PROJECT CCS CARBON CAPTURE OSLO

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QRA FOR OSLO CARBON CAPTURE - FEED


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Lilleaker Consulting a.s.

Report	QRA for Oslo carbon capture - FEED		
Client	Fortum Oslo Varme AS	Client contact person	Terje Egeberg
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EXECUTIVE SUMMARY

A risk analysis has been performed for the FEED phase of the planned CO_2 capture, intermediate storage and transport facilities at Klemetsrud and Oslo Harbour. The facilities include:

- Process facilities for CO_2 capture, liquefaction and intermediate storage at Klemetsrud
- Truck loading and transport
- Intermediate storage and export at Oslo Harbour

Hazards in the carbon capture plant include release of flue gas, gaseous CO_2, cooling medium and chemicals such as solvents. These scenarios represent risks to personnel at the plant and must be controlled in adequate ways.

Intermediate storage involves relatively large tanks, at Klemetsrud and at Oslo Harbour. This can potentially lead to large gas clouds representing a threat to persons at and outside the facility. Maps with indicative restricted area zones have been developed for Klemetsrud and Oslo Harbour.

The risk contribution from truck transport accidents is concluded low. However, in an unlikely accidental release of liquid CO_2, consequences could be severe.

Details of the liquefaction plant is not available, but preliminary information indicate that the risk to third party will be modest.

Release of nitrosamines from the solvents applied in carbon capture plants has been a concern for CO_2 capture facilities. This study does not address the risk related to release of nitrosamines with the flue gases.

The overall conclusion is that the risk picture will be acceptable in relation to relevant criteria both for the Klemetsrud and Oslo Harbour facilities.

In rev 02, the study was updated to reflect the risk contribution from the CO_2 carrier ship, reflecting information received from Equinor (see chapter 9.4.2).

02	30.11.2019	Jo Wiklund	Marianne Fauskanger	Ingvild Aker
01	03.06.2019	Jo Wiklund	Marianne Fauskanger	Ingvild Aker
Draft	24.05.2019	Jo Wiklund	Marianne Fauskanger	Ingvild Aker

Lilleaker Consulting as
Leif Tronstad plass 7
1337 Sandvika

Tlf: +47 67 52 09 50
Org.nr.: 981635701 MVA
www.lilleaker.com

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Appendix:

1 Introduction

1.1 Scope of work

This document contains the FEED risk analysis for the Oslo Carbon Capture (CC) project. This includes risk assessments of both the CC plant facilities at Klemetsrud and at Oslo Harbour as proposed by Contractor.

1.2 Limitations

The risk analysis is limited to the operational phase, which means that risk related to construction work is not included.

Accidents at the Klemetsrud energy from waste facilities and at neighbouring facilities at Oslo Harbour are not addressed in detail in this analysis.

The risk analysis focuses on risks related to accident scenarios and releases with major accident potential. Occupational accidents are not focused. Possible effects of continuous or planned release of substances is not focused. Release of nitrosamines could be a concern for carbon capture facilities, depending on the chemicals to be applied in the process.

1.3 Governing regulations

A set of relevant regulations is listed in Appendix B (in Norwegian).

2 System description

Klemetsrud Energy from Waste (WtE) plant produces approximately 460,000 tons CO_2 a year from the three incineration lines K1, K2 and K3. The capture plant will be designed to capture approximately 90% (average) of produced CO_2. Any CO_2 produced will be compressed and conditioned for water and oxygen content. Following compression and conditioning CO_2 will be liquified and sent to intermediate storage at WtE site. Liquid CO_2 will be transported to Oslo Harbour using truck transport where it will be stored in a tankage facility before being exported and shipped via a CO_2 Terminal located at the Jetty. The CO_2 capture plant (CC plant) will be located east of the original WtE plant (see Figure 2-1).

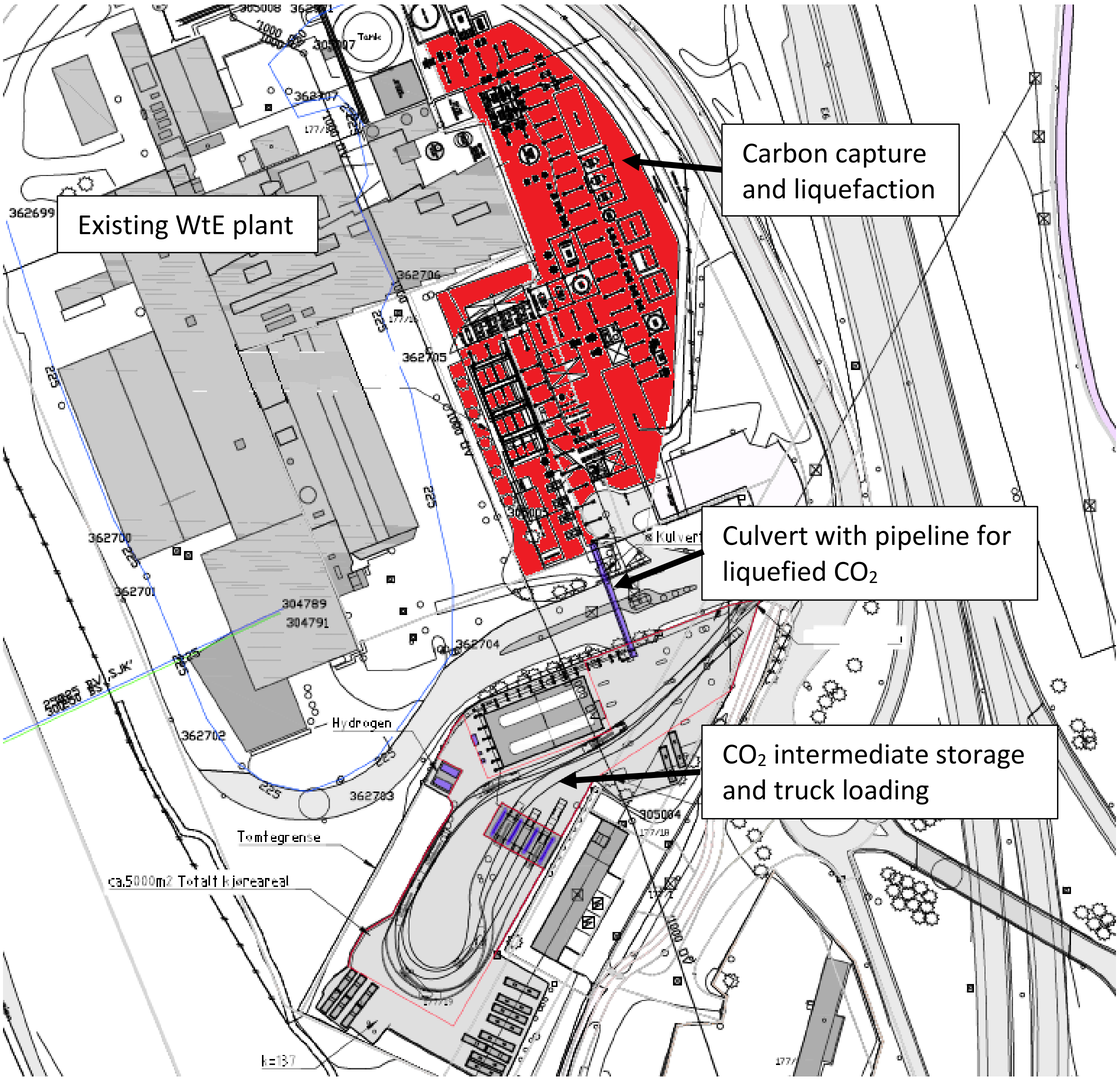


Figure 2-1: Original WtE plant marked with grey, CO_2 capture plant to the east.

Klemetsrud Energy from Waste (WtE) plant is located at Klemetsrud in Oslo, near E6 (south direction). As can be seen in Figure 2-2 there are residential areas and schools nearby the facility. Hilly terrain and partly wooded area surrounding the facility will be beneficial considering direct exposure from plant to nearby areas.

Figure 2-2: Klemetsrud WtE and nearby areas

2.1 Carbon capture plant

An overview of the carbon capture process is shown in Figure 2-3.

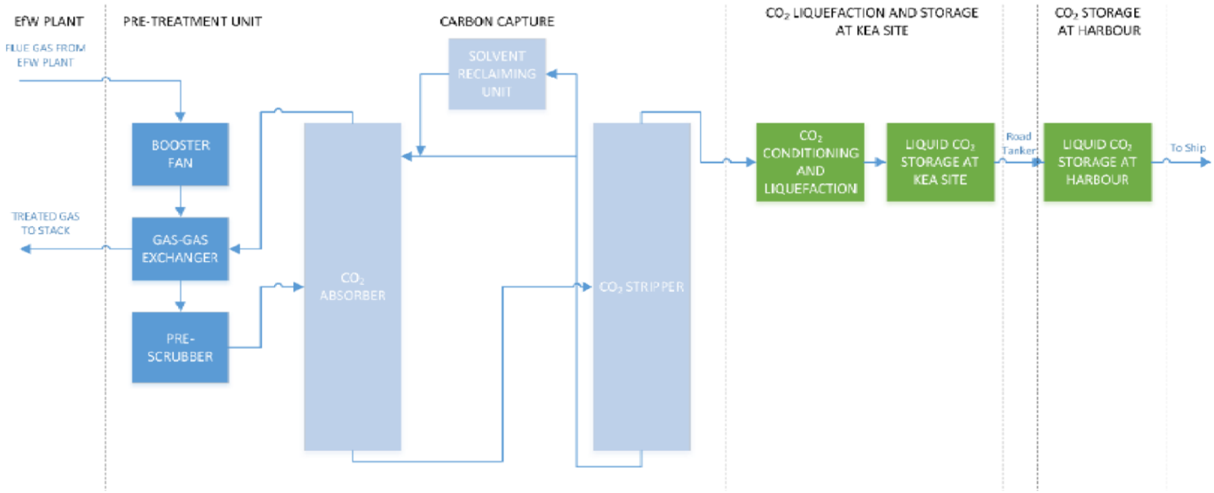


Figure 2-3: Overview - Carbon capture process

In the pre-treatment unit the booster fan provides the flue gas with sufficient pressure to flow through the carbon capture plant. The pre-scrubber cools the flue gas to the required temperature for the capture process.

The pre-treated flue gas from the pre-scrubber is routed through the carbon capture plant and then returned to the existing flue gas stacks for proper dispersion. The CO_2 produced from the capture unit is sent to the compression and conditioning unit. The compressed CO_2 passes further through an oxygen removal reactor and driers before sent to liquefaction. In the liquefaction unit the CO_2 is compressed, dried and liquefied. Liquid CO_2 from Intermediate Storage at WtE plant is transported using trucks to Intermediate Storage in Oslo Harbour.

2.2 Intermediate storage solutions

At Klemetsrud, the capacity requirement for the intermediate storage is based on one day's worth of CO_2 production, while at Oslo Harbour, the storage capacity is four times larger. Four 30m long bullet tanks are currently being planned for at Klemetsrud, and 16 at Oslo Harbour. Each tank has a working capacity of 342m^3 (364 t). The storage tank configuration is a two- level structure shown in Figure 2-4. In the concept phase, large spherical tanks were assumed at Oslo Harbour. An assessment of the risk aspects of tank configuration is included in Appendix E.

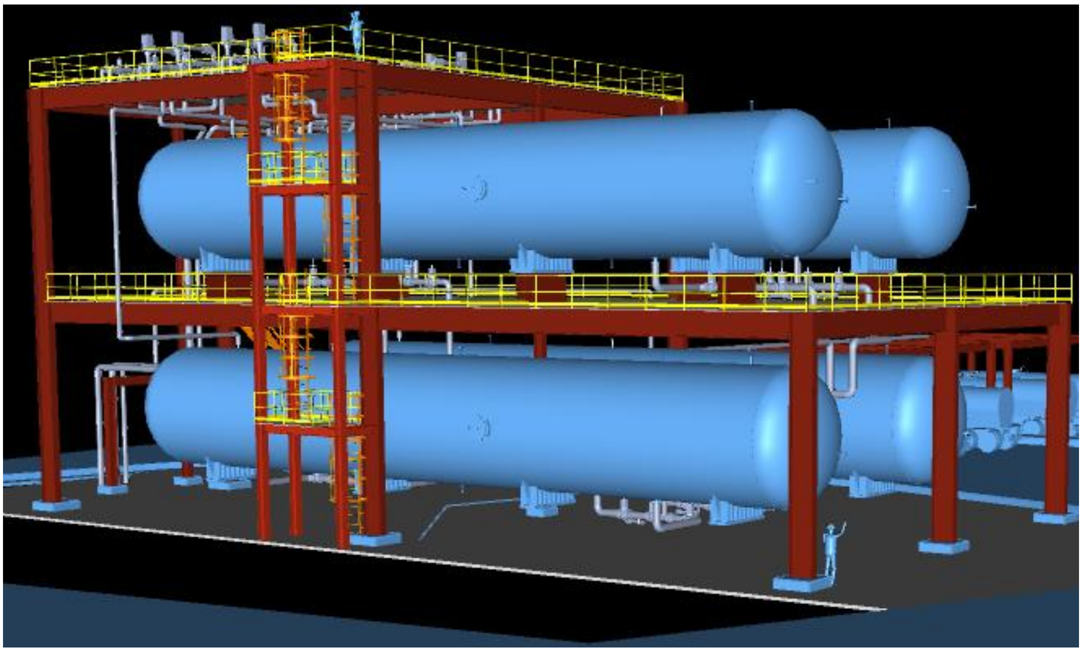


Figure 2-4: Storage tanks at Klemetsrud

From the liquefaction facility the liquefied CO_2 enters the four intermediate storage tanks. A schematic sketch of the storage tanks with piping and valves can be seen in Figure 2-5. The tanks are filled sequentially through the manifold. Valves to the tanks not being loaded will then be closed. The heat which is transferred into the tank is absorbed by the liquid CO_2 in the tank and will cause some of the CO_2 to be vaporized. The flashed and displaced vapour from the storage tanks is sent to a displaced vapour header for reliquefication.

