hose crane to a small ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

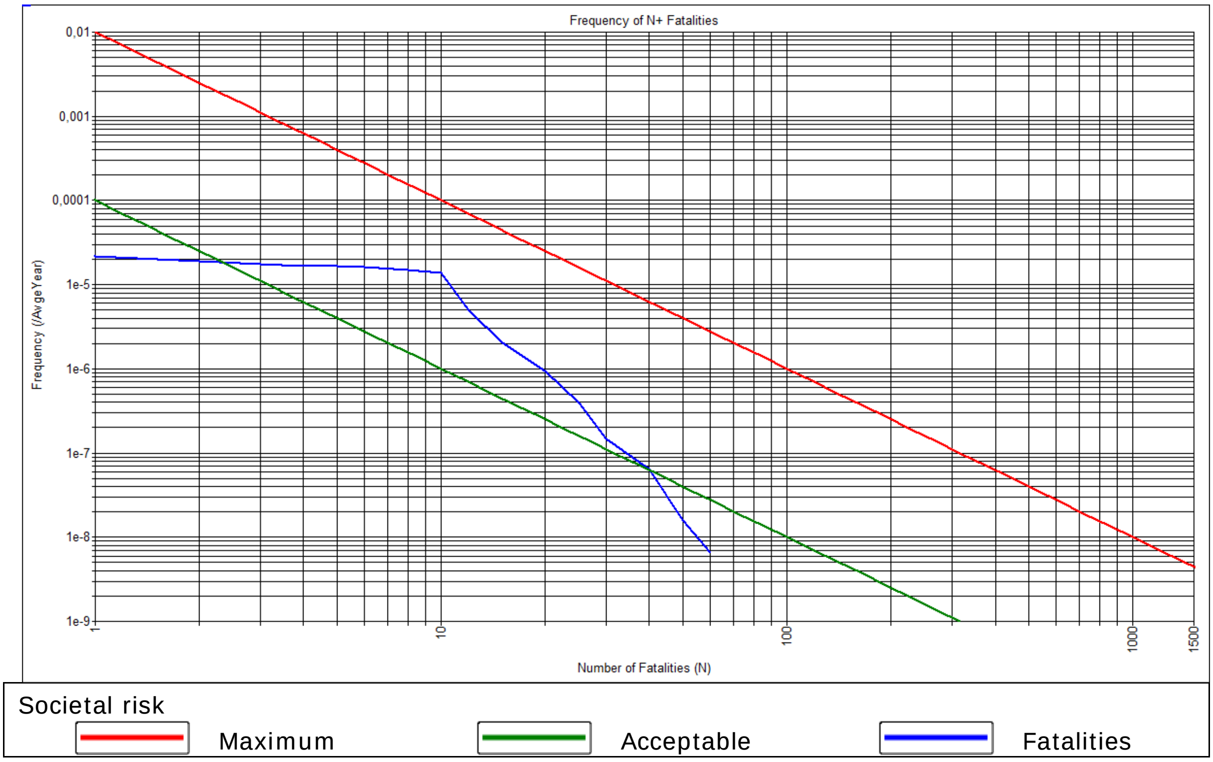
The iso risk curves are identical to the calculation of "Large ferry with cars and passengers".



Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a small ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

The iso risk curves are identical to the calculation of "Large ferry with cars and passengers".



The risk calculations are compared to the same calculation basis (drawing 1 West coast winds) but for a large ferry with more passengers (see section 6.1.1).

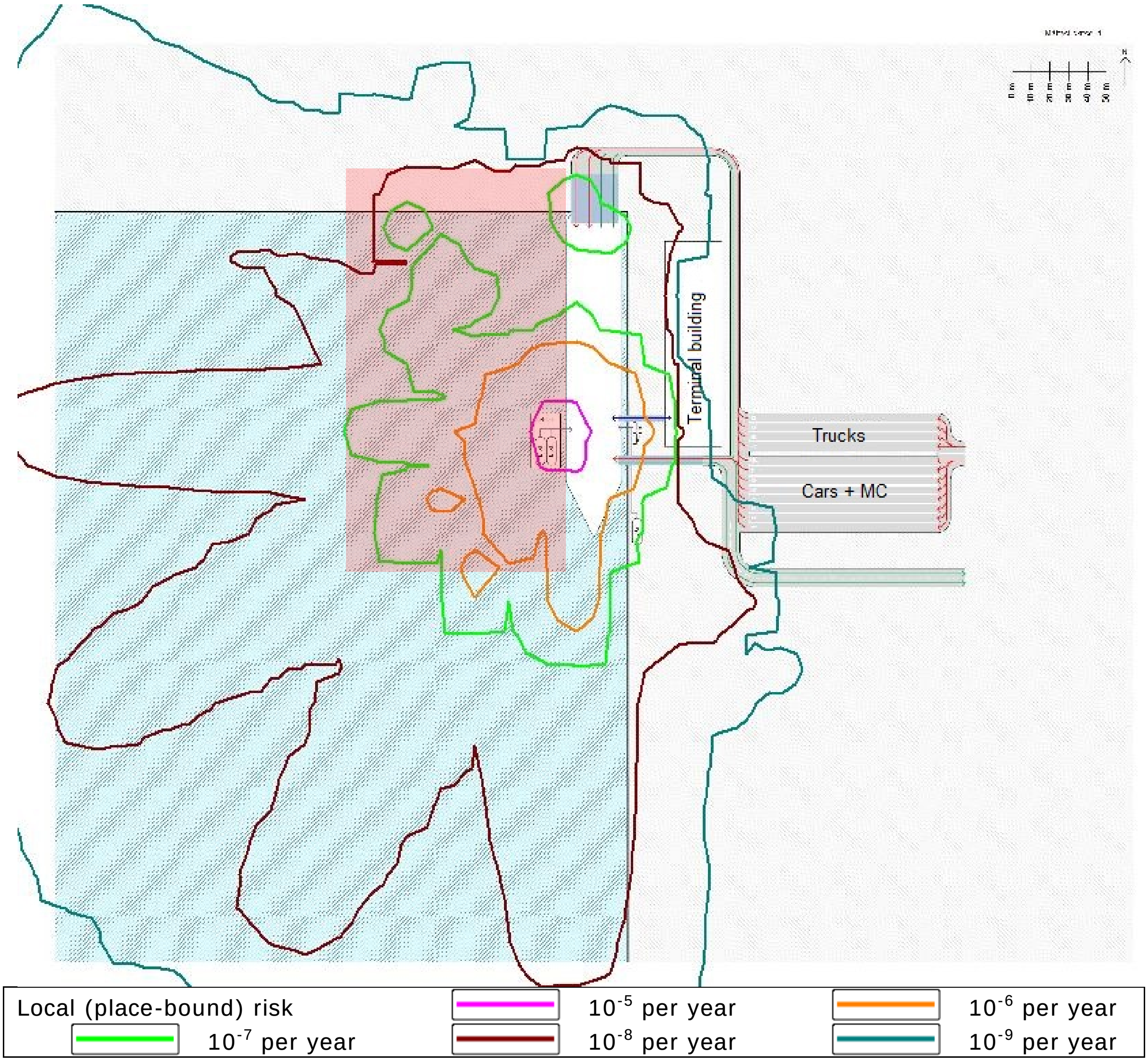
A small ferry with passengers gives a lower societal risk, as there are fewer persons present.

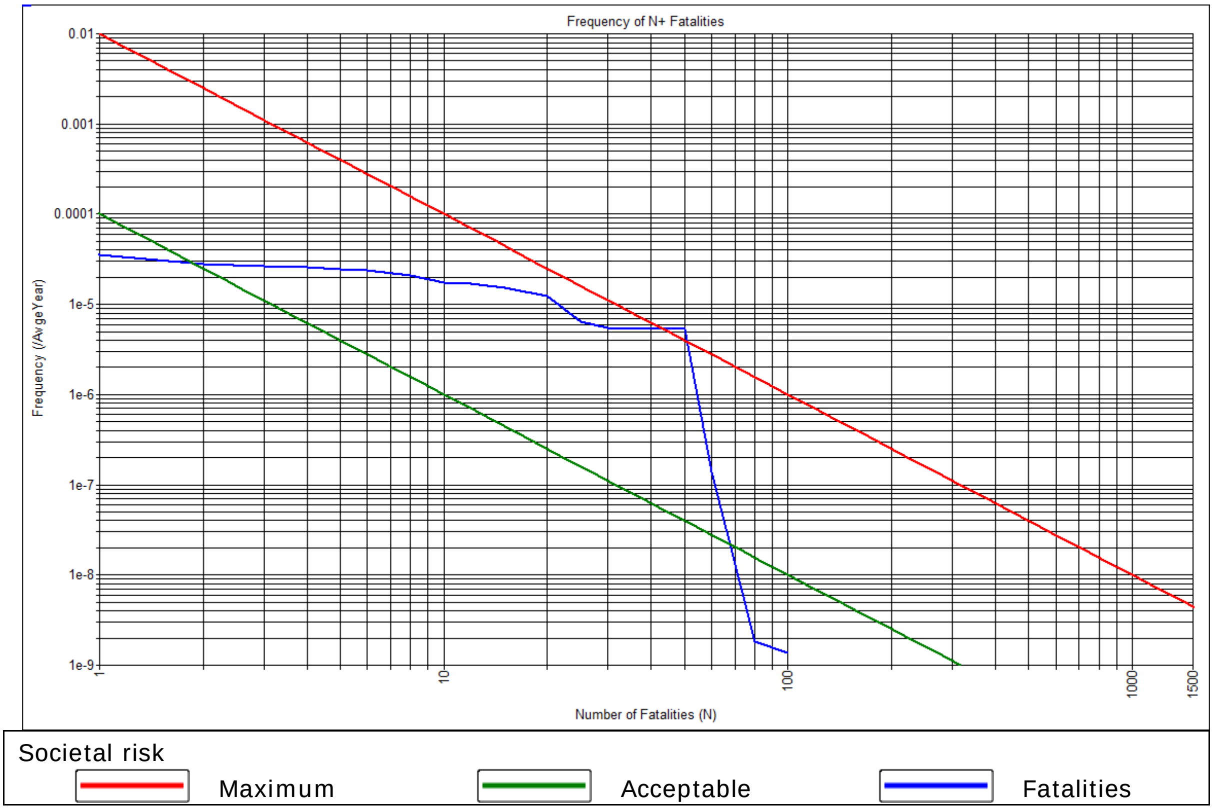
6.1.6 Drawing 1 – South coast winds - Large ferry with cars and passengers – 6 bar

Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with South coast wind conditions in drawing 1.

In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.

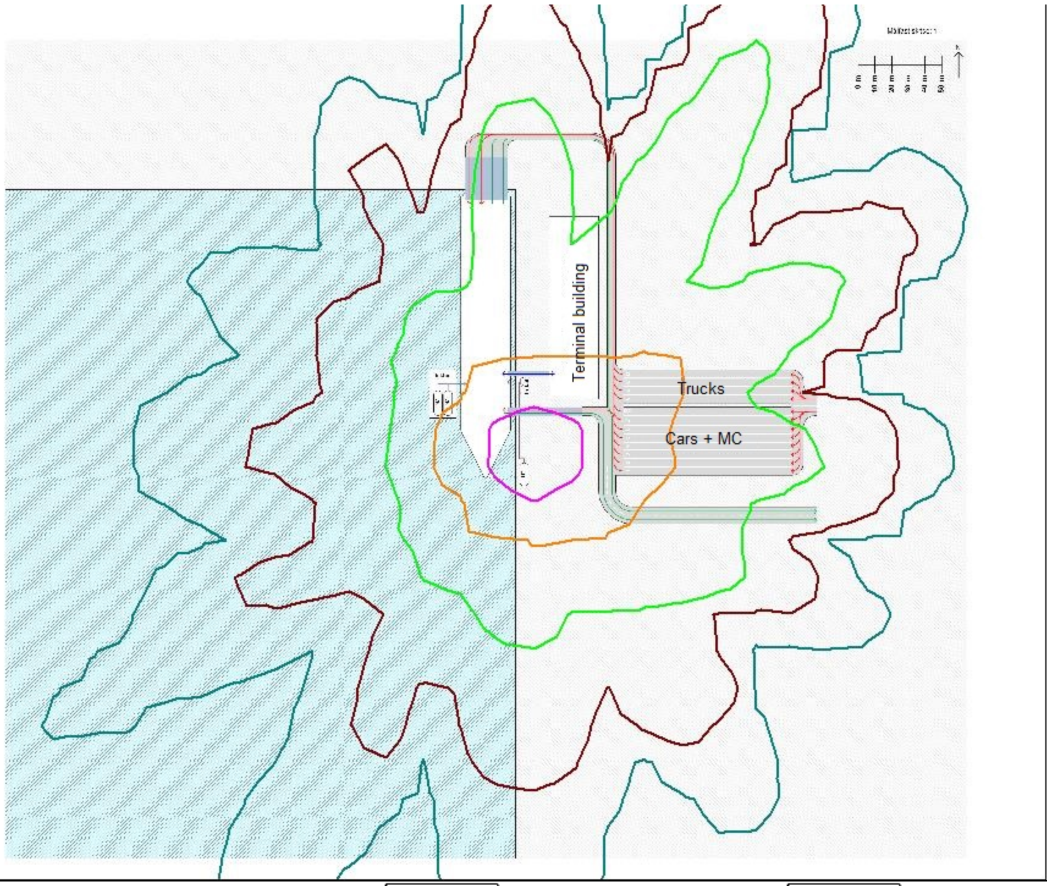




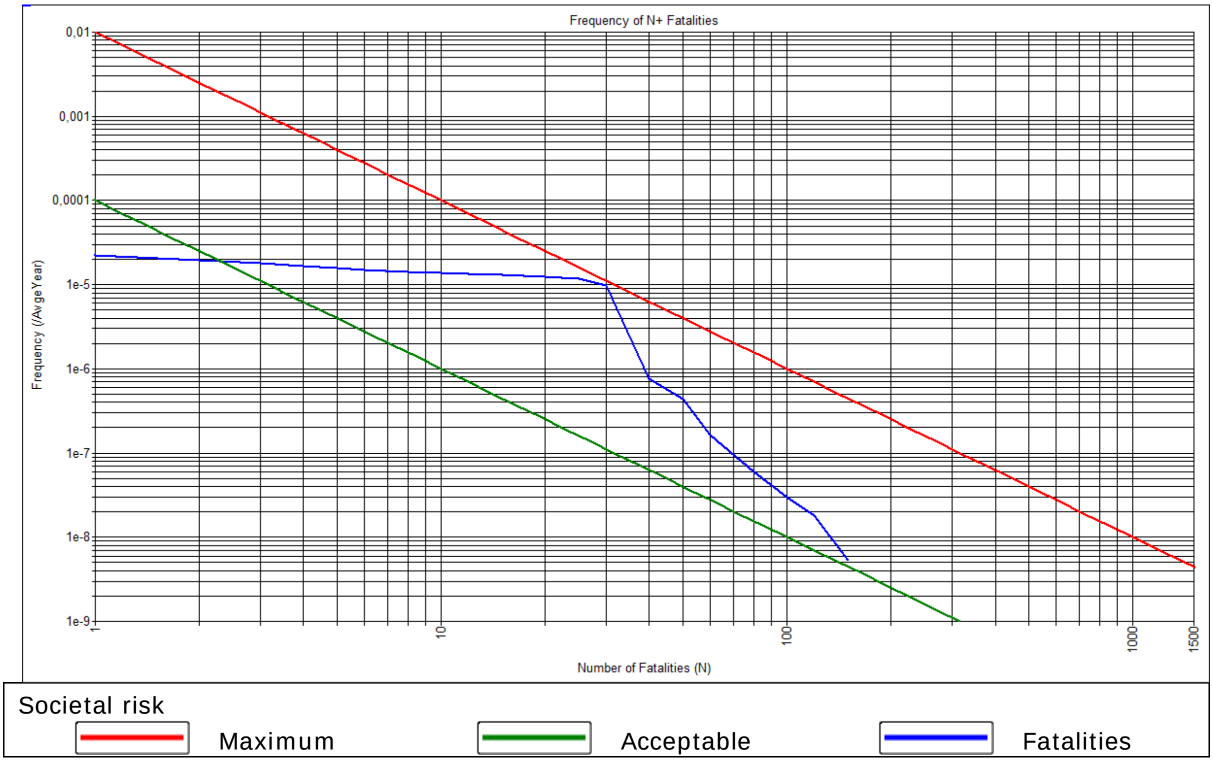
Frequency of N+ Fatalities
Frequency (/AvgeYear)
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with South coast wind conditions in drawing 1.



Local (place-bound) risk		(magenta line)	10^{-5} per year	(orange line)	10^{-6} per year
(green line)	10^{-7} per year	(dark red line)	10^{-8} per year	(teal line)	10^{-9} per year



The risk calculations are compared to the same calculation basis but for a wind-rose for West coast wind conditions (see section 6.1.1).

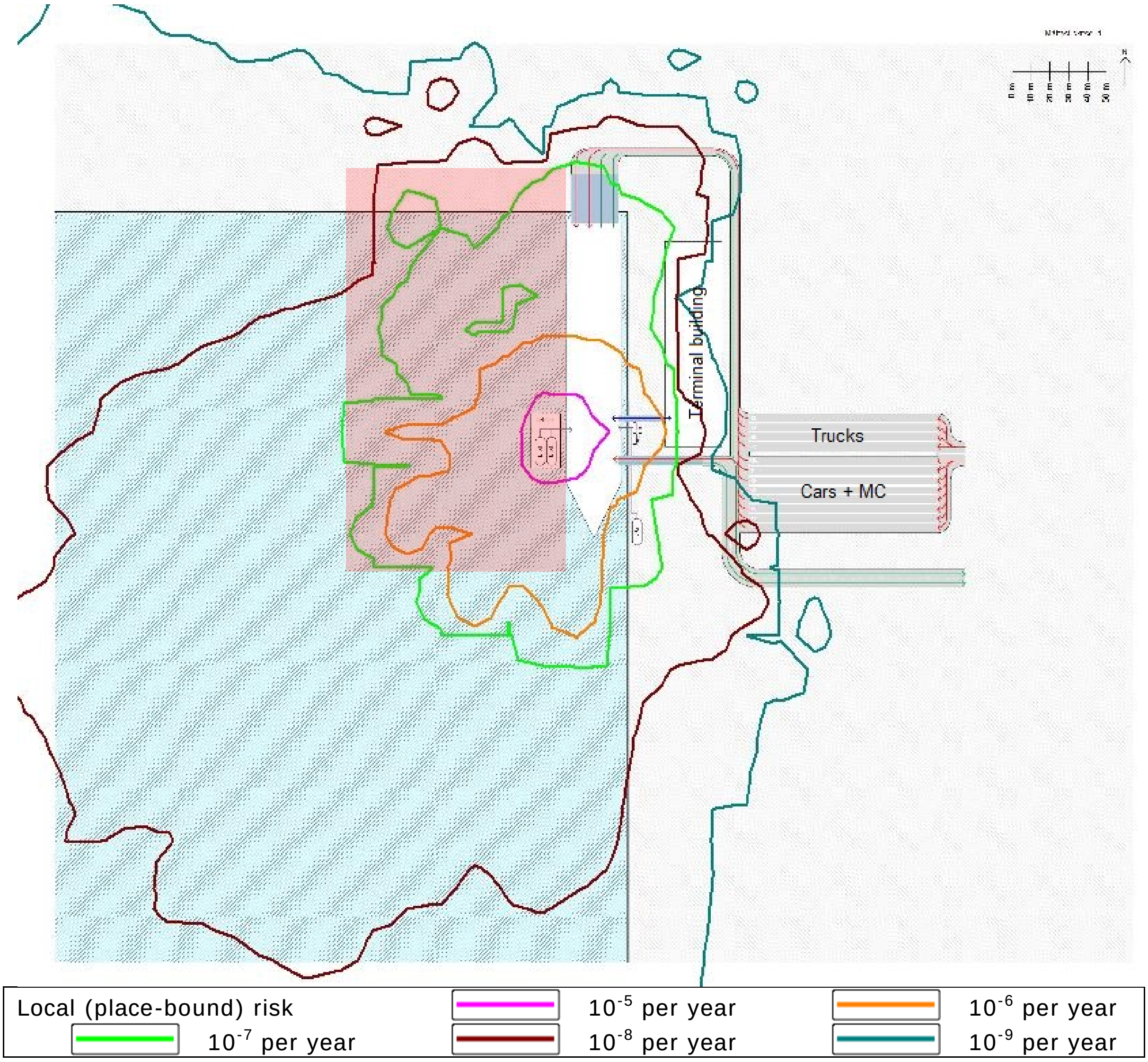
Calculations with a wind-rose corresponding to the South coast of Norway do not result in a significant change in the overall risk scenario.

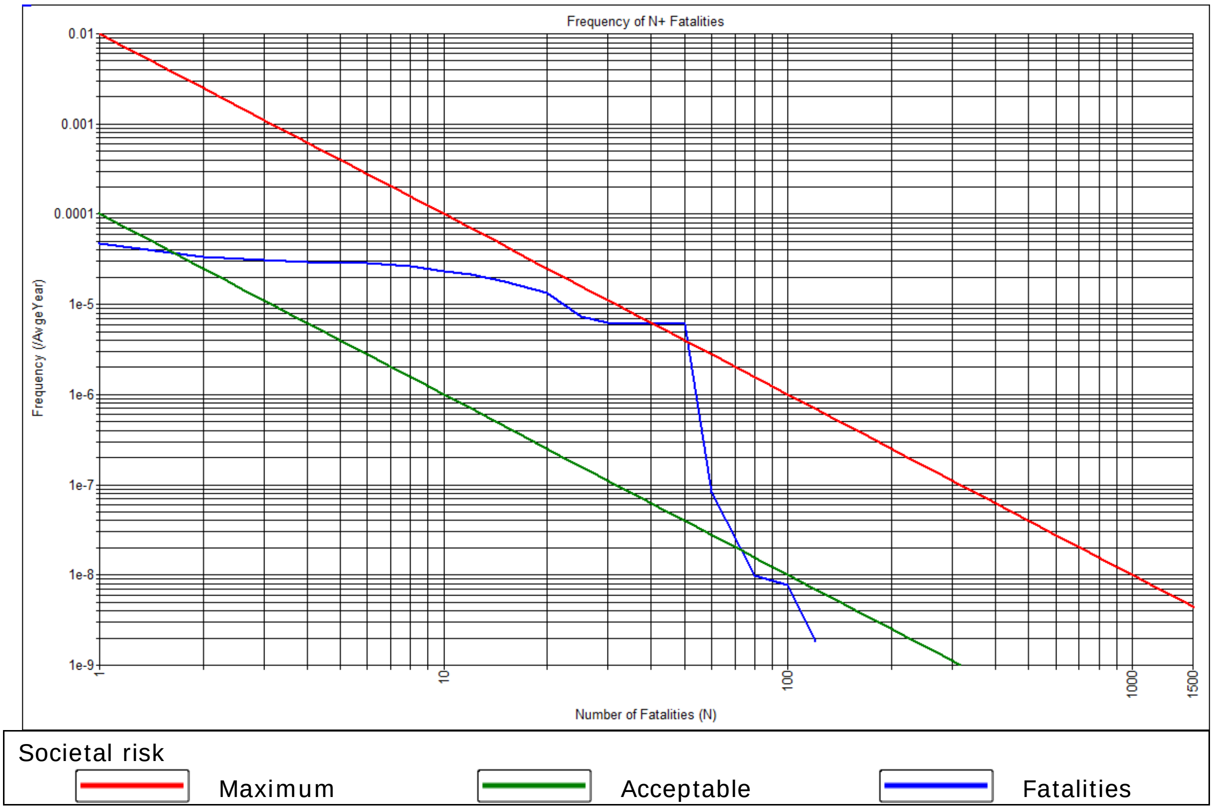
6.1.7 Drawing 1 – Fjord winds - Large ferry with cars and passengers – 6 bar

Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with fjord wind conditions in drawing 1.

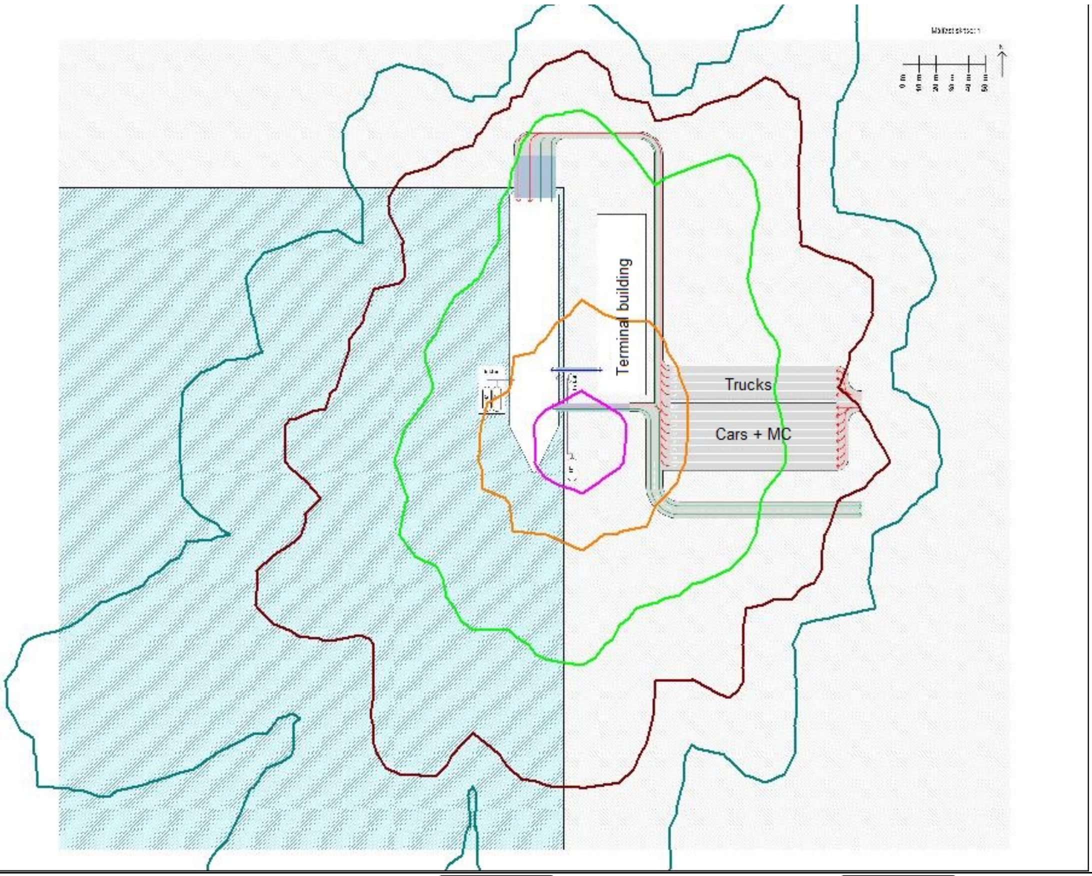
In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.




Frequency of N+ Fatalities
Frequency (/AvgeYear)
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

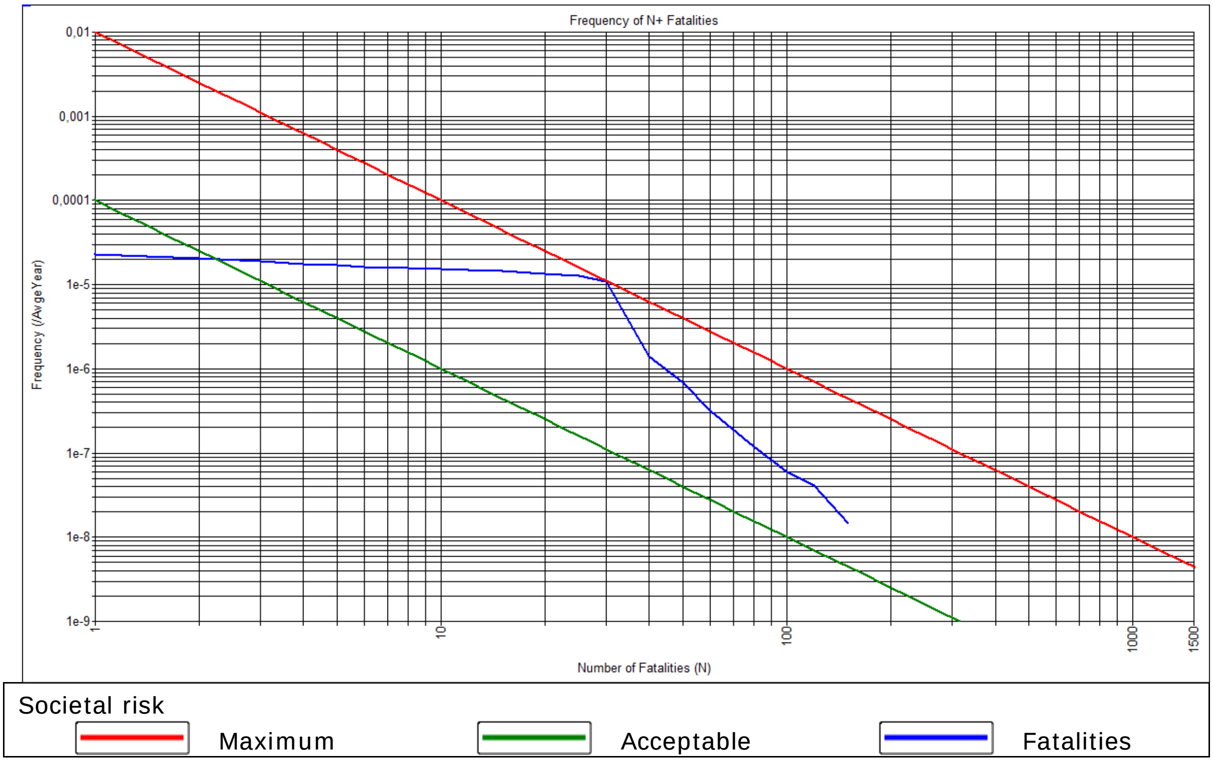
Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with fjord wind conditions in drawing 1.



Local (place-bound) risk

- 10^{-5} per year
- 10^{-6} per year
- 10^{-7} per year
- 10^{-8} per year
- 10^{-9} per year



The risk calculations are compared to the same calculation basis but for a wind-rose for West coast wind conditions (see section 6.1.1).

Calculations with a wind-rose corresponding to the wind conditions in the Norwegian fjords do not result in a significant change in the overall risk scenario.

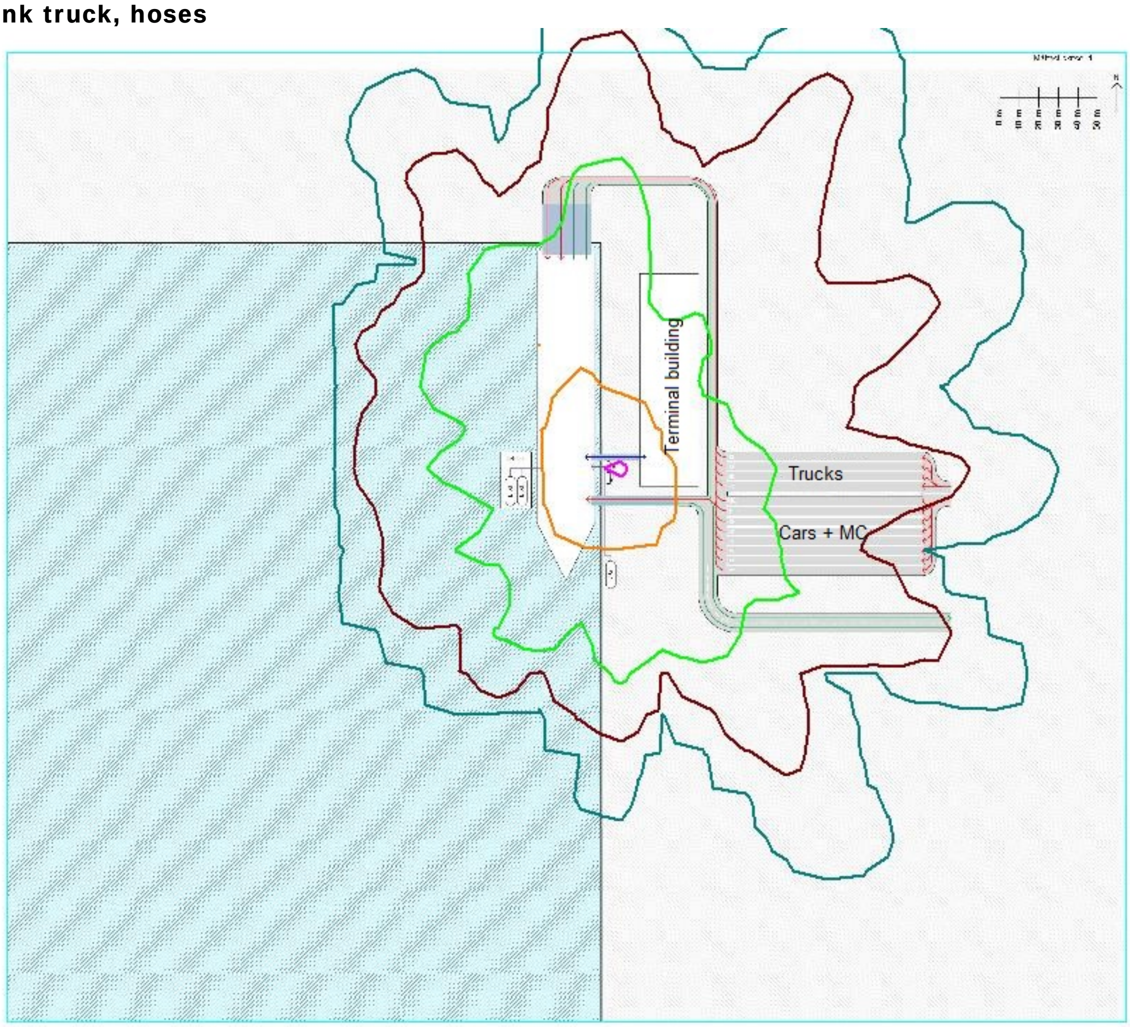
6.1.8 Drawing 1 – West coast winds - Excess flow valves - Large ferry with cars and passengers – 6 bar

Excess flow valves can be fitted for tank trucks, since centrifugal pumps are assumed for tank trucks, whereas positive displacement pumps are assumed for fixed tanks and barges. The comparison has therefore been carried out for tank trucks only.