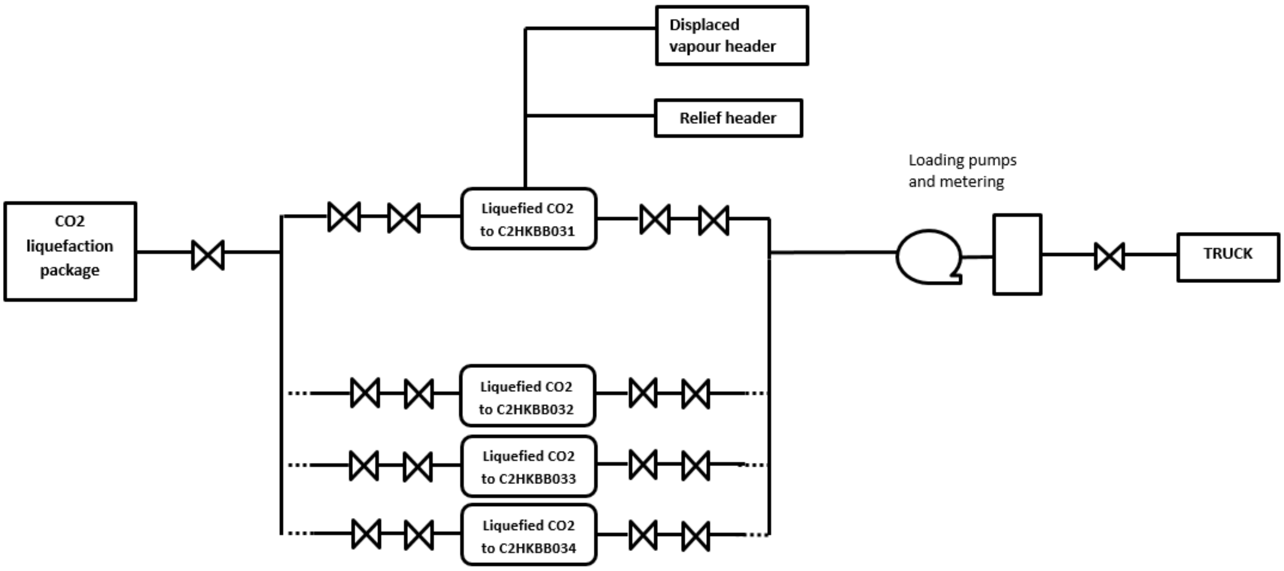


Figure 2-5: Schematic overview of lines in and out of storage tanks at Klemetsrud

At Oslo Harbour there are 16 storage tanks; each with a working capacity the same as at Klemetsrud (342m^3). The tanks are arranged in two levels as shown in Figure 2-6.

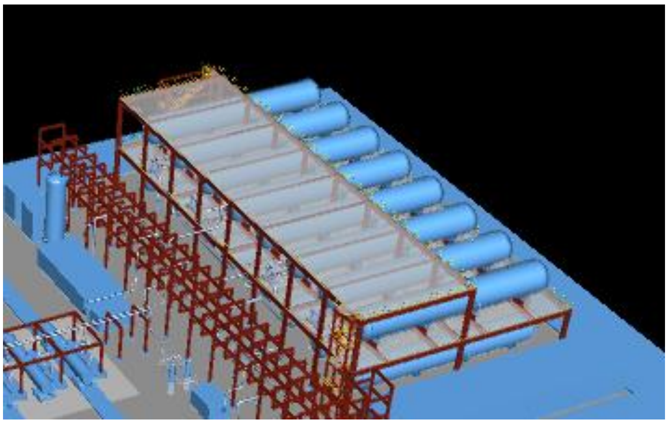


Figure 2-6: Storage tanks at Oslo Harbour

The storage tanks to be applied are designed as double walled “thermos bottles” to prevent heat transfer into the tank. There will be vacuum in the annular space between the inner and outer vessel. The heat which is transferred into the tank is absorbed by the liquid CO_2 in the tank and will cause some of the CO_2 to be vaporized. The vaporized gas will be recovered in the relief system and re-liquefied to prevent pressure build-up (or it could be vented to the atmosphere). Design basis for the proposed storage tank configuration is shown in Table 2.1.

Table 2.1: Design basis for storage tanks

Products	Inside diameter [mm]	Length [mm]	Working capacity [m^3]	Design pressure [barg]	Design temperature [°C]
Liquefied CO_2	4000	27500	342	17	-52 to 85

There will be a pressure relief system for the intermediate storage tanks with two PSVs and a blowdown valve as shown in Figure 2-7. Leaks in the inner or outer tank will be detected by pressure sensors in the annulus and in response to pressure build-up in the annulus, the tank will be depressurized. During blowdown the pressure will be reduced to 50% of design pressure in 11.5 minutes and 35% of design pressure in 15 minutes. There will be back-pressure in the relief system to prevent tank pressure from falling below the triple point and freeze.

Liquid CO_2 will solidify when the pressure drops below 4.18 bar. Blowdown lines as well as all PSV discharges from liquid CO_2 sources are routed to relief system with 4 bar(g) backpressure. This will prevent formation of dry ice and blockage of the relief lines.

At Klemetsrud venting through the flue stack is proposed, while at Oslo Harbour a dedicated vent stack will be required.

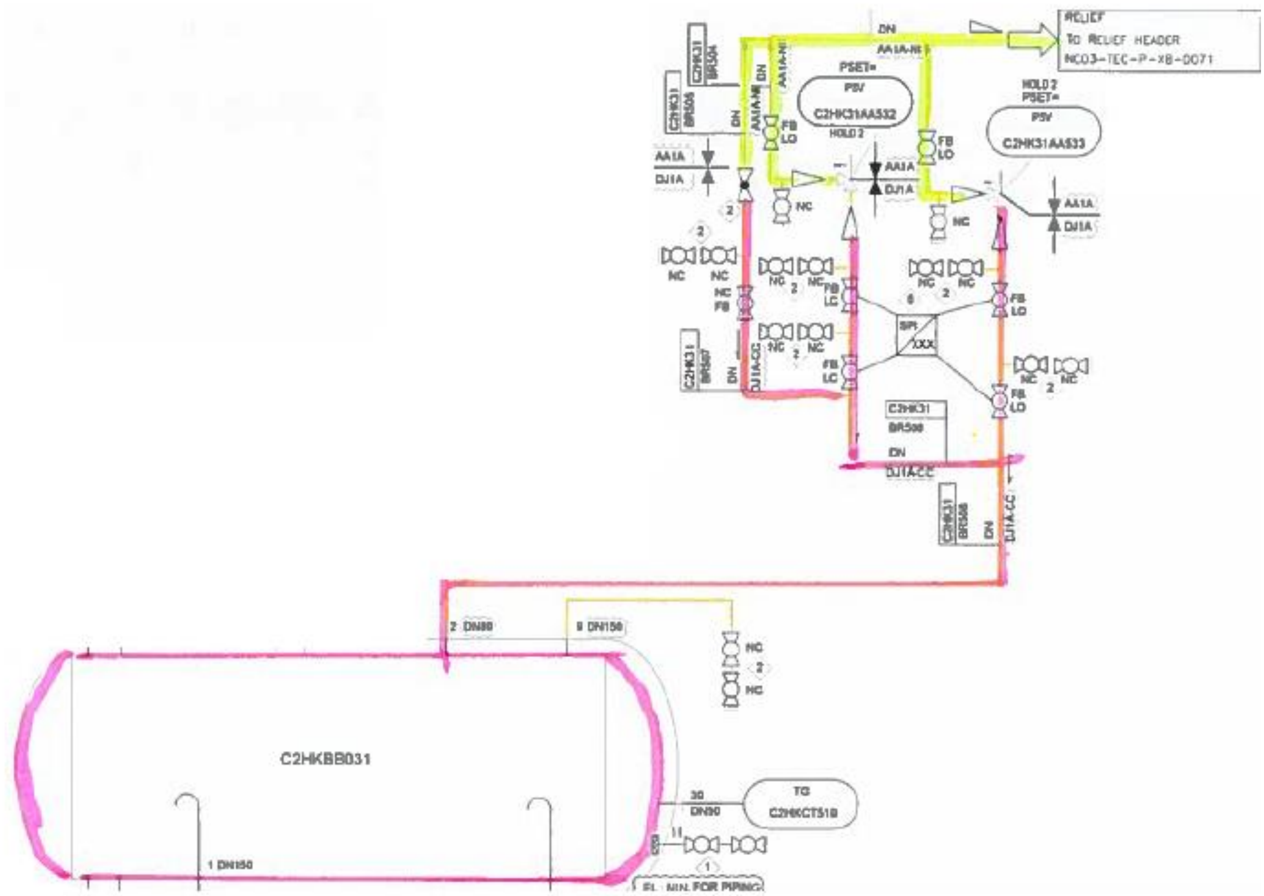


Figure 2-7: Storage tanks with pressure relief system

2.3 Truck loading and offloading

At Klemetsrud the liquefied CO_2 will be pumped to the trucks at a filling rate of approximately 75m^3/hour. The trucks will be unloaded in the harbour, and liquefied CO_2 transferred to the harbour storage tanks. The truck and storage tank will be connected by a displaced vapor line. Truck loading and offloading operations will be performed day and night, using 7 trucks in all. The total operation time for the trucks at the facility will be about 45 minutes. The duration of the filling operation will be about 25-30 minutes.

2.4 Truck transport

The preferred route to transport CO_2 from Klemetsrud to Oslo Harbour will be along E6 heading north to Ryen, continuing down the Ekeberg tunnel and Vålerenga tunnel and the southwest along E18 to Oslo Harbour (Figure 2-8). Note that the last part at Oslo Harbour may deviate from the indicated route.

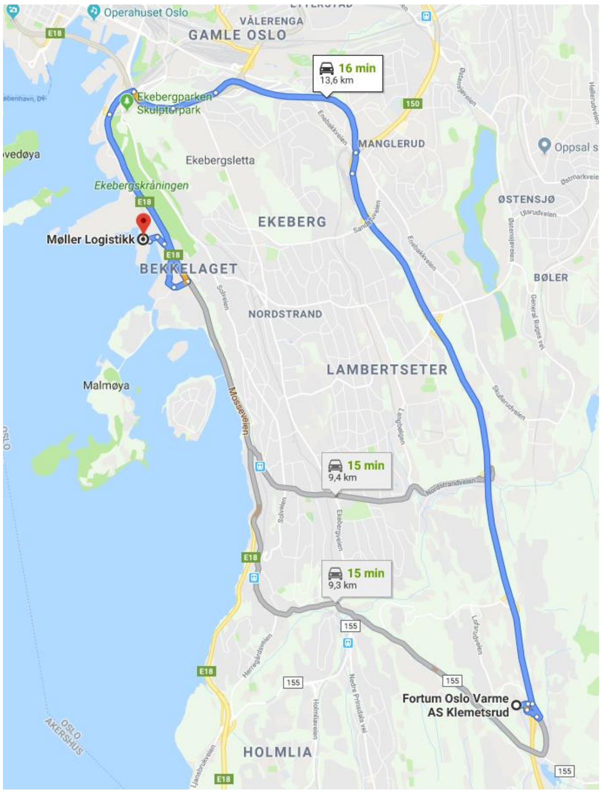


Figure 2-8: Truck transport route (blue)

Tank trucks will be purpose-built for this mission. Size of the trucks are assumed to be 50 ton. A truck of this size can transport a volume of 25m³ CO_2 at temperature -25°C and 15 barg pressure.

2.5 Harbour facilities

The current location being considered for storage and loading at Oslo Harbour is Sydhavna (Figure 2-9).

Figure 2-9: Oslo Harbour - Sydhavna

The south part of Oslo Harbour (Sydhavna) is considered a national centre for logistics and includes container handling, storage and distribution of petroleum products and more. Sydhavna is a harbour area with several different activities and facilities including container handling, storage and distribution of petroleum products. The oil terminal supplies about 40% of Norway's fuel consumption including jet fuel for Gardermoen airport.

Oslo Harbour has several major accident scenarios prior to introducing the CO_2 storage and offloading facilities. The facilities include the following

- Offloading facilities for CO_2 trucks
- 16 storage tanks
- Pipeline (300m, 6") to ship
- Loading system for CO_2 transport ship
- CO_2 transport ship

Location of the CO_2 storage tanks and nearby petroleum storage facilities can be seen in Figure 2-10.

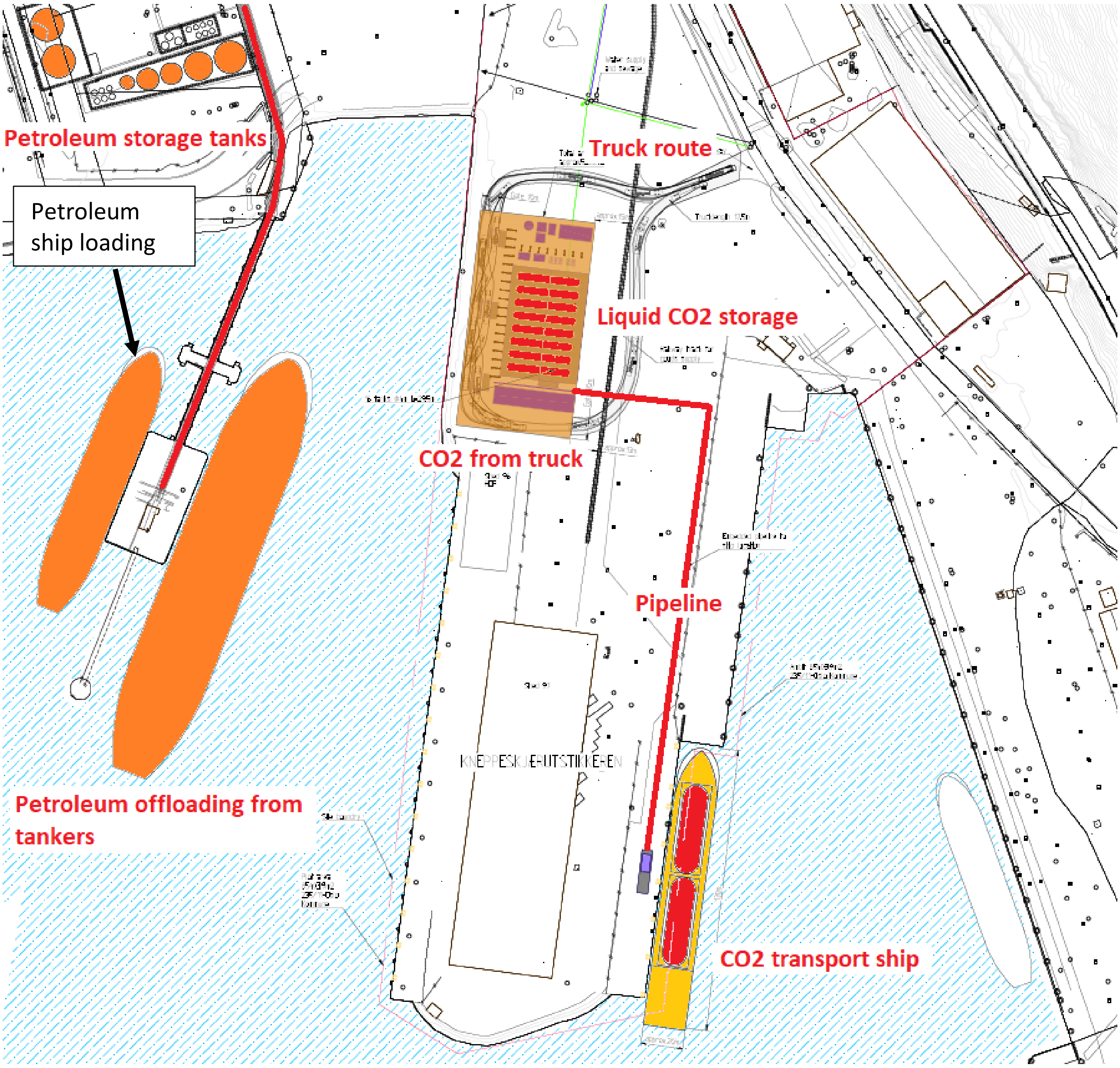


Figure 2-10: Intermediate storage at Oslo Harbour and nearby petroleum storage facilities

Port security – International ship and port facility security code (ISPS) is implemented at Oslo Harbour. This means that access control is implemented for the area. The intention is to reduce the risk for terror and sabotage.

The Norwegian Coastal Administration is the national authority responsible for implementing international regulations on port security. This includes supervision of port facilities concerning compliance with security and safety regulations

2.6 Weather conditions

Wind measurements from [1] are available from Bleikøya (near Sjursøya) and from Solveien between Sjursøya and Klemetsrud. It is 5 km between the two locations. According to these measurements the average wind speed at Bleikøya is 1 m/s, while the average wind speed at Solveien is 2 m/s. The dominant wind direction is from south. It seems the resolution in the wind direction measurements from Bleikøya has some limitations and does not match the resolution in the radar plot.

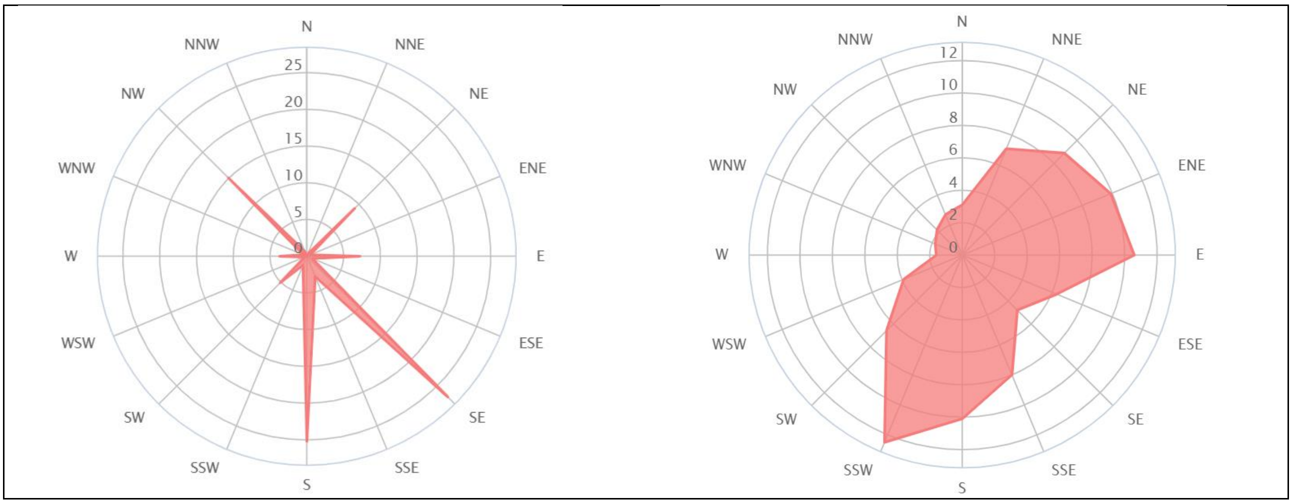


Figure 2-11: Wind direction distribution in %. Left: Bleikøya 2014-2019, right Solveien 2012-2019

2.7 DSB requirements/guidance for risk acceptance criteria

2.7.1 Minimal endogenous mortality

In a DSB guideline [2], Minimal Endogenous Mortality (MEM) is used to define risk acceptance criteria. The MEM method is based on experienced mortality rates in society, depending on age and sex. MEM compares the risks due to a proposed system or facility with already existing risks caused by "natural" mortality. MEM demands that the new system/facility does not significantly contribute to the existing mortality.

Statistics shows that for 10 to 14-year-old girls in Norway, the mortality rate is $7 \cdot 10^{-5}$ per year. For a planned new facility, $1 \cdot 10^{-5}$ deaths per 3rd party person and year are considered a noteworthy contribution to this background rate. Therefore, additional risk exceeding $1 \cdot 10^{-5}$ per year for an individual is not considered acceptable. This is used as basis for defining requirements to restricted area zones and criteria for individual risks in [2].

2.7.2 DSB guidance on restricted area zones

Based on the assessments in the previous chapter, $1 \cdot 10^{-5}$ per year fatality rate is proposed as a criterion for the intermediate zone (outside facility). This is the risk exposure for a person located near the facility's fence at all times.

Proposed risk acceptance criteria (DSB) for hazardous substances [2] (Lilleaker's translation)

- Individual risk shall be less than 10^{-5} per year for personnel outside the facility
- For 3rd party persons in residential areas, individual risk shall be less than 10^{-6} per year
- For particularly vulnerable persons in residential areas, individual risk shall be less than 10^{-7} per year
- Identified accident scenarios with a frequency 10^{-8} per year or less are considered broadly acceptable

In addition, the rules for restricted areas are included as part of the risk acceptance criteria. These zones are defined in accordance with Norwegian Regulations on handling of hazardous substances, (*FOR-2009-06-08-602, §16),* see Appendix B for more details.

DSB has used the term "hensynssoner" for restricted areas outside facilities with a risk potential. Figure 2-12 shows the different zones and the objects that are allowed in each zone. Defined this way, the restricted area zones outside the facility are stricter than the individual risk criterion, since a person will not always be exposed to high risks.

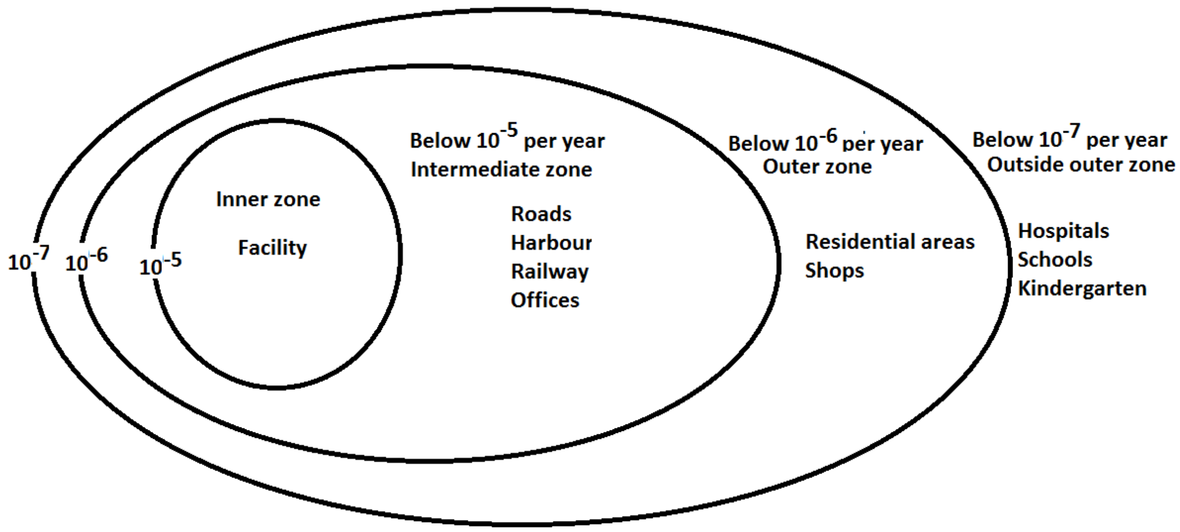


Figure 2-12: Restricted area zones

3 Methods and data

3.1 General

A general reference quantitative risk assessment that has been applied for this study is DSB's guidance for quantitative risk assessments [3].

3.2 Generic accident data

Relevant data sources and generic accident frequencies, focusing on leak frequencies, are presented in Appendix A. The data applied are historical data, frequencies based on fault tree analysis and expert judgement.

Leak frequencies are mainly based on HSE data, but other data sources have been used as well when considered relevant. The main leak sources to be considered at Klemetsrud and Oslo Harbour is piping and storage tanks.

Piping

When considering leaks from piping at Klemetsrud and Oslo Harbour, HSE data as shown in Table 3.1 has been applied.

Table 3.1: HSE data – piping leaks

Hole size (diameter), ref. HSE data	Hole size categories	Failure rates (per m per y) for pipework diameter			
		50mm to 149mm	150mm – 299mm	300mm – 499mm	500mm-1000mm
		2" to 5"	6" to 11"	12" to 20"	21" to 40"
4 mm	1 mm-10 mm	$2{\cdot}10^{-6}$	$1{\cdot}10^{-6}$	$8{\cdot}10^{-7}$	$7{\cdot}10^{-7}$
25 mm	11 mm-49 mm	$1{\cdot}10^{-6}$	$7{\cdot}10^{-7}$	$5{\cdot}10^{-7}$	$4{\cdot}10^{-7}$
1/3 pipework	-	-	$4{\cdot}10^{-7}$	$2{\cdot}10^{-7}$	$1{\cdot}10^{-7}$
Rupture	-	$5{\cdot}10^{-7}$	$2{\cdot}10^{-7}$	$7{\cdot}10^{-8}$	$4{\cdot}10^{-8}$

Considering leaks from flanges some of the considered data sets have included this in the leak frequency for piping. HSE and PLOFAM have specific data for these leaks. Details with regards to flanges has not been looked into in this project but depending of type of flange/gasket the leak frequency per year would be in the order of $1.0{\cdot}10^{-5}$ to $1.\ 0{\cdot}10^{-6}$ per flange joint.

Storage tanks

Liquefied CO_2 is stored in pressurised tanks both at Klemetsrud and at the harbour. Release of liquid CO_2 could be either from connected piping and flanges or from a crack or rupture of the tank itself.

When establishing frequencies for the CO_2 storage tanks it has been necessary to consider data for several types of vessels in order to reflect the design and content for the vessels to be used for CO_2 storage. As basis data from HSE has been used. The HSE has established frequencies for single- and double walled refrigerated vessels, and specific data have been derived for LNG storage vessels.

The HSE data divides the catastrophic tank scenarios into 3 main causes:

- Defaults developing in service
- Pressure/temp. outside design limits
- External damage

This is further discussed in chapter 3.3 and appendix A.

Table 3.2: HSE data, basis for establishing frequencies for catastrophic tank rupture scenarios

Vessel	Catastrophic failure frequency (per vessel year)	Comments
Pressure vessels	$1{\cdot}10^{-6}$	External impact excluded
Refrigerated ambient pressure vessels	$5{\cdot}10^{-7}$	
LNG vessels	$5{\cdot}10^{-8}$	Double walled

Leaks in the connection between pipe and tank are considered as leaks from vessel (with various hole sizes) or as leaks in piping (with frequencies from HSE as described above).

Loading/unloading hose

Both hose and loading arms are being considered for loading/unloading operations. Basis for this analysis is use of hose between truck and storage tanks and use of loading arms between ship and storage tanks. Leak frequencies from [4] have been use for establishing hose rupture frequencies. The frequency for full bore loss of containment incidents is $4.9{\cdot}10^{-8}$ per operation. Leak frequencies for loading arms (for ships) have been based on Purple book. Frequency for full bore rupture is $6{,}0{\cdot}10^{-5}$ per transhipment.

Other leak sources

In Appendix A frequencies for other leak sources such as process vessels, heat exchanger and pumps have been addressed as well. This is equipment that can be found on Klemetsrud and Oslo Harbour, but they have been judged to have minor effect on the total risk picture and are hence not looked further into.

3.3 Catastrophic failure of CO_2 storage tanks

Tank rupture or BLEVE are scenarios with major CO_2 release potential. For a BLEVE, there will be blast effects, with a potential for escalation to neighbouring tanks. Generic frequency for rupture of refrigerated- and pressurized storage tanks is addressed in Appendix A.

The HSE has established frequencies for single- and double walled refrigerated vessels. Specific data have been derived for LNG storage vessels. The double walled storage vessels at Klemetsrud and harbour might be compared to double walled LNG storage vessels but note that the recommended frequencies are applicable only if the outer wall is designed to retain fluids in the tank.

There are no recorded incidents as background for storage LNG vessel frequency and the HSE data does not give detailed background information regarding the frequencies. Potential causes can be divided into three categories as shown in Figure 3-1; failures developing in service, pressure or temperature outside design limits or external damages.

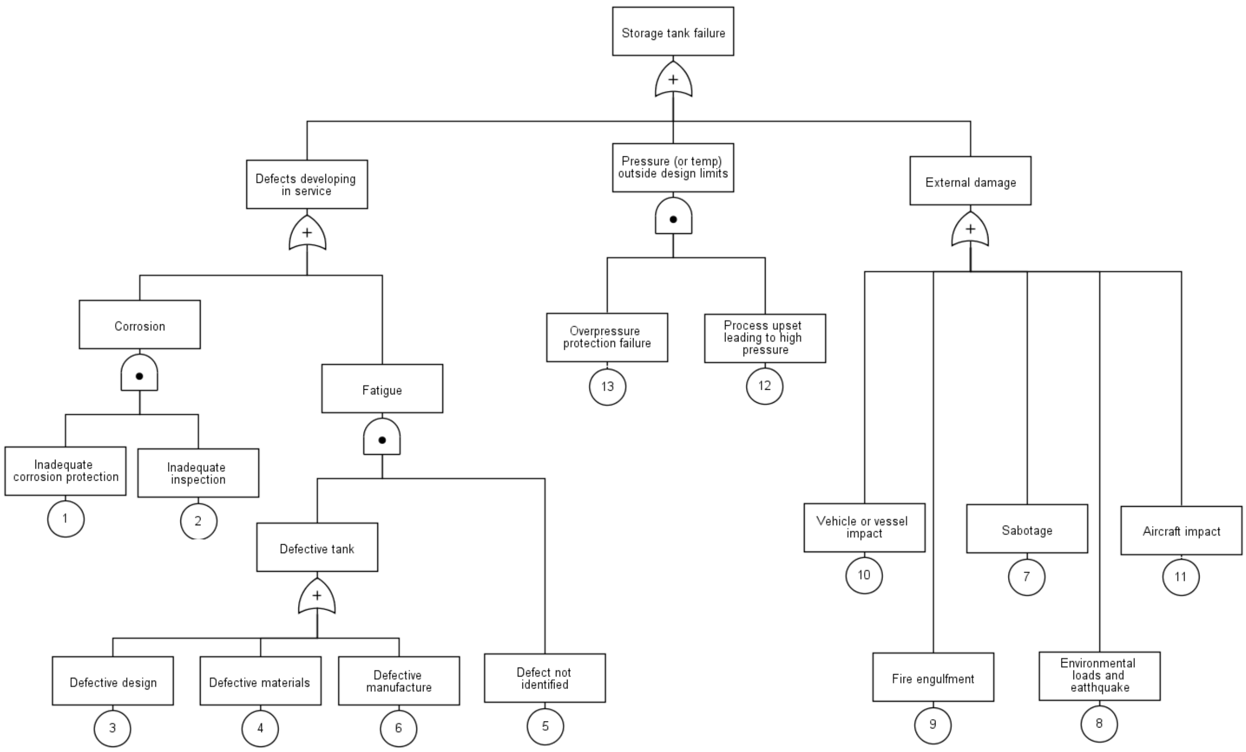


Figure 3-1: Causes for storage tank failure

Defects developing in service includes corrosion and fatigue that may undetected develop to a catastrophic failure. The CO_2 storage will consist of double walled tanks with pressure detection in the annulus, and this will possibly reduce the risk for undetected faults. Even minor leaks in the inner (or outer) shell will be detected since the vacuum in the annulus will be lost.