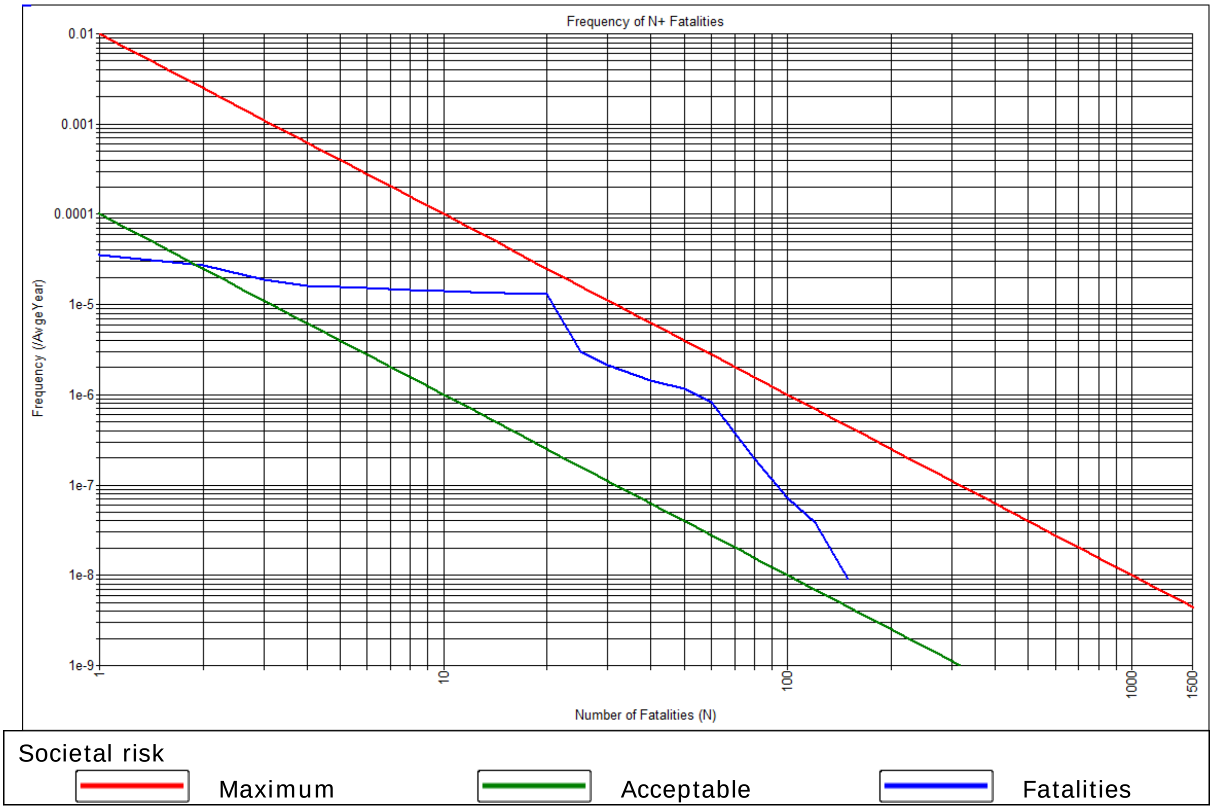
Calculation of bunkering from a tank truck onshore with hoses to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

The system has been fitted with excess flow valves as close to the tank truck as possible.

Tank truck, hoses



Local (place-bound) risk			
		magenta line	10^{-5} per year
		orange line	10^{-6} per year
green line	10^{-7} per year	dark red line	10^{-8} per year
		teal line	10^{-9} per year



The risk calculations are compared to the same calculation basis (drawing 1 West coast winds) but without excess flow valves (see section 6.1.1).

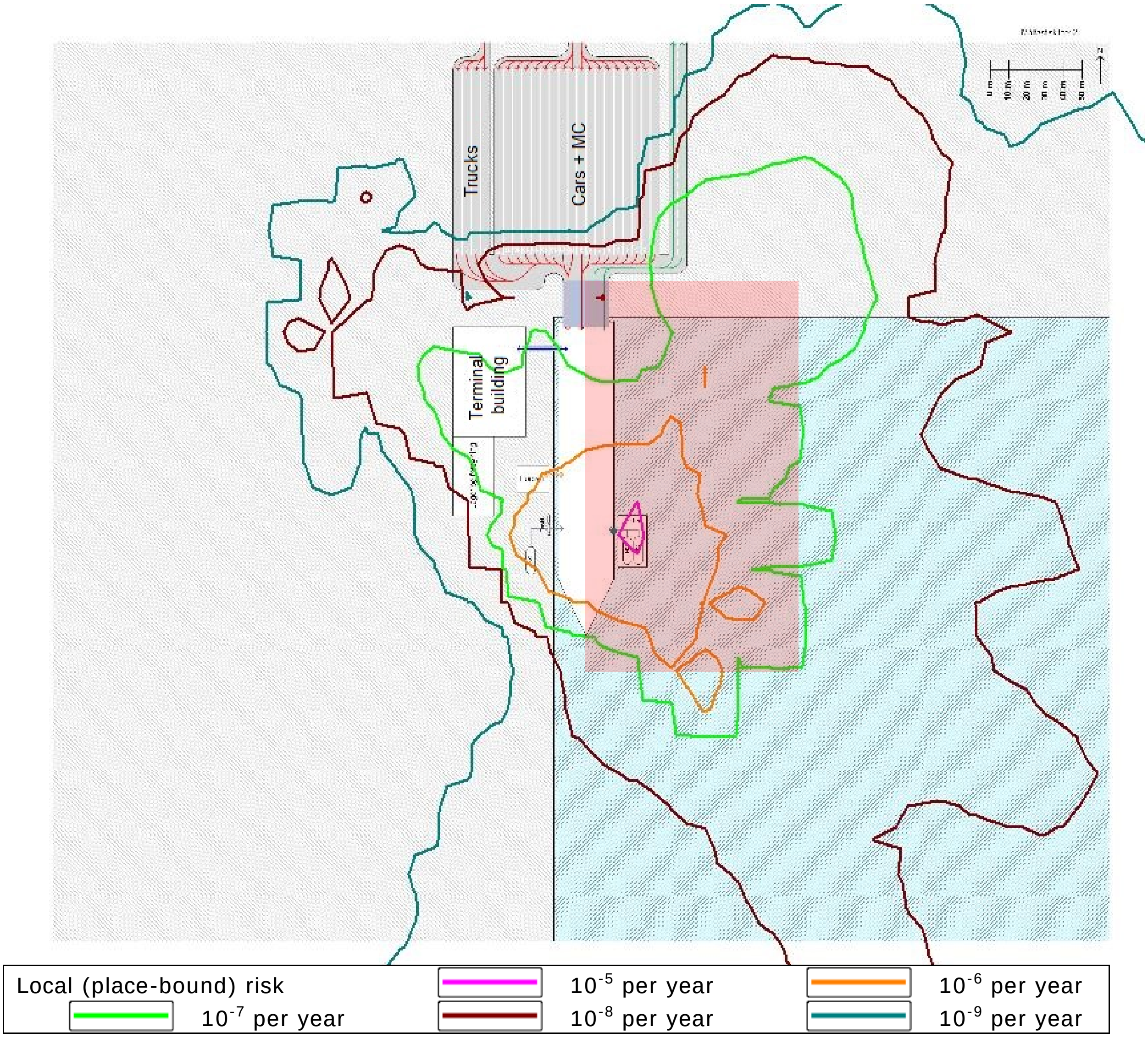
Excess flow valves give significantly lower risks (but only for tank trucks).

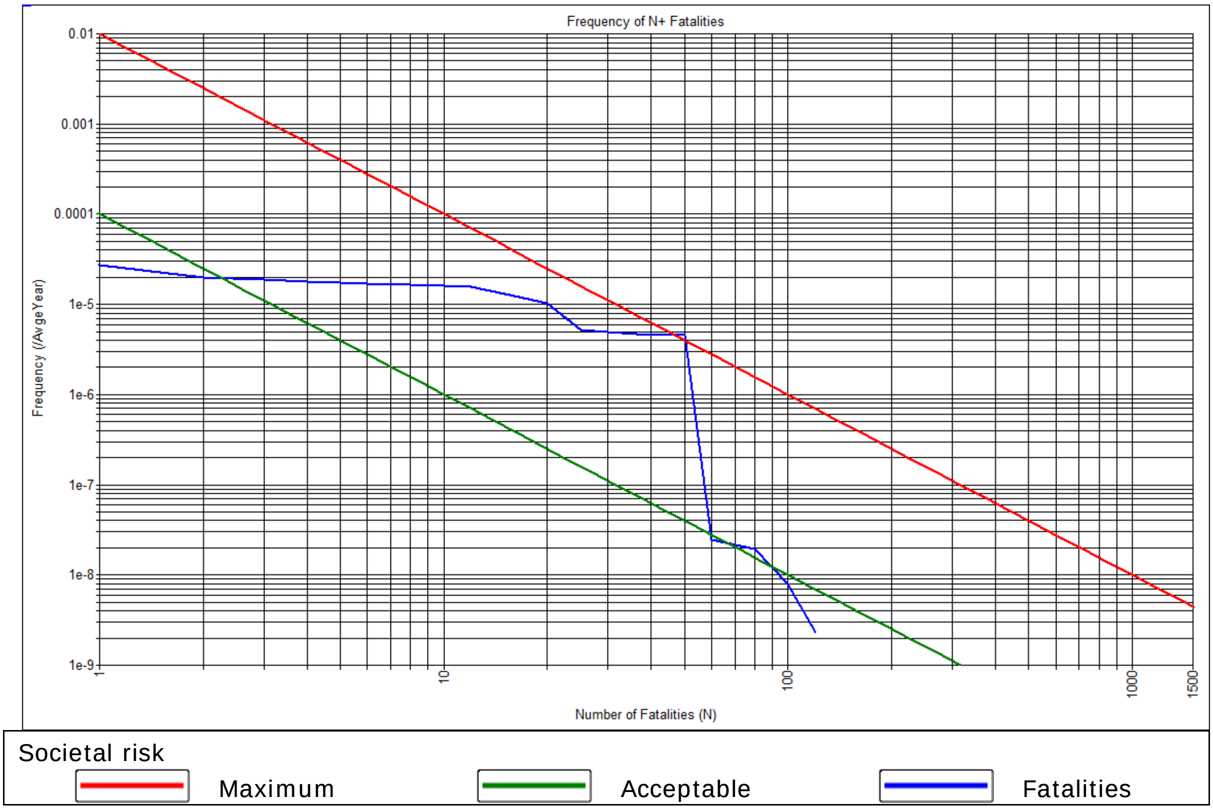
6.1.9 Drawing 2 – West coast winds - Large ferry with cars and passengers – 6 bar

Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 2.

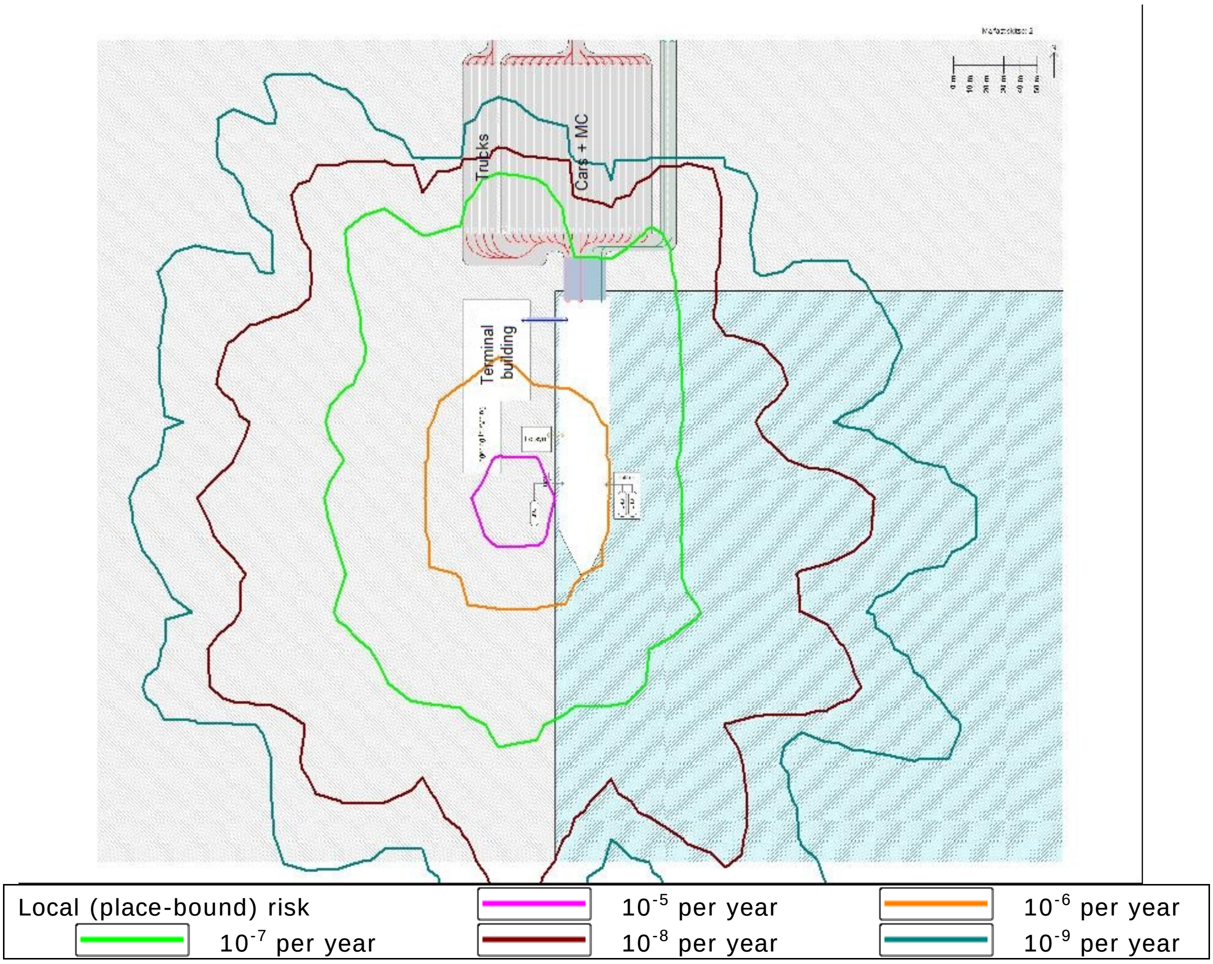
In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.

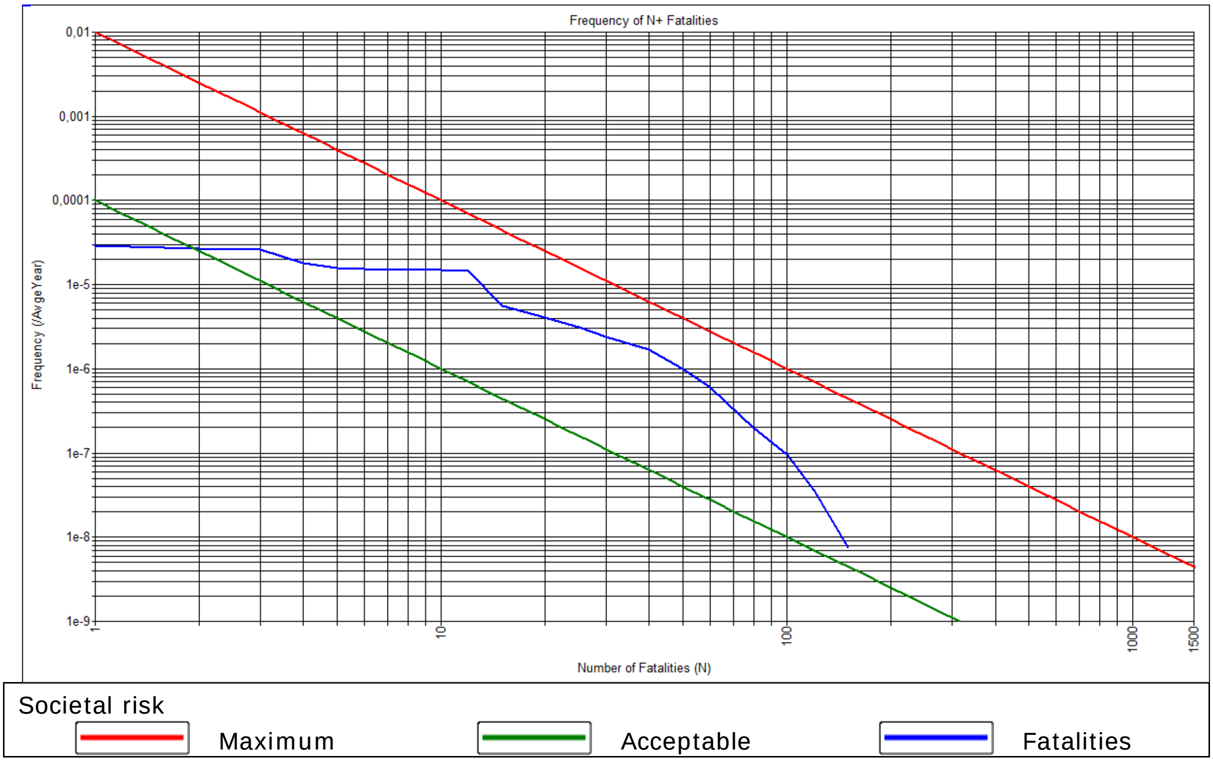



Frequency of N+ Fatalities
Frequency (/AvgeYear)
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 2.





The risk calculations are compared to the same calculation basis (West coast winds) but using drawing 1 (see section 6.1.1).

The calculations in drawing 2 show that the placement of the bunkering interface is important with regard to terminal bridge and transit area for cars, but not with regard to onshore or offshore.

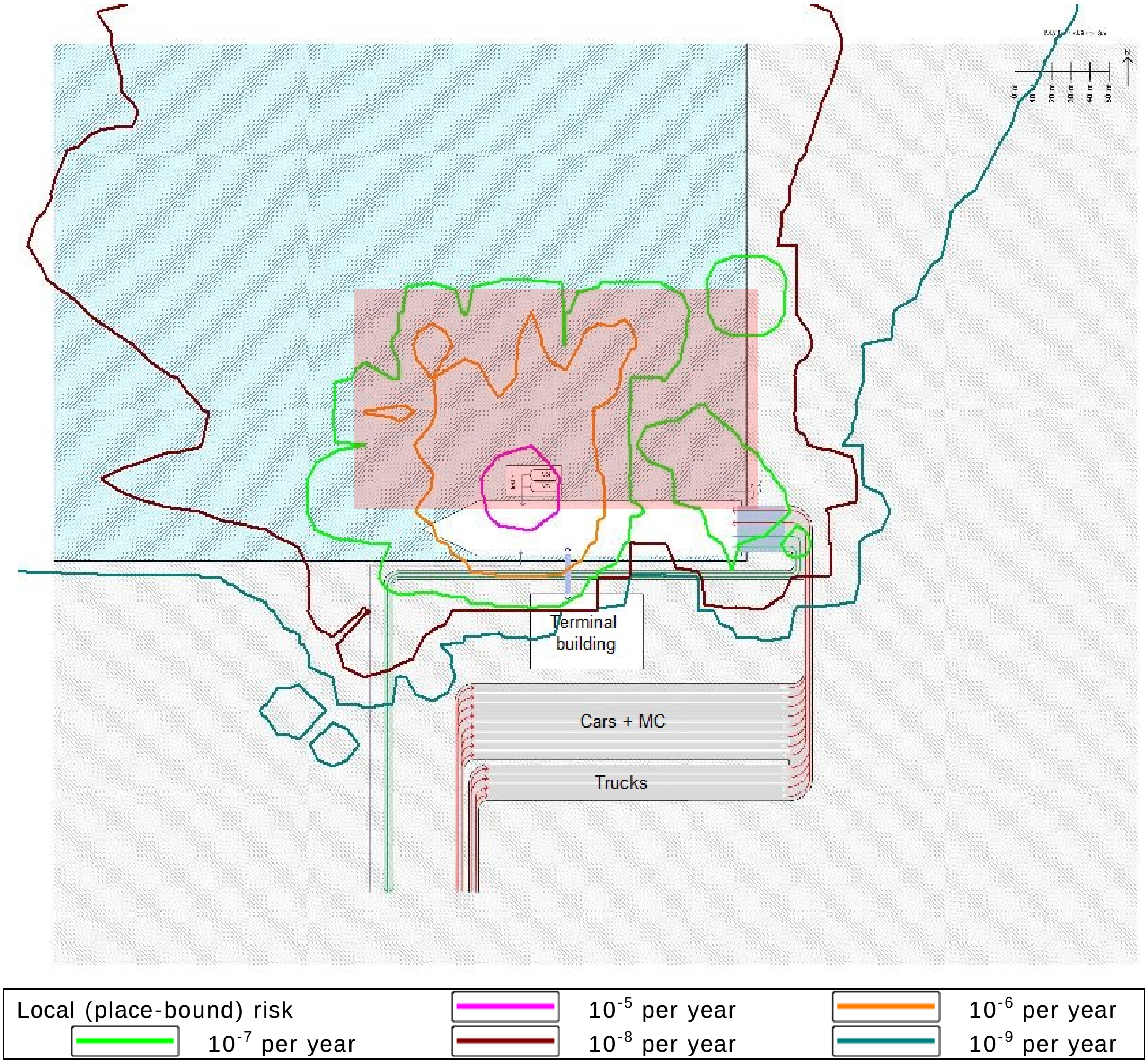
The societal risks related to bunkering from barge in drawing 3 are about the same as the risks related to bunkering from barge in drawing 1, while the societal risks related to bunkering from fixed tank in drawing 3 are lower compared to the risks related to bunkering from fixed tank in drawing 1.

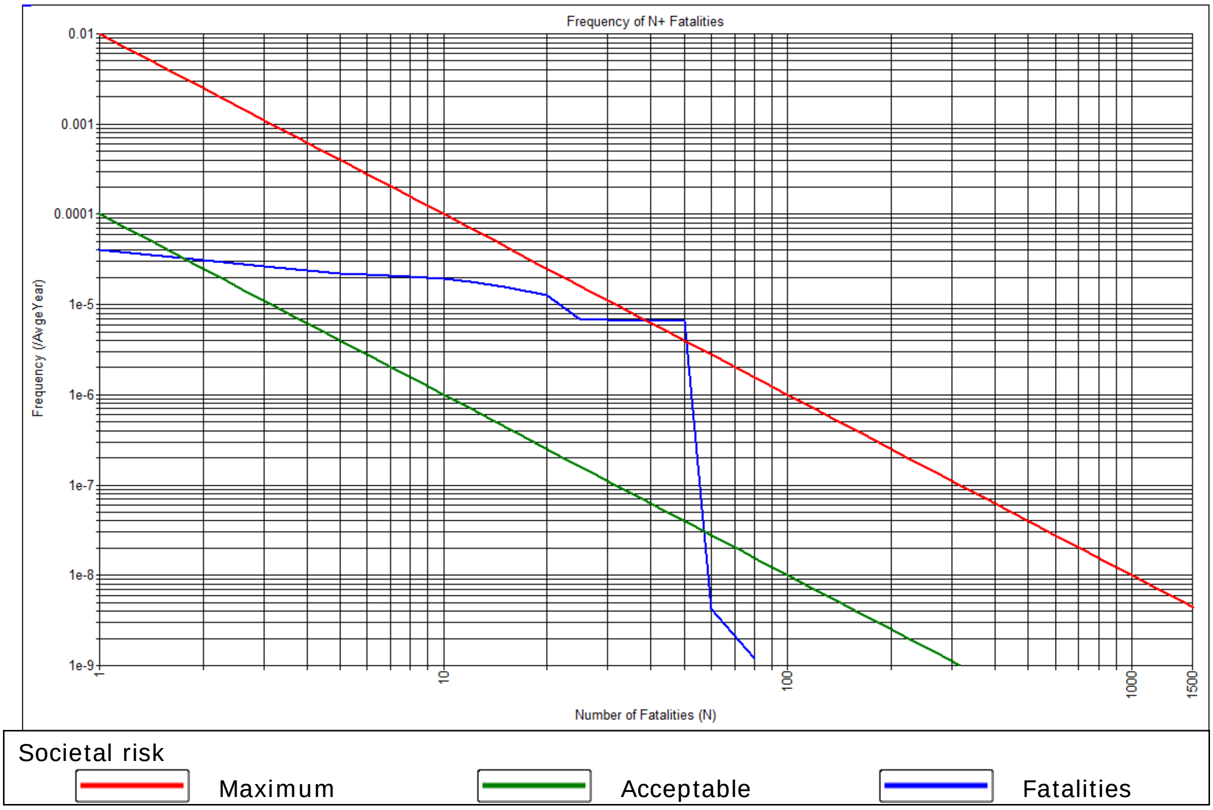
6.1.10 Drawing 3 – West coast winds - Large ferry with cars and passengers

Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

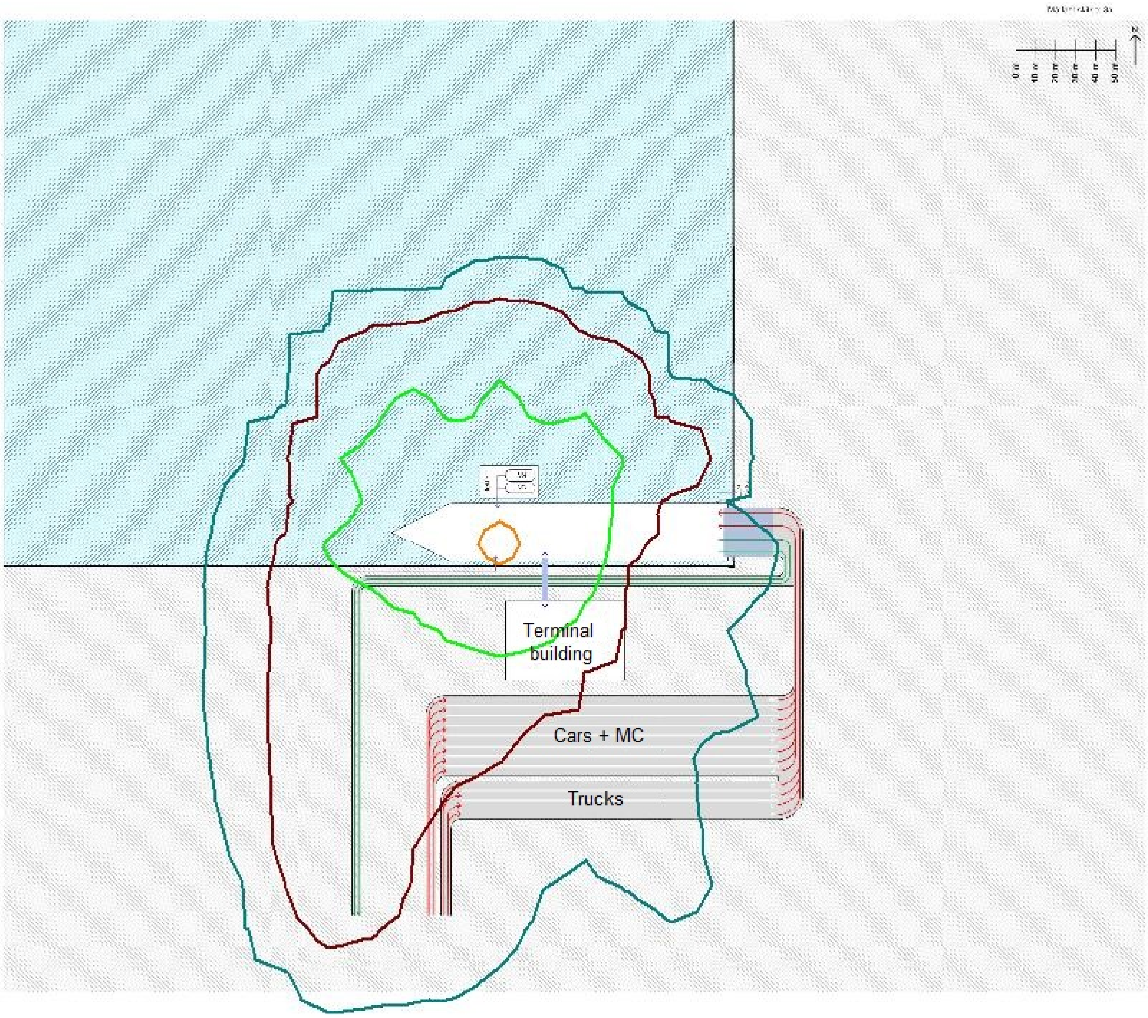
In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.



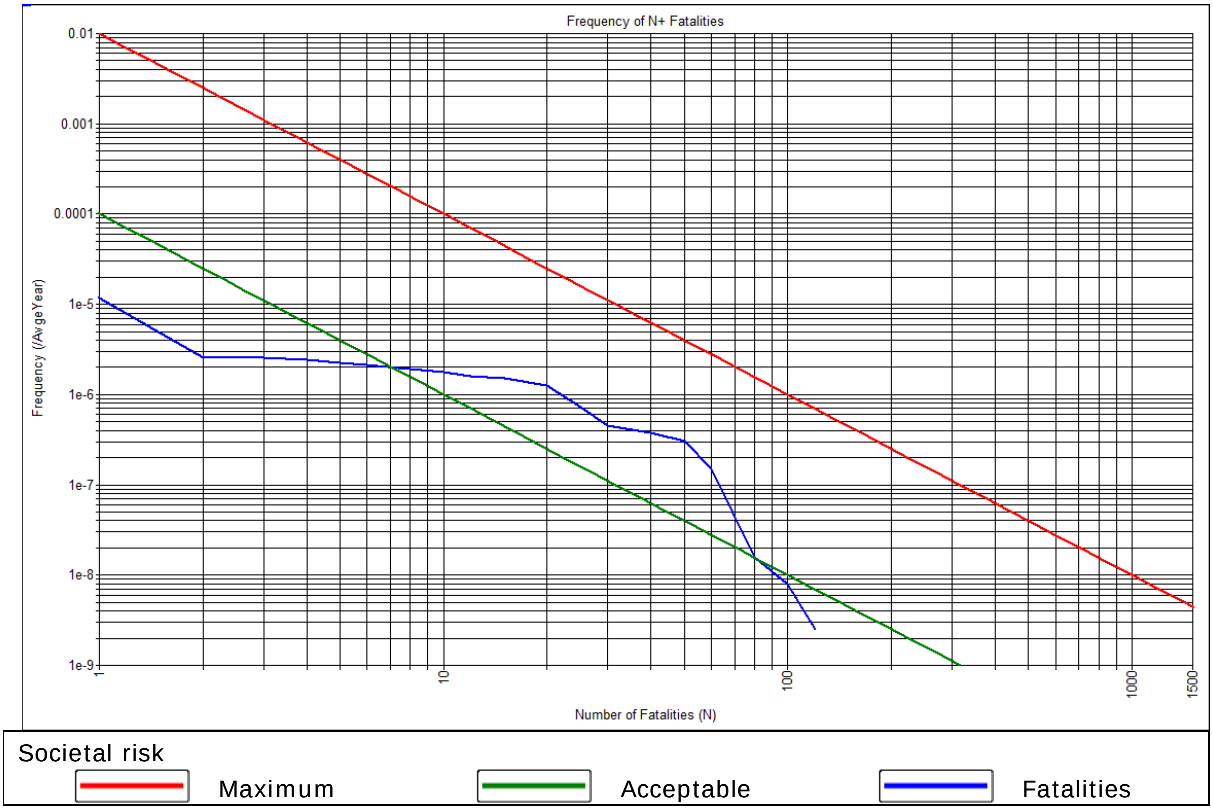

Frequency of N+ Fatalities
0.01
0.001
0.0001
1e-5
1e-6
1e-7
1e-8
1e-9
Frequency (/AvgeYear)
1
10
100
1000
1500
Number of Fatalities (N)
Societal risk
Maximum
Acceptable
Fatalities

Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore placed outside the risk sensitive area, with piping via a hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.