As observed from previous accidents, failures caused by *pressure outside design limits* can be catastrophic. For a fully isolated tank (relief valves closed or otherwise blocked), pressure would increase to about 60 bara as the temperature approach the ambient temperature. This overpressure scenario is prevented by the pressure control system including the PSVs. The considered tanks are relatively large and heating that cause pressure build-up will take long. Sensors will monitor temperature and pressure increase inside the tank and detect abnormal pressure and temperature.

The accidents described in Appendix A involved quite violent explosions (BLEVE) and caused fatal consequences and material damages. Relief system failure (blocked outlet/valve could be due to for example manually closed valves or ice) and gradual heating of tank inventory has caused some of these accidents. Note that with a BLEVE, there is risk for escalation to neighbouring tanks. Among the incidents reviewed in Appendix A, there is one example of an escalated scenario (Hungary 1969).

External damage includes threats as shown to the right in the fault tree in Figure 3-1. Safeguards are implemented to ensure that this risk contribution is as low as possible. Potential external threats will not necessary be the same for Oslo Harbour and Klemetsrud.

Relating these scenarios to the fault three shown in Figure 3-1, “pressure outside design limits” and “external damage” are considered causes to vessel rupture and BLEVE scenarios, while “defects developing in service” are considered causes for leaks in connection point between vessel and piping.

3.4 Leak and dispersion modelling

3.4.1 General

Dispersion modelling has been performed by DNVGL as a separate study. The study has been performed using a version of KFX that can handle solid CO_2 particles. A description of the simulation tool, the simulated scenarios and the geometry model applied is included in Appendix D.

The primary parameters that determine the hazardous distance for a liquid CO_2 release are:

Table 3.3: Parameters and the effect on gas dispersion

Parameter	Comment
Leak rate	The leak rate is the most important parameter determining hazardous distances, provided the inventory is sufficiently large such that a steady state gas cloud can be formed.
Leak duration	The leak duration is estimated assuming the tank is full, and the leak rate is constant. The time to establish a steady state gas cloud depends on the cloud size.
Leak direction	The simulations have assumed a jet release vertically downwards hitting a relatively flat surface. This is a wall-jet scenario with relatively little air entrainment and a good starting point for a heavy gas dispersion scenario with long hazardous distances.
Geometry/terrain	The scenarios simulated are heavy gas scenarios that to a large degree are affected by the terrain.
Wind	With moderate wind speeds it is seen that the terrain dominates the dispersion direction rather than the wind. Wind is the governing factor in flat surfaces such as the sea.

3.4.2 Modelling leak rates and durations

Leak rate is a function of fluid properties (pressure, density, etc.) and hole size. Initial leak rate modelling is described in Appendix A.

In this risk analysis and for the CFD simulations performed, CO_2 leaks are modelled with constant leak rate. The leak rate is determined by the initial conditions. During the leak scenario, pressure will drop, and the actual leak rate will fall. Intermediate storage at Klemetsrud and Oslo Harbour is planned with a blowdown system as described in chapter 2.2. Pressure drop may be a result of the leak itself, blowdown or a combination of the two. For leaks from liquid CO_2, pressure drop could lead to phase change of the inventory. The result could be vessel failure, or the leak could stop due to solid CO_2 clogging the leak.

Considering the transient nature of actual leak scenarios, the hazardous distances found using CFD (Appendix D) should be conservative.

3.5 Vulnerability of humans

3.5.1 CO_2 toxicity

According to the HSE, data available for carbon dioxide indicate that it does not meet the criteria for classification as a dangerous substance [5]. Nevertheless, releases of CO_2 have the potential to cause fatalities either due to short time exposure at high concentrations or due to long time exposure to more moderate concentrations.

Mortality for CO_2 exposure is given as probit functions is described in detail in Appendix A. The resulting mortality is shown in Figure 3-2. For exposure time one hour or less, 6% CO_2 concentration is used as the lower concentration that could pose risk for fatal accidents. This is also used as the lower concentration in the plots from CFD simulations.

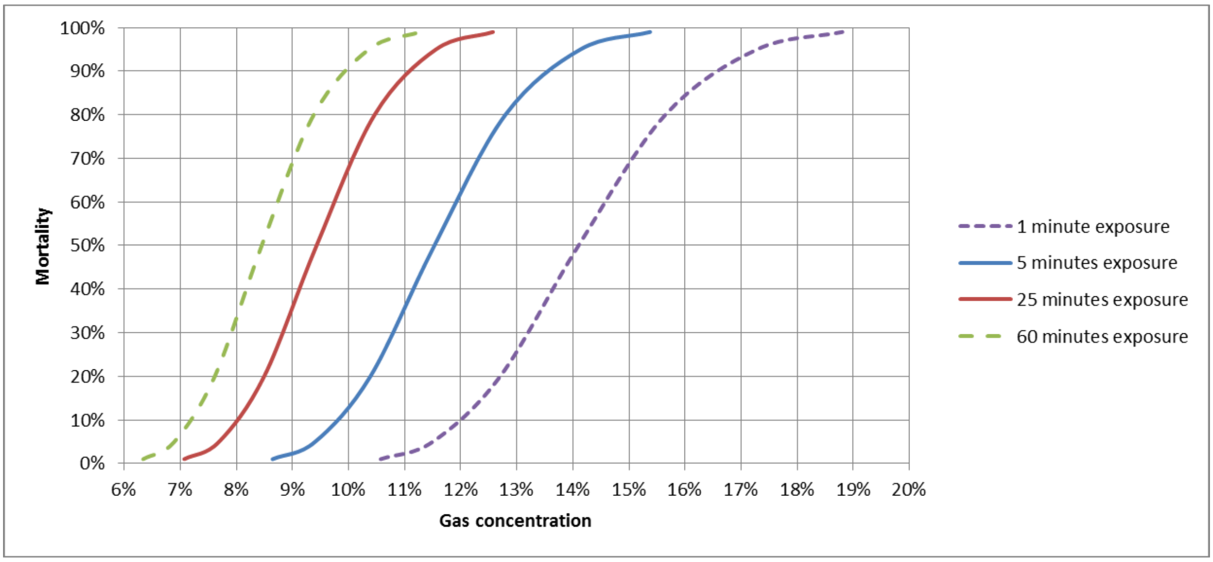


Figure 3-2: Mortality curves for CO_2 exposure for different exposure times

3.5.2 Exposure time

The accident scenarios identified give different dispersion distances and exposure periods. As to the vulnerability of humans, long exposure to low concentrations is “equally dangerous” as short exposure to high concentrations. The duration of a leak is therefore of significance for determination of fatal concentration levels.

Provided a fast-responding detection and alarm (PA) system, site personnel and third-party personnel will start evacuating. At the CC plant, personnel will be trained to evacuate to safe haven (mustering areas) which should be at high elevations (CO_2 is a heavy gas). Evacuation speed (walking speed) is normally set to 1 m/s which means it takes approx. 5 minutes to evacuate 300 meters. Although evacuation routes and muster areas are still not determined it is reason to believe that a safe haven can be established within this distance.

Evacuation of 3rd party personnel is more unpredictable since alarms and contingency plans are not established and because drills are not easily undertaken for persons in residential areas or for the public in general. For the input to the restricted area zones evaluation, one-hour exposure time has been applied in this study, unless the exposure time is judged to be shorter because the leak and exposure has short duration. This is judged to be a conservative approach, as it is believed that exposure times exceeding 30 minutes will be rare in most occasions. One-hour exposure means there is a risk for fatalities if concentration exceeds 6% (Figure 3-2).

3.6 Calculation of risk contours

Risk contours are obtained by combining the frequencies for the different leak scenarios by the gas dispersion results, using applicable models for quantifying fatality risk. The probit functions described in chapter 3.5.1 are applied for this purpose.

The principle applied for setting the risk contours in this report is best explained with an example. In Figure 3-3 there are four example scenarios, each with a frequency and a probability for fatal outcome as a function of distance in a chosen direction. The sum of the four scenarios is shown, and three bullets show the distance to the 10^{-5}, 10^{-6} and 10^{-7} iso-risk contours. In this simple case, we see that scenario B determines the 10^{-6} and 10^{-7} contours, while scenario B and C in combination determine the 10^{-5} zone.

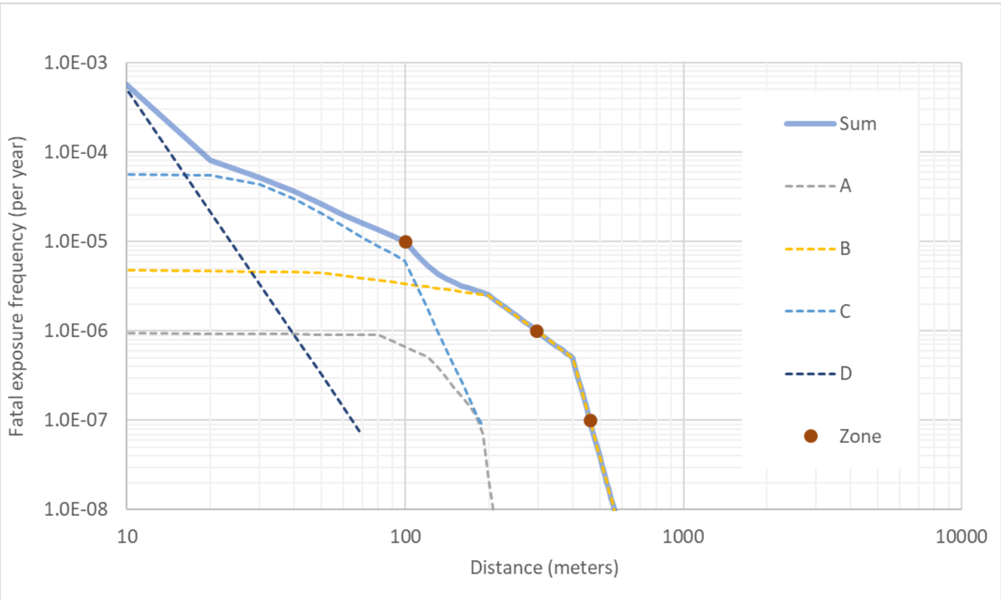


Figure 3-3: Calculation example for risk contours

4 Hazard identification (HAZID)

A combined HAZID and ENVID workshop was performed 31st of January 2019. The HAZID and ENVID is documented in separate reports; [6] and [7], respectively.

The HAZID forms the basis for the scenarios to be evaluated as part of the risk analysis. The HAZID did primarily focus on major accident hazards. These are hazards that could cause multiple casualties at the facility or expose 3rd party outside the plant area to accident effects such as toxic gases.

With respect to major accident risks, massive releases of CO_2 are the primary concern. The worst-case accident scenario is a catastrophic failure of the intermediate storage tank. This could either be a large leak or a BLEVE scenario.

There will be use of hydrogen in the oxygen removal process. Use of hydrogen also means the need for hydrogen storage. Hydrogen will most likely be stored in bottles at the facility, since quantity will be modest. A hydrogen leak could be a potential hazard as hydrogen is both flammable and potentially explosive.

Collision is a risk contributor for truck transport from Klemetsrud to the harbour. Most collision accidents will not involve any release of the cargo. The high number of daily round-trips means that the collision frequency is significant. The chosen transport route has dense traffic. Part of the route is downhill through tunnels, which means increased accident risk. In a worst-case collision scenario, 25 tons of liquid CO_2 could be released, which represents a severe accident scenario.

Storage and offloading to ship at Oslo Harbour include risk for leak of large quantities of liquid CO_2. Collision impacts to storage tanks and piping; overpressure and mechanical failure are among causes for acute large leaks. Explosion and fire loads from nearby sources may represent a threat to the storage. This was not addressed in the HAZID, as exact location of the facility at Oslo Harbour was subject to change at the time. The intermediate storage at Oslo Harbour is very similar to the intermediate storage at Klemetsrud, but there will be a larger tank farm (16 bullet tanks in two levels).

The identified hazards to be further evaluated when establishing risk contours are summarized in Table 4.1.

Table 4.1: Identified hazards to be further evaluated and reference to chapter in report

No.	Hazard	Description	Chapter
1	Gaseous CO_2 leak from the carbon capture plant.	a. Low pressure CO_2 leak upstream the compression package. b. High pressure CO_2 leak downstream the compression package.	6.1
2	CO_2 leak from liquefaction at Klemetsrud.	a. Liquefied CO_2 leak downstream liquefaction	6.3
3	CO_2 leak scenarios from storage tanks at Klemetsrud.	a. CO_2 leak from storage tank	6.4
4	Storage tank rupture at Klemetsrud.	a. An instantaneous release of tank inventory, incl. BLEVE	7
5	CO_2 leak in truck loading area at Klemetsrud.	a. CO_2 leak from loading hose b. Tank rupture/BLEVE truck	6.5
6	CO_2 leak in truck offloading area at Oslo Harbour.	a. CO_2 leak from loading hose b. Tank rupture/BLEVE truck	9.3.1
7	CO_2 leak scenarios from storage tanks at Oslo Harbour.	a. CO_2 leak from storage tank	9.3.2
8	Storage tank rupture at Oslo Harbour.	a. An instantaneous release of tank inventory, incl. BLEVE	7
9	CO_2 leak scenarios during offloading to ship	a. CO2 leak during offloading	9.3.3
10	Truck transport accidents	a. CO_2 leak from truck	8
11	Potential threats from neighbouring facilities.	A report has been issued by the DSB [8] specifically addressing the safety aspects at and near Sjursøya. Results will be considered when establishing risk contours at Oslo Harbour.	9.2.3
12	Hydrogen fire and explosion risks	Release from high pressure hydrogen equipment/piping of explosion of hydrogen bottles	6.2
13	CO_2 carrier ship collision with CO_2 and/or LNG release	Risks quantification for the CO_2 carrier was originally not part of the scope for this analysis. Relevant information and a coarse risk analysis is documented in chapter 9.4.2. CO_2 carrier collision frequency is quantified in consistence with assessments performed for the Northern Lights project [9].	9.4.2

In addition to the hazards identified and listed above, there is a general concern and risk for liquid CO_2 being blocked between closed valves in a shut-down situation. As the liquid CO_2 is heated, pressure will increase up to about 60 bar. Pipe rupture will occur when the structural capacity is reached. This could result in risk to personnel and possible damages to adjacent equipment.

Release of other substances and other hazards were discussed in the HAZID session as well. However, these hazards will not be evaluated further as they have been judged to have minor relevance for risk of 3rdparty. Hazards not further evaluated is listed in Table 4.2.

Table 4.2: Identified hazards that are not quantified further

Hazard	Description
Other releases in CC plant: • Flue gas • Solvent (amines dissolved in water) • Degraded solvent (sludge) • Refrigerant (R-1234ZE and ammonia seem to be viable options) • Caustic soda / NAOH (diluted to about 20% during pumping to consumers) • Hot water • Lube oil • Glycol	It has however been concluded that the amounts are too small being a concern for personnel outside the vicinity of the leak or for people outside the plant area (3rd. party). Such releases are therefore subject to WHERA sessions. Further description can also be seen in the HAZID/ENVID log sheets [6], [7].
Occupational risk	Occupational risks will be subject to the WHERA; a separate study in the project.
Sabotage	The probability for sabotage is not quantified. It is assumed that necessary mitigating measures to prevent this is implemented.

5 CFD simulation scenarios

A set of gas dispersion simulations was performed as part of the concept risk analysis [10]. This set of simulations have been documented in [11]. The simulations from the concept phase included the following:

- Large leaks from large spherical tanks at alternative locations in Oslo Harbour (a 10" hole with release rate 1270 kg/s)*
- Gaseous leaks from pipeline
- Large leaks from intermediate storage at Klemetsrud (254 kg/s)

* Note that the piping dimension now has changed from 10" to 6". Hence, the frequency for a 1270 kg/s are remote (since all piping is 6" or less).

A set of new gas dispersion simulations have been performed for the FEED phase. These simulations are documented in Appendix D to this report. The new simulations

- Intermediate storage in Oslo Harbour is at Sjursøya-Kneppeskjær
- Intermediate storage in Oslo Harbour is in bullet tanks significantly smaller than the previous spherical tanks, and the piping dimension is reduced to 150mm
- Layout and arrangement at Klemetsrud have been revised

Chapter 3.4 lists the input data for the gas dispersion simulations and discusses the use of constant leak rates until the inventory is emptied (blowdown and pressure drop are not reflected).

Table 5.1: Loss of containment scenarios simulated using KFX for the FEED phase

Case	Location	Rate kg/s	Jet direction (towards)	Comment
1 (2-Phase)	Interm. Storage, Klemetsrud	617	Down	600 kg/s is approximate rate for 6" hole Leak from tank at upper level Constant leak for 8 minutes
2 (2-Phase)		617	East	600 kg/s is approximate rate for 6" hole Leak from tank at lower level Constant leak for 8 minutes
3 (2-Phase)		119	Down	20% of full rupture, lower level
4 (2-Phase)		119	East	20% of full rupture, upper level
6 (gas)	Gas compression, Klemetsrud	17	East	Gas leak, long duration
7 (gas)		30	South	Gas leak, 2 minutes
8 (gas)		50	Down	Gas leak, 1 minute
9 (2-phase)	Truck loading, Klemetsrud	50	Down	Hose rupture scenario, 1 minute
10 (2-phase)		250	Down	Diameter is maximum 100mm. Maximum (initial) rate is about 250 kg/s. 20 sec. duration.
11 (2-Phase)	Sjursøya	617	Down	6" hole, leak from tank at upper level Constant leak for 8 minutes
12 (2-Phase)		617	Down	6" hole, leak from tank at lower level Constant leak for 8 minutes
13 (2-Phase)		617	East	6" hole, leak from tank at upper level Constant leak for 8 minutes
14 (2-Phase)		617	West	6" hole, leak from tank at lower level Constant leak for 8 minutes

6 Risk assessment – carbon capture plant and storage at Klemetsrud

6.1 CO_2 leaks at the carbon capture and conditioning plant

The carbon capture plant will handle large quantities of gaseous CO_2. The plant is naturally ventilated. Depending on exposure time, CO_2 leaks are considered potentially lethal at about 6 % concentration.

CO_2 rich absorbent is routed to the CO_2 stripper. The pressure in the feed line upstream and downstream the stripper is modest, about 1 barg. Downstream the stripper gaseous CO_2 is routed further to compression. The low-pressure gaseous CO_2 is transported through piping with diameter of 800mm (30 inch). After four stages of compression the gaseous CO_2 has a pressure of about 43 barg. The CO_2 is transported and conditioned through several vessels for i.e. oxygen removal and dehydration before liquefaction. The piping for compressed gas has a diameter of 200mm (8 inch).

There is a shut-off valve between the liquid CO_2 volume in the liquefaction process and the gaseous CO_2 volume. For the piping with low pressure gaseous CO_2 between stripper and compressor package, the length of piping is approximately 150 meters. The leak rate depends on the pressure (and partly on the temperature) inside the segment. Down-stream the stripper where the pressure is low (1 barg) the leak rates will be relatively low given a small hole. Large holes or rupture may provide large leak rates initially, but upon detection and shutdown the leak rate will drop rapidly, and the duration will be short due to limited CO_2 mass in the segment. It is expected that this scenario will not affect personnel outside the facility and hence the scenario is not quantified further.

For the piping with high pressure gaseous CO_2, between compressor- and liquefaction package, the length of piping is considered to be approximately 100 meters. The duration of a rupture scenario will due to the quantities be short. Smaller leak hole sizes could last for some minutes.

It is assumed a Gaseous CO2 inventory in the CC plant of approximately 3000 kg. This assumption is based on the volume of the Oxygen Removal Reactor (C2HKAZ002) with an approximately volume of about 20m^3, and some piping.

Release of gaseous CO_2 in the capture and conditioning plant

Scenarios with leak rates of 17 kg/s, 30 kg/s and 50 kg/s have been simulated by use of KFX. The results show that the lower rates will to a small degree expose the area outside the process area to lethal CO_2 concentrations. A leak with rate 50 kg/s can be seen in Figure 6-1.

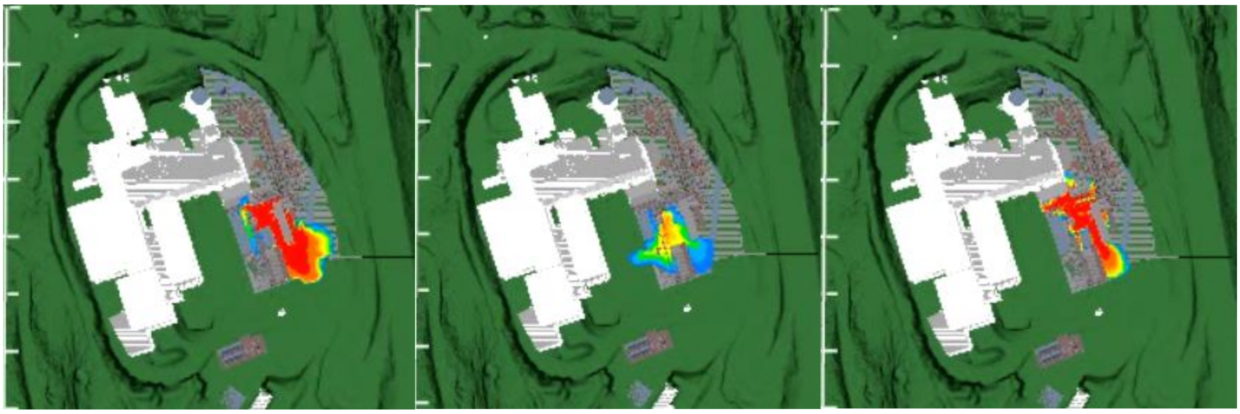


Figure 6-1: Gas cloud when release stops and 3000kg CO_2 has been released. Case 06, 07 and 08

The plots in Figure 6-1 show the following (3000 kg CO_2 released):

- Case 06 - 17 kg/s leak towards east, 3 minutes after the leak started
- Case 07 - 30 kg/s leak towards east, 1.5 minutes after the leak started
- Case 08 - 50 kg/s leak towards east, 1 minute after the leak started

It will take some time before gas is removed from all the area. The rightmost picture in Figure 6-1 shows the 50 kg/s scenario when the leak is assumed to stop after 1 minute. Figure 6-2 shows the gas remaining in the area after the leak is stopped. After about 30 minutes there is still some gas in the area. The wind speed in this case is 3 m/s with direction from south.

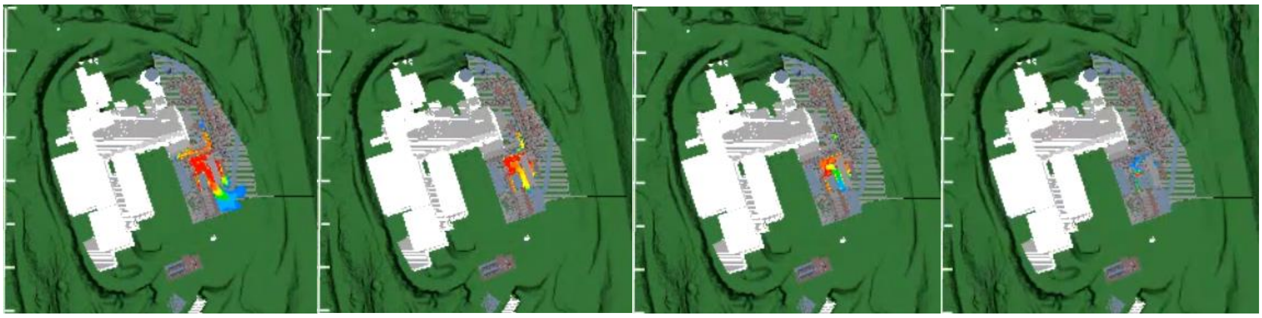


Figure 6-2: Case 08 at 4, 9, 14 and 28 minutes after the leak is stopped

From these simulations it is seen that there is not very much difference between a 17 kg/s leak and a 50 kg/s leak when it is reflected that the larger leak will have longer duration. What is more important is whether the leak is obstructed or not. An unobstructed jet will not form a large gas cloud, and the gas will disappear very fast when the leak is stopped. Case 04 (Figure 6-4) shows an example of an unobstructed jet for comparison.

The frequency for leaks from piping have been based on HSE data and is shown in Table 6.1. The rupture scenario is assessed to potentially affect a larger area, but the average mortality within this area is expected to be relatively low, since duration of CO_2 exposure is likely to be short.

Table 6.1: Leak rates- and frequencies for CO_2 gaseous leaks at carbon capture plant

Hole size	4 mm	50 mm	70 mm	Rupture
Leak rate [kg/s]	1	17	30	>50
Leak frequency per year	1.0E-04	7.0E-05	4.0E-05	2.0E-05

Considering leaks from flanges some of the considered data sets have included this in the leak frequency for piping, but HSE and PLOFAM have specific data for these leaks. Details with regards to flanges has not been looked into in this project but depending of type of flange/gasket the leak frequency per year would be in the order of $1.0 \cdot 10^{-5}$ to $1.0 \cdot 10^{-6}$ per flange joint.

A coarse quantification of individual risk level in the area can be performed by distributing the risk contribution over the area with high pressure CO_2 equipment and piping. For these cases, the impacted area is about $50m \cdot 70m$. With 50% lethality in average for the area, the individual risk level for a person in the process area is $8.5 \cdot 10^{-4}$ per year.

6.2 Hydrogen leak scenario at the carbon capture and conditioning plant

Hydrogen is used for oxygen removal; hence there is a risk for jet fire and gas explosion.
At the suction of the fourth stage of compression, hydrogen is injected. From this stage the CO_2 is routed to the Oxygen Removal Reactor (C2HKAZ002). This vessel has a volume about 20m^3 and will contain high pressure CO_2 (with some hydrogen). The hydrogen injected reacts with oxygen to form water, reducing the concentration of oxygen to the specified level. The average dosing rate of hydrogen is 4.8 kg/d og 1600 kg/year [12]. This reference has a note that says hydrogen will be delivered from a tube trailer, but with the modest quantities applied delivery from bottles will be chosen [13].

In any case, there will be hydrogen at high pressure handled and stored and used at the facility. There is a fire and explosion risk related to the hydrogen use. Hydrogen storage must be well protected from possible impact and fire exposure. Where hydrogen is used indoors, the gas explosion risk must be considered. A hydrogen gas detection system must be considered. A vent system for pressure relief and other safety measures may also be required. With moderate quantities of hydrogen stored and handled at the facility, risk contribution outside the fence should be very low. This risk is not further quantified in this FEED QRA.

6.3 CO_2 leak scenario from liquefaction at Klemetsrud

The liquefaction process comprises several steps of compression and cooling, H_2O and O_2 removal to reach the CO_2 export specification. Few details about the liquefaction package are available at current stage, and both the frequency estimates and the leak durations are thus uncertain. The focus in the risk assessment is on 3rd party risk, and the focus is therefore on large release scenarios. There will be shutdown valves downstream the liquefaction package. This will prevent the storage tank(s) to be emptied in case of a leak in the liquefaction package.

Gaseous CO_2 leaks upstream the liquefaction package was evaluated in chapter 6.1. Approximately 250m of 6`` piping will be installed for transporting the liquefied CO_2 from liquefaction package to the storage tanks. Most of the piping will however be underground. The potential release points will then be close to the package or close to the storage tanks.

The frequency for leaks from piping have been based on HSE data and is shown in Table 6.2.

Table 6.2: Leak rates- and frequencies for CO_2 leaks from liquefaction at Klemetsrud

Hole size	4 mm	25 mm	50 mm	Rupture (150 mm)
Leak rate [kg/s]	1	17	70	650
Leak frequency per year	2.5E-04	1.8E-04	1.0E-04	5.0E-05

If the compression and liquefaction equipment is located within a building, a leak may quickly fill the building with lethal concentrations of CO_2. Procedures for building entrance and gas detection must be in place to ensure that personnel do not enter the building without proper protection if a CO_2 leak has occurred.

Leaks outside could be comparable to CO2 leaks from the filling station and CFD simulation results for these scenarios are described in chapter 6.5. Personnel outside the facility is not likely to be exposed in these scenarios.

6.4 CO_2 leak scenario from storage tanks at Klemetsrud

Figure 6-3 shows the piping and valve arrangement for the CO_2 storage tank outlet. There is about 2 meters of piping to the first shutdown valve. This means that in case of a pipe rupture on the tank outlet or inlet there is a potential for emptying the whole tank inventory through the hole (given there is no system or arrangement inside the tank to prevent tank content to be emptied).

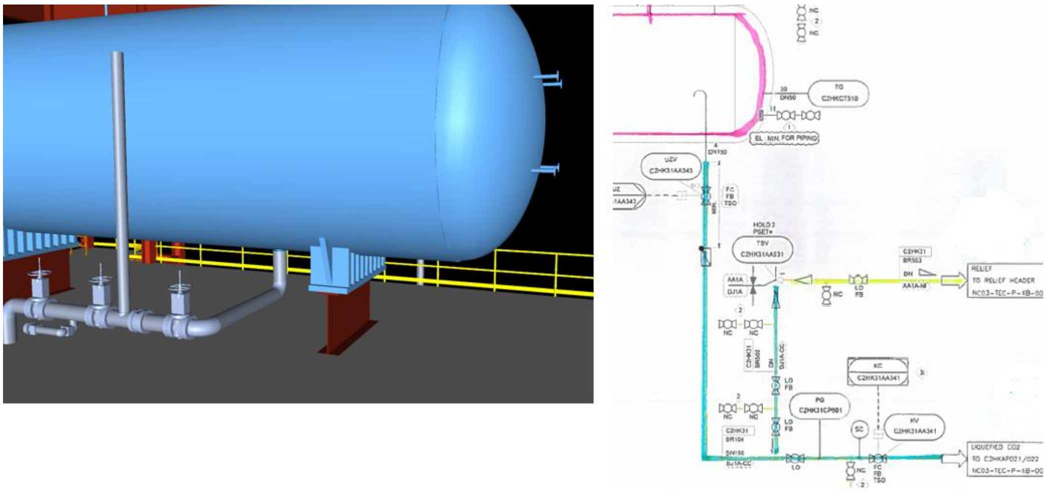


Figure 6-3: Piping and valves downstream the CO_2 storage tank (arrangement is equal upstream the storage tank)

The leak frequencies are based on HSE data; both for piping and pressure vessels. Basis for the frequencies in Table 6.4 can be found in Appendix A. Lengths and number of storage tanks that has been used as basis when calculating the frequencies are summarised in Table 6.3.