Local (place-bound) risk		10^{-5} per year		10^{-6} per year
	10^{-7} per year		10^{-8} per year	10^{-9} per year



The risk calculations are compared to the same calculation basis (West coast winds) but using drawing 1 (see section 6.1.1).

The calculations in drawing 3 show that the placement of the bunkering interface is important with regard to terminal bridge and transit area for cars, but not with regard to onshore or offshore.

The societal risks related to bunkering from barge in drawing 3 are about the same as the risks related to bunkering from barge in drawing 1, while the societal risks related to bunkering from fixed tank in drawing 3 are lower compared to the risks related to bunkering from fixed tank in drawing 1.

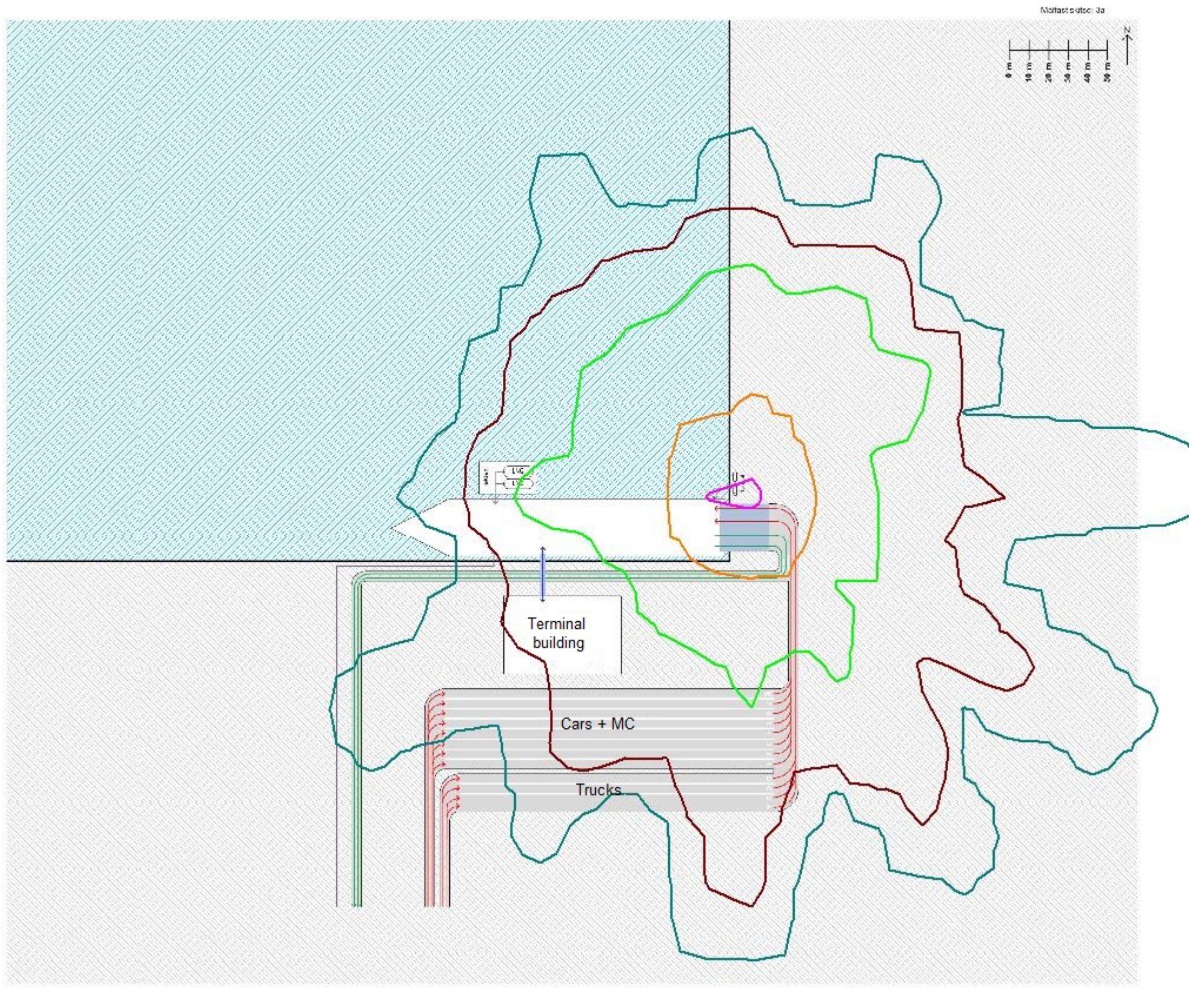
The reason for the lower risks for fixed tank in drawing 3 is that the pump is placed by the tank (outside the map) and does not contribute to the risks.

6.1.11 Drawing 3 – West coast winds - Excess flow valves - Large ferry with cars and passengers

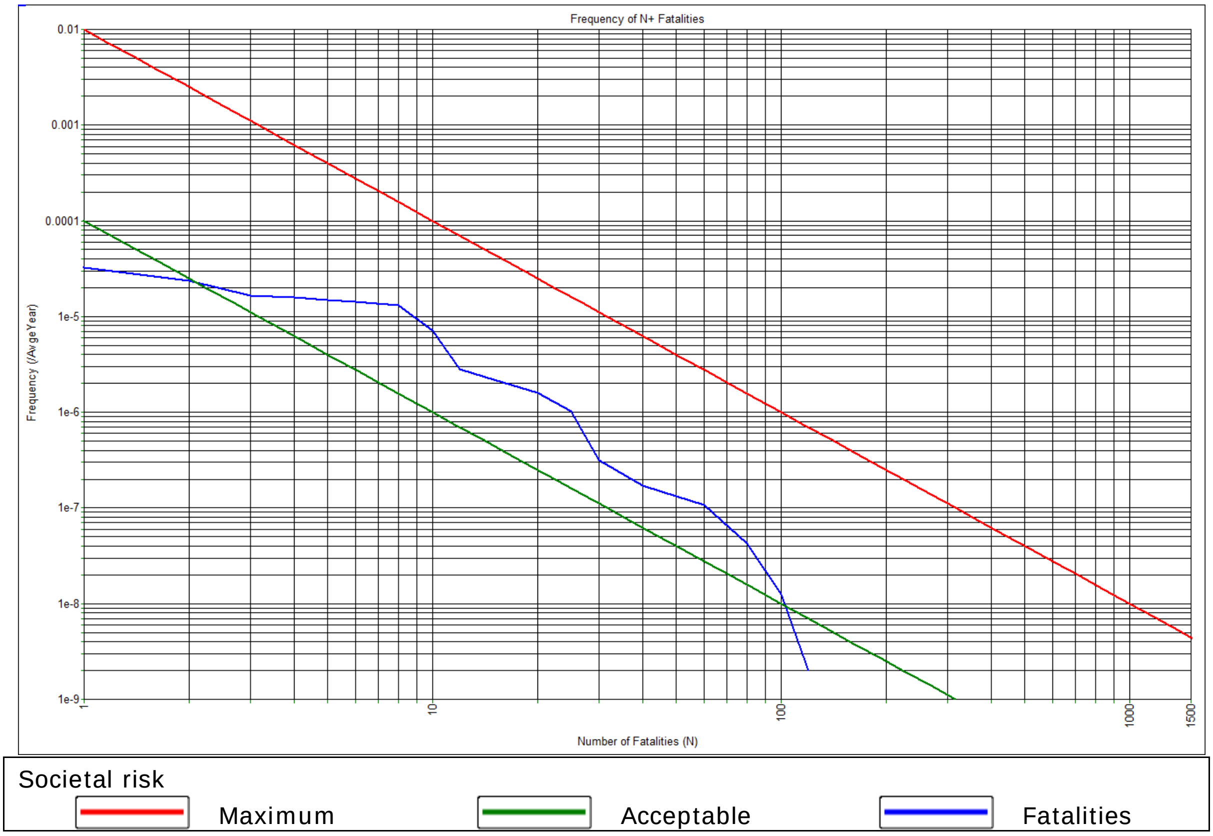
Tank truck, hoses to rig to hose crane

Excess flow valves can be fitted for tank trucks, since centrifugal pumps are assumed for tank trucks, whereas positive displacement pumps are assumed for fixed tanks and barges. The comparison has therefore been carried out only for tank truck.

Calculation of bunkering from a tank truck onshore with hoses to a rig and onwards with a hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3. The system has been fitted with excess flow valves as close as possible to the tank truck.



Local (place-bound) risk		(magenta line)	10^{-5} per year	(orange line)	10^{-6} per year
(green line)	10^{-7} per year	(dark red line)	10^{-8} per year	(teal line)	10^{-9} per year



The risk calculations are compared to the same calculation basis (West coast winds, excess flow valves) but using drawing 1 (see section 6.1.8).

The calculations in drawing 3 show that the placement of the bunkering interface is important with regard to terminal bridge and transit area for cars, but not with regard to onshore or offshore.

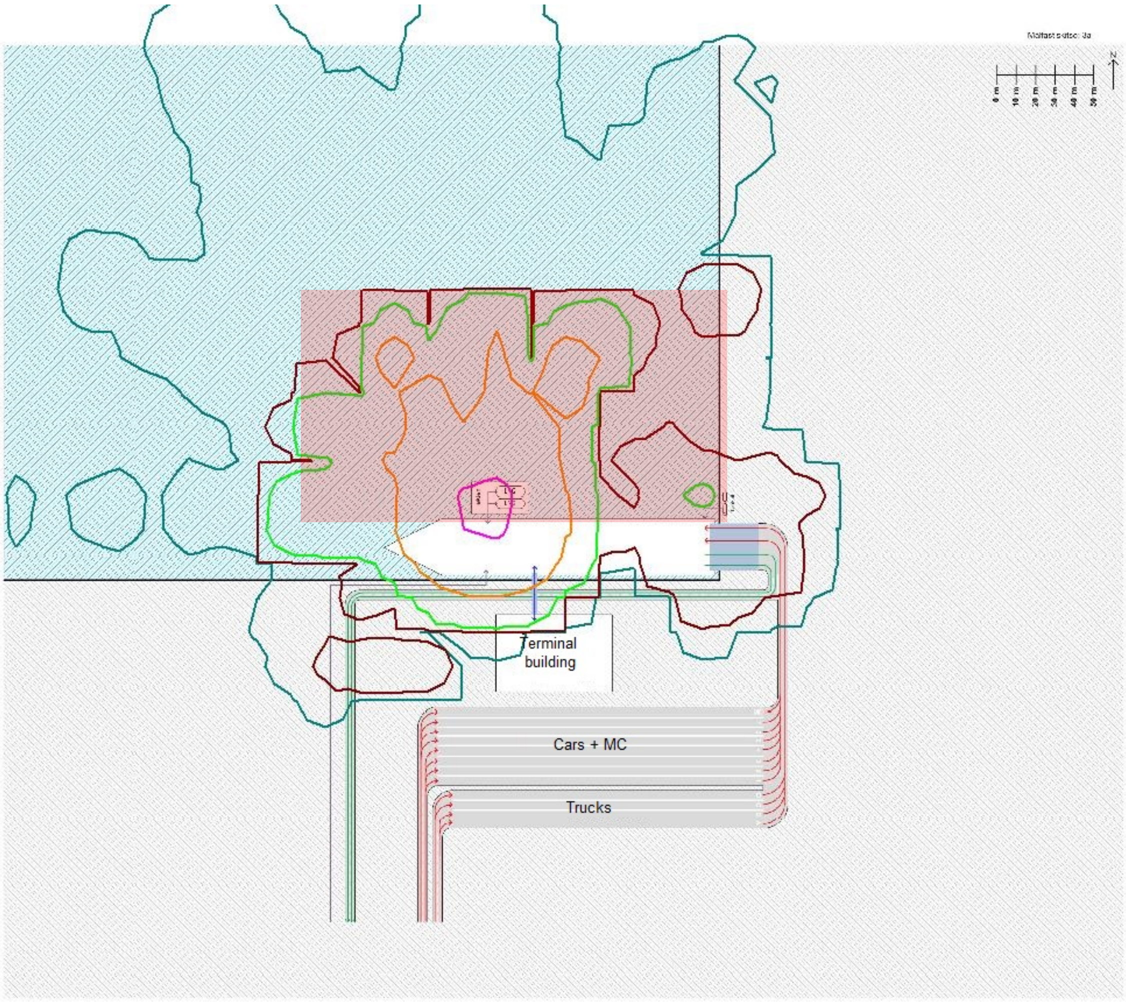
The societal risks related to bunkering from tank truck in drawing 3 are lower than the risks related to bunkering from tank truck in drawing 1. The reason for the lower risks for tank trucks in drawing 3 is the location further away from the terminal building and vehicle holding lanes.

6.1.12 ESD 5 sec - Drawing 3 – West coast winds - Large ferry with cars and passengers

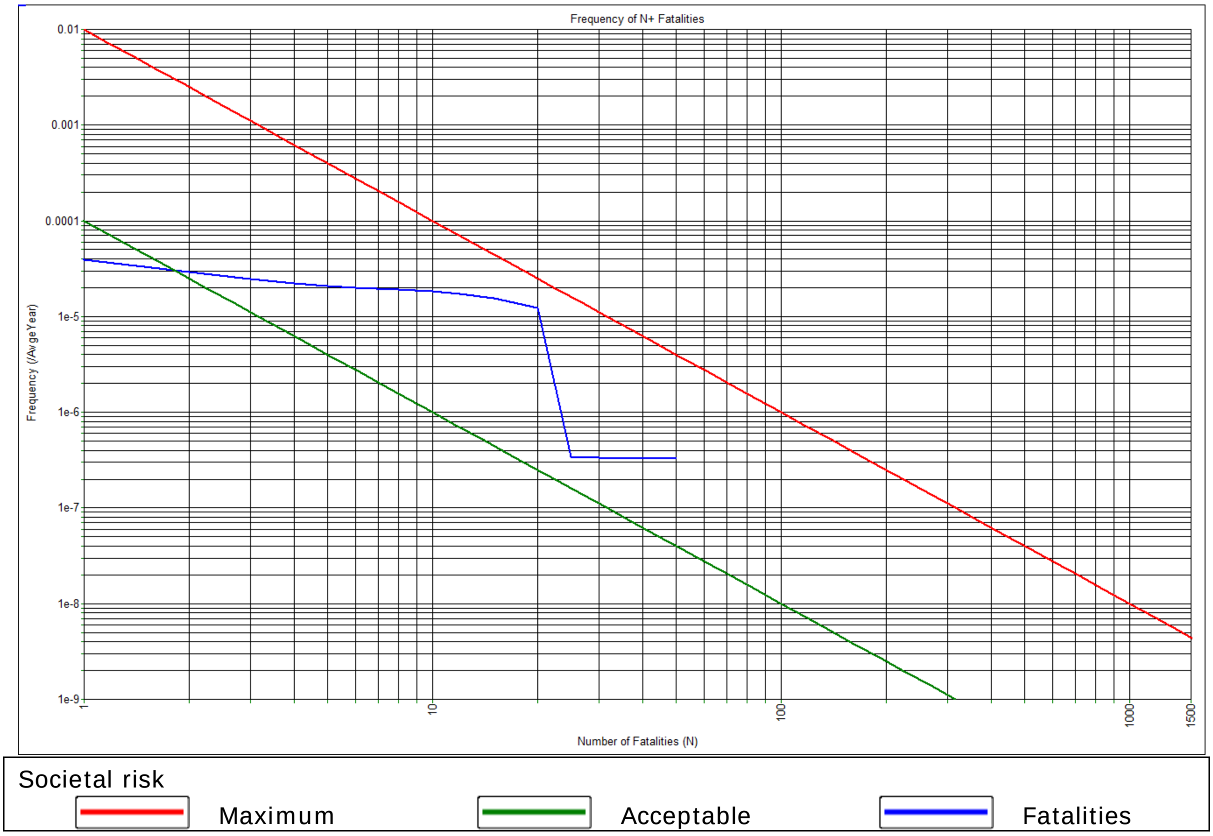
Barge, hose crane

Calculation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

The system ESD is optimised to a maximum overall response time and closing time of 5 seconds. In order to model the quay's retention effect and the ferry's sheltering effect, the risk calculation for the barge-side of the ferry is incorrect. This has been indicated by a red square, see section 4.3.5.



Local (place-bound) risk					
			10^{-5} per year		10^{-6} per year
	10^{-7} per year		10^{-8} per year		10^{-9} per year



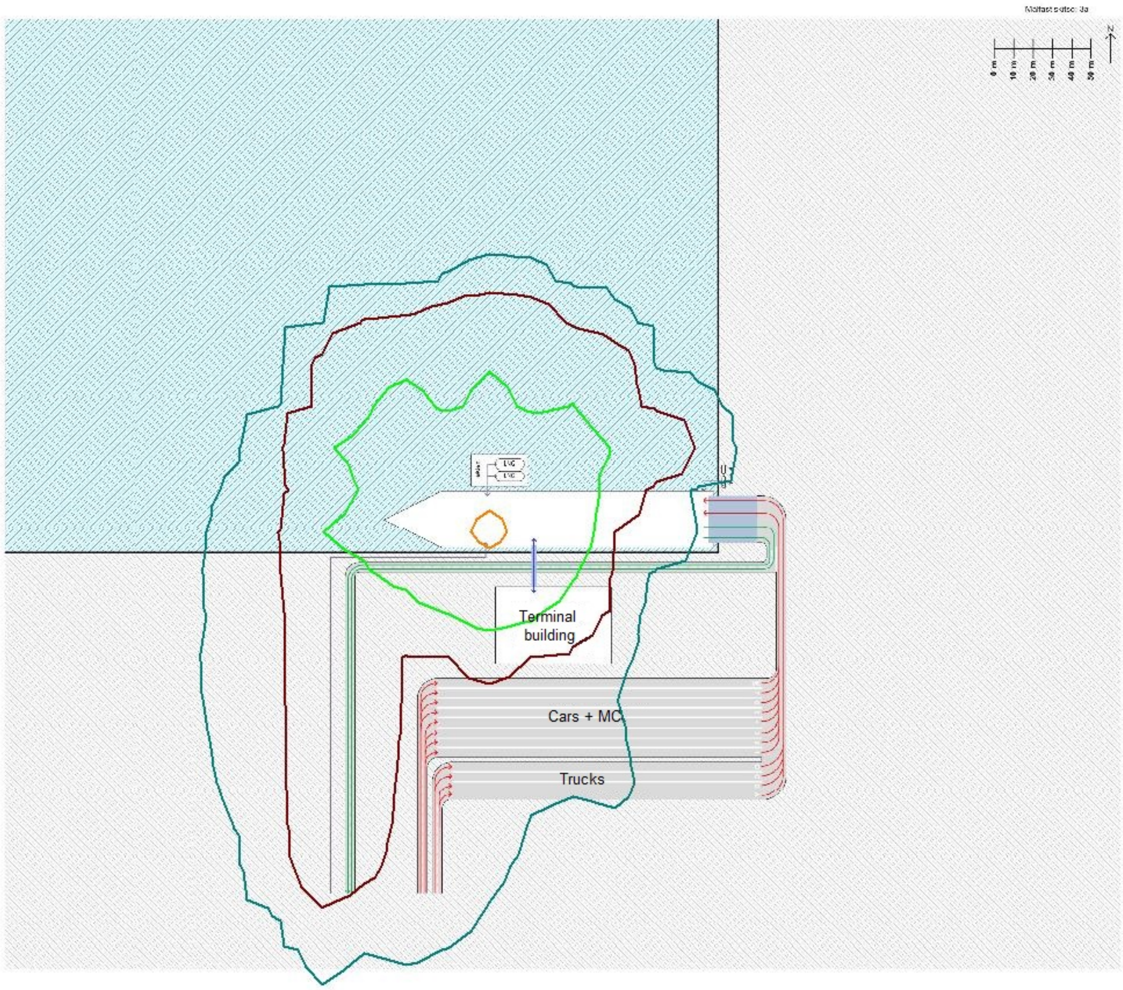
The risk calculations are compared to the same calculation basis (drawing 3 West coast winds) but with an overall ESD response time and closing time of 10/60 seconds (see section 6.1.10).

It is estimated that an optimisation of the ESD function with a maximum overall response time and closing time of 5 seconds gives a significant reduction in the iso curves for 10^{-8} and 10^{-9}, especially on the long fan-shaped clouds over water. The iso curves for 10^{-5} and 10^{-7} are also reduced, but not significantly. The iso curve for 10^{-6} remains unchanged.

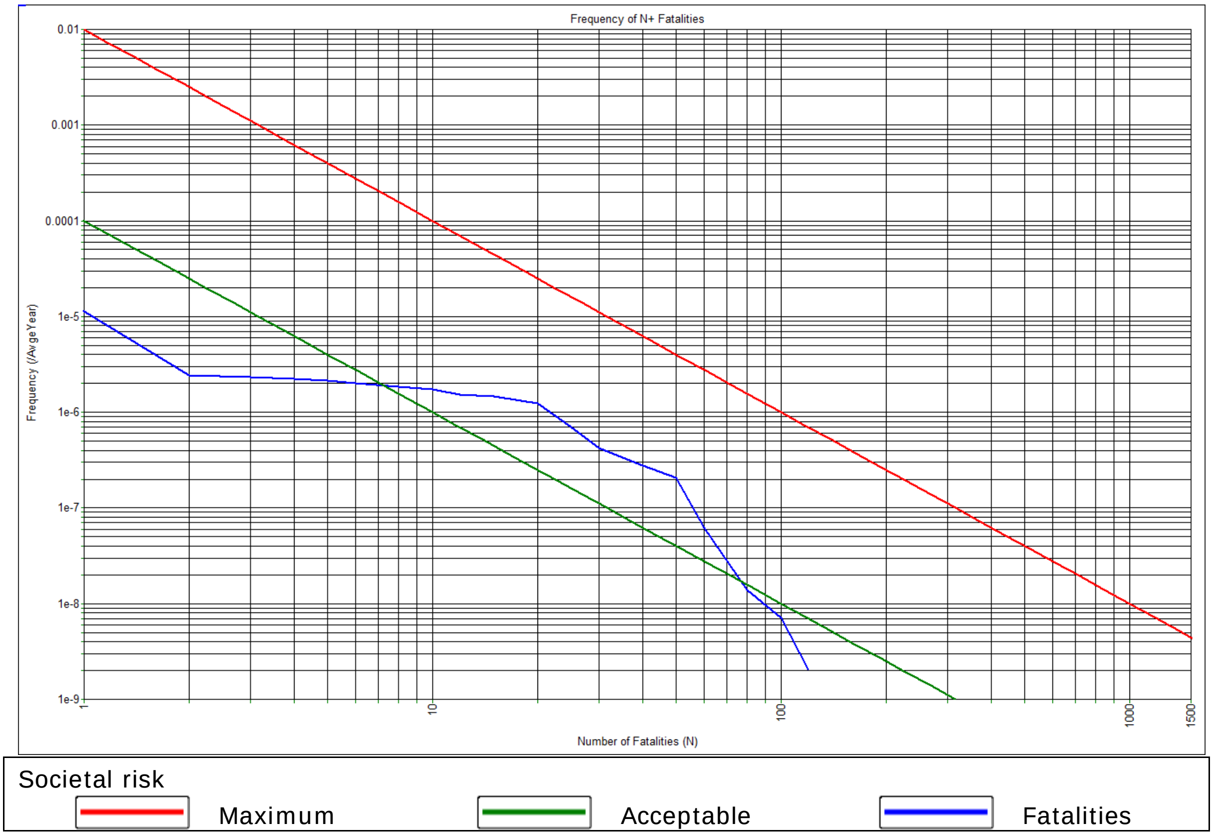
The societal risk of more than 20 fatalities is reduced significantly to the ALARP area (between maximum and acceptable) and the probability of more than 50 fatalities is reduced to about 2 * 10^{-10} and lower. These fatalities are therefore not included in the curve.

Fixed tank, hose crane
Calculation of bunkering from a fixed tank onshore placed outside the risk sensitive area, with piping to a hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

The system ESD is optimised to a maximum overall response time and closing time of 5 seconds.



Local (place-bound) risk			10^{-5} per year		10^{-6} per year
		10^{-7} per year	10^{-8} per year		10^{-9} per year



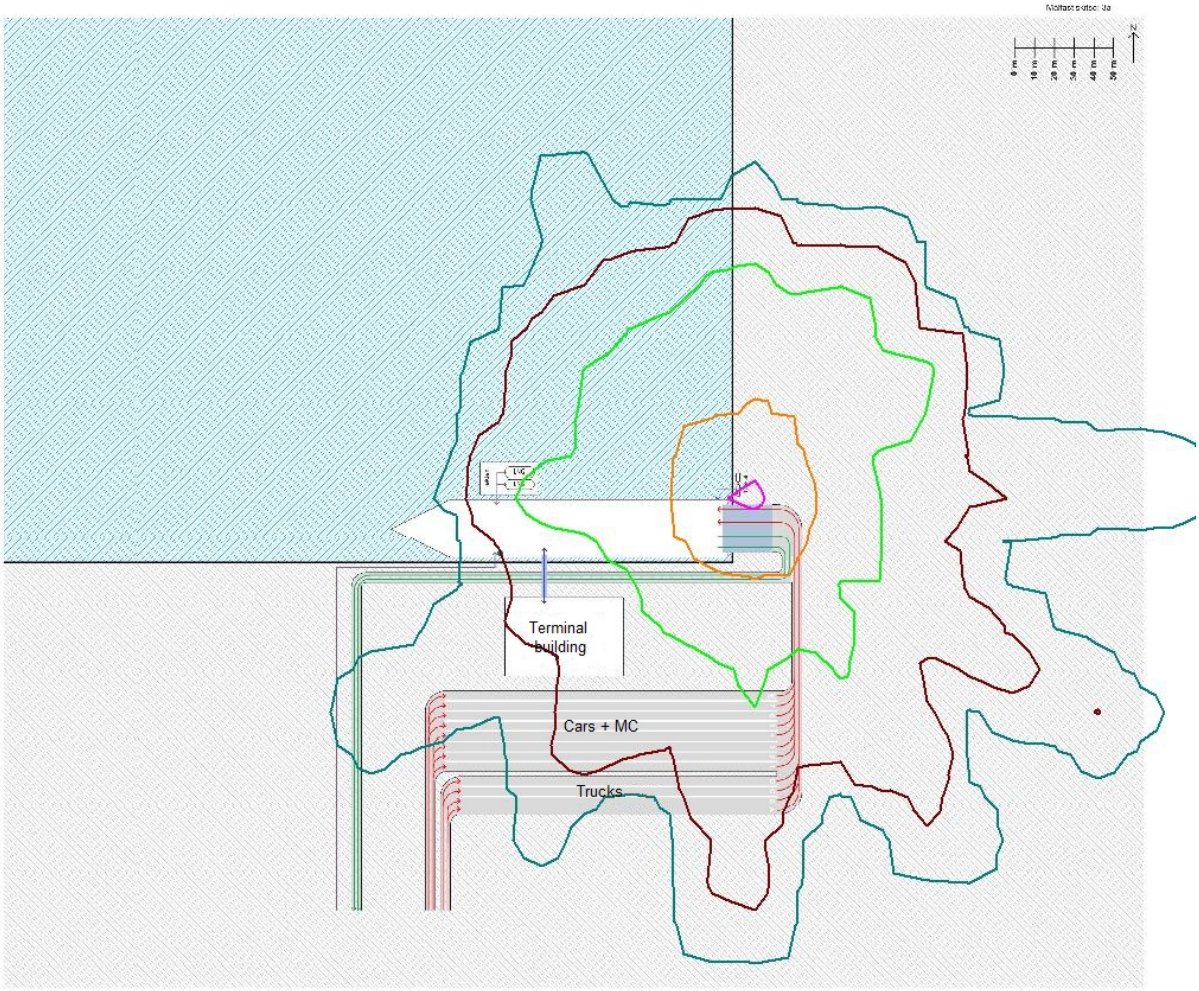
The risk calculations are compared to the same calculation basis (drawing 3 West coast winds) but with an overall ESD response time and closing time of 10/60 seconds (see section 6.1.10).

It is estimated that an optimisation of the ESD function with a maximum overall response time and closing time of 5 seconds gives a reduction in the iso curve for 10^{-9} and a smaller reduction in the iso curve for 10^{-8}. The iso curves for 10^{-5} to 10^{-7} are not significantly reduced. There is practically no change in the societal risks when optimising the ESD function with a fixed tank placed outside the risk sensitive area with piping to the ferry.

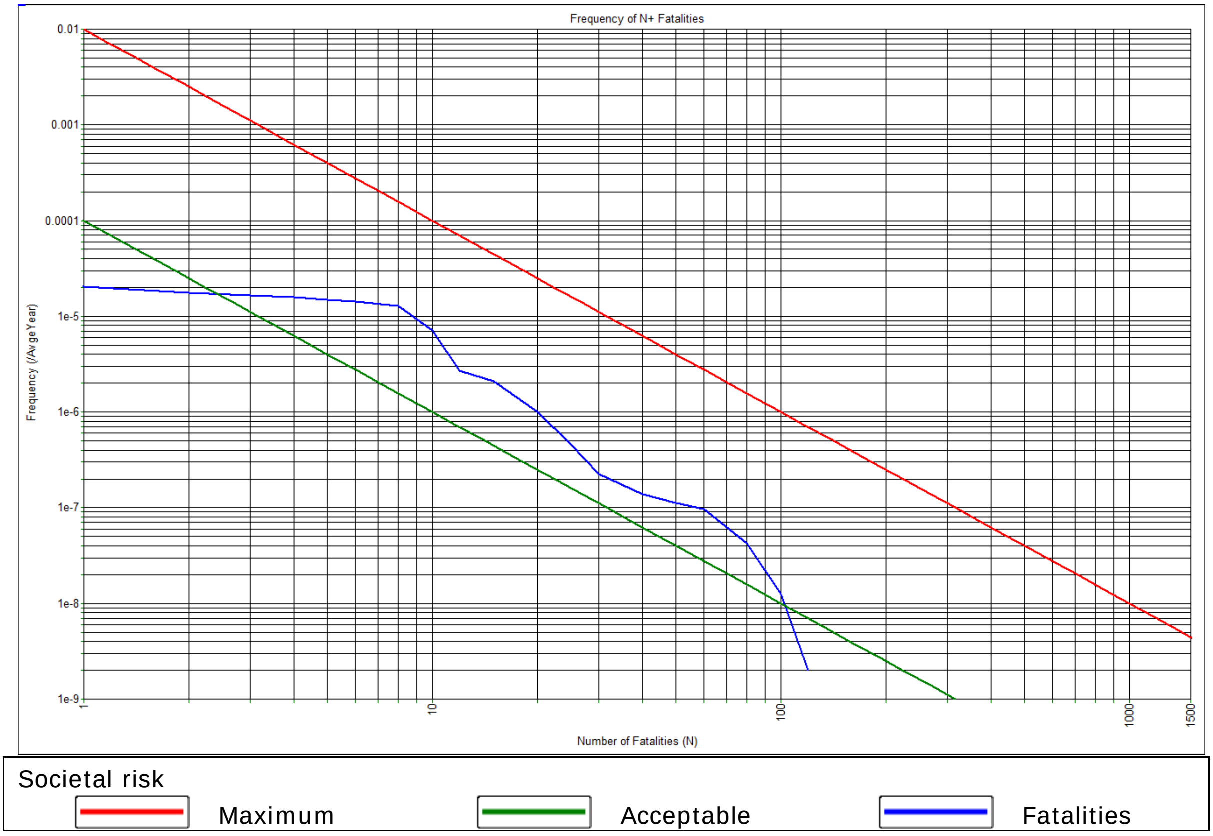
Tank truck, hoses to rig to hose crane

Calculation of bunkering from a tank truck onshore with hoses to a rig and onwards with a hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

The system ESD is optimised to a maximum overall response time and closing time of 5 seconds. The system has been fitted with excess flow valves as close as possible to the tank truck.



Local (place-bound) risk — 10^{-5} per year — 10^{-6} per year — 10^{-7} per year — 10^{-8} per year — 10^{-9} per year



The risk calculations are compared to the same calculation basis (drawing 3, West coast winds, excess flow valves) but with an overall ESD response time and closing time of 10/60 seconds (see section 6.1.11).