Table 6.3: Lengths and number of storage tanks used as basis for frequency calculations at Klemetsrud

Leak source	No./ m
Storage tanks	4
Piping length	16

A scenario of 650 kg/s, corresponding to a rupture of a 6" piping, is considered as the as the worst credible scenario when establishing the restricted area zones. A hole size of 50mm will (approximately) correspond to 20% of the cross section of a 6" pipe.

Table 6.4: Leak rate- and frequencies for CO2 leak scenarios from storage tanks at Klemetsrud

Hole size	10 mm	25 mm	50 mm	Rupture
Leak rate [kg/s]	3	17	120	650
Leak frequency per year	1.6E-05	1.1E-05	1.0E-05	3.6E-06

6.4.1 120 kg/s release scenarios

The simulation cases 3 and 4 illustrate the dispersion pattern for 120 kg/s constant leak rates from a storage tank with liquid CO_2. The duration of such a leak can be 50 minutes, but this is a rather theoretical case since pressure drop would make the scenario transient.

Figure 6-4 shows the unobstructed jet dispersion for a 120 kg/s jet. The jet length is about 100 meters, and the cloud will disappear almost instantly when the leak stops. This scenario is not considered very likely, since for most leak points there will be at least some obstructions that will disturb the free jet.

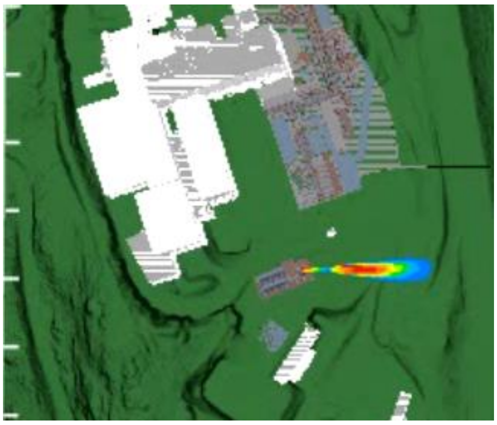


Figure 6-4: Gas dispersion for a 120 kg/s unobstructed jet (Case 04)

For an obstructed jet, there a gas plume driven by gravity and wind forces will result. A downward directed jet can be considered a worst-case scenario and representative for an obstructed jet dispersion. The transient development of the gas cloud from a 50 minutes constant rate leak scenario is shown in Figure 6-5 and Figure 6-6.

Figure 6-5 shows the developing cloud after 1 minute and 10 minutes into the leak scenario. After about 30 minutes, the gas cloud is fully developed and remains about steady until the leak stops at 50 minutes. The maximum gas extent is shown to the left in Figure 6-6.

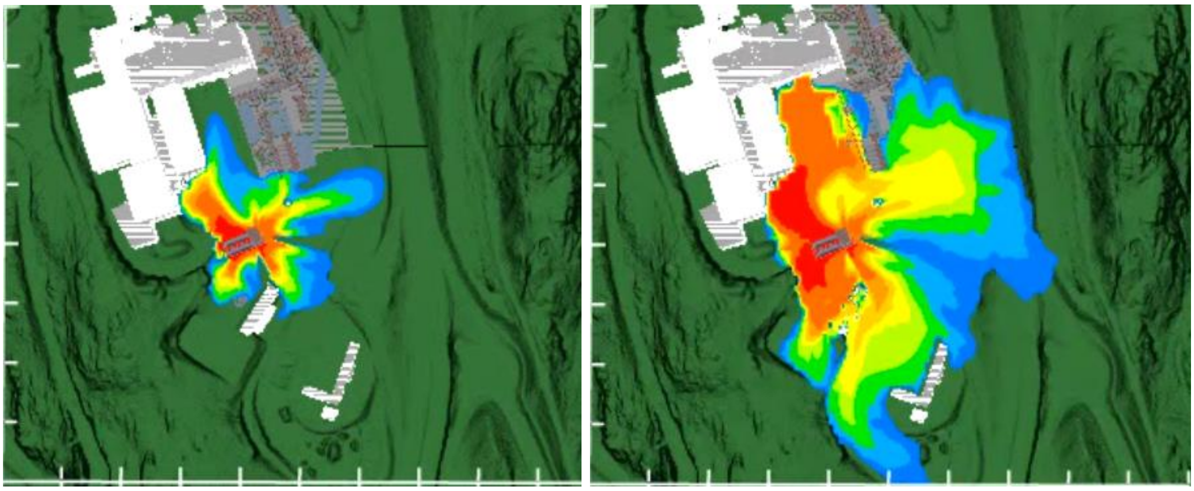


Figure 6-5: 120 kg/s downward jet, after 1 min and 10 min constant release (Case 03)

After the leak stops, it takes some time for the gas to be diluted. The two pictures to the right in Figure 6-6 show the situation 15 and 30 minutes after the leak stops. Gas remains in low spots and there is also gas trapped in the carbon capture plant. In this case there is 3 m/s wind from south, and this probably contributes to trapping gas at and near the carbon capture and waste to energy facilities.

Form an escape and emergency response perspective it is observed that the north side of the plant is virtually free from gas.

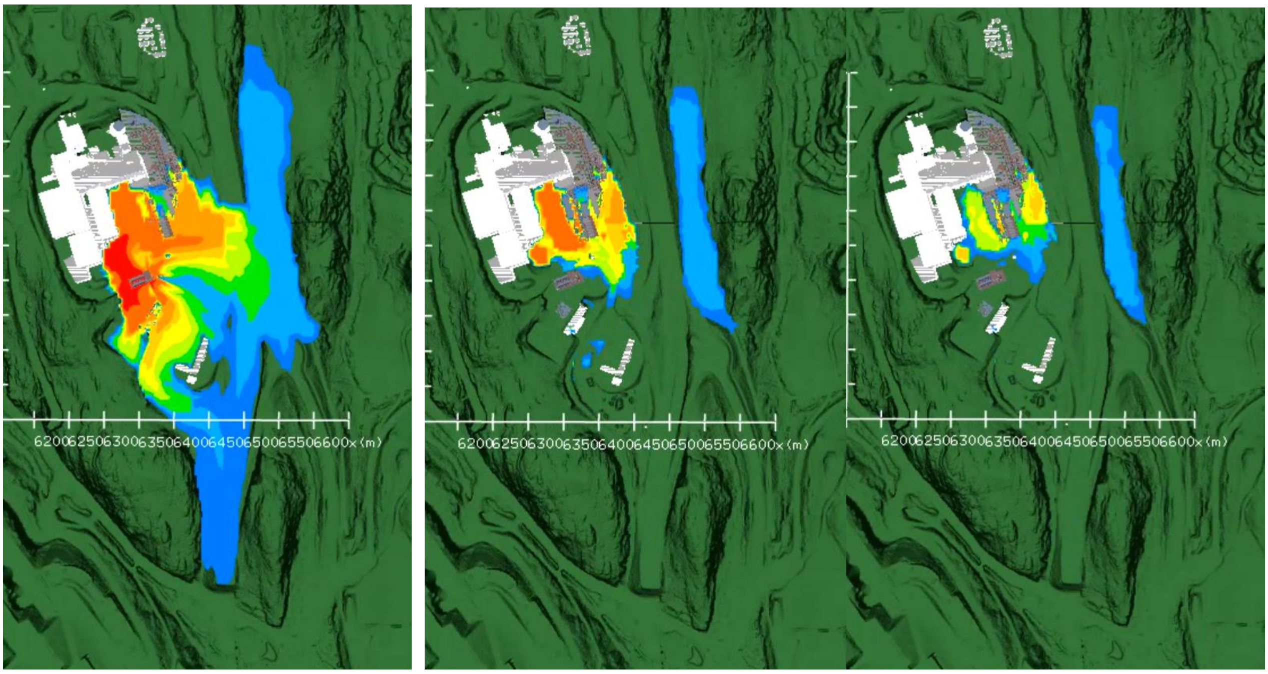


Figure 6-6: 120 kg/s downward jet, when leak stops, 15 minutes and 30 minutes later (Case 03)

6.4.2 600 kg/s release scenarios – 6" hole size

The 600 kg/s case corresponds to the initial release rate for a 6" pipe rupture. As for the 120 kg/s scenario, a large gas cloud is formed if the jet is obstructed. A free horizontal jet for this case would appear as shown in Figure 6-7.

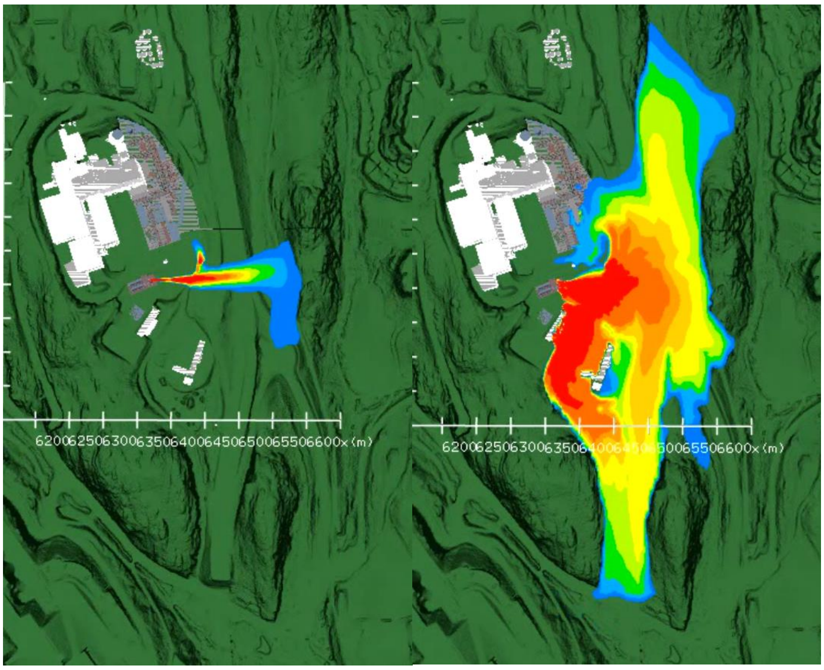


Figure 6-7: 617 kg/s horizontal jet. Left: unobstructed (case 02) and right, obstructed (case 02a)

A downward directed jet will result in an even larger gas cloud than the obstructed horizontal jet shown in Figure 6-7. The transient development of this scenario (Case 01) is shown in Figure 6-6. It is seen that there is dense gas at the highway after about 2-3 minutes and that a large area will be exposed to a high concentration CO_2 gas plume within 8 minutes. Then, the gas cloud continues to grow while other parts are diluted, reaching the max extension about 8 minutes after the leak is stops (16 minutes after start of the leak).

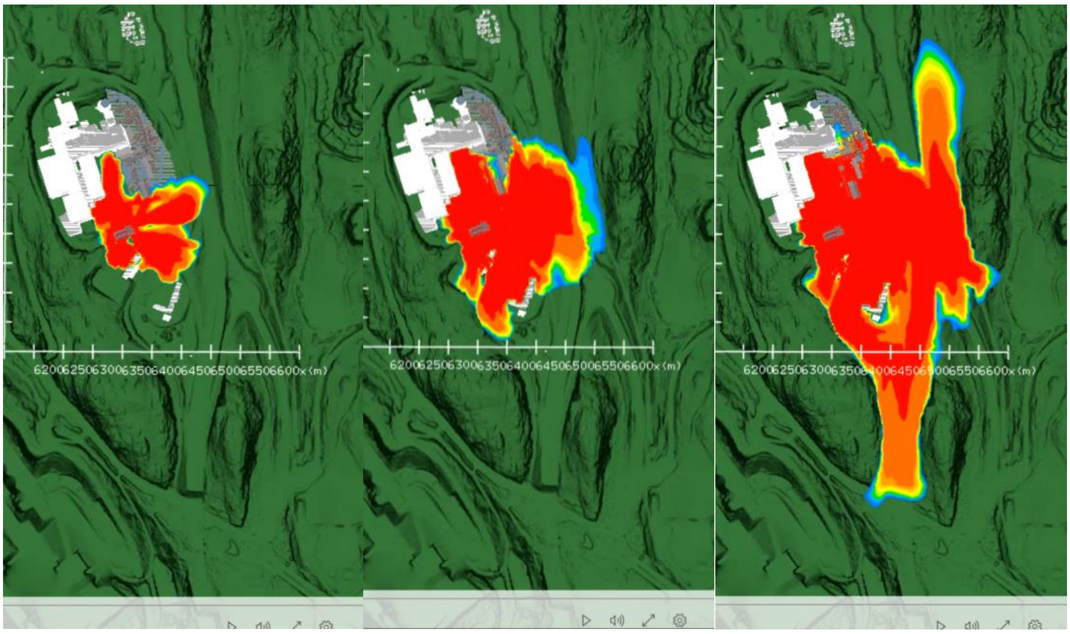


Figure 6-8: 617 kg/s down after 1, 3 and 8 minutes

After the cloud reaches its maximum extension, the gas is diluted gradually. Figure 6-9 shows that there are still areas with high (and lethal) gas concentration half an hour after the leak stops. The simulation was stopped at this point, but still illustrates that it may take hours before the area is gas-free.