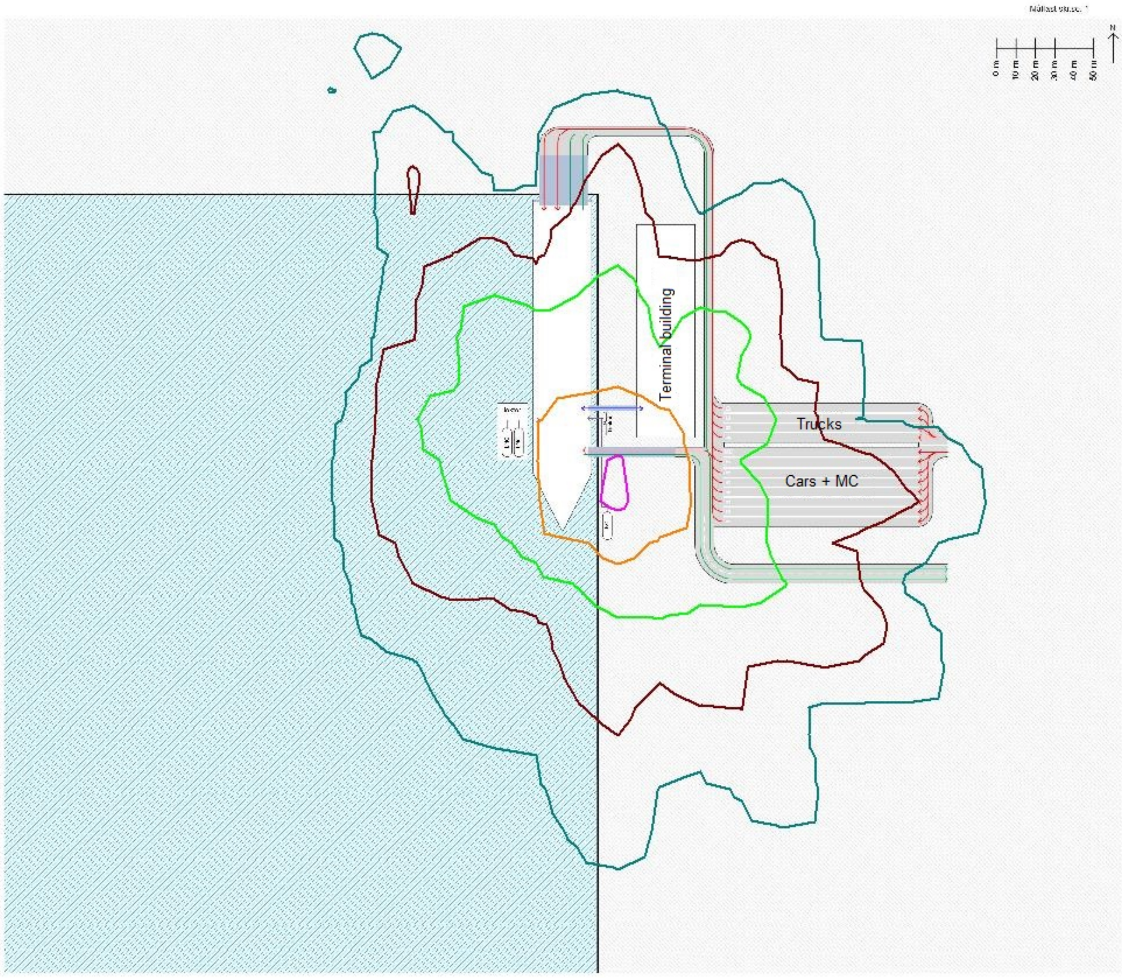
Since excess flow valves are more efficient when it comes to stopping release scenarios, the effect of a time-related optimisation of ESD is hardly visibly. The iso curve for 10^{-5} is significantly reduced, whereas the iso curves for 10^{-6}, 10^{-7} and 10^{-8} remain unchanged and the iso curve for 10^{-9} is insignificantly reduced. The societal risks are insignificantly reduced.

6.1.13 ESD 5 sec - Drawing 1 – West coast winds - Large ferry with cars and passengers

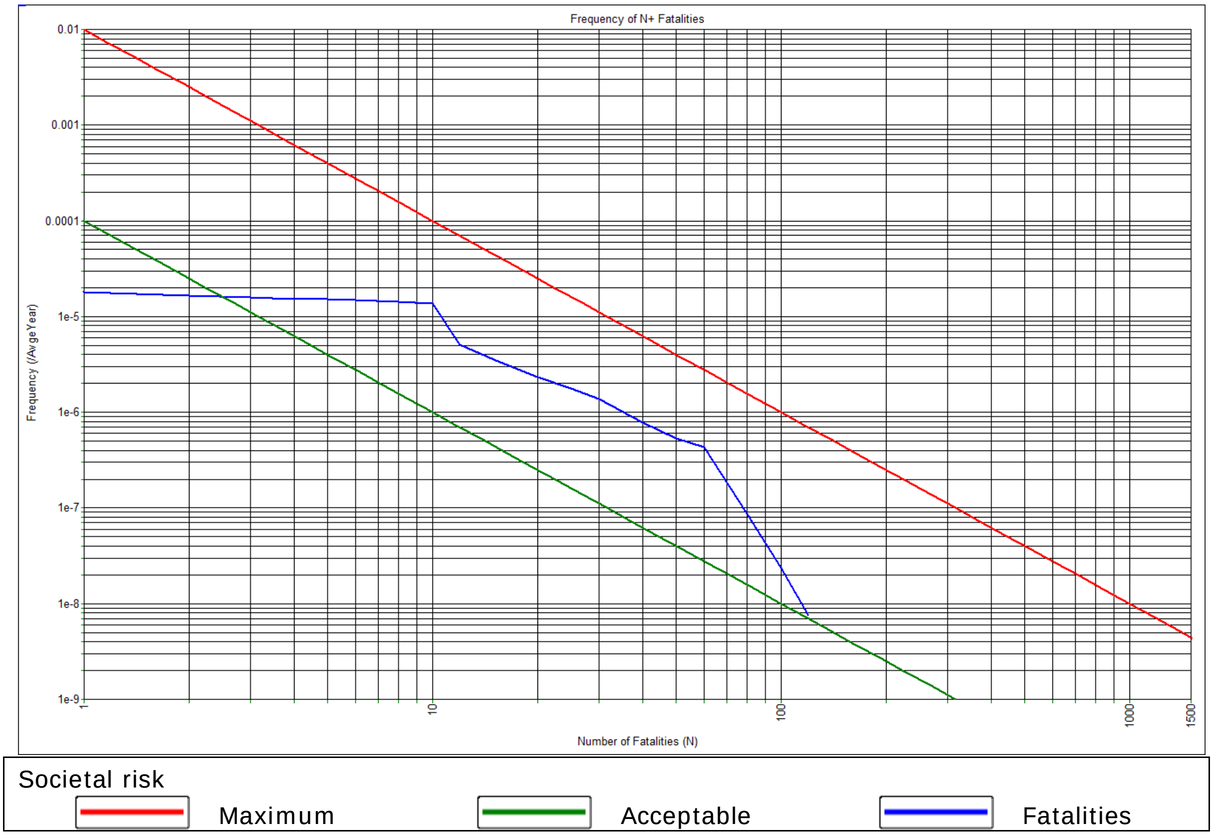
Fixed tank, hose crane

Calculation of bunkering from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 1.

The system ESD is optimised to a maximum overall response time and closing time of 5 seconds.



Local (place-bound) risk		10^{-5} per year		10^{-6} per year
	10^{-7} per year		10^{-8} per year	10^{-9} per year



The risk calculations are compared to the same calculation basis (drawing 1 West coast winds) but with an overall ESD response time and closing time of 10/60 seconds (see section 6.1.1).

It is estimated that an optimisation of the ESD function withs a maximum overall response time and closing time of 5 seconds gives a significant reduction in all the iso curves, especially on the long fan-shaped clouds over water. The societal risk of more than 10 fatalities is reduced significantly to the ALARP area (between maximum and acceptable).

6.2 Discussion of risk results

The basic risk calculations show a small difference in the risks related to the various types of bunkering interfaces. The societal risks when using barge with hose crane are almost identical tos the societal risks when using fixed tank. The societal risks when using tank truck are slightly higher than the societal risks related to the use of fixed tank.

The calculations indicate that it is safer to use crane hoses than loose hoses on barge. There is basically no difference between using hoses, hose cranes or loading arms for installations with a fixed tank, and there is basically no difference between using hoses or hoses to rig to crane hose for installations with tank trucks.

When bunkering ships carrying only passengers and not vehicles, there is no significant change in the societal risks.

Calculations with an open terminal bridge give a considerable aggravation of the risks compared to the calculations with a closed terminal bridge.

Calculations with a wind rose corresponding to the wind conditions on the South coast of Norway do not result in a considerable change in the overall risk scenario compared to the calculations with a wind rose corresponding to the West coast of Norway.

Calculations with a wind rose corresponding to the wind conditions in the Norwegian fjords do not result in a considerable change in the overall risk scenario compared to the calculations with a wind rose corresponding to the West coast of Norway.

The calculation in drawing 2 indicates that the risks are very dependent on the placement of the bunkering interface with regard to terminal bridge and transit area for cars, but not with regard to onshore or offshore, but.

Optimisation of the overall ESD response time and closing time does not have a significant influence on the risks related to bunkering from tank truck when the truck is fitted with excess flow valves. Optimisation has a limited influence on the overall risk scenario for bunkering from barge.

In case of bunkering from fixed tank with piping to the ferry, and where the tank is placed outside the risk-sensitive area, the optimisation does not give a significant risk reduction. On the other hand, in case of bunkering from fixed tank where the tank is placed near the ferry, the optimisation gives a significant risk reduction.

Therefore, the type of equipment used for bunkering (tank on barge, fixed tank or tank truck) is not of main importance, but the ESD response time is essential (the time from release to closing of ESD valves). The key aspect is the distance from the equipment to the areas where there are people, along with the number of people found in these areas.

The number of people within iso risk curves
From the accept criteria for societal risks, the following can be derived:
If people are considered to be located 100% outdoors, it will be possible to place up to 100 people on (or outside) the curve with a local (place-bound) risk of 10^{-6} per year, in order to meet the maximum criteria (the red line), as well as up to 10 people on (or outside) the curve with a risk of 10^{-6} per year, in order to meet the minimum criteria (the green line). Correspondingly, if people are 25% outdoors, it will be possible to place up to 4 times as many people, and if people are 20% outdoors, it will be possible to place up to 5 times as many people.

In Table 6-2 the maximum number of people at 10^{-6} per year, 10^{-7} per year and 10^{-8} per year are shown when considered 100%, 25% and 20% outdoors.

Curve (risk per year)	Outdoor percentage (%)	Maximum criteria (number of people)	Minimum criteria (number of people)
10^{-6}	100	100	10
10^{-6}	25	400	40
10^{-6}	20	500	50
10^{-7}	100	316	32
10^{-7}	25	1265	126
10^{-7}	20	1581	158
10^{-8}	100	1000	100
10^{-8}	25	4000	400
10^{-8}	20	5000	500

Table 6-2 The number of people on or outside the curves for maximum (red) and minimum (green) accept criteria for the FN curves.

For example, if 100 people (100% outdoors) are placed on the curve with a local (place-bound) risk of 10^{-6} per year, then there could be 216 people (100% outdoors) on the curve with a local (place-bound) risk of 10^{-7} per year in order to meet the maximum criteria (red curve). Correspondingly, 784 people (100% outdoors) could be on the curve with a risk of 10^{-8} per year.

Weaknesses in the model calculations

PHAST cannot model the wind influence between barge and ship for scenarios involving a barge. This means that the risks are overestimated if the barge is located on the opposite side from the areas where people are present. On the other hand, there could be higher risks at the end point of the ship, as the LNG will be forced in that direction when hitting the ship. This effect has been modelled, but as there are a great number of conditions in the calculations, the effect can only be used as an indication of the tendency connected with bunkering from barge.

PHAST cannot model that an ignition in a confined area, e.g. between ship and terminal building, can cause a pressure build-up (an explosion instead of a flash fire). PHAST can only model that an explosion could occur in arbitrary places (based on a fixed percentage). Impact studies have however been carried out for confined explosions, see section 4.3.7

When considering areas close to an incident, PHAST is generally not precise.

7. LOCAL (PLACE-BOUND) AND SOCIETAL RISKS WITH CFD SIMULATIONS

7.1 General assumptions

Several CFD simulations have been carried out to illustrate the consequences and risks for drawing 3. For the consequence analysis, the commercial CFD code Ansys CFX v. 14 was used. Pipe ruptures from 4 different layouts were examined; from tank truck (A), from barge (B), from fixed shore installation on quay (C) and from piping on quay (D). The layouts are shown in Figure 7-1.

For each layout 8 wind directions and 3 different wind speeds of 1m/s, 4m/s and 9m/s, respectively, were examined. For some release points, releases in several directions were examined. Depending on the position and direction of the release, a certain amount of the LNG will leak into the water. For releases directly into water and releases along quays it is assumed that 100% and 50%, respectively, of the LNG will leak into the water. Onshore, it is assumed that 14% of the LNG release will flash, and offshore a complete vaporisation of the LNG will occur. In order to enable a complete vaporisation of the LNG, the LNG must come into contact with water. However, since the reaction between water and LNG is not modelled, it has been assumed that there is enough water to achieve 100% vaporisation of the LNG.

A scenario where the ESD system works, giving a release duration of 5 seconds, was examined for all layouts. Releases until empty tank, if the ESD system fails, were also examined for selected scenarios. For these scenarios volumes of 50 m^2 for the tank truck and 250 m^2 for fixed tank on quay and on barge were applied. Wind speed of 9 m/s was not examined for the releases of long duration, higher wind speed is less conservative due to the more extensive mixing of the LNG with air due to higher turbulence. The duration, direction and mass flow can be seen in table 6-1.

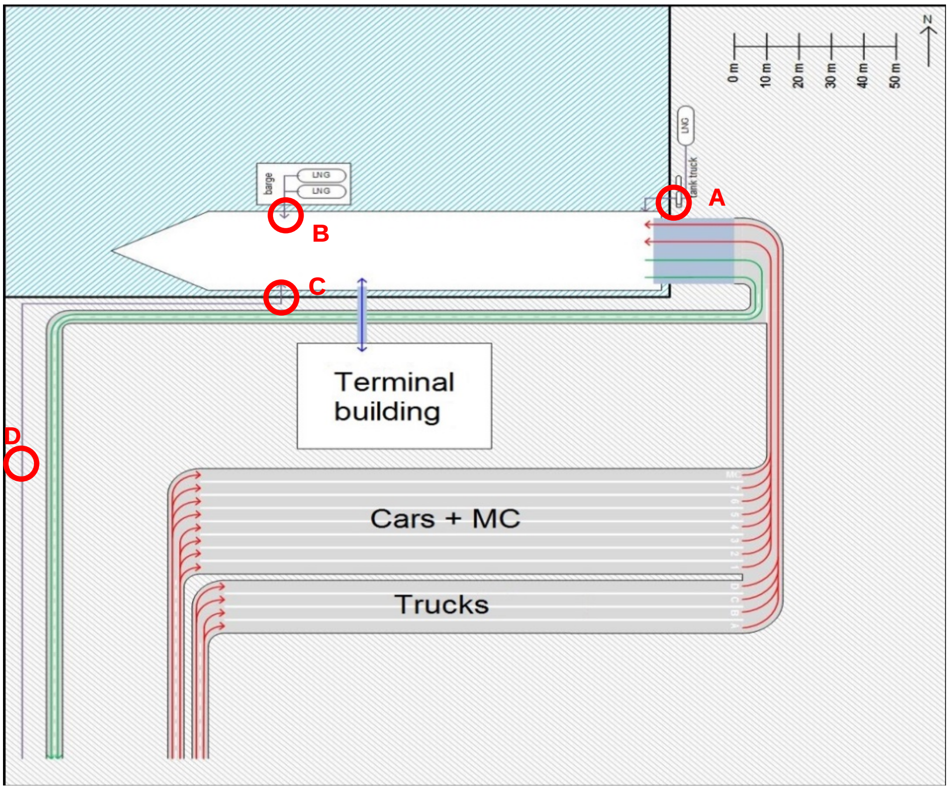


Figure 7-1: Drawing 3 – Shows the modelled harbour area with placement and orientation of ship, terminal building and vehicle holding lanes.

Position	Release direction	Gas mass flow, land [kg/s]	Gas mass flow, water [kg/s]	Release duration [s]
A Tank truck	West	6.76	42	5
B Barge	South, Up	5.24	32	5
C Fixed tank	North, East, Up	5.24	32, 16, 16	5,5,5
D Road	North	5.24	0	5

Table 7-1: Scenarios with release duration of 5 seconds examined in the CFD simulations.

Position	Release direction	Gas mass flow, land [kg/s]	Gas mass flow, water [kg/s]	Release duration [s]
A Tank truck	West	6.76	42	436
B Barge	South	5.24	32	2812
C Fixed tank	North	5.24	32	2812

Table 7-2: Scenarios with release duration until empty tank examined in the CFD simulations.

The place-bound risks are calculated for the release layouts A, B, C and D. The risks of release from the layouts C and D can be merged since these releases occur from the same part of piping. The overall risk includes the probability of bunkering, the probability of release, the probability of the ESD system working, wind statistics and the probability of ignition of the LNG for each release layout. When assessing the results, the terms Lower Explosion Limit (LEL), corresponding to a volume concentration of LNG of 4.4%, and half Lower Explosion Limit (½LEL), corresponding to 2.2%, are used. For the calculation of the place-bound risk, the overall probability in the area where there is an LNG volume concentration corresponding to or above ½LEL is multiplied.

Since the area covered by an LNG concentration of ½LEL varies with time, the probability of ignition of the LNG will also vary with time. Therefore, the final maps of iso risk curves summarises the place-bound risks for selected time intervals (after the release has commenced).

7.2 Impact studies

In order to illustrate the potential dispersion of LNG, a few consequence plots of ½LEL concentrations are shown for selected scenarios. Figure 7-2 shows release A from the tank truck to the west 50 seconds after the release has commenced, for northerly and southerly winds, respectively. Figure 7-3 shows release C from the quay to the north 50 seconds after the release has commenced, for northerly and southerly winds, respectively. Figure 7-4 shows a release C of long duration from the quay to the north, 2 minutes and 10 minutes after the start of the release.

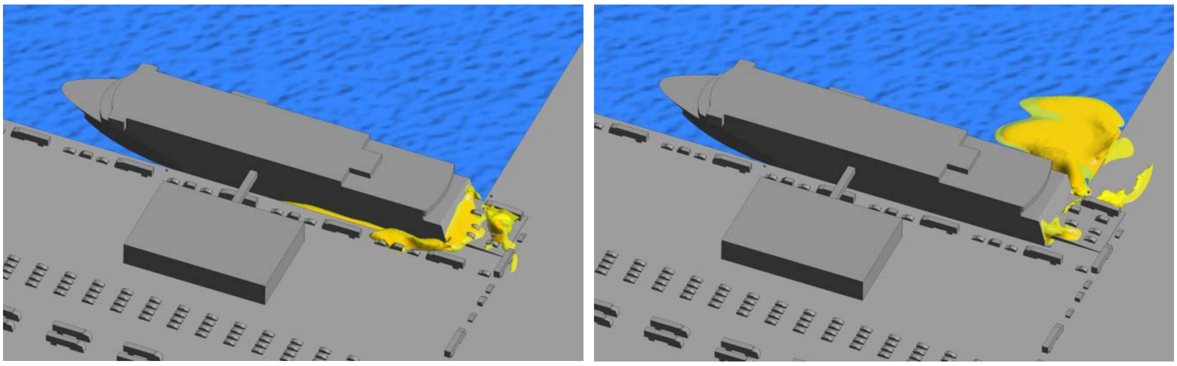


Figure 7-2: Release A of 5 second duration from tank truck 50 seconds after the release has commenced. ½LEL concentration of LNG for northerly (left) and southerly (right) winds.

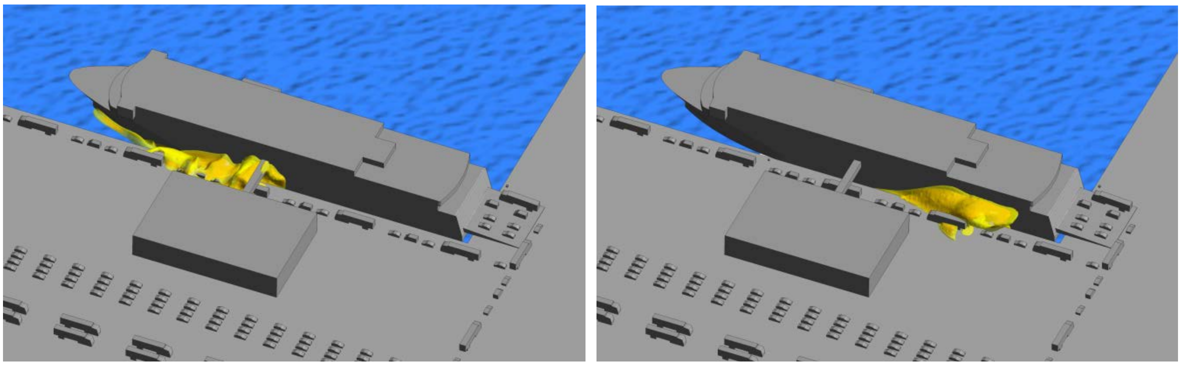


Figure 7-3: Release C of 5 second duration from quay 50 seconds after the release has commenced. ½LEL concentration of LNG for northerly (left) and southerly (right) winds.

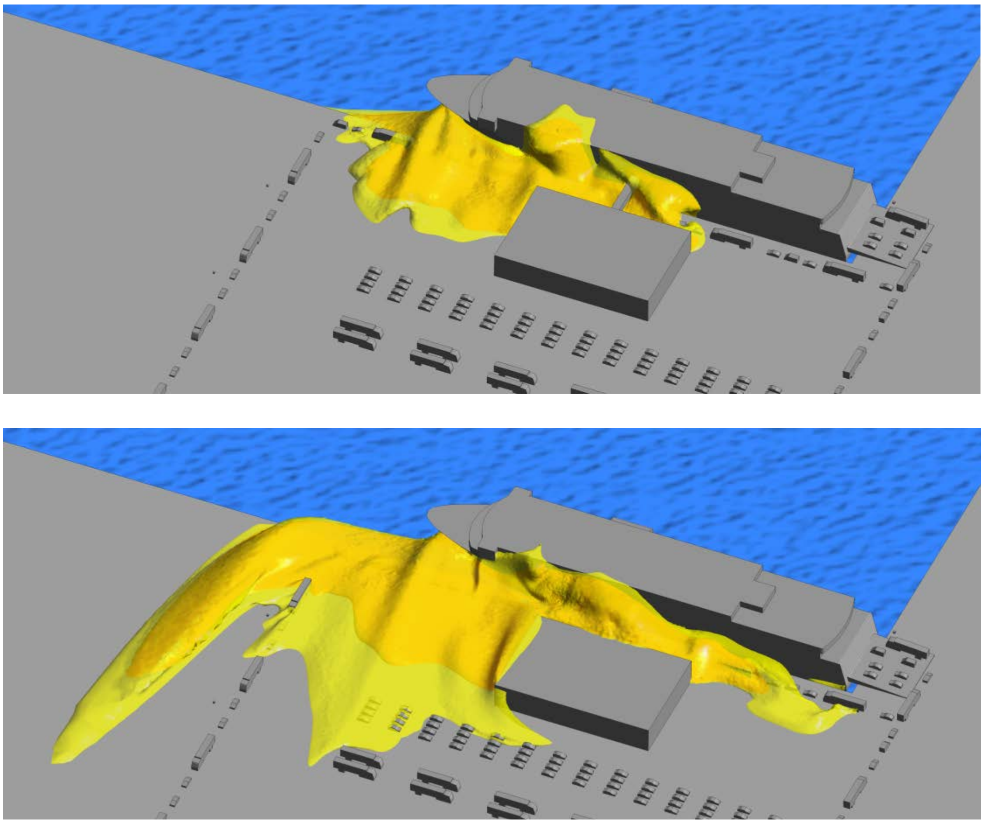


Figure 7-4: Release C of long duration from the quay to the north 2 min (top) and 10 min (bottom) after the release has commenced. ½LEL concentration of LNG for northerly winds.

7.3 Risk results

The local (place-bound) risks and societal risks, which are calculated based on the CFD simulations, are indicated in this section. These calculations have been carried out for a facility without gas return and fitted with break-away valves, for a large ferry transporting both cars and passengers and exposed to a wind-rose corresponding to the West coast of Norway.

All calculations are indicated by a map of iso risk curves and an FN curve for drawing 3.

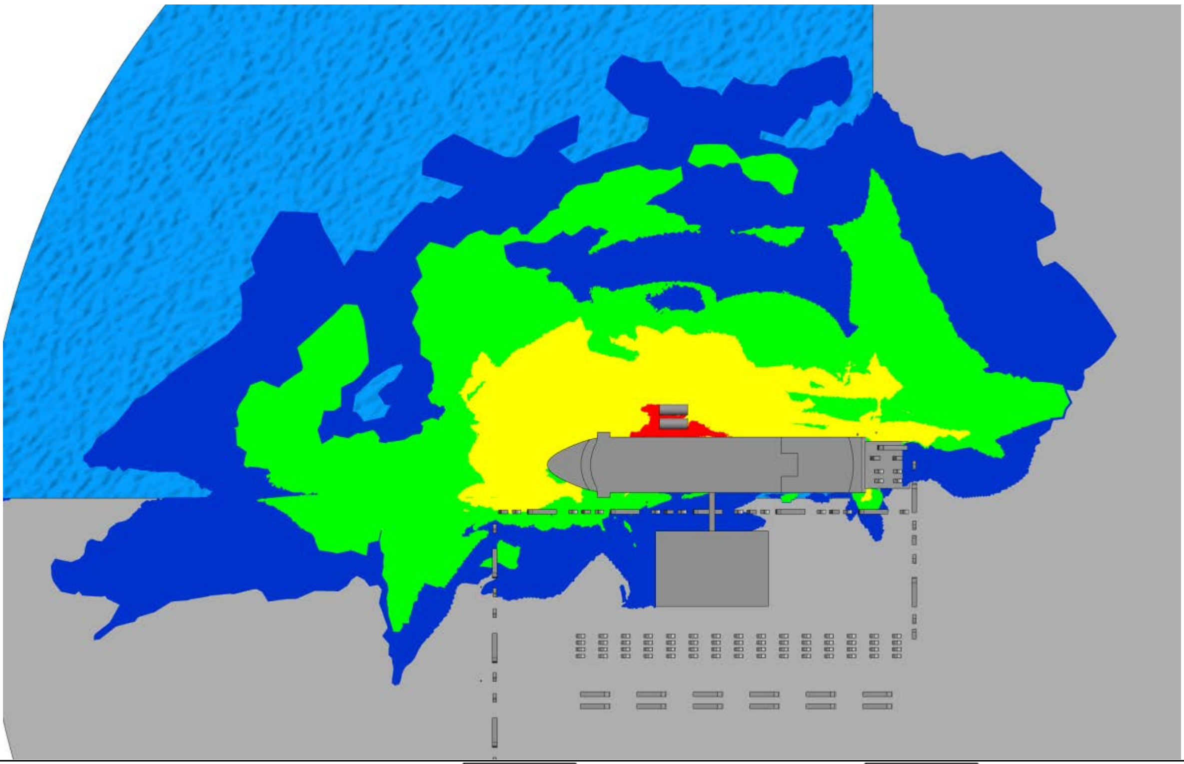
7.3.1 CFD - ESD 5 sec - Drawing 3 – West coast winds - Large ferry with cars and passengers

Barge, hose crane

CFD simulation of bunkering from barge with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

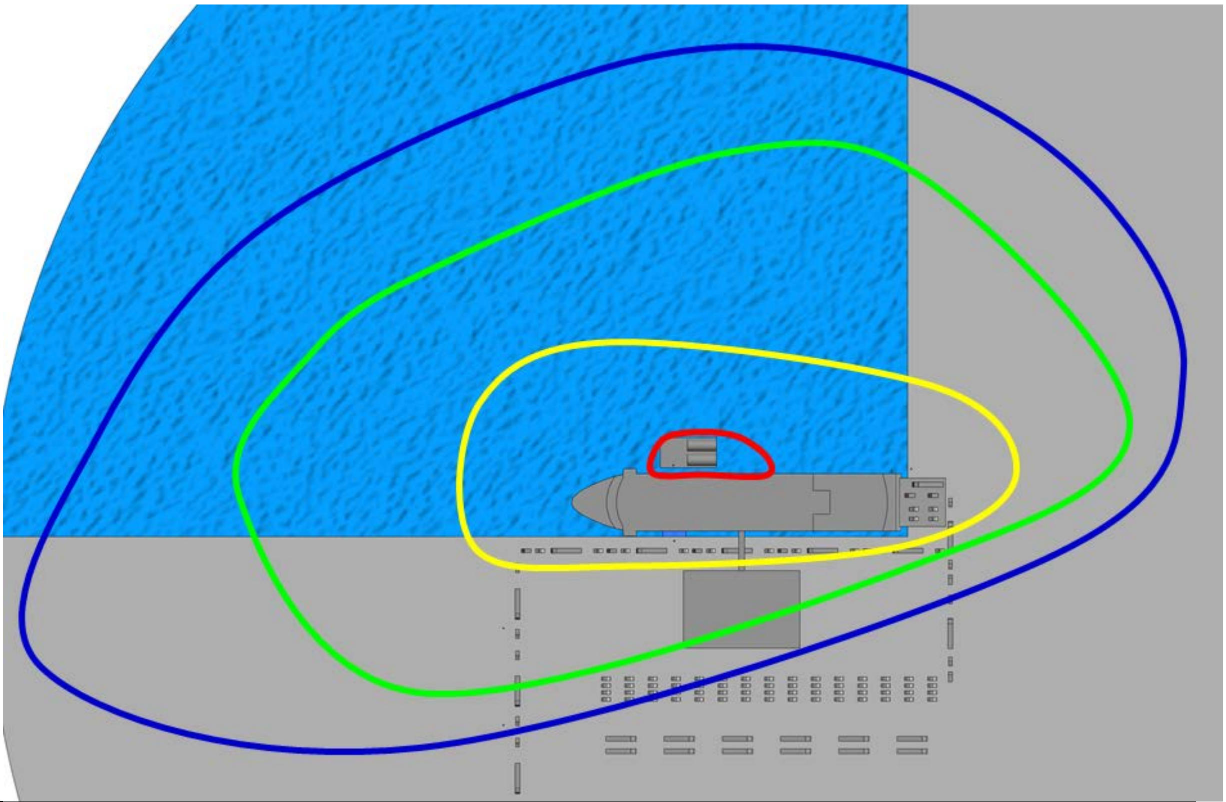
The system ESD is optimised to a maximum overall response time and closing time of 5 seconds.

The calculated place-bound risks are indicated below:

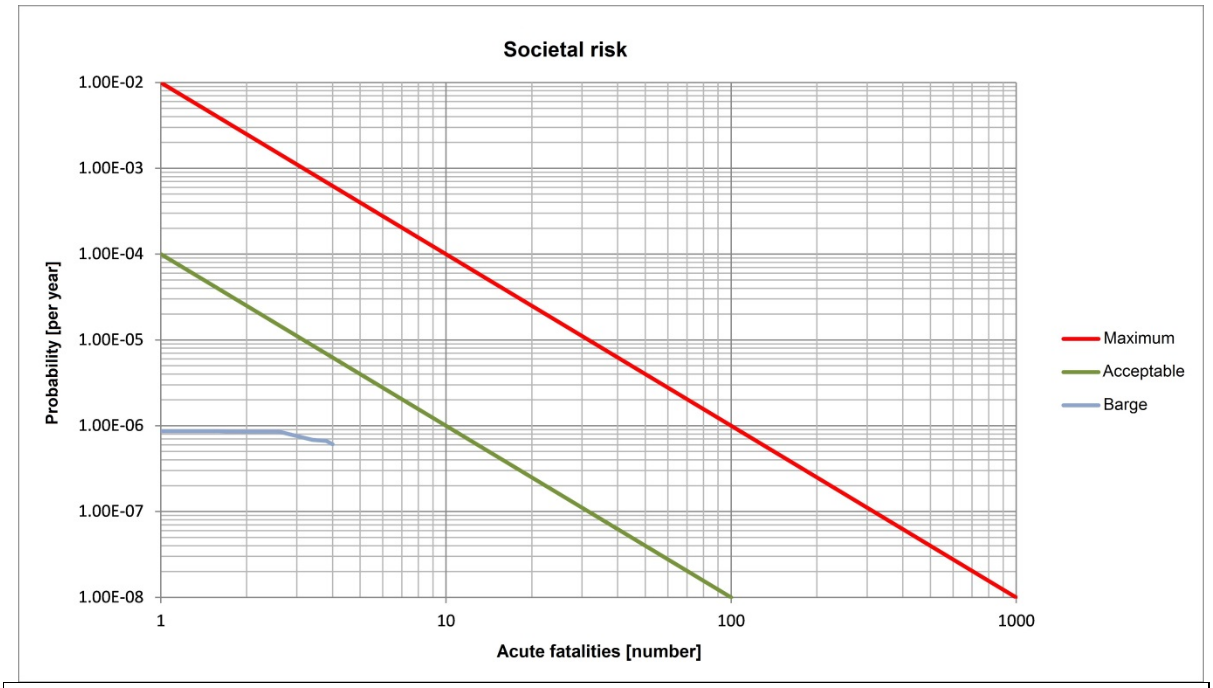


Local (place-bound) risk		10^{-6} per year		10^{-7} per year
		10^{-8} per year		10^{-9} per year

From the calculated place-bound risks, visually corrected iso risk curves have been plotted in the figure, since the calculations are only carried out for 8 wind directions in CFD:



Local (place-bound) risk	(red line)	10^{-6} per year	(yellow line)	10^{-7} per year
	(green line)	10^{-8} per year	(blue line)	10^{-9} per year



Societal risk	(red line)	Maximum	(green line)	Acceptable	(light blue line)	Fatalities

The CFD simulation illustrates that the ship acts as a dike in relation to the shore-side, where the LNG is retained and mixed, resulting in a reduction of the area of impact. The quay front has thus an effect on the dispersion of the gas, but not to the same extent as the ship. The location of the barge along the ship can also influence to which extent the gas is drawn into leeward in the shore-side area of the ship.

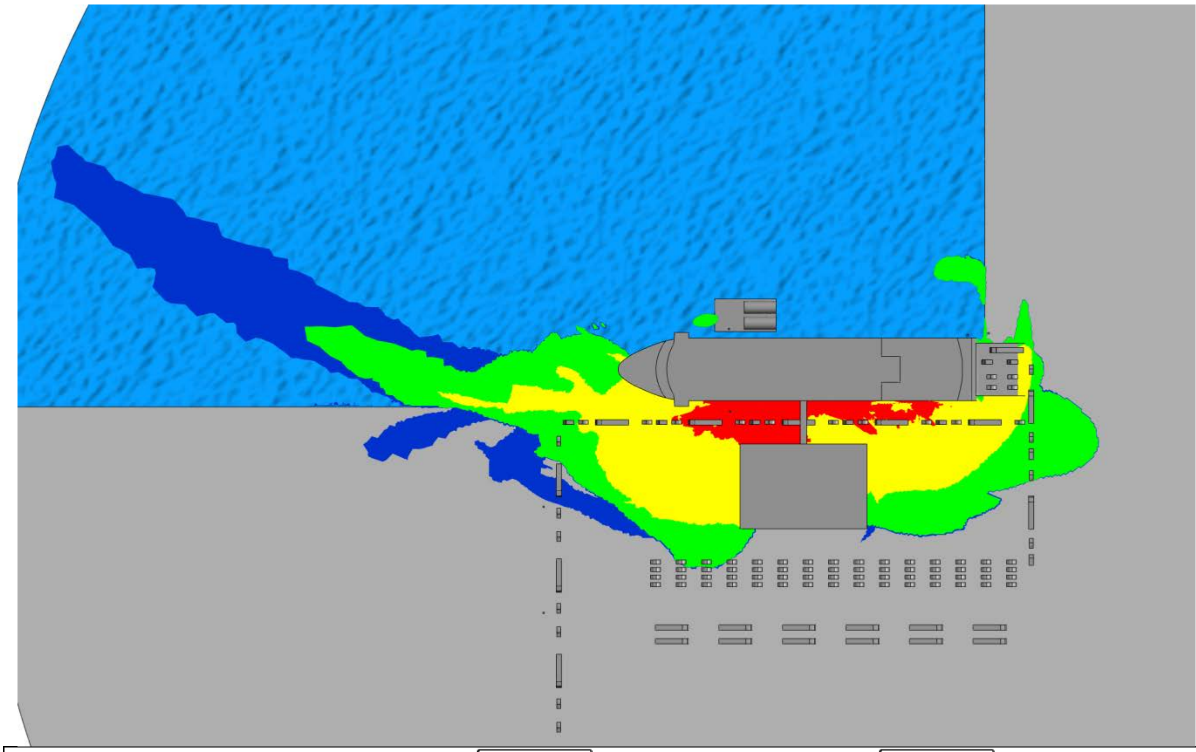
The societal risks indicate up to 4 fatalities, corresponding to the 4 people on the barge. No further people are immediately affected (they are either placed safely inside vehicles in transit, on the gangway, in the terminal building or on the ship deck above the release).

Fixed tank, hose crane
CFD simulation of bunkering from a fixed tank onshore with hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

The system ESD is optimised to a maximum overall response time and closing time of 5 seconds.

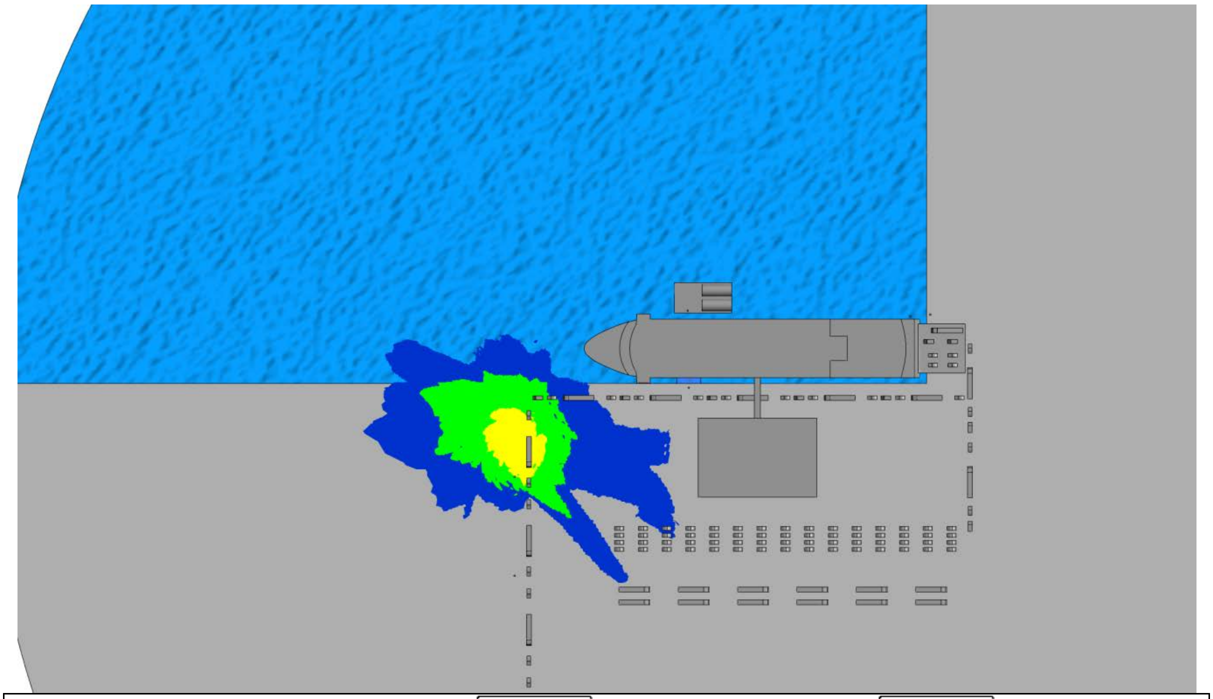
The piping between the fixed tank and the bunkering interface is included in the map of iso risk curves below.

The calculated place-bound risks are indicated below:



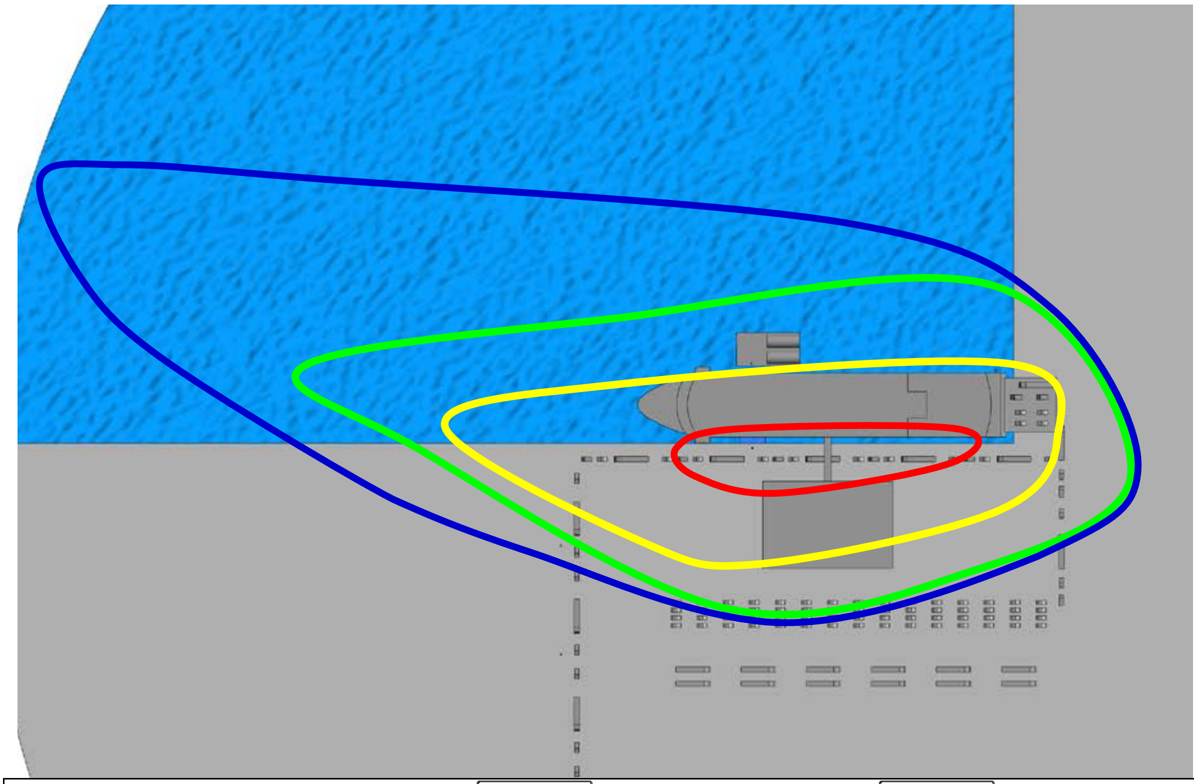
Local (place-bound) risk	Red	10^{-6} per year	Yellow	10^{-7} per year
	Green	10^{-8} per year	Blue	10^{-9} per year

The calculated place-bound risks for the piping between the fixed tank and the bunkering interface are indicated below (calculated for a point with a probability of 10 m piping):



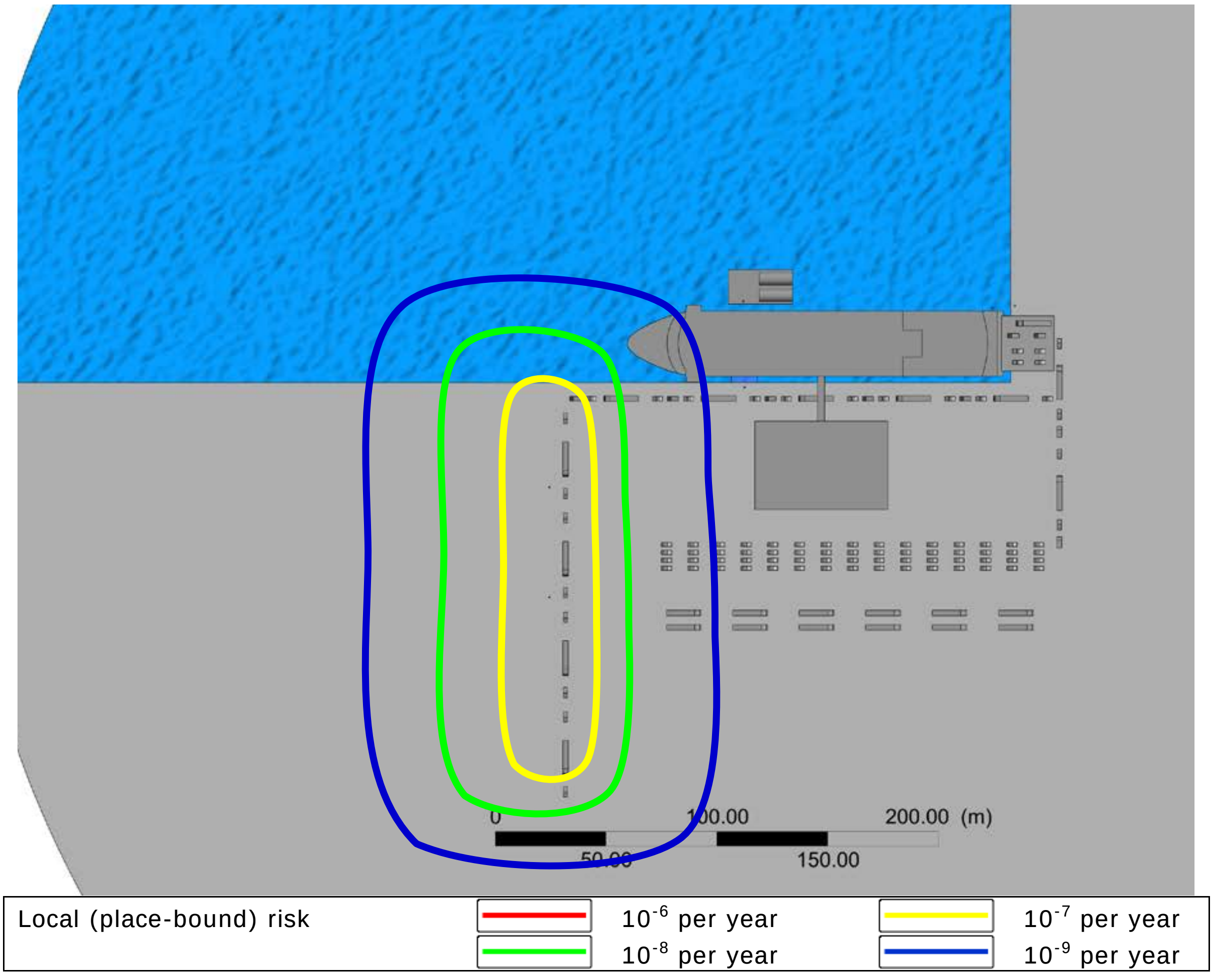
Local (place-bound) risk	red	10^{-6} per year	yellow	10^{-7} per year
	green	10^{-8} per year	blue	10^{-9} per year

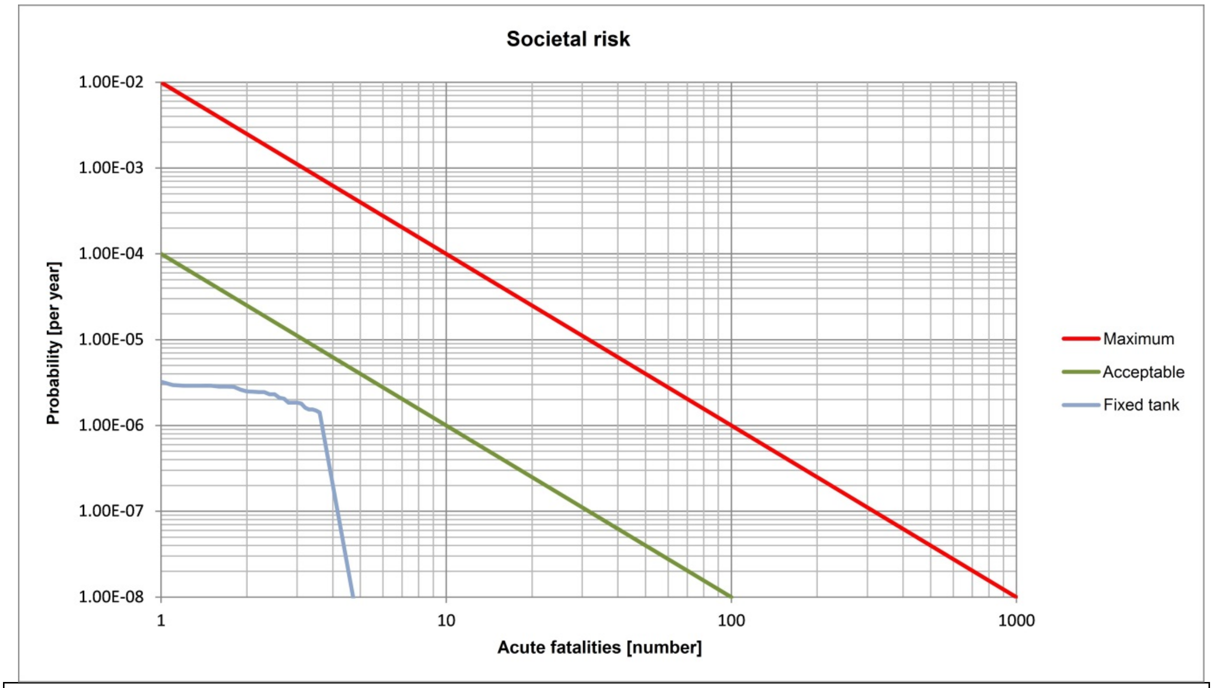
From the calculated place-bound risks for the bunkering interface, visually corrected iso risk curves have been plotted in the figure, since the calculations are only carried out for 8 wind directions in CFD:



Local (place-bound) risk	red line	10^{-6} per year	yellow line	10^{-7} per year
	green line	10^{-8} per year	blue line	10^{-9} per year

From the calculated place-bound risks for the piping along the road, visually corrected iso risk curves have been plotted in the figure, since the calculations are only carried out for 8 wind directions in CFD:





Societal risk

Maximum Acceptable Fatalities

The CFD simulation illustrates that the ship acts as a dike and keeps the releases primarily on the shore-side. The release is drawn along the ship due to the channelling effect created by the void between the ship and the quay. The terminal building provides considerable shelter for the area behind the building. The risks for the bunkering interface are dominated by a risk contribution corresponding to 90 m of piping. If this contribution was removed, a risk of 10^{-6} per year would not occur.

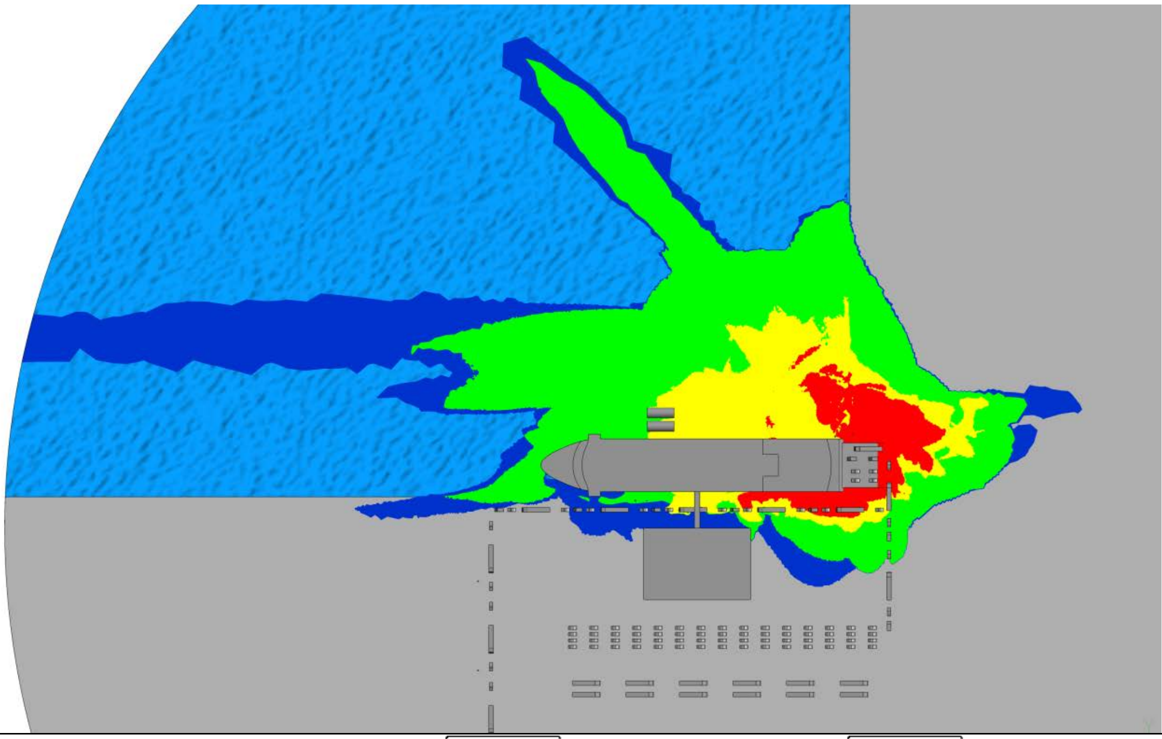
The societal risks indicate up to 5 fatalities, corresponding to the 4 people in the bunkering interface as well as one single fatality in the vehicle holding lanes. The 3D plot of the release in Figure 7-4 shows that in the event of large releases (failure of the ESD), there could be potential fatalities on board the ferry (outside and due to vapour, if any, drawn into the ship). These fatalities have not been included in the societal risks since they have been calculated for 1.5 m above the quay.

Tank truck, hoses to rig to hose crane

CFD simulation of bunkering from a tank truck onshore with hoses to a rig and onwards with a hose crane to a large ferry with cars and passengers in an area with West coast wind conditions in drawing 3.

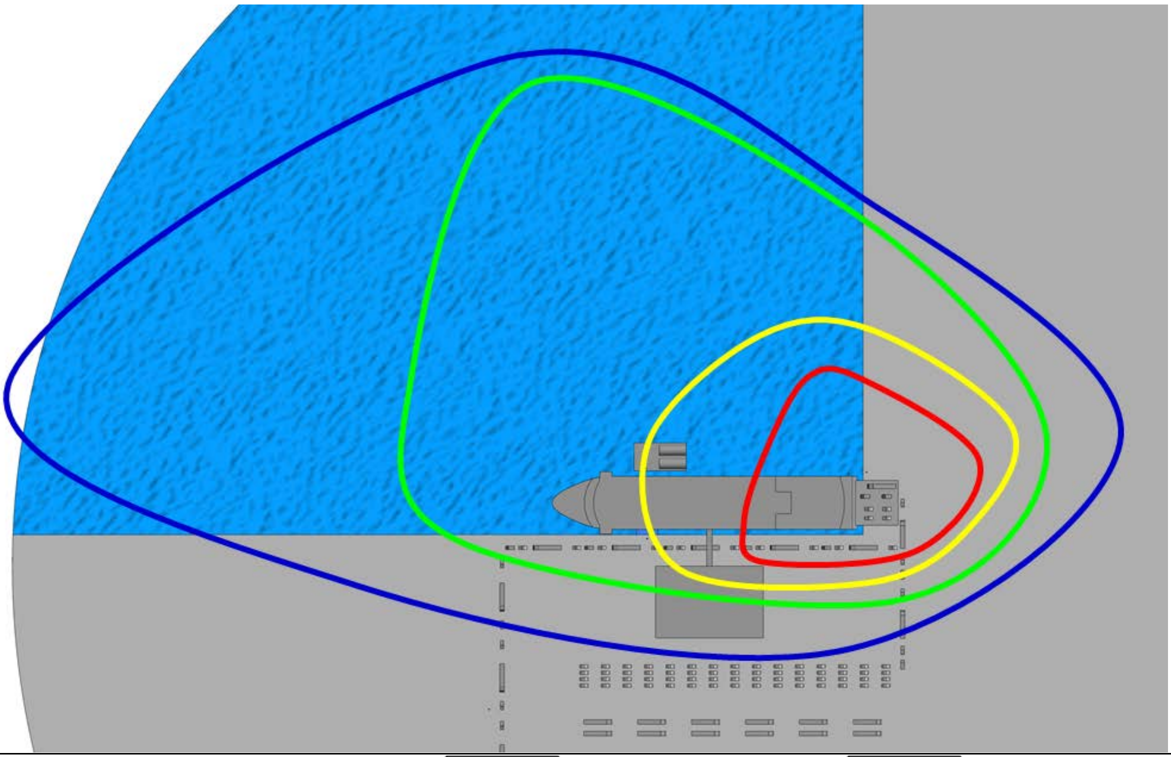
The system ESD is optimised to a maximum overall response time and closing time of 5 seconds.

The calculated place-bound risks are indicated below:

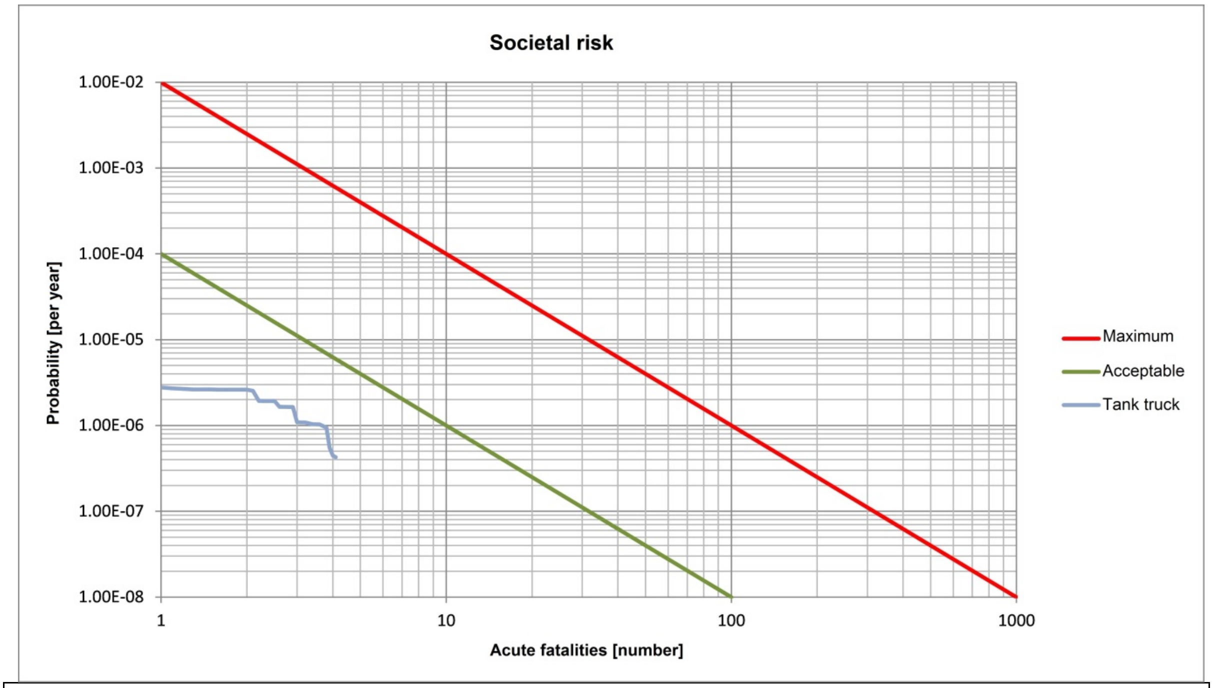


Local (place-bound) risk	red	10^{-6} per year	yellow	10^{-7} per year
	green	10^{-8} per year	blue	10^{-9} per year

From the calculated place-bound risk, visually corrected iso risk curves have been plotted in the figure, since the calculations are only carried out for 8 wind directions in CFD:



Local (place-bound) risk — red: 10^{-6} per year; yellow: 10^{-7} per year; green: 10^{-8} per year; blue: 10^{-9} per year



Societal risk — red: Maximum; green: Acceptable; light blue: Fatalities

The CFD simulation illustrates that the ship acts as dike the same way as the canal between the ship and quay. The location of the release in relation to the ship causes the gases to be drawn around the ship both on the water-side and the shore-side.

The societal risks indicate up to 4 fatalities, corresponding to the 4 people on the barge. No further people are immediately affected (they are either placed safely inside vehicles in transit, on the gangway, in the terminal building or on the ship deck above the release).

7.4 Discussion of risk results

The CFD simulations illustrate that the wind field around the ship is critical for the dispersion of the gas, and thus for the consequences of releases. The ship's size and the height difference between shore and water is of a great significance for retention and dilution of the LNG, both in sheltered areas and in horizontal and vertical whirlwinds.

The quality of the ESD, in the form of reliability and response time, is decisive for the risk, particularly for the major releases (rupture), but to a lesser extent for leakages.

The location of possible ignition sources is decisive for the consequences, as an early ignition of the gas cloud gives a more limited scenario than a delayed ignition. This can be compared to the Buncefield fire, where a delayed ignition caused a flash fire with an explosion pressure resulting in considerable damage over a large area (it has not been possible to demonstrate the Buncefield explosion with the modelling tool, including CFD simulation).

The underlying ignition model indicates that a reduction in the ignition sources will lead to a change in the risk profile. Minor incidents (such as leakages and ruptures where ESD is activated) are assumed to lead to a lower risk, because a larger percentage of non-ignited releases will take place. Major incidents (ruptures where ESD fails) are assumed to lead to a higher risk, since the consequences will be more significant but have the same probability. A reduction in the ignition sources is overall assumed to lead to a smaller place-bound risk zone for 10^{-6} per year, and larger place-bound risk zones for 10^{-8} and 10^{-9} per year.

If the flash fire scenarios are replaced by explosion scenarios, the societal risks will increase significantly, because fatalities of people in transit in cars and on the terminal bridge (up to 100 people) could be expected.

8. DISCUSSION REGARDING THE DIFFERENCES BETWEEN PHAST RISK AND CFD SIMULATIONS

When directly comparing the CFD simulations and the PHAST Risk simulations (section 7.3.1 compared to section 6.1.12), it is seen that the CFD simulations do not result in iso curves of 10^{-5} per year, and that the shape of the iso curves is generally more similar to the shape of the ship compared to PHAST Risk, where the iso curves tend to be rounded (or star shaped due to the segmentation into 12 wind directions).

For the scenario describing bunkering from barge, the calculated risks onshore are lower in the CFD simulations compared to calculations in PHAST Risk. The iso risk curve for 10^{-6} per year is also reduced in size. The iso risk curves for 10^{-7} to 10^{-9} per year cover about the same area, but have different shapes.

For the scenario describing bunkering from fixed tank, the iso curve for 10^{-6} per year is larger in the CFD simulations compared to the PHAST Risk calculations, but not if the contribution from pipe releases is removed. Long pipelines are difficult to simulate with CFD because of the long calculation time and the large amount of generated data that needs to be processed. The contribution from pipe releases are therefore not plotted 100% correctly in the CFD simulations. The iso curves for 10^{-7} to 10^{-9} per year also cover a larger area, but with different shapes compared to the PHAST Risk calculations. (In the place-bound risk calculations for CFD the full length of the piping between the fixed tank and the bunkering interface has not been included, but if included, the CFD simulations would also have a southbound finger of the same size as indicated in the PHAST Risk calculations.)

For scenario describing bunkering from tank truck, the iso curves cover about the same area, but the majority of the risks are located onshore with PHAST Risk and offshore with the CFD simulations. The assumption of the number of exposed people on the ferry leads to the primary difference between the PHAST Risk calculations and the CFD simulations. A test without exposed people on the ferry for bunkering from tank truck resulted in up to 5 fatalities. The CFD simulations indicate that releases without ESD and with wind against the ship could result in LNG gas in deck height, where people on the ship could be exposed. The probability of this is around 2-3 x 10^{-7} per year.

The primary reason why the calculated risks in PHAST Risk are not significantly higher than the risks calculated with CFD simulations, is that PHAST Risk does not include all released LNG. In PHAST Risk only between 30% and 60% of the LNG is released as gas, whereas between 70% and 100% of the LNG is released as gas in the CFD simulations, which implies that PHAST Risk does not model entire releases, and does not take rapid phase transition into account in the model. Since PHAST Risk is a black box model, it is often not possible to avoid these intermediate models.

The comparison between the CFD model and PHAST Risk also indicates that near-field effects, such as sheltering surfaces and horizontal and vertical whirlwinds, cannot be calculated in PHAST Risk. These effects have a crucial significance for the mixing of LNG gas and for the dispersion prior to ignition.

The calculated risks with PHAST Risk and CFD simulations also differ, as PHAST cannot include contours in the vicinity of the release, the CFD simulations include a risk reduction of conditions outside the LNG facility as well as an identification of unfortunate contours, providing a more realistic risk scenario. Generally, PHAST Risk can only specify risks associated with an LNG facility on a generic level, whereas CFD simulations can place risks at site.

9. REFERENCES

Ref.	
/1/	Comparative study on gas dispersion, Scandpower, Report nr. 101368/R1, 24 January 2012
/2/	Offshore ignition probability arguments, Report number: HSL/2005/50, Health and Safety Laboratory, 2005
/3/	Hazardous Materials Release and Accident Frequencies for Process Plant, J.R. Taylor/Taylor Associates ApS, 2006
/4/	LNG ship to ship bunkering procedure, Swedish Marine Technology Forum
/5/	Buncefield Major Incident Investigation Board, The final report of the Major Incident Investigation Board, December 2008
/6/	*Human Vulnerability to Thermal Radiation Offshore*, Report number: HSL/2004/04, Health & Safety Laboratory, 2004
/7/	*Risk Analysis for Process Plant, Pipelines and Transport*, J.R. Taylor, E&FN Spoon, 1994
/8/	J.R.Taylor: *QRA Pro Manual*, Version 7, 2006

APPENDIX 1

PHAST PARAMETERS

Standard parameters and assumptions

Many of the standard parameters in PHAST have not been changed for these calculations. Below is an overview of the parameters found necessary to change/consider.

Model level:

Pipe length in the event of pipe rupture	10 m
Material roughness for pipes	Standard value: 0.0457 mm (Commercial steel or wrought iron)

Discharge:

The model was set up without pressure drop from valves or pipe elbows and manifolds.

Dispersion:

Surface where dispersion occurs	Land Water

Explosions:

Explosions are modelled as corresponding TNT.