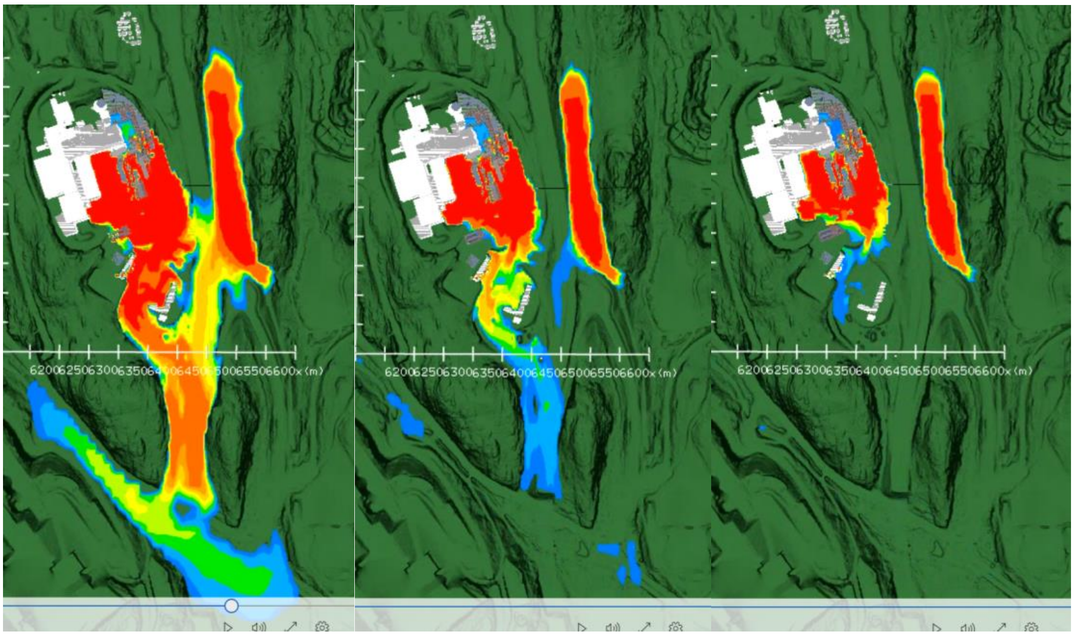


Figure 6-9: 617 kg/s down after 16, 26 and 36 minutes (leak stopped after 8 minutes)

6.5 CO_2 leak scenario from truck/hose at Klemetsrud

6.5.1 Leak from loading hose

With 90% of CO_2 captured, the initial transport demand is approximately 400 000 t/yr, with a future capacity demand at 587 400 t/yr (future line 4). It is assumed 25m^3 CO_2 capacity per truck. The resulting number of loading and offloading operations per year is approximately 16 000. This means in average 45 round trips per day for the initial case.

Flexible loading hoses are applied. With a filling rate of approximately 75 m^3/hour the total loading time is:

Loading time = 25 m^3/ 75 m^3/h ≈ 20 minutes

In total it is assumed that the truck will be at the facility 30 – 40 minutes.

It is assumed that the offloading system is provided with an automatic shutdown valve to stop outflow from the tank in the event of a hose leak. It is also assumed there is an automatic shutdown valve on the upstream side of the tank close to the first tank flange. The quantity of liquid CO_2 released is set to 3000 kg for the consequence evaluation.

Table 6.5 shows the leak frequencies based on the chosen generic data. Reference is made to Appendix A for more details on generic leak frequencies. Due to the high number of load transfer operations, the leak frequencies are relatively high.

Table 6.5: Leak frequencies for hose load transfer operations - KLEMETSRUD

Leak hole diameter (mm)	Frequency (per operation)	Leak rate (kg/s)	Number of operations at KLEMETSRUD	Leak frequency (per year)
15	$2.8 \cdot 10^{-6}$	7	16 000	0.044
25	$2.0 \cdot 10^{-7}$	17		0.0031
Full rupture	$4.9 \cdot 10^{-8}$	250		0.00076

Leak consequences

Leak consequences for truck loading has been assessed based on gas dispersion case 09 and 10. For both cases the wind speed is 3 m/s and the wind direction from west.

- Case09: 50 kg/s for 1 minute directed down (3000 kg released)
- Case 10: 250 kg/s for 20 seconds directed down (5000 kg released)

Figure 6-10 shows the resulting gas cloud. The last picture shows some solid CO_2 (dry-ice) at the ground. Case 11, which is a 250 kg/s leak for 20 seconds is has a marginally larger footprint.

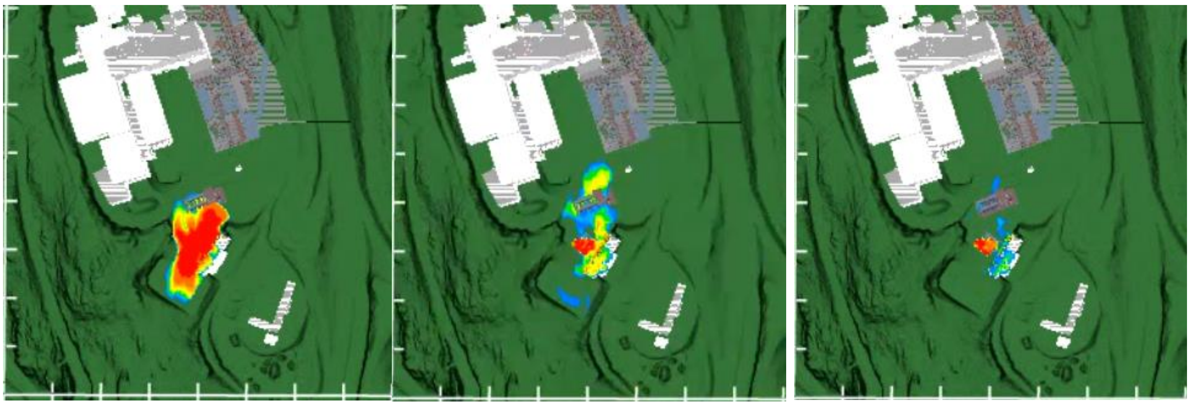


Figure 6-10: Case 09 (50 kg/s for 1 minute) when leak stops, 1 minute later and 2 minutes later

Note that if a tanker is emptied, the inventory is about 25 tons, and this is significantly more than assumed in these simulations. The leftmost picture in Figure 6-10 gives an illustration of the worst-case scenario.

It is assumed that the offloading system is provided with an automatic shutdown valve to stop outflow from the tank in the event of a hose leak. It is also assumed there is an automatic shutdown valve on the upstream side of the tank close to the first tank flange. Releases during loading and offloading operations are therefore found to lead to limited quantities of CO_2 release, and will primarily pose a risk to nearby personnel. The restricted area zones are judged not to be affected by incidents during loading and offloading.

6.5.2 Tank rupture/BLEVE - truck

Scenarios like heat exposure of truck tank or overfilling could cause pressure build-up in the tank and could potentially result in a BLEVE scenario. HSE proposes failure rates for road tankers; $2.2 \cdot 10^{-7}$ (per km). With a relatively short driving distance at the Klemetsrud area, the frequency is estimated to approximately $1 \cdot 10^{-7}$ per year. The trucks will be "purpose built" for transporting CO_2 and t is therefore assumed that these tankers will be robust. Also, if measures are implemented to reduce probability for overfilling, an even lower frequency could be argued.

Explosion/BLEVE consequences

The results in Table 6.6 have been derived using relations between explosion energy, blast pressure and lethality as described in chapter 7.4.

Explosion energy corresponds to change in internal energy from the storage condition to the triple point:

$$E = 25\,000 \text{ kg} \cdot (139 - 130.4) \text{ kJ/kg} \approx 0.22 \text{ GJ}$$

Table 6.6: Distance and consequences for BLEVE from a truck

Distance(m)	Dimensionless distance	Pressure (bar)	Fatal probability for blast
10	0.77	0.42	100 %
20	1.55	0.18	100 %
50	3.87	0.06	25 %
70	5.42	0.04	5 %

7 Risk assessment - storage tank rupture and BLEVE scenarios

7.1 General

The storage tanks will be designed equal at Klemetsrud and Oslo Harbour. The tanks will be designed with double walls with monitored annulus.

The storage tanks will have a design pressure of 17 barg and temperature range from -52°C to 85°C. With operational pressure at 15 barg, there is not much margin from the operational pressure to the tank design pressure. At -22.9°C, which is about 3°C above normal storage temperature, the saturation pressure will equal the design pressure.

The normal operating temperature is -26°C, which is well above the lower temperature limit at -52°C. However, a fast pressure drop in the tank could occur, i.e. due to fast depressurization or opened bypass for the PSV/relief system. If pressure drop is too fast, temperature could fall below -52°C, and there is a potential for brittle fracture that could threaten tank integrity. Process safety systems will be designed to prevent this scenario.

Pressure and temperature must be carefully controlled, and any increase or decrease in temperature or pressure therefore need to be detected. The PSVs and blowdown system will control pressure build-up, but due to the characteristics of CO_2, icing and blockage of relief valves is a concern. Historically it has been seen that these failures have caused accidents with quite violent explosions (BLEVE) with fatal consequences and significant material damages.

To the extent safety critical task is involved in safe operation of the tank farm, tank failure will be affected by the reliability of operators carrying out such tasks. External impact from operation of cranes and vehicles are possible failures related to manually operated equipment. In relation to overpressure incidents, manual closure of a valve in the safety relief system contributed to one of the CO_2 BLEVE accidents, and in different ways human error can contribute to either overpressure or too low temperature and brittle fracture. Inspection and maintenance are other manual operations that are critical to the safe operation of the facility. A systematic analysis to identify safety critical tasks (manual operations) that could cause overpressure or otherwise lead to tank failure has not been performed as part of this analysis. Note that some of the more relevant human errors that potentially could contribute to tank failure relates to incorrect operation of valves related to pressure relief.

7.2 Storage tank rupture frequency at Klemetsrud

The frequency for storage tank rupture/BLEVE scenario is calculated as:

$$f_{\text{tank rupture}} = f_{\text{pressure outside design limits}} + f_{\text{external damage}}$$

Reference is made to Appendix A for further details. The frequency for "pressure outside design limits" was in Appendix A estimated to be around 1.0E-07 per year. Potential external impacts that may pose a risk to the storage tanks at Klemetsrud are discussed in Table 7.1.

Table 7.1: External impacts at Klemetsrud

Type of threat – external impact	Safeguards
Vehicle/crane impact to storage facilities	Mechanical impact to the storage tank shall be prevented primarily by use of physical barriers. The tanks at Klemetsrud are protected by the structure and are not likely to be exposed to collision impacts. It should however be ensured that the structure is protected or robust enough to sustain potential impacts.
Aircraft	HSE recommends a generic aircraft crash frequency of $3.8 \cdot 10^{-5}$ per $km^2 \cdot yr$, which means that the frequency for the plant at Klemetsrud will be very low and considered negligible).
Fuel (gasoline, diesel, paraffine) fire/explosion scenarios	Fuel storage, transformer buildings or other buildings close to the CO_2 tank storage could cause heat exposure to the tanks. Currently no such potential scenarios are identified near the tanks but should be considered when location of storage have been concluded. There are no other potential fire-/explosion scenarios identified that will threaten the storage tanks.
CO_2 BLEVE from truck	There is a possibility for tank explosion for the truck during loading operation. The effect could be a blast load and shrapnel impacting the tank farm. The probability for such a scenario to affect the storage tanks is considered very low, but design blast load should be considered.
Sabotage	Physical protection and access control are implemented.

Based on the above discussion the contribution from external damages at Klemetsrud are considered negligible. The annual frequency for tank rupture is hence estimated to:

$$f_{\text{tank rupture Klemetsrud}} = 1 \cdot 10^{-7} + \text{negl.} = 1.0 \cdot 10^{-7}$$

7.3 Storage tank rupture frequency at Oslo Harbour

The frequency for storage tank rupture/BLEVE scenario is calculated as:

$$f_{\text{tank rupture}} = f_{\text{pressure outside design limits}} + f_{\text{external damage}}$$

Reference is made to Appendix A for further details. The frequency for “pressure outside design limits” was in Appendix A estimated to be about 1.0E-07 per year. Potential external impacts that may pose a risk to the storage tanks at Klemetsrud are discussed in Table 7.2.

Table 7.2: External damage to storage tanks - Oslo Harbour

Type of threat – external impact	Safeguards
Vehicle/ship/train/crane impact to storage facilities	Mechanical impact to the storage tank shall be prevented primarily by use of physical barriers.
Aircraft	HSE recommends a generic aircraft crash frequency of $3.8 \cdot 10^{-5}$ per $km^2 \cdot yr$, which means about $8 \cdot 10^{-8}$ for the storage tank farm. This generic figure is dominated by light aircrafts, helicopters and military combat aircrafts. Helicopter, military and light traffic over Sjursøya is limited, and using the generic frequency is considered conservative.
Fuel (gasoline, diesel, paraffine) fire scenarios	Fire scenario could be at ground, from storage tanks or at sea. A fire scenario with storage tank engulfed in flames is not considered credible, provided measures are implemented to prevent a running pool fire to reach the tank farm. The pressure relief system (and PSV) in addition to tank insulation shall be sufficient to prevent overheating and pressure build-up in the CO_2 tank. Integrity of support structures must be ensured.
Fuel (gasoline, diesel, paraffine) explosion scenarios	Blast pressure will be modest, but a design explosion load from the nearby petroleum facilities including ship at jetty should be considered. The storage tanks are robust, but support structure may have to be designed for a blast load. Risk analysis for nearby facilities could serve as input to design accidental loads.
CO_2 BLEVE from truck	There is a possibility for tank explosion for the truck during unloading operation. The effect could be a blast load and shrapnel impacting the tank farm. Design blast load to be considered.
CO_2 BLEVE or LNG BLEVE from CO_2 transport ship	In addition to CO_2 storage, the CO_2 carrier ship has LNG tanks at deck and battery packs that could possibly represent a risk for fire and subsequent explosion scenarios. With current layout, the CO_2 carrier is located further away from the CO_2 storage tank farm than the tankers unloading fuel oil. Accident scenarios at the ship will therefore not be governing for the design of the tank farm.
Sabotage	Physical protection and access control are implemented (ISPS regulations implemented).

The annual probability for CO_2 storage tank rupture at Oslo Harbour is hence estimated as:

$$f_{\text{tank rupture Sjursøya}} = 1 \cdot 10^{-7} + 1 \cdot 10^{-7} = 2.0 \cdot 10^{-7}$$

7.4 Accident consequences of storage tank rupture scenarios

Blast consequences (BLEVE)

The liquid CO_2 inventory in the tank is assumed $340\ m^3 \cdot 1064\ kg/m^3 \approx 360\ 000$ kg. In the following calculation of blast effects, it is assumed the blast is from spontaneous boiling of the liquid. The expansion effects of vapor will also result in a blast wave, but there will be much less energy involved in this process.

The explosion energy for a CO_2 BLEVE has been coarsely estimated based on the internal energy at storage conditions compared to the internal energy of vapor at the triple point (which is the lowest pressure CO_2 can exist as vapor).

Table 7.3: Fluid properties table

State	Pressure (bara)	Internal energy (kJ/kg)		Specific volume (m³/kg)		Entropy (kJ/kgK)	
		u_{liq}	u_{gas}	v_{liq}	v_{gas}	s_{liq}	s_{gas}
1	16	139	399	0.00094	0.024	0.778	1.98
2	6	86	394	0.00086	0.063	0.552	2.12

Internal energy at state 1 (storage condition) is Table 7.3 is 139 kJ/kg

Vapor mass fraction (or quality) in liquid phase after expansion: $X = \frac{s_{liq\_1} - s_{liq\_2}}{s_{gas\_2} - s_{liq\_2}}$ = 0.144

Internal energy for the liquid at state 2 (triple point) is calculated using the appropriate fractions of liquid and vapor.