Explosion efficiency	10%
Air or ground burst	Air burst
Overpressure table	Standard values: 0.02068 bar (Occasional breaking of large glass windows already under strain) 0.1379 bar (Partial collapse of walls and roofs of houses; Concrete or cinder block walls, not reinforced, shattered) 0.2068 bar (Steel frame building distorted and pulled away from foundations; vessels overturned)

General parameters:

Height of concentrated output	0 m
Maximum release time	3,600 sec

Weather parameters:

Atmospheric temperature	9.85°C
Relative air humidity	70%
Insolation	0.5 kW/m^2
Surface temperature for dispersion calculations	9.85°C
Surface temperature for pool calculations	9.85°C
Wind speed profile (correction of wind speed for low heights)	• Height of wind speed reference: 10 m • Method of correction: Exponential • Lowest height for correction: 1 m

Terrain:

Surface roughness (Surface roughness in the risk calculations is adjusted by the wind-rose parameters)	Land: "High crops; Scattered large obstacles": • Surface Roughness Length = 25 cm • Surface Roughness Parameter = 0.108 Water: "Open water": • Surface Roughness Length = 0.2 mm • Surface Roughness Parameter = 0.037

Wind conditions

PHAST uses Pasquill-Gifford's classification for vertical updrafts and turbulence in the atmosphere:

Wind speed measured at 10 m above the earth's surface [m/s]	Day Solar insolation			Nighttime *	
	Strong	**Moderate**	**Slight**	**Thin overcast or > ½ low clouds**	**< 3/8 cloudiness**
< 2	A	A-B	B	F	F
2 - 3	A-B	B	C	E	F
3 - 5	B	B-C	C	D	E
5 - 6	C	C-D	D	D	D
> 6	C	D	D	D	D

* Night is defined as the period from 1 hour before sunset to 1 hour after sunrise.

The different stability classes, as they are defined in PHAST, are specified below:

Stability class	Description	
A	Extremely unstable	Sunny, light winds
A/B	Unstable	Same as A, but less sunny or stronger winds
B	Unstable	Same as A/B, but less sunny or stronger winds
B/C	Moderately unstable	Moderately sunny and moderately windy
C	Moderately unstable	Strong winds/sun or cloudy/light winds
C/D	Moderately unstable	Moderately sunny and strong winds
D	Neutral	Some sun and strong winds or cloudy/windy night
E	Moderately stable	Less cloudy and less windy night than D
F	Stable	Night with moderate cloudiness and light/moderate wind
G	Extremely stable	Possibility of fog

For low wind speeds and stable atmospheric conditions the limited turbulence will result in the gas cloud from a release remaining more concentrated and therefore dangerous over longer distances, compared to stronger wind forces or more unstable atmospheric conditions.

Based on this, the following preliminary list of wind and stability classes in the calculations has been developed. Relevant stability classes are indicated with D for day and N for night. Selected stability classes are marked with a grey background:

Interval [m/s]	Used in the calculations [m/s]	Stability class								
		A	A/B	B	B/C	C	C/D	D	E	F
0.5 - 2	1.5	D	D	D						N
2 - 4	3		D	D	D	D		N	N	N
4 - 7	5.5					D	D	D/N	N	
7 - 10	8.5					D		D/N		
10 - 16	13					D		D/N		
> 16	16							D/N		

Calm conditions, defined as < 0.5 m/s, are not included in the calculations, as the calculation models are not valid for such low wind speeds, and because local turbulence is decisive for the migration of the gas cloud.

Pipe/hose rupture scenarios have been calculated for each wind combination. The calculations indicate (as expected) that the most stable class results in the largest range of impact and covers the largest area of impact, measured as LFL and ½LFL, with a few exceptions.

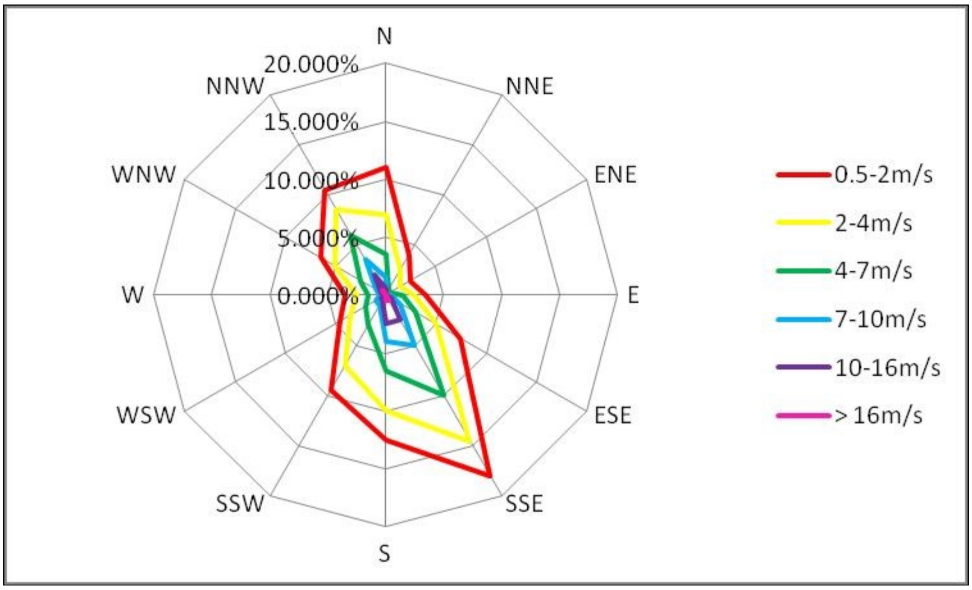
For the wind speeds from 0,5 m/s to 7 m/s the approximate average stability class has been selected in order to counteract the calculations becoming too conservative, as well as to counteract the few scenarios where the order is reversed (unstable class has the largest impact). For wind speeds higher than 7 m/s the most stable class has been selected.

In order to find representative wind-roses for the calculations, wind-roses for 16 harbours (or areas near harbours) in Norway were reviewed and analysed. It was found that 3 wind-roses will be representative for most of the harbours in Norway:

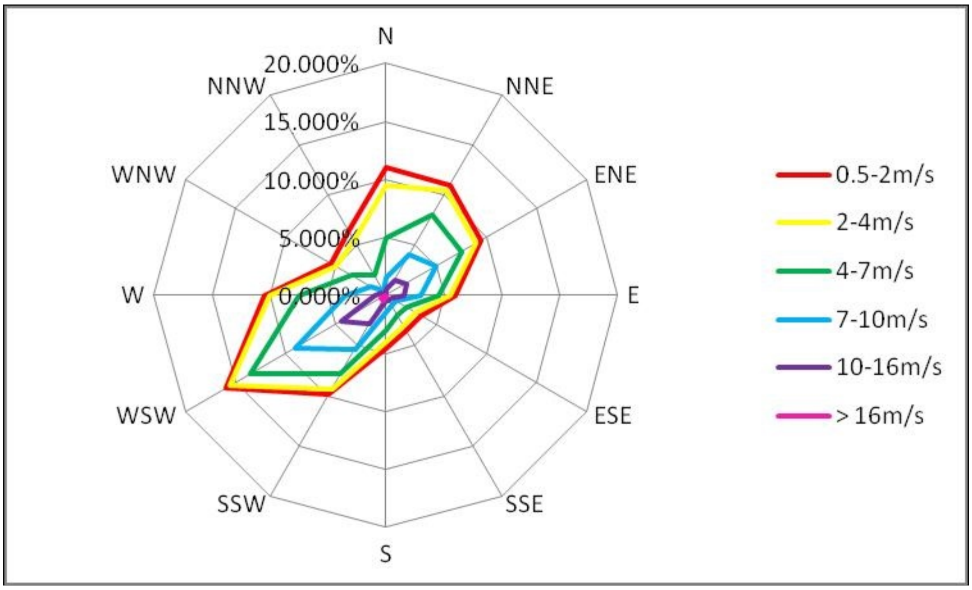
- wind-rose for harbours on the West coast
- wind-rose for harbours on the South(-East) coast
- wind-rose for harbours in fjords

The 3 wind-roses for the calculations have been developed by performing an average of wind-roses that exist for the various harbour locations.

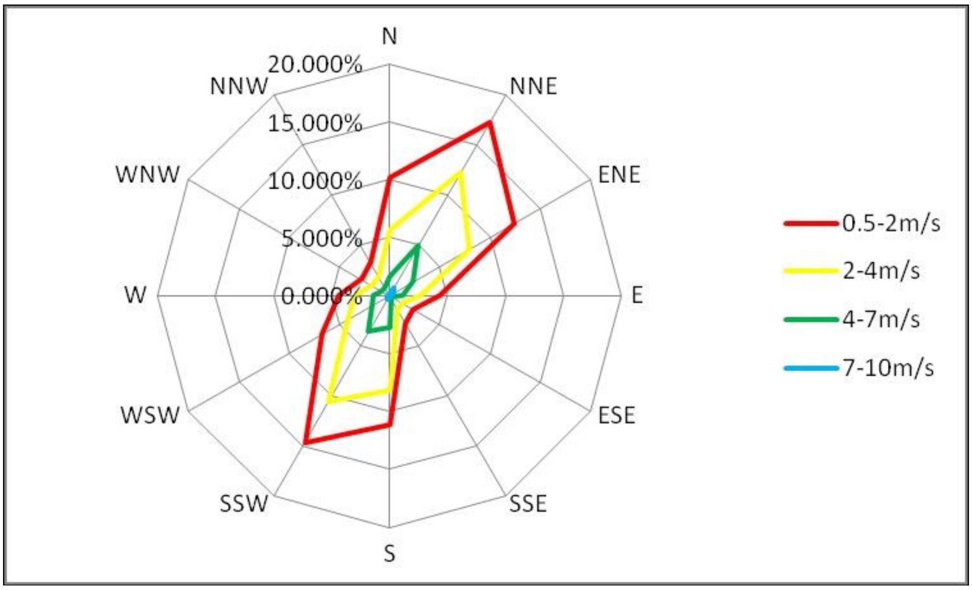
Wind-rose for the harbours on the West coast:



Wind-rose for the harbours on the South coast:



Wind-rose for the harbours in the fjords:



It is evident from the wind-rose figures that there will be a tendency towards northerly winds on the West coast, whereas there will be a tendency towards easterly wind on the South coast. In the fjords there will also be northerly winds, but high wind speeds (10-16 m/s and above 16 m/s) will not occur.

APPENDIX 2

EVENT TREES IN PHAST

A set up in PHAST Risk enables the use of event trees for indication of the probability of different scenarios. 6 different event trees have been used, which are determined by the scenario parameters:

Description	**Event Tree Probabilities tab in PHAST**
Continuous releases of short duration (≤ 20 sec) without rainout	Cont./No Rainout – Immediate ignition
Continuous releases of non-short duration (> 20 sec) without rainout	Cont./No Rainout – Delayed ignition of cloud
Continuous releases of short duration (≤ 20 sec) with rainout	Cont./Rainout – Immediate ignition
Continuous releases of non-short duration (> 20 sec) with rainout	Cont./Rainout – Delayed ignition of cloud
Instantaneous release without rainout	Inst./No Rainout
Instantaneous release with rainout	Inst./ Rainout

Without rainout means that a given release consists of a gas phase only.

With rainout means that a given release consists of a liquid phase (and perhaps a gas phase), along with a gas fan from evaporation from the formed liquid pool.

The set limit between releases of short duration and non-short duration – 20 sec – is a parameter value in PHAST. It was decided not to change this parameter.

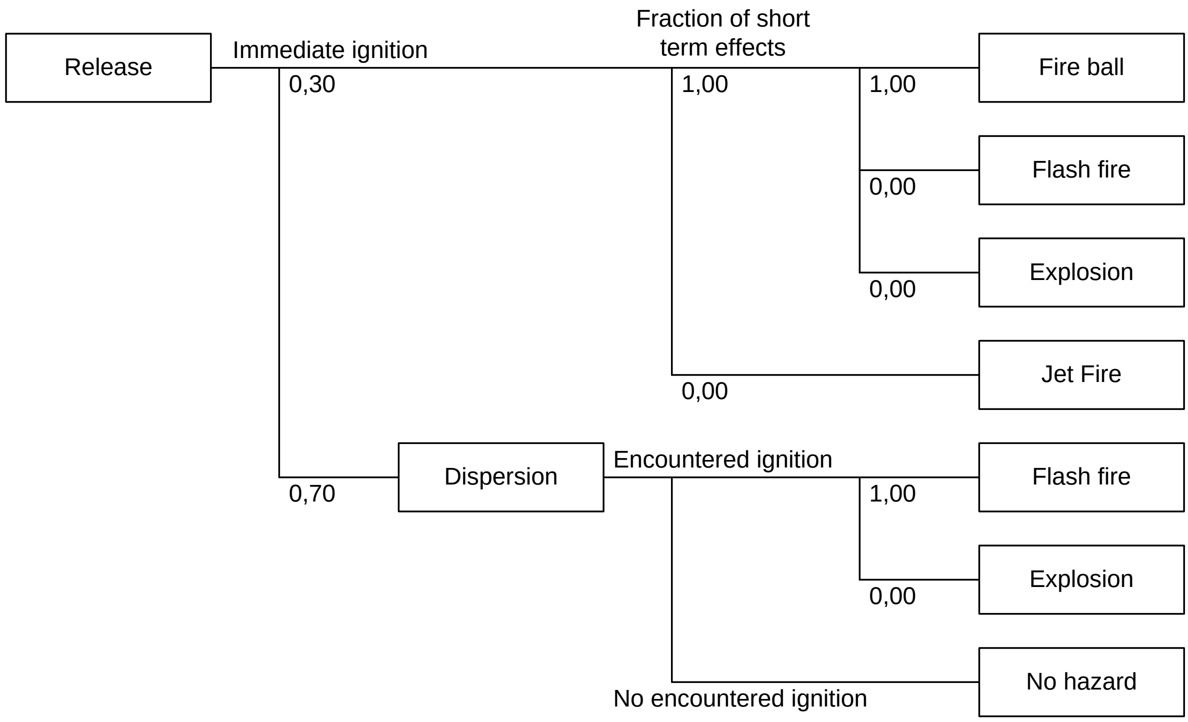
Cont./No Rainout

This type of releases may occur in the event of pipe ruptures or leakages, as well as tank leakages, with release of the actual gas phase of the tank contents.

Immediate ignition

This event tree is used for determining the probability of different scenarios for releases of short duration, e.g. if a pipe fracture valve or if ESD ends the scenario before it has time to develop.

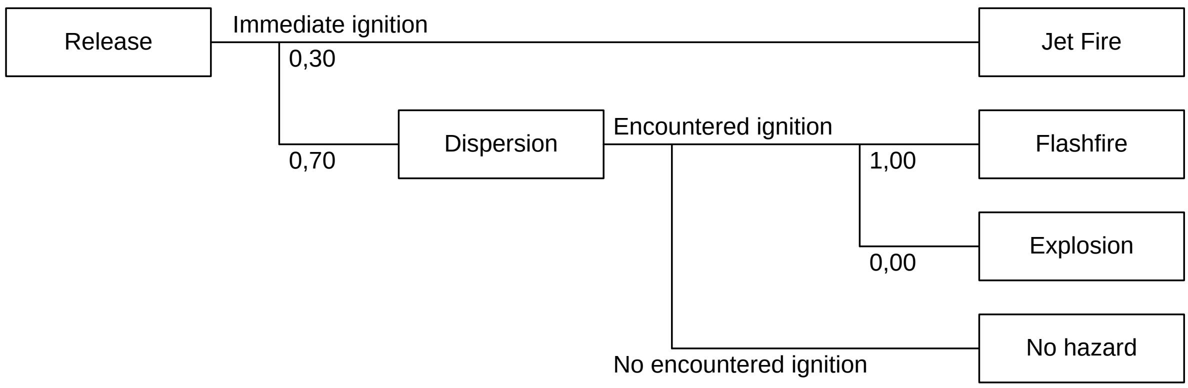
Continuous Release without rainout, short duration (< 20 sec.)



Delayed ignition of cloud

This event tree is used for determining the probability of different scenarios for releases of non-short duration, e.g. if safety measures fail and the scenario has time to develop.

Continuous Release without rainout, long duration (>= 20 sec.)



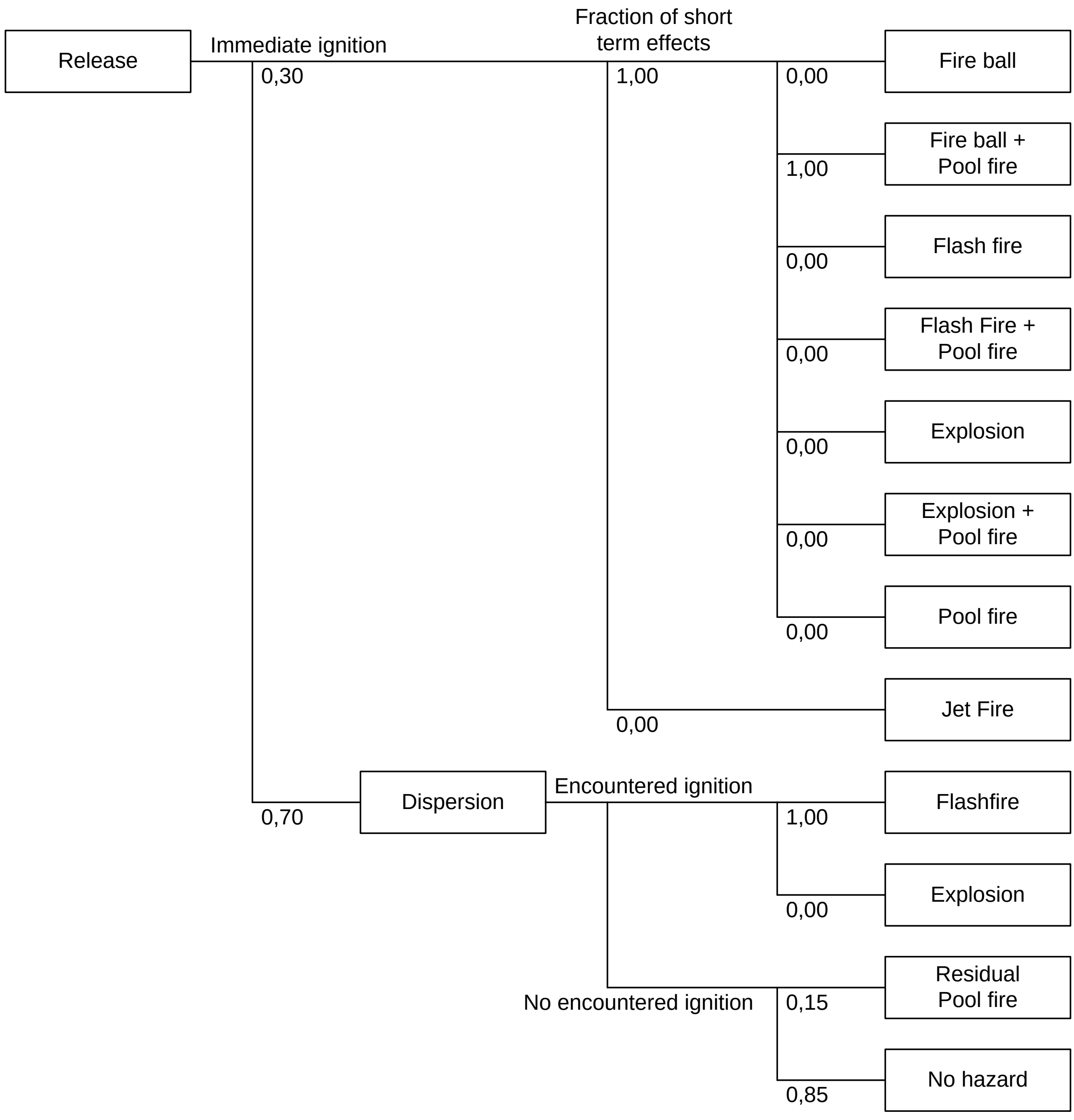
Cont. / Rainout

This type of release may occur in the event of pipe ruptures or leakages, as well as tank leakages, with release of the actual liquid phase of the tank contents.

Immediate ignition

This event tree is used for determining the probability of different scenarios for releases of short duration, e.g. if a pipe fracture valve or if ESD ends the scenario before it has time to develop.

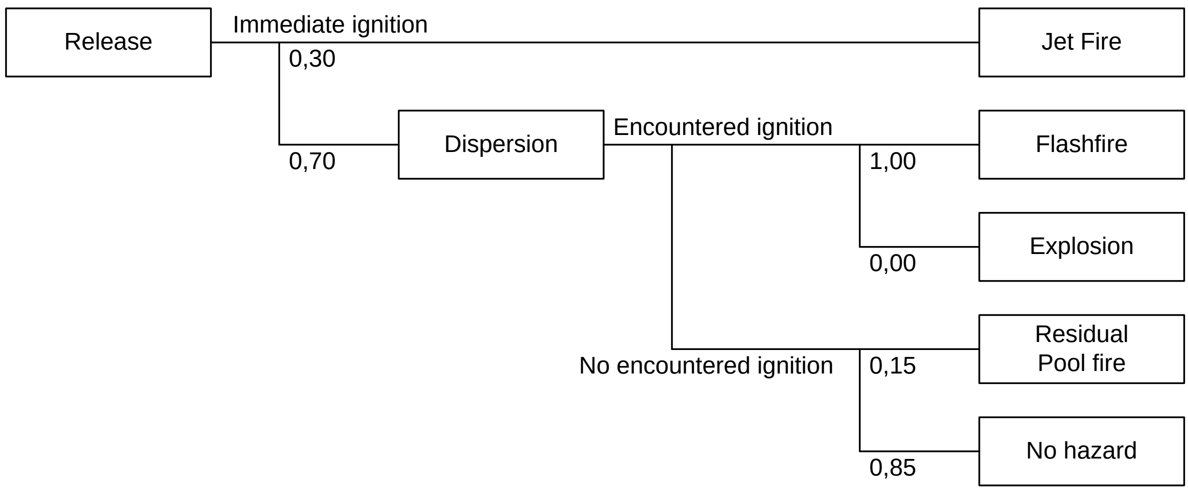
Continuous Release with rainout, short duration (< 20 sec.)



Delayed ignition of cloud

This event tree is used for determining the probability of different scenarios for releases of non-short duration, e.g. if safety measures fail and the scenario has time to develop.

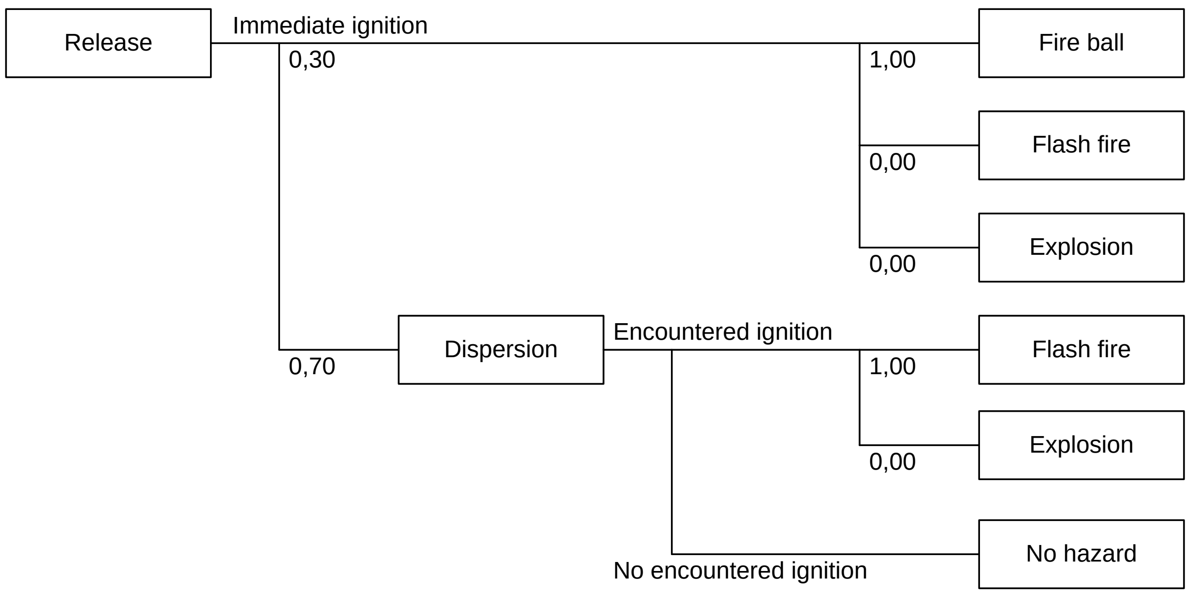
Continuous Release with rainout, long duration (>= 20 sec.)



Inst. / No Rainout

This type of release may occur in the event of a catastrophic tank failure with release of gas, i.e. no liquid in the tank.

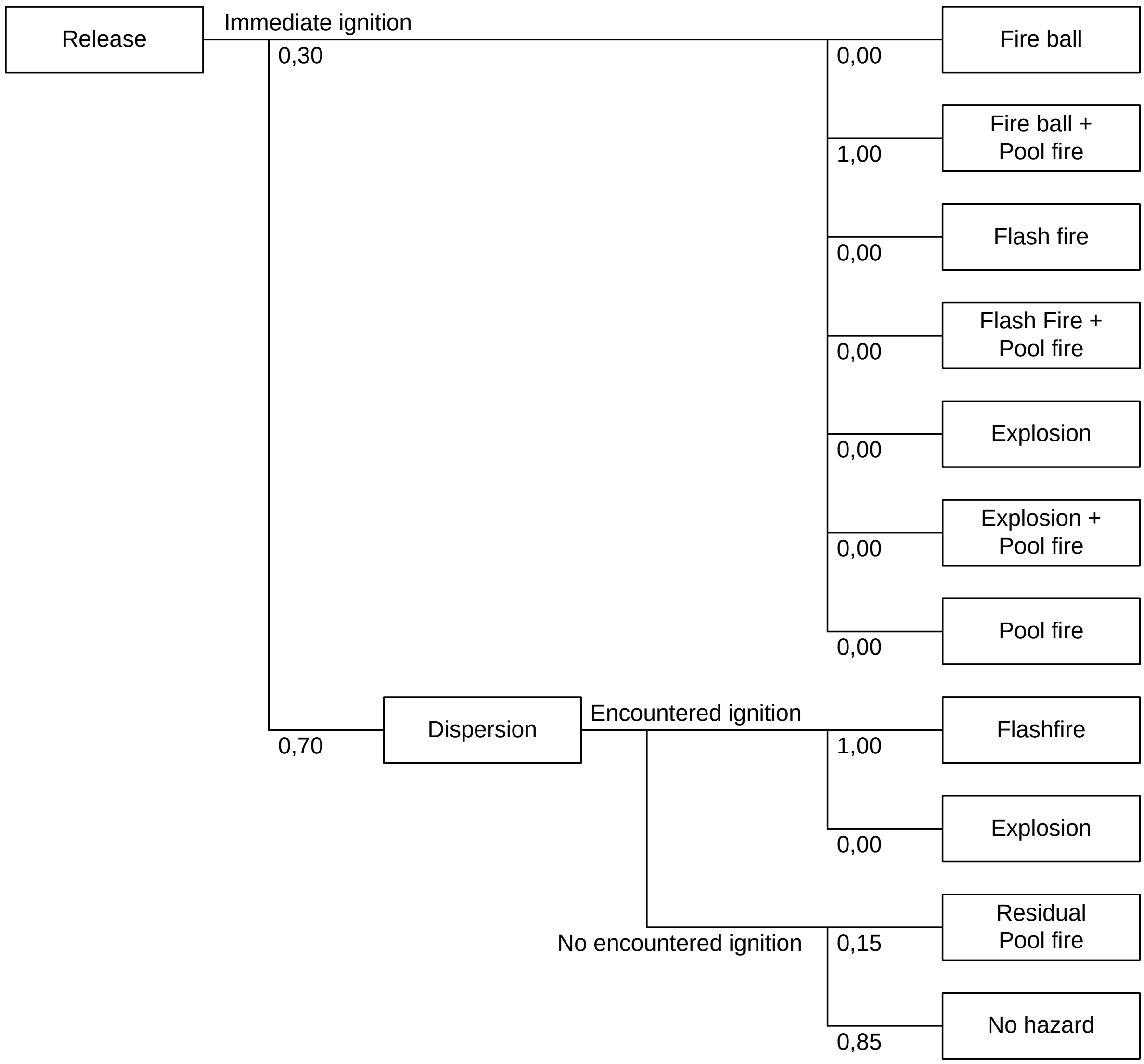
Instantaneous Release without rainout



Inst. / Rainout

This type of release may occur in the event of a catastrophic tank failure with release of liquid as well as gas from the headspace of the tank.

Instantaneous Release with rainout



APPENDIX 3

EQUIPMENT RESPONSE TIMES AND FAILURE PROBABILITIES

The release probability is based on ref. /3/ and is made up of a basic probabilities for different hole sizes and a probability contribution to the individual hole sizes from different specific incident types and from different equipment parts. The probabilities originate from a large collection of incident data, and they are thus based on incidents in many different standards within each equipment type (pipes/loading arms/pumps/hoses/hose cranes).

The release probability has been adjusted in the risk calculations so that bunkering is carried out for 1½ hour every day, all year round.

The probability calculations have also been adjusted for specific measures for the individual equipment types. This is explained in more detail in the following sections.

Pipes, loading arms and pumps
The probability of releases from pipes has been reduced based on:
- Inspection of pipes during installation / modern equipment
- Collision protection (safety zone)
- Procedure for not bunkering in strong winds

The probability of releases from loading arms has been reduced based on:
- Collision protection (safety zone)
- Modern equipment

The probability of releases from pumps has been reduced based on:
- Inspection of pumps during installation / modern equipment
- Temperature control
- Break-away coupling
- Time to replace - calculation

The probability of releases from pipes for different hole sizes:

Hole size	Probability per metre per year
Small	$3.56 \cdot 10^{-5}$
Medium	$5.35 \cdot 10^{-6}$
Large	$4.54 \cdot 10^{-6}$
Rupture	$6.61 \cdot 10^{-6}$

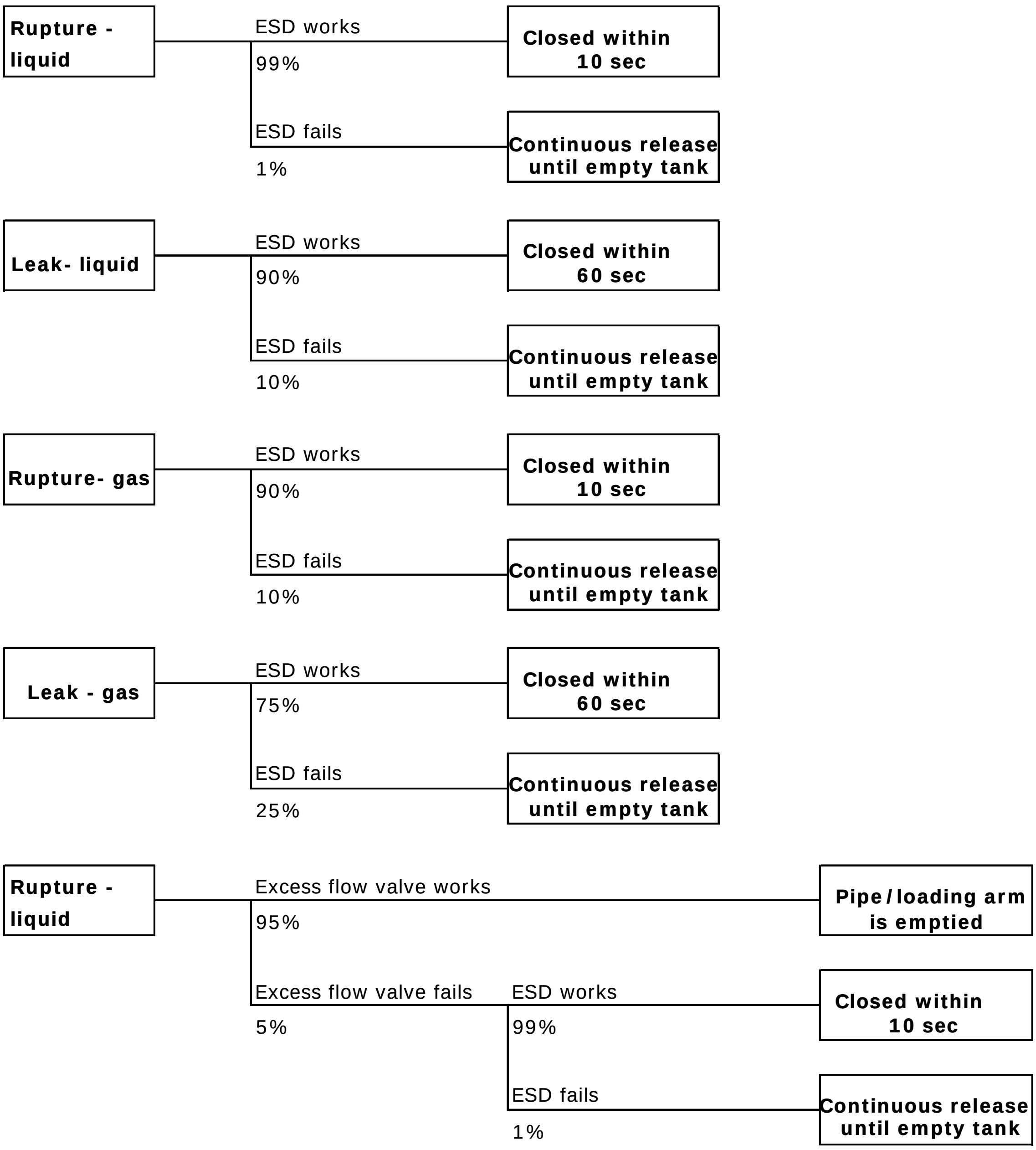
The probability of releases from loading arms for different hole sizes:

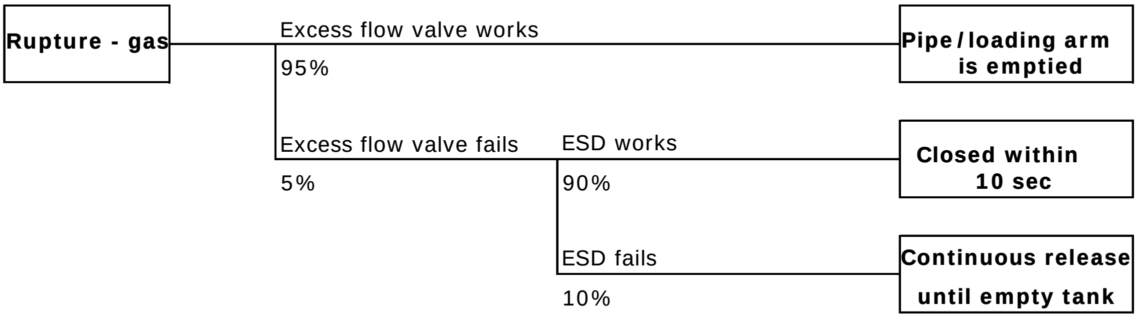
Hole size	Probability per year
Small	$9.55 \cdot 10^{-3}$
Medium	$1.50 \cdot 10^{-4}$
Rupture	$1.34 \cdot 10^{-4}$

The probability of releases from pumps for different hole sizes:

Hole size	**Probability per year**
Small	$8.45 \cdot 10^{-3}$
Medium	$5.00 \cdot 10^{-5}$
Large	$9.32 \cdot 10^{-4}$
Rupture	$5.60 \cdot 10^{-4}$

The failure probability for the ESD system and excess flow valves depends on the release scenario. The different release scenarios for pipes, loading arms and pumps, which are used in the calculation model and where excess flow valves and/or ESD are relevant, can be seen in the following event trees. It is assumed that the ESD will be activated by emergency stop and gas detection.





Hoses and hose cranes

The probability of releases from hoses and hose cranes has been reduced based on:

- Overdimensioning
- Break-away coupling
- Pressure test

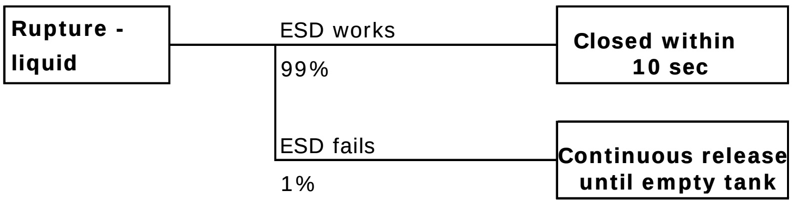
The probability of releases from hoses for different hole sizes:

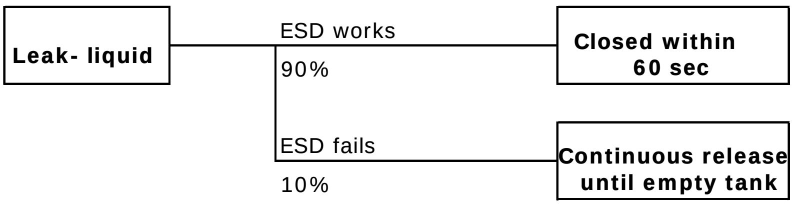
Hole size	Probability per year
Small	$1.21 \cdot 10^{-2}$
Medium	$1.04 \cdot 10^{-3}$
Rupture	$6.65 \cdot 10^{-5}$

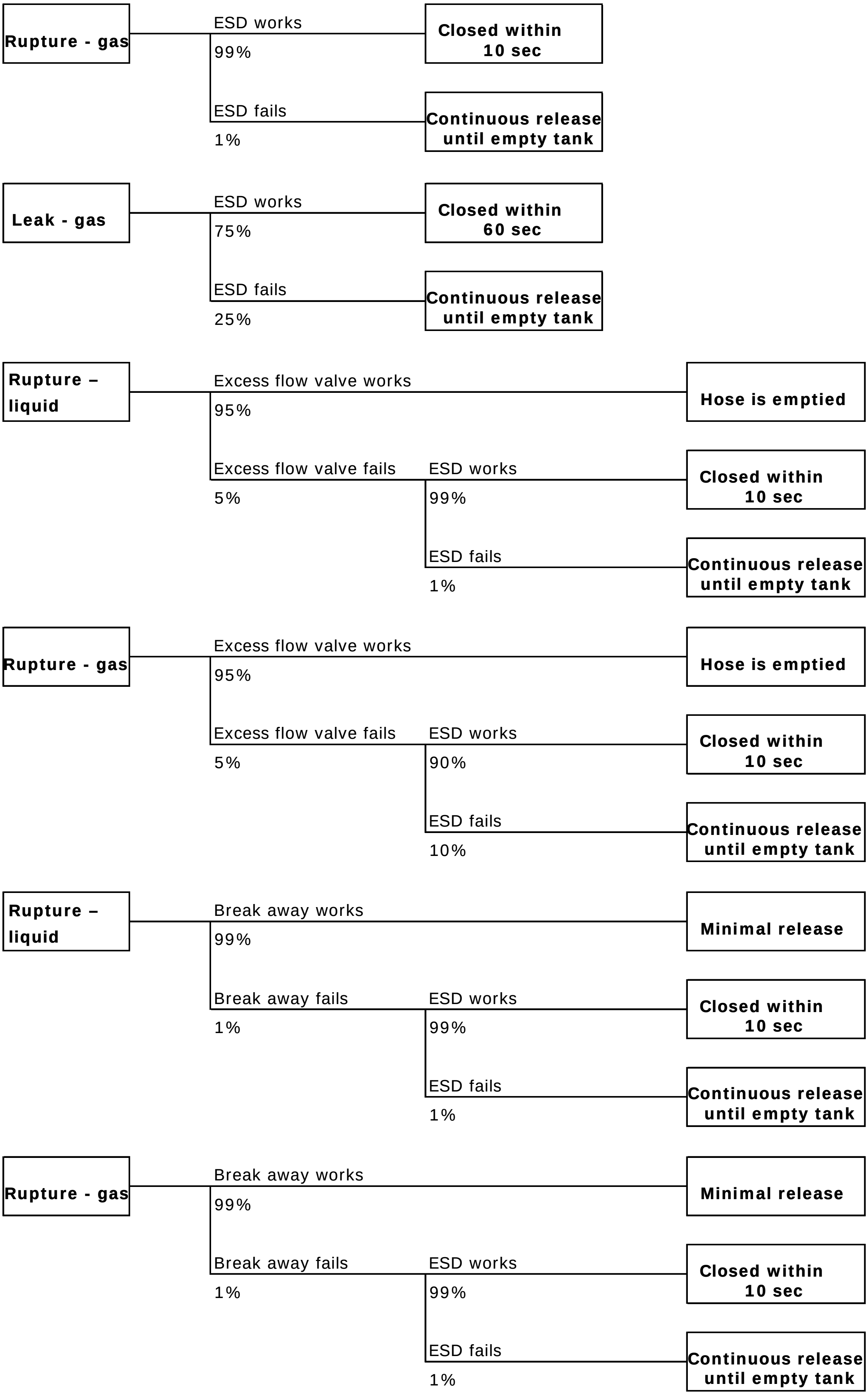
The probability of releases from hose cranes for different hole sizes:

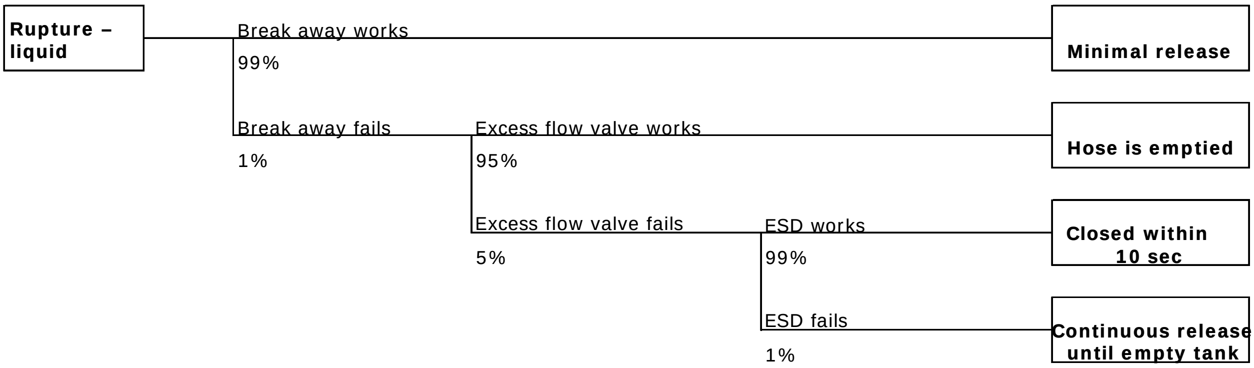
Hole size	Probability per year
Small	$1.21 \cdot 10^{-2}$
Medium	$1.01 \cdot 10^{-3}$
Rupture	$6.65 \cdot 10^{-5}$

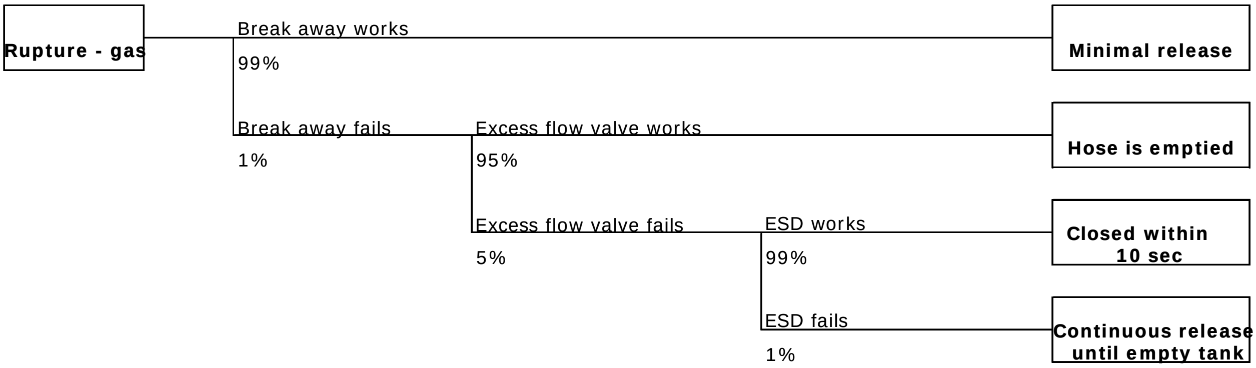
The failure probability for the ESD system, excess flow valves and break-away coupling depends on the release scenario. The different release scenarios for hoses and hose cranes, which are used in the calculation model and where excess flow valves, break-away couplings and/or ESD are relevant, can be seen in the following event trees. It is assumed that the ESD will be activated by emergency stop, gas detection, loss of vacuum and differential pressure detection.






Rupture - gas
ESD works
99%
Closed within 10 sec
ESD fails
1%
Continuous release until empty tank
Leak - gas
ESD works
75%
Closed within 60 sec
ESD fails
25%
Continuous release until empty tank
Rupture – liquid
Excess flow valve works
95%
Hose is emptied
Excess flow valve fails
5%
ESD works
99%
Closed within 10 sec
ESD fails
1%
Continuous release until empty tank
Rupture - gas
Excess flow valve works
95%
Hose is emptied
Excess flow valve fails
5%
ESD works
90%
Closed within 10 sec
ESD fails
10%
Continuous release until empty tank
Rupture – liquid
Break away works
99%
Minimal release
Break away fails
1%
ESD works
99%
Closed within 10 sec
ESD fails
1%
Continuous release until empty tank
Rupture - gas
Break away works
99%
Minimal release
Break away fails
1%
ESD works
99%
Closed within 10 sec
ESD fails
1%
Continuous release until empty tank





The following safety measures have been identified in addition to the mentioned measures:

- Safety valve
- Flame detection

Safety valves are not included in the model, as these will be activated by overpressure in the tank, and scenarios with overpressure in the tank / tank failure have not been modelled.

Flame detection has not been included in the model, as these will be activated after the end points in the event trees. There are, in other words, several other safety appliances that must fail before the ESD is triggered by flame detection.

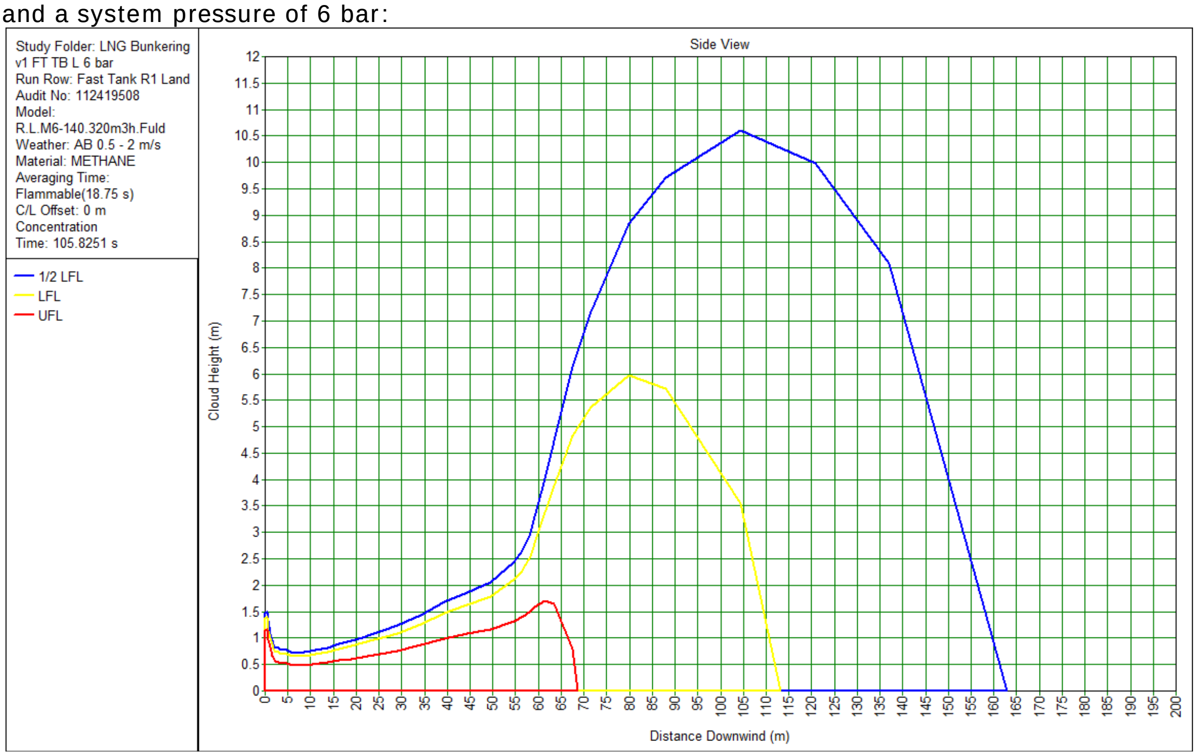
APPENDIX 4

SENSITIVITY ANALYSIS

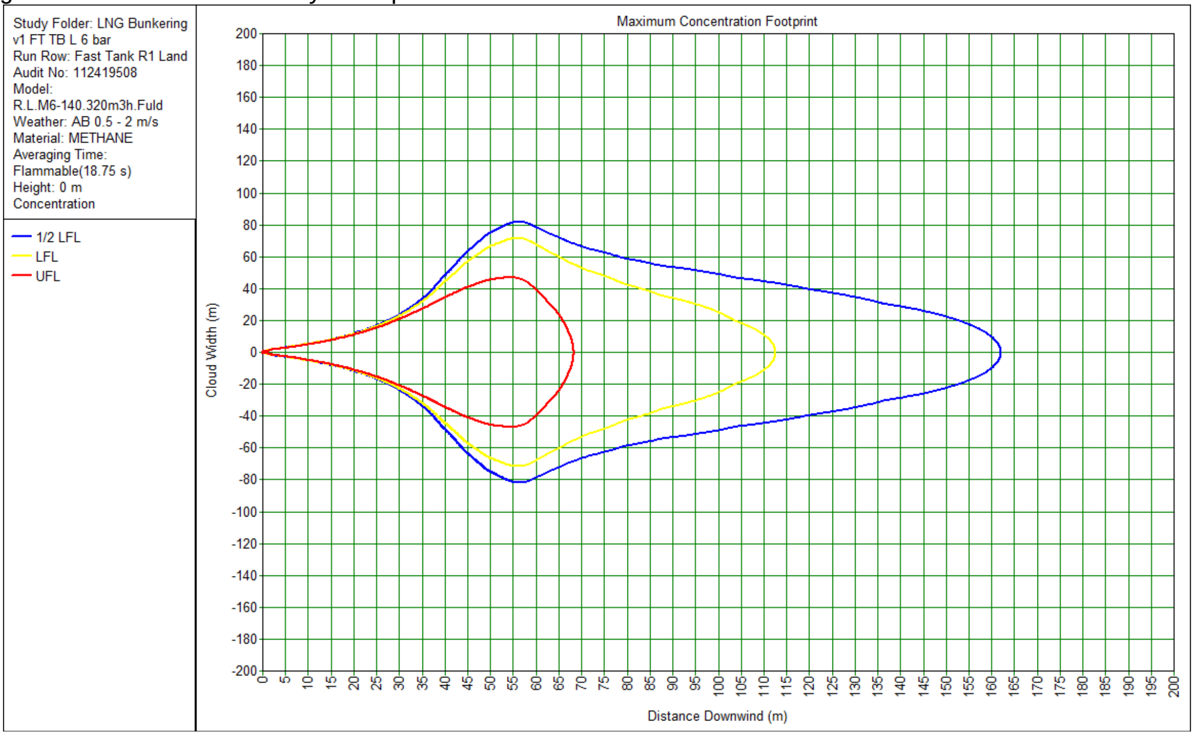
In order to evaluate the effect of the assumptions, Rambøll has carried out sensitivity analyses, where the risks are also calculated under changed assumptions, and where the achieved results have been commented.

The various sensitivity analyses have been carried out in relation to pipe ruptures onshore with a release height of 0.5 m above the ground at -140°C and a system pressure of 6 bar, and in relation to pipe ruptures over water with a release height of 3 m above the water level at -140°C and a system pressure of 6 bar.

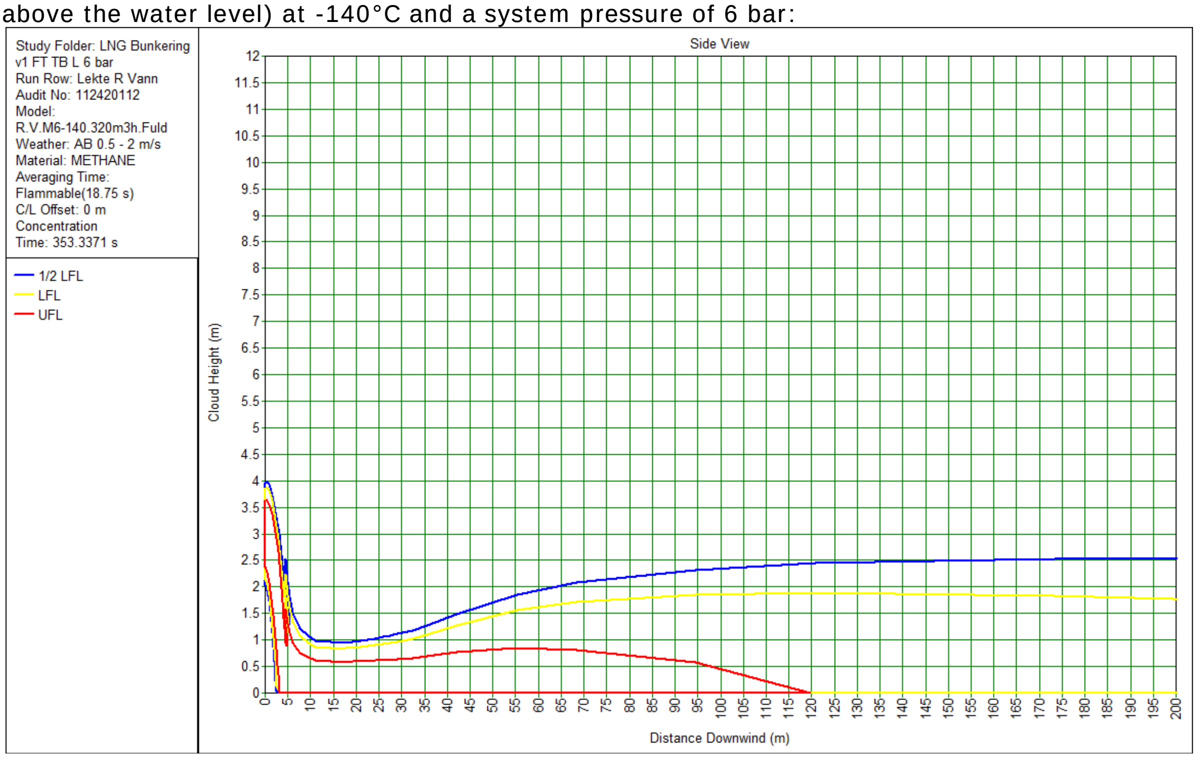
Side plot of a pipe rupture onshore with a release height of 0.5 m above the ground at -140°C and a system pressure of 6 bar:



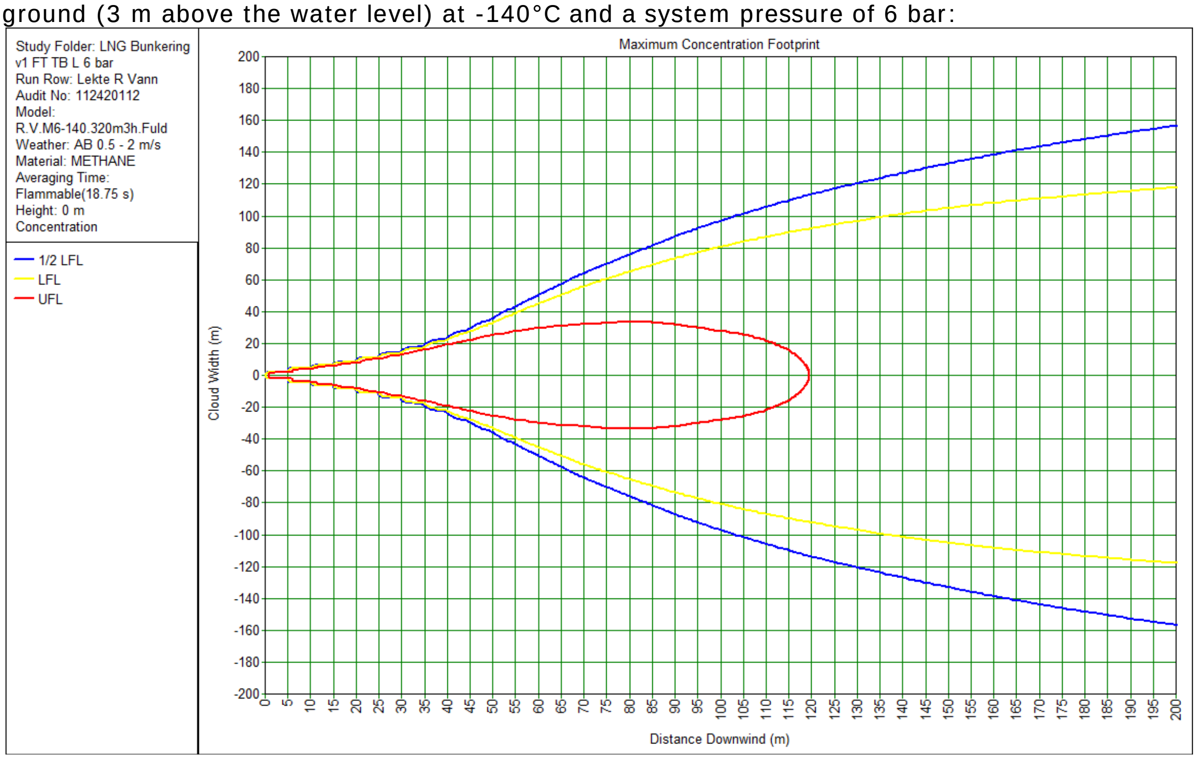
Dispersion on ground level of a pipe rupture onshore with a release height of 0.5 m above the ground at -140°C and a system pressure of 6 bar:



Side plot of a pipe rupture over water with a release height of 0.5 m above the ground (3 m above the water level) at -140°C and a system pressure of 6 bar:

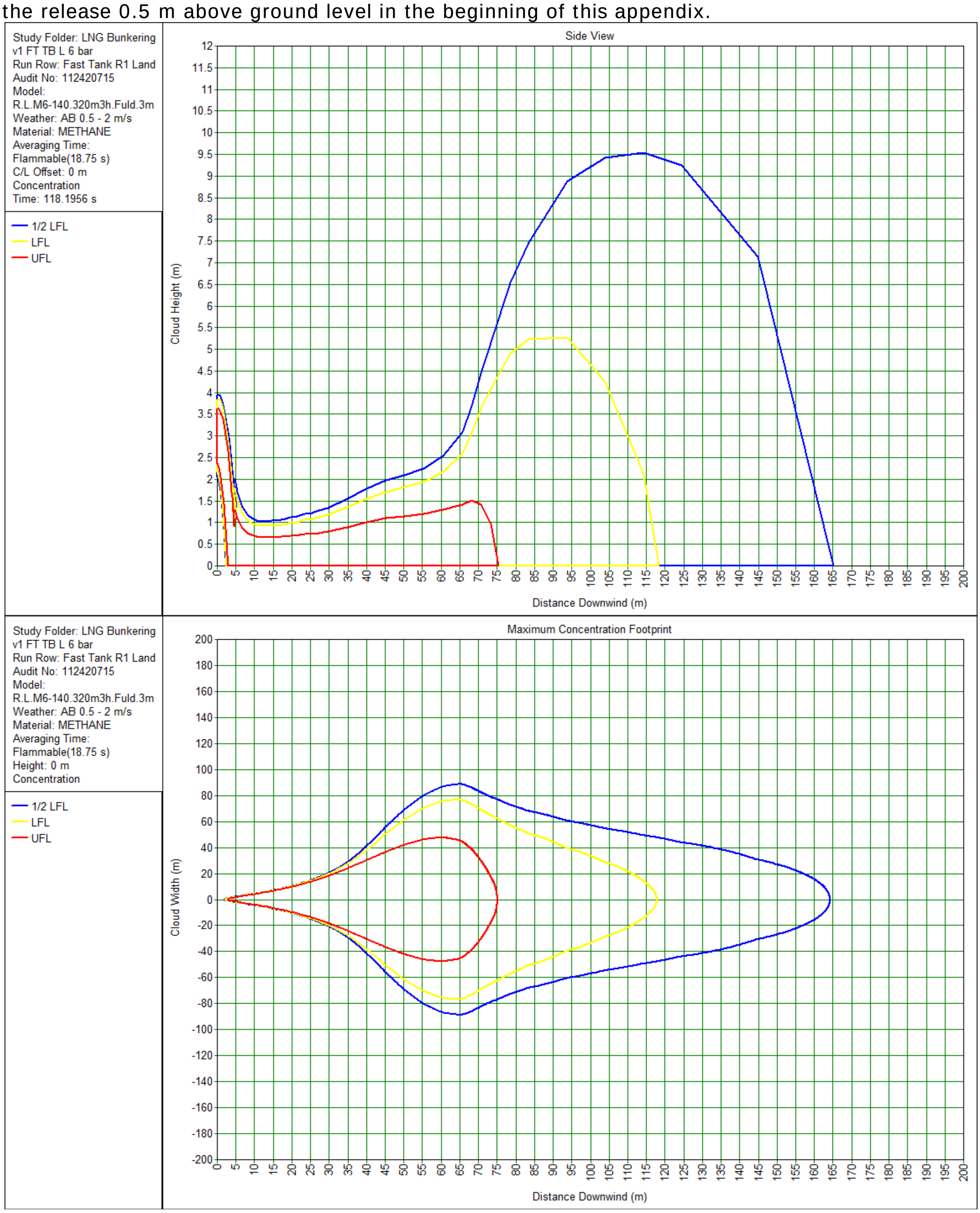


Dispersion on ground level of a pipe rupture over water with a release height of 0.5 m above the ground (3 m above the water level) at -140°C and a system pressure of 6 bar:



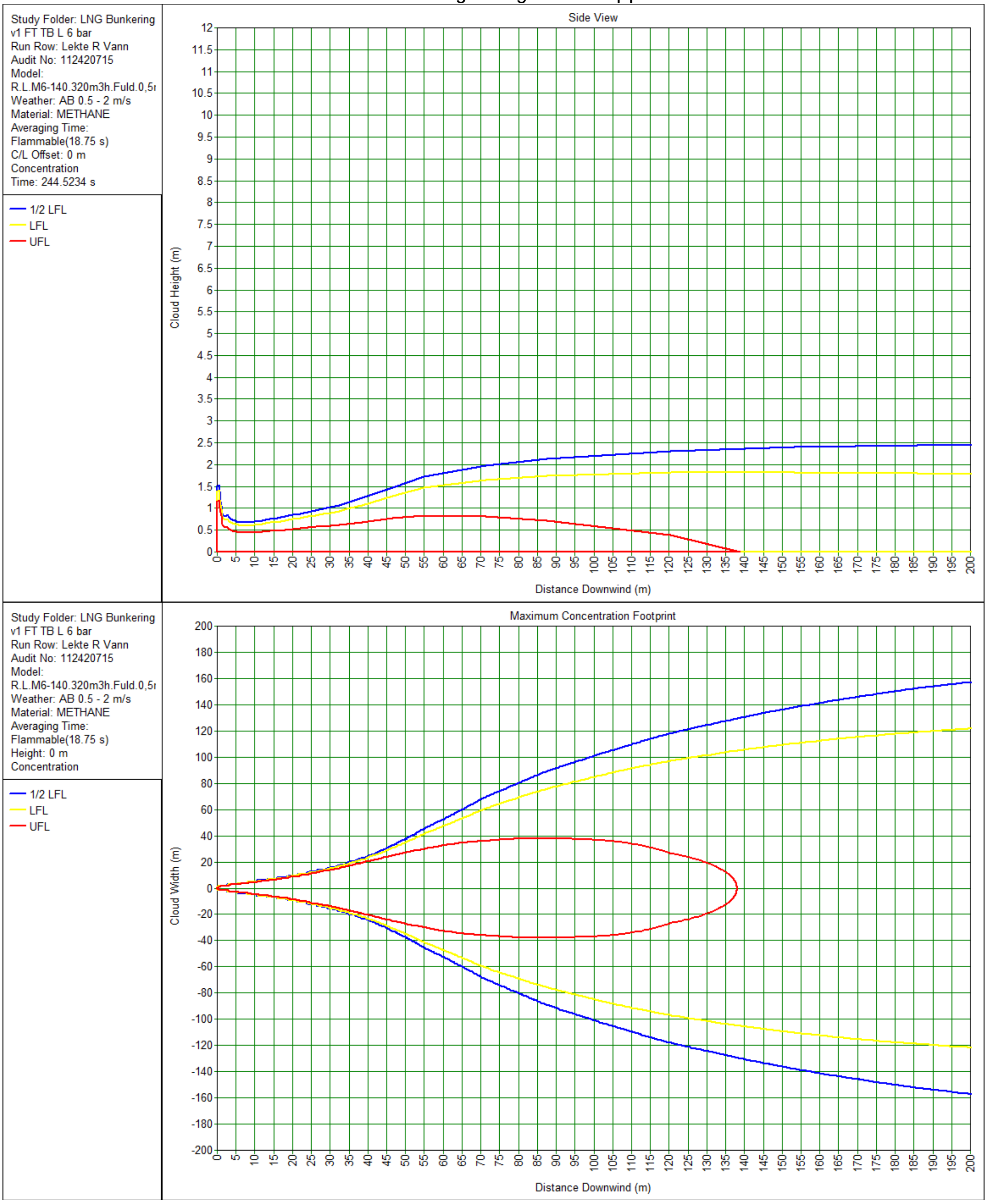
Release height

The release height sensitivity is evaluated by comparing the profile for pipe ruptures onshore with a release height of 3.0 m above the ground with the applied release height of 0.5 m above the ground. The following shows the release at 3.0 m above ground level, which is compared with the release 0.5 m above ground level in the beginning of this appendix.



The differences between a release height of 0.5 and 3.0 m for pipe ruptures onshore are not significant for the risks.