U= (1 - 0.144) · 86 kJ/kg + 0.144 · 394 kJ/kg = 130.4 kJ/kg

Explosion energy corresponds to change in internal energy from state 1 to state 2:

E = 360 000 kg · (139 -130.4) kJ/kg ≈ 3.1 GJ

The chart (Figure 7-1) applies the non-dimensional range: $\bar{R} = R\left(\frac{P_0}{E_{ex}}\right)^{\frac{1}{3}}$

A ground reflection factor of 2 is applied in the calculations; $E_{ex} = 2 \cdot E$

$$\frac{\bar{R}}{R} = \left(\frac{P_0}{2 \cdot E}\right)^{\frac{1}{3}} = \left(\frac{100000\ Pa}{2 \cdot 3.1 \cdot 10^9\ Joule}\right)^{\frac{1}{3}} = 0.025$$

This means the dimensionless distance is $\bar{R}$ = R·0.025 where R is distance in meters from the explosion to the receptor. Since P0 ≈ 1 bar, explosion overpressure in bar is practically the same as dimensionless pressure in the chart.

The red line in Figure 7-1 shows the part of the graph that is used to establish the blast loads in Table 7.4. The distances considered are in the range 50 meters to 400 meters. This corresponds to a dimensionless distance is in the range 1.25 to 10. It is seen from the Baker-Tang chart that the dimensionless pressure is in the range 0.23 to 0.02 (which means the pressure is 0.23 bar to 0.02 bar.

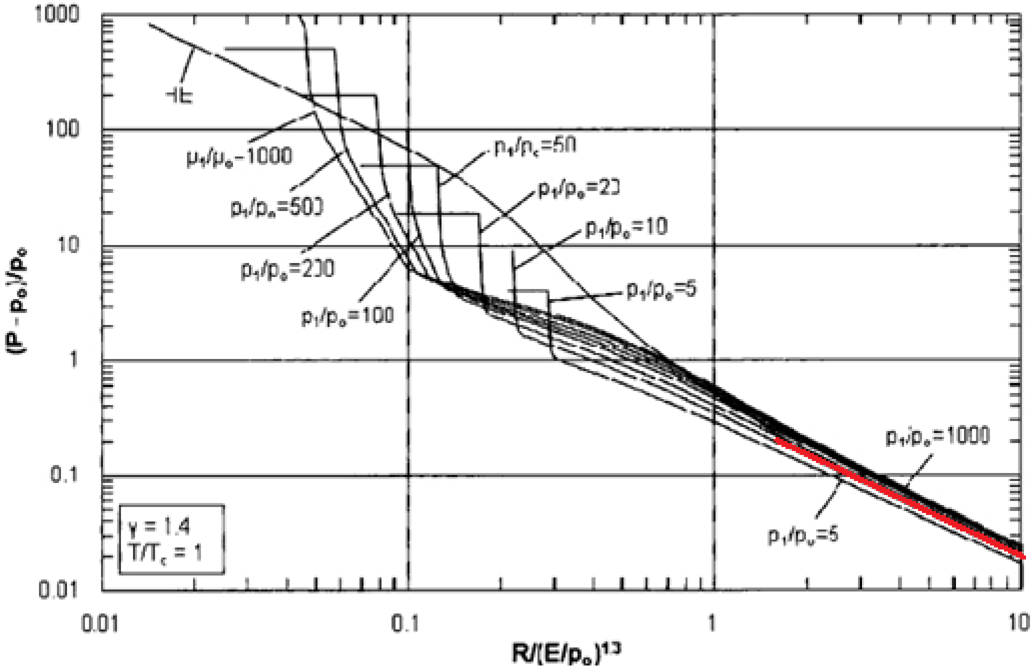


Figure 7-1: Baker-Tang blast curves [14]

Based on the pressures, the probability for fatal outcome is found from Figure 7-2. The results are shown in Table 7.4. According to this relation, the fatal probability for 0.23 bar (23 kPa) is close to 100%, while the fatal probability for 0.02 bar (2 kPa) is close to zero. This relation is recommended by DSB and is found conservative compared to other relations in use[1].

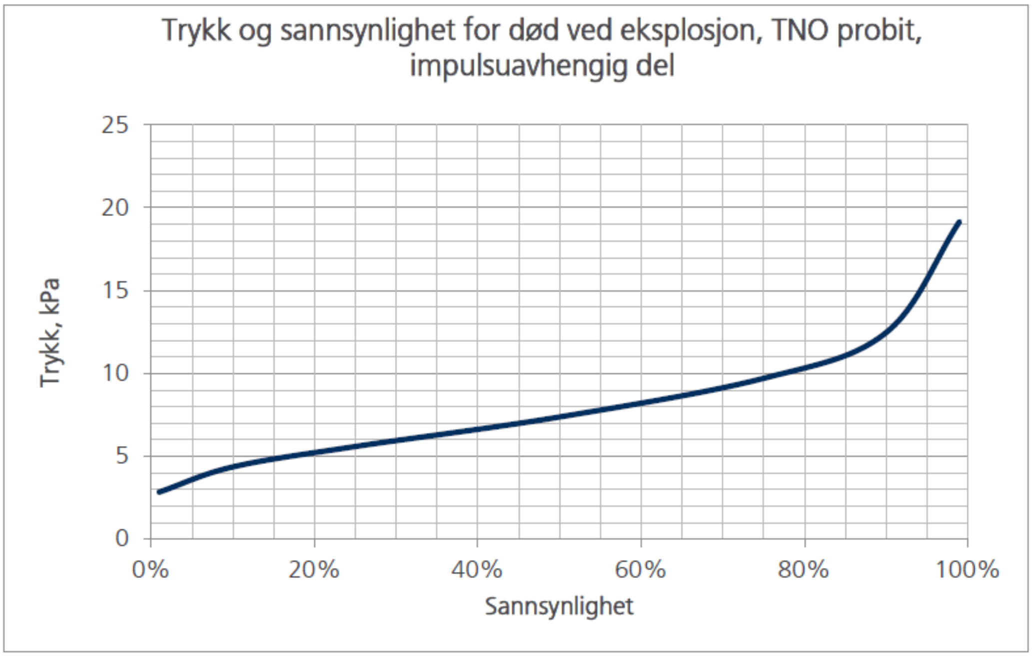


Figure 7-2: Relation between explosion pressure and fatality risk [DSB]

[1] Alternative figures are available from for example by NIOSH

Table 7.4: Hazardous distances from storage tank BLEVE (360 000 kg CO_2)

Distance	Dimensionless distance (m)	Pressure (bar)	Fatal probability for blast
50	1.25	0.23	100 %
100	2.5	0.1	75 %
150	3.75	0.06	30 %
200	5	0.04	5 %
300	7.5	0.03	0.10 %
400	10	0.02	0.00 %

For a truck tank, the inventory is about 25 000kg, and $\bar{R}$ = R·0.061. The hazardous distance from an explosion is less than half, see Table 7.5.

Table 7.5: Hazardous distances from truck BLEVE (25 000 kg liquid CO_2)

Distance	Dimensionless distance (m)	Pressure (bar)	Fatal probability for blast
21	1.25	0.23	100 %
41	2.5	0.1	75 %
62	3.75	0.06	30 %
82	5	0.04	5 %
123	7.5	0.03	0.10 %
164	10	0.02	0.00 %

Dispersion from a tank rupture or explosion scenario

In a tank rupture scenario, about 360 000 kg CO_2 can be released instantaneously. At atmospheric pressure and -52°C, the CO_2 density in vapor phase is about 2.5 kg/m^3. Neglecting the solids, the CO_2 volume could therefore reach about 140 000 m^3. Upon a tank rupture or explosion, the gas will be diluted. A rule of thumb is that the gas concentration could be about 10% in the diluted gas cloud [15], but this should be considered a very rough estimate. The initial gas cloud can be imagined as a cylinder with radius = height ≈ 75 meters. This gas cloud will be diluted as it disperses with wind and gravitational effects.

A very coarse dispersion assessment has been performed in Table 7.6. The duration of exposure will depend on the wind speed and the terrain, but exposure will normally not be very long in a tank rupture scenario. Based on wind statistics is assessed that duration of exposure for this scenario could typically be in the range 5 minutes to 15 minutes.

Table 7.6: Hazardous distances from storage tank rupture – CO_2 exposure

Distance (m)		Typical gas concentration range	Fatal probability due to exposure of CO_2
360t tank	25t tank		
50	21	15% - 30%	100 %
100	41	10% - 20%	50 %
150	62	5%-15%	10 %
200	82	0%-10%	3 %
300	123	0% - 7%	1 %
400	164	0% - 5%	0.1 %

Combined fatality risk – BLEVE and gas exposure for tank rupture accidents
The combined fatality risk for blast and gas exposure has been calculated considering the two effects as independent and assuming the conditional probability for significant blast loads given a tank rupture scenario, P_{blast}, is 50%.

Table 7.7: Hazardous distances from storage rupture (BLEVE risk and CO_2 risk combined)

Distance (m)		Fatal probability, blast	Fatal probability, gas	Fatal prob, total (assuming P_{blast} = 0.5) $P_{fatal} = 1 - (1 - P_{fatal,dispersion}) \cdot (1 - P_{blast} \cdot P_{fatal,blast})$
360t tank	25t tank			
50	21	100 %	100 %	100.0 %
100	41	75 %	50 %	68.8 %
150	62	30 %	10 %	23.5 %
200	82	5 %	3 %	5.4 %
300	123	0.1 %	1 %	1.0 %
400	164	-	0.1 %	0.1 %

8 Risk assessment for truck transport

Collision accidents will in most cases not result in release of CO_2 but can still result in casualties for persons involved. Collision accident statistics is available. Driving downhill through the tunnels involves additional risks. The driving distance is about 13 kilometres each direction and takes about 15 minutes each direction (Figure 2-8).

Norwegian statistics on traffic accidents indicates $3.36 \cdot 10^{-9}$ fatalities per vehicle kilometre for 2014. This is for all vehicles, and the statistics is dominated by cars. For the period 2011-2015 there were in average 19.4 fatalities per year related to heavy transport [16]. The number of accidents with injuries for the same period was 191.

According to Statistic Norway [17] large truck traffic volume was $1964 \cdot 10^6$ kilometres in 2015. With 19.4 fatalities in $1.96 \cdot 10^9$ kilometres, the fatal accident rate is about $1 \cdot 10^{-8}$ per kilometre. This means the fatal accident rate is a factor 3 higher for heavy transport as compared to all vehicles. Assuming $1 \cdot 10^{-8}$ fatalities per kilometre, a coarse estimate of traffic accident risk for truck transport is obtained.

For each trip, fatalities from traffic accidents is quantified as PLL = $13 \cdot 2 \cdot 10^{-8} = 2.6 \cdot 10^{-7}$. In one trip, about 25 tons of CO_2 is transported. An alternative way to present the figures is $1 \cdot 10^{-8}$ fatalities per ton CO_2 transported to Oslo Harbour.

With the lines K1, K2 and K3 in operation, 460 000 t CO_2 is produced per year. Capturing 90% of this means that the transport requirement is 414 000 t CO_2 per year. The resulting potential loss of lives (PLL) from traffic accidents is calculated as follows:

$$PLL = 400\,000 \text{ t/yr.} \cdot 10^{-8} \text{ fatalities/t} = 0.004 \text{ fatalities/yr.}$$

This figure does not include the risk contribution from CO_2 releases following a traffic accident or other scenarios that could lead to a large leak from the truck. The exposure time at road is:

$$\text{Exposure time: } 0.25 \text{ hours} \cdot 400\,000 / 25 = 4000 \text{ hours} \approx 0.5 \text{ years}$$

Assuming a pressure vessel failure rate at 10^{-6} per year also for the truck (Purple book table 3.19), the frequency for a large release from the truck during transport is $5 \cdot 10^{-7}$ per year. It is not clear from this reference if releases related to traffic accidents should be added – it probably should.

The Purple book includes some relevant data on leak frequency. For "motorway" (highway), the proposed generic leak frequency is $4.32 \cdot 10^{-9}$ per km. The distance travelled with full tank is 13 km · 400000/25 ≈ 200 000 km. Annual frequency for "outflow" during driving is then: 200 000 · $4.32 \cdot 10^{-9}$ = $8.6 \cdot 10^{-4}$. The outflow frequency is defined as the frequency of an accident with a hazardous substance transport unit where at least 100 kg of the transported substance is released. It is not specified what fraction of these loss of containment incidents that are large and could pose a risk to persons along the route.

Truck transport includes frequent manual loading and offloading operations with potential for operational and equipment failure. In addition, there is risk for traffic accidents. The potential loss of lives from these operations is however found low.

9 Risk assessment for Oslo Harbour

9.1 Accident statistics for Oslo Harbour

Risk picture for Sydhavna is summarised in [8]. There have been several accidents over the last years, and recorded accidents at Oslo Harbour before 2014 include the following:

- August 14th, 1990: Fire and explosion in a cavern at Ekeberg Oil storage. Damages were limited to mechanical equipment.
- February 17th, 2003: Collision between train and tanker (truck) loaded with 38 m^3 fuels in a roundabout. The railway is crossing the roundabout which has dense traffic of dangerous goods. The collision resulted in a leak which was ignited.
- June 13th, 2009: Overfilling of cavern and diesel/aircraft fuel mixed, Oil spill to gangways etc.
- March 24th, 2010: Railway accident. Empty train set of 7 container wagons totalling 194 tons was rolling uncontrolled downhill to Oslo Harbour. The speed was up to 125 km/h on the way from Alnabru to the container terminal. The consequence was three fatalities, four injuries damages to buildings, cars and infrastructure, two wagons ended up in the sea. (Train with aircraft fuel was not hit.)
- December 26th and 27th, 2012: Spill of 340 m^3 (and some paraffin) diesel from storage tank farm.

Figure 9-1: Roundabout with crossing railway side-track

Accident statistics for Oslo Harbour includes 35 incidents for the period 2007-2013. There are accidents related to crane operations, material handling and vehicle impacts.

9.2 Risk assessment, prior to introducing the CO_2 facilities

9.2.1 Existing activities and risks

The south part of Oslo Harbour (Sydhavna) is considered a national centre for logistics and includes container handling, storage and distribution of petroleum products and more. Sydhavna has been categorized as an area with elevated risk (*forhøyet risiko*) by DSB [8]. A dedicated report has been prepared to describe these risks.

Risk contribution from CO2 handling facilities in Sydhavna will be additional to existing risk exposure

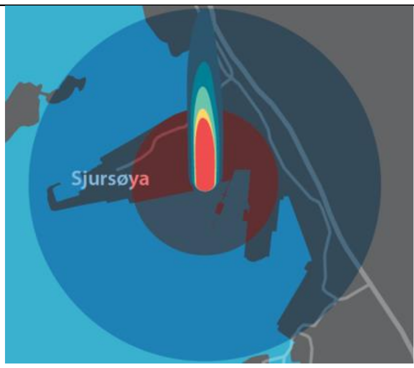
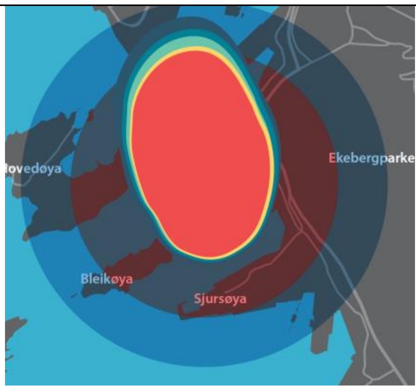
9.2.2 Ship incidents and accident