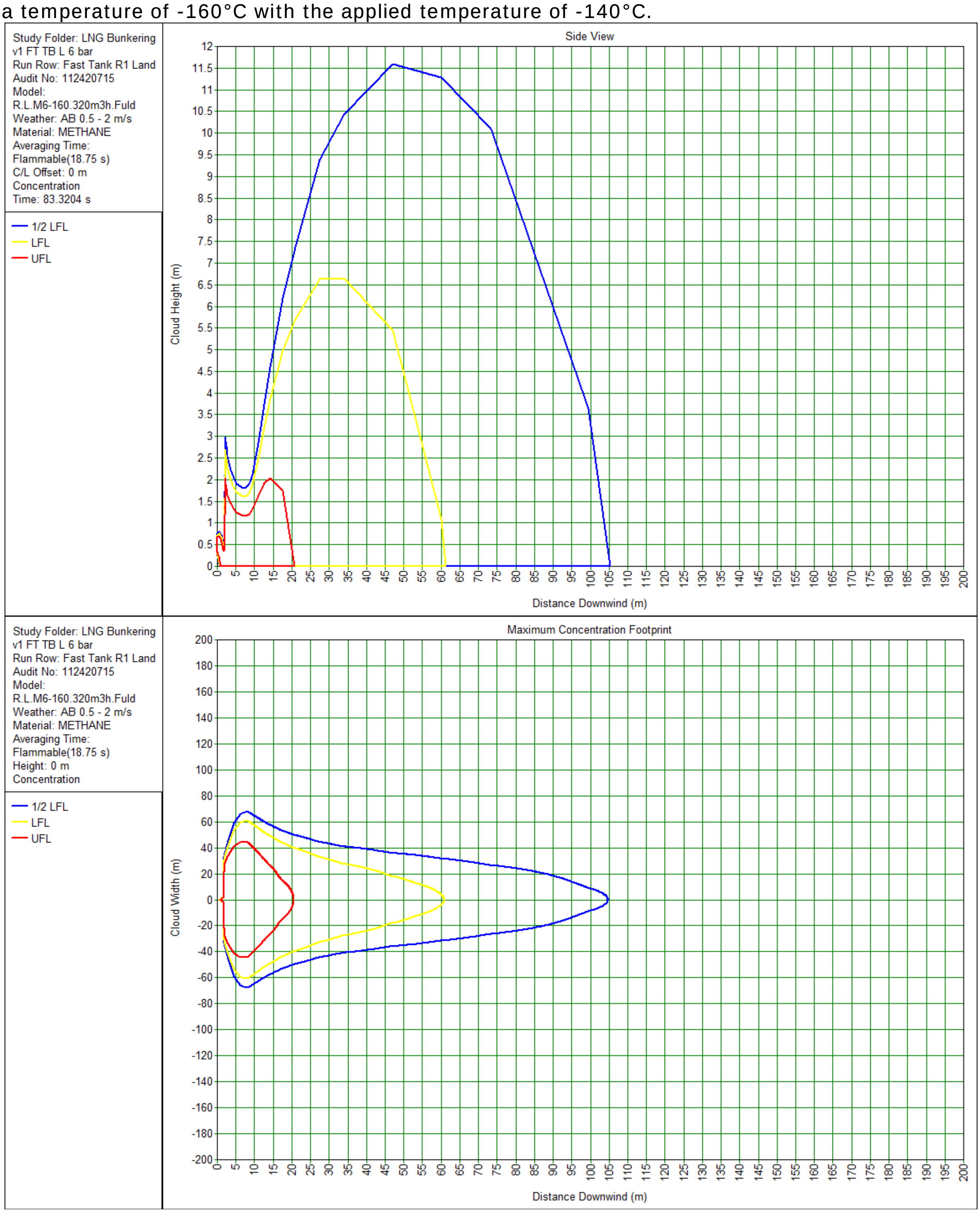
Correspondingly, the sensitivity is evaluated by comparing the applied release height of 3.0 m above water level for pipe ruptures over water with the profile for a release height of 0.5 above water level. The following shows the release at 0.5 m above water level, which is compared with the release 3.0 m above water level in the beginning of this appendix.



For releases over water, a lower release height entails that the fan becomes narrower and more concentrated, but not considerably as to alter the risks significantly.

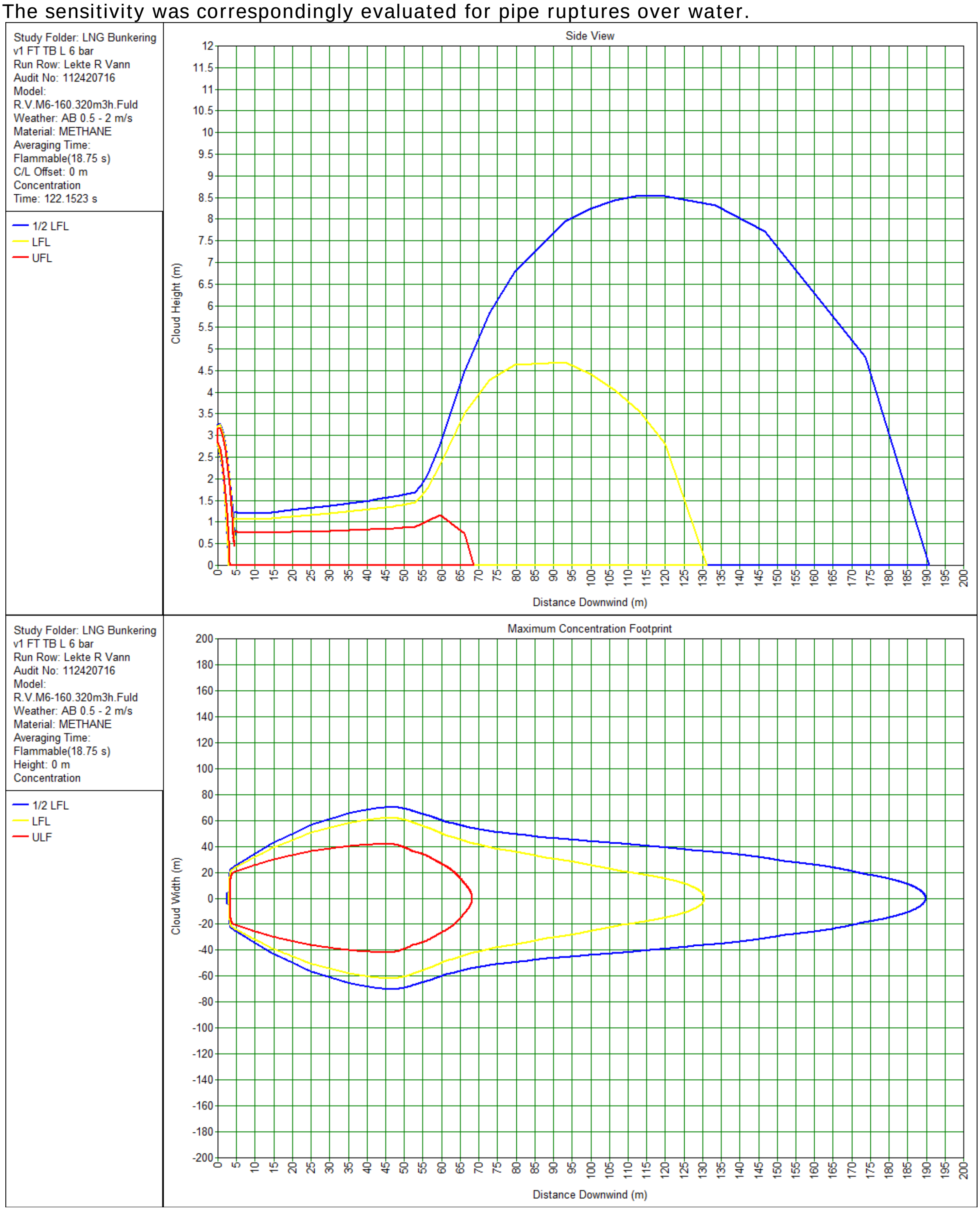
LNG temperature

The temperature sensitivity is evaluated by comparing the profile for pipe ruptures onshore with a temperature of -160°C with the applied temperature of -140°C.



The area of impact for releases onshore, measured in both length and width, is significantly smaller at a lower LNG temperature, since there is a considerable pool formation at lower temperatures.

The sensitivity was correspondingly evaluated for pipe ruptures over water.



The area of impact for releases over water, measured in both length and width, is significantly smaller at a lower LNG temperature, since there is a considerable pool formation at lower temperatures.

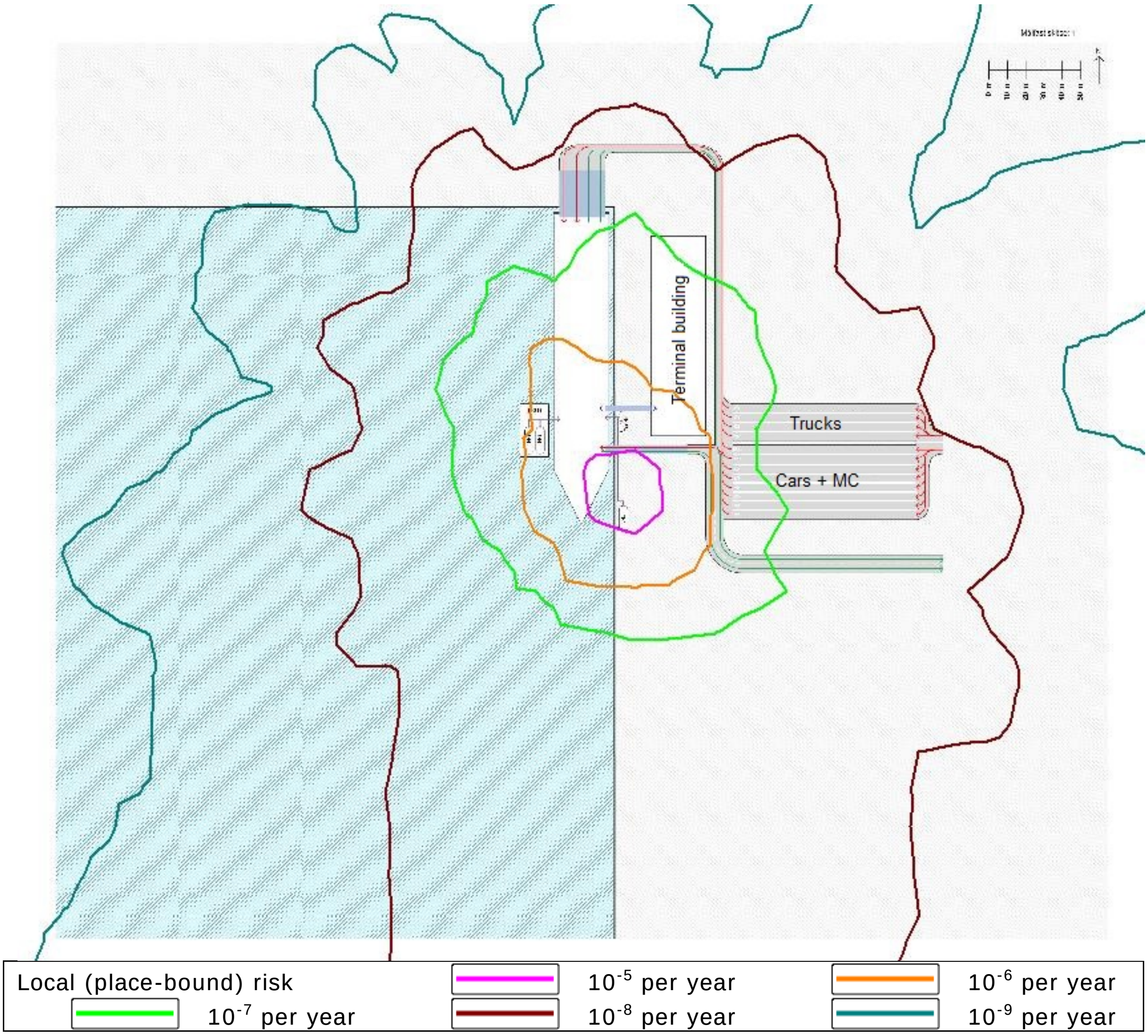
Hole size for pipe ruptures and leaks

The release rate (and thus indirectly the hole size) differs for fixed tank and tank truck. The release rate is 320 m^3/s and 413 m^3/s for fixed tank and tank truck, respectively. The calculations indicate that the risks are higher at a higher release rate (tank truck), and that this has a greater significance than the actual release amount. Release amount for tank trucks is considerably smaller.

Leak direction
The leak direction for ruptures will always be along the pipe. In the calculations, all pipes have been placed horizontally, making the leak direction for ruptures horizontal. All releases from holes/penetrations are furthermore also horizontal in the calculations.

Location of ignition sources
The location of ignition sources has been partially considered in the calculations. As indicated by the calculations for a ship carrying only passengers and not cars, the risks are slightly lower compared to a ship with passengers and cars, since the number of ignition sources is smaller for a ship not carrying cars. However, in this case, there will be more people in the vicinity of the release (since the total number of people is the same), where the overall risk scenario is not significantly changed.

The local (place-bound) risks have been calculated for a fixed tank with hose crane at a ferry landing with passengers and cars, but the ignition sources from cars, street lights and signals have been removed.



This calculation indicates that the ignition sources (where the cars represent the largest group) are very significant for the distribution range of the vapour clouds. This means that an early ignition of releases contributes to reducing the risks related to rare incidents, whereas the risk of incidents with a probability of 10^{-5} to 10^{-6} is not considerably affected.

Effects of near-field geometry
PHAST is not particularly precise when it comes to the near-field areas, see sections 4 and 6 for more details about these weaknesses in the calculations.

Drip tray or culvert size
Drip trays or culverts under pipes will primarily have an effect for small incidents. In the event of pipe ruptures, drip trays or culverts underneath pipes will only be capable of collecting a very small part of the release, and it will therefore not be of a great significance for the risks.

Pipe-in-pipe/double pipes will also have an effect for small incidents only. Major incidents will most often lead to destruction of both pipes, and pipe-in-pipe/double pipes will therefore not be significant for the risks.

Wind-rose (wind speed and atmospheric stability class)
The significance of wind-roses has been taken into account in the calculations. As demonstrated by the calculations for South coast winds and fjord winds, and the equivalent calculations for West coast winds, there will not be a significant change in the risks.

Location of harbour
The harbour location has been taken into account in the calculations. As demonstrated by the calculations for drawing 2 and 3 and the equivalent calculations for drawing 1, the location of the harbour will not be significant for the risk. The differences in the calculations stem from the wind-rose, and for fixed tank in drawing 3 where the pump being located away from the ferry.

APPENDIX 5

CFD METHOD

Computational Fluid Dynamics (CFD) is a powerful tool for analysis of fluid flows. As the name indicates, it is a computer-based method used for solving the governing equations for fluid flows. This is done in all three dimensions.

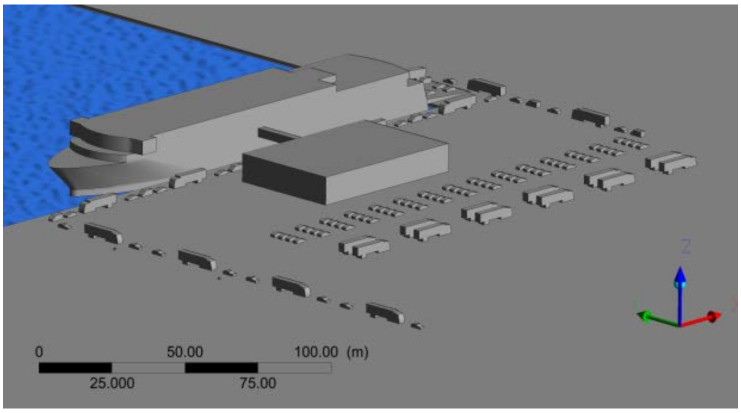
The first step of CFD modelling is to create a CAD model of the entire flow area to be simulated. A calculation grid is then created by dividing the area into much smaller volumes, so-called control volumes. In theory, there is no limit for the size of the CAD model and for the level of detail in the grid, however, the computer power will constitute the limit.

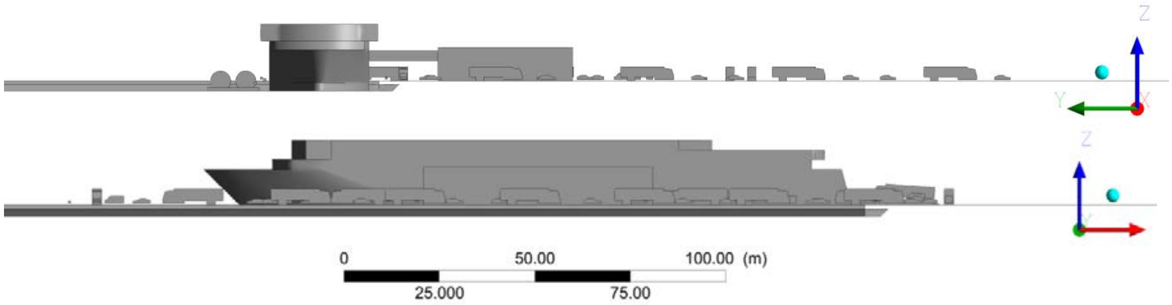
The next step is to place the actual CFD model on top of the generated grid. The CFD software used by Rambøll in this analysis is ANSYS CFX v. 14 (www.ansys.com). This is a general 3D CFD program that can handle fluid flows, turbulence, multicomponent flows, multiphase flows, chemical reactions, combustion and radiation. The combination of models used in a given model is selected so that all significant physics is included in the simulated system.

Finally, the CFD model is solved iteratively. The result of the simulations is values for all important variables, such as pressure, air velocity, temperature and turbulence level in each control volume. These values may be represented both qualitatively by way of plots on planes or surfaces and quantitatively by way of calculated values, e.g. the average speed at the outlet of a calculation domain or the force on a surface.

Calculation model

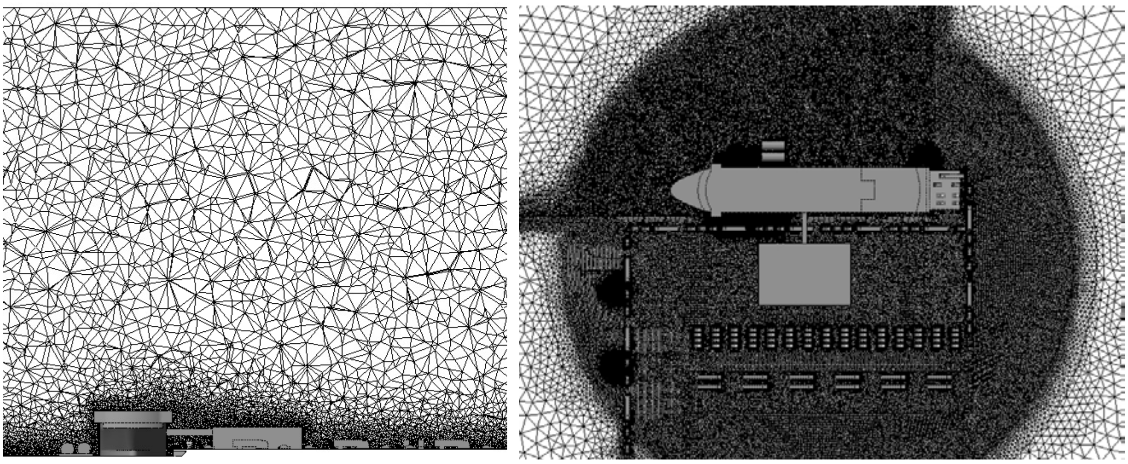
A 3D CAD model of the vicinity around the bunkering positions and the surrounding harbour area is built up. The model includes the quay itself, the terminal building, vehicles and a moored ship to be bunkered with LNG. The model is a simplification of the constructed geometry. Small details have been omitted, while the general geometry has been modelled in order to achieve the correct wind profile. The 3D model is shown in perspective and from the side:





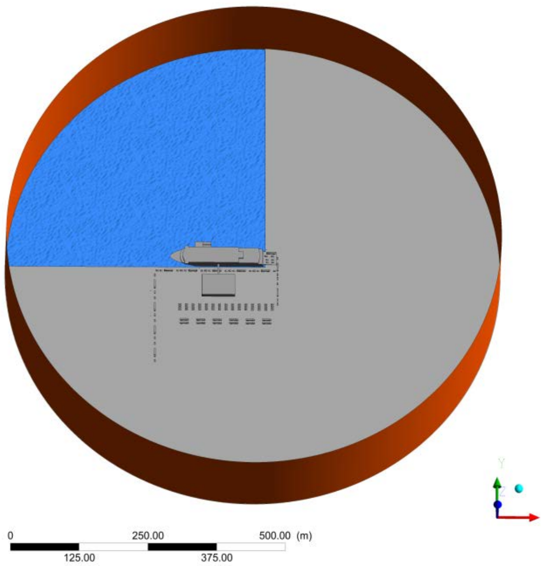
Calculation grid

A so-called unstructured calculation grid is used, consisting of two types of calculation elements: approximately 2 million prism elements close to all boundary surfaces such as buildings, water surface, and approximately 13 million tetrahedral elements in the rest of the domain. The calculation grid is shown below in a vertical and horizontal section through the domain. With an unstructured grid generation method, various grid controls were applied in order to refine the grid in regions of particular interest. The grid was refined around the modelled geometry and around the release layouts.



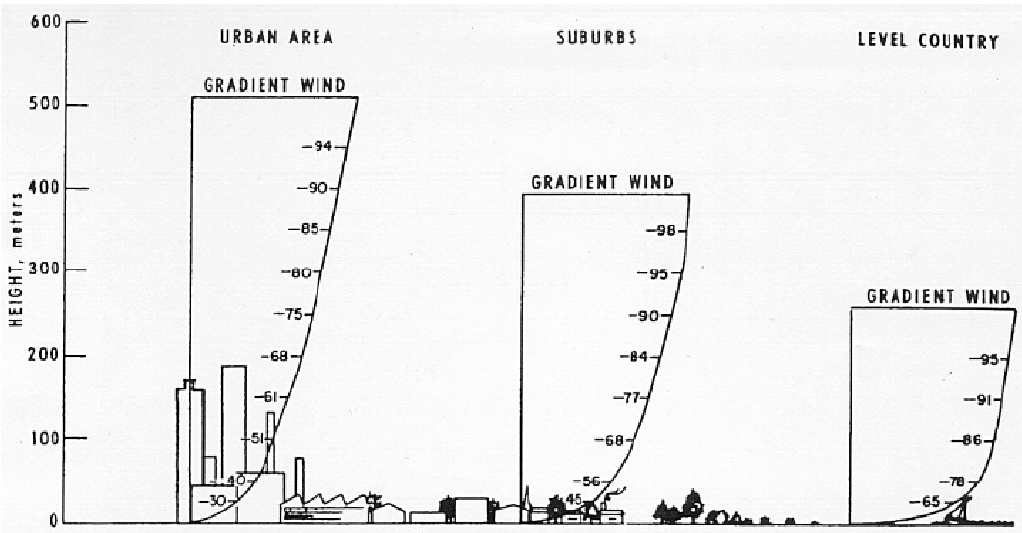
Boundary conditions

A circular calculation domain with a radius of 450 m and a height of 200 m was created around the modelled geometry. The domain boundaries were placed far away from the release layouts to avoid impacts on the calculations. The figure below illustrates the dimensions of the domain surrounding the constructed geometry. The orange area is the wind inlet zone for the domain.



Wind inlet zone

When wind passes over a landscape, a so-called atmospheric boundary layer will gradually be built up, i.e. a wind profile where the air velocity increases gradually as a function of the height above ground. The shape of the boundary layer is a function of changes in terrain height, vegetation and buildings:



In an undisturbed flow passing over a terrain, a logarithmic boundary layer will be built up based on the following equation:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \qquad \text{(Equation 1)}$$

where

U(z)	is the wind speed at the height z above ground level [m/s]
U_*	is the friction velocity [m/s]
κ	is the von Karman constant (0.41 [-])
Z	is the height above the ground [m]
Z_0	is the terrain's aerodynamic roughness length [m]

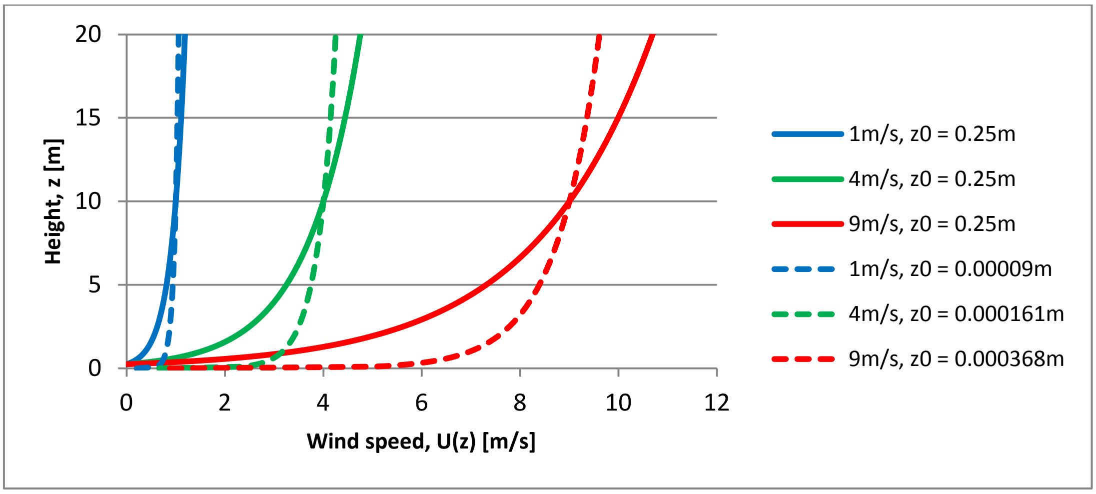
This equation can be used to define the speed profile of the calculation domain inlet, but the accuracy of this equation is very dependent on the selected aerodynamic roughness length. The roughness factor is normally selected based on assumptions of the surrounding buildings and vegetation, e.g. height and density. This selection is necessarily subjective. Since the roughness length is different for water and ground surfaces, the speed profile will also be different depending on whether the wind comes from the shore-side or the water-side. Due to the circular domain used in the CFD simulation, it is only possible to define an inlet profile for U for the entire domain, i.e. it is not possible to distinguish between whether the wind comes from land or water. The wind profile is set to z_0 = 25 m, corresponding to "High crops; Scattered large obstacles" which represents the surface roughness onshore. The speed profile, up to a height of 20 m, from equation 1 is shown in the figure on the next page, where U_{10} is set to 1, 4 and 9 m/s, respectively. The corresponding speed profile for a roughness corresponding to the surface roughness offshore is also illustrated in the figure. If the wind comes from open waters, the speed under the reference height of 10 m will be underestimated, since a lower z_0 value gives a "sharper" profile. It is a conservative selection since a lower speed results in less mixing of the LNG. The inlet temperature has been set to 10°C.

The friction velocity is determined by:

$$u_* = \frac{\kappa \cdot U_{10}}{\ln\left(z_{uref} / z_o\right)} \qquad \text{(Equation 2)}$$

where

U(z)	is the wind speed at the height z above ground level [m/s]
U_{10}	is the wind speed measure 10 m above the ground at a meteorological station [m/s]
Z_{uref}	is the height at which the wind speed U_{10} is measured [m]

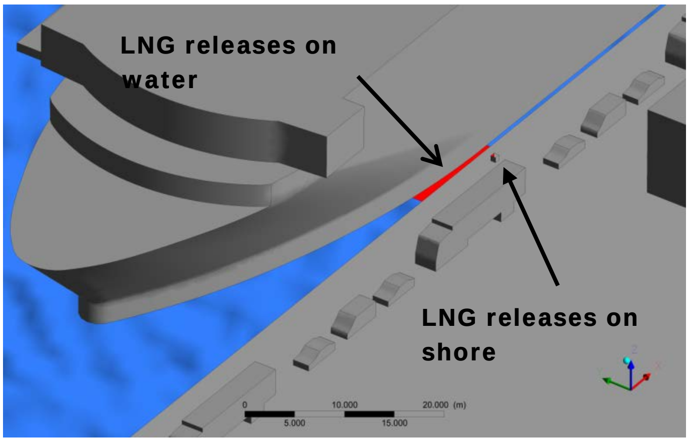


Top
A friction-free surface is selected for this boundary, i.e. the surface does not represent a flow resistance for the wind.

Terrain
In order to include the effect of various objects in the wind path, a roughness is imposed on the actual terrain surface. The roughness is set to a sand grain size of 3 cm. A roughness of 3 cm has been selected since the majority of the geometry such as the terminal building and vehicles have been modelled.

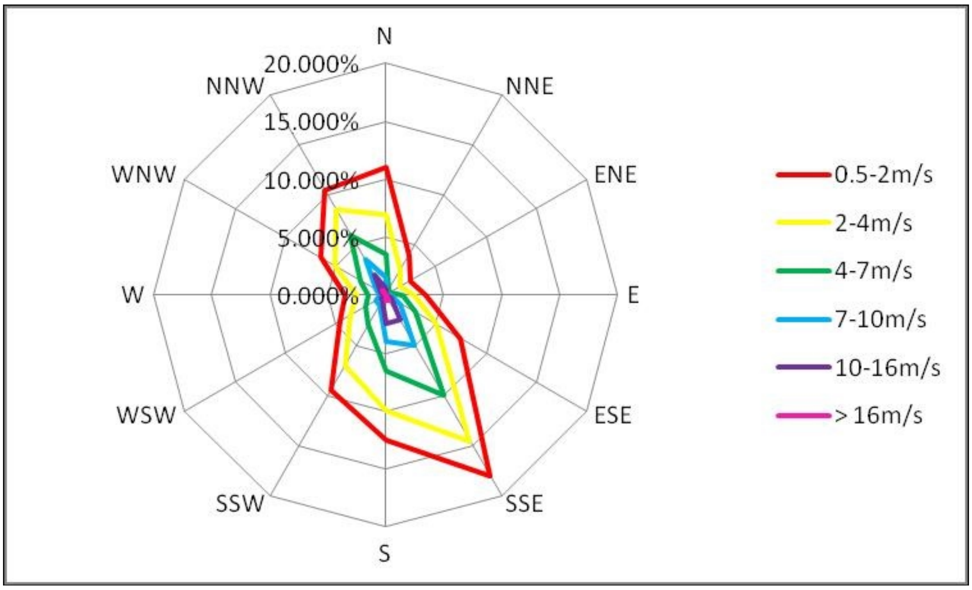
Buildings
Finally a roughness corresponding to a sand grain size of 1 cm is set in order to take into account that the buildings are not completely smooth.

Release of LNG
An LNG release onshore is modelled as a cube in the CFD model, thus the direction of the release can be controlled. For releases offshore an area is defined with regard to the release point, where LNG vaporisation is assumed to occur. Both onshore and offshore releases are defined with a mass flow in kg/s and a temperature of -140°C. The shape of the release in the CAD model can be seen in the figure below for release point C on the quay south of the ship, where the red areas indicate the area in which the release is defined. For the release on the quay, the red area indicates that the release direction is defined to the north.



Probability of wind direction and speed

A wind-rose representative for harbours on the West coast has been applied in the calculations:



The probability of the examined 8 wind directions and 4 wind speeds:

Wind [m/s]	N	NE	E	SE	S	SW	W	NW	**Total**
1	0.055	0.01	0.035	0.035	0.05	0.01	0.025	0.02	**0.24**
4	0.08	0.015	0.055	0.095	0.12	0.025	0.06	0.05	**0.5**
9	0.015	0	0.02	0.05	0.05	0.01	0.015	0.035	**0.195**
Total	**0.15**	**0.025**	**0.11**	**0.18**	**0.22**	**0.045**	**0.1**	**0.105**	**0.935**

For releases until empty tank, and where only wind speeds of 1 and 4 m/s have been examined in the CFD calculations, the probability of 9 m/s has been added to the probability of 4 m/s.

Probability of tanking and release

The release probability per year used in the risk calculations is specified below. The release probability is multiplied by the tanking probability of 6.25 corresponding to tanking of LNG for 1.5 hours per day.

Layout	Contribution	Amount	Probability per year	Probability per year
A - Tank truck				
	Hose	1	$6.65 \cdot 10^{-5}$	$6.65 \cdot 10^{-5}$
	Hose crane	1	$6.65 \cdot 10^{-5}$	$6.65 \cdot 10^{-5}$
	Pump	1	$5.60 \cdot 10^{-4}$	$5.60 \cdot 10^{-4}$
	Pipe	20m	$6.61 \cdot 10^{-6}$	$1.32 \cdot 10^{-4}$
			Total =	$\mathbf{8.25 \cdot 10^{-4}}$
B - Barge				
	Hose crane	1	$6.65 \cdot 10^{-5}$	$6.65 \cdot 10^{-5}$
	Pump	1	$5.60 \cdot 10^{-4}$	$5.60 \cdot 10^{-4}$
	Pipe	20m	$6.61 \cdot 10^{-6}$	$1.32 \cdot 10^{-4}$
			Total =	$\mathbf{7.59 \cdot 10^{-4}}$
C - Fixed tank				
	Pipe	90m	$6.61 \cdot 10^{-6}$	$5.95 \cdot 10^{-4}$
	Hose crane	1	$6.65 \cdot 10^{-5}$	$6.65 \cdot 10^{-5}$
			Total =	$\mathbf{6.62 \cdot 10^{-4}}$
D - Road				
	Pipe	10m	$6.61 \cdot 10^{-6}$	$6.61 \cdot 10^{-5}$
			Total =	$\mathbf{6.61 \cdot 10^{-5}}$

For release layout C, a release has been simulated in three different directions (to the north, east and upwards). The release probability for this layout has therefore been multiplied by a reduction factor of 1/3 when each individual case in considered in the risk calculations.

Probability of the ESD system working or failing

For CFD calculations of releases with a duration of 5 seconds, an ESD system activation probability of P_{ESD} = 99% has been applied, and for releases of long duration an ESD system failure probability of P_{ESD} = 1% has been applied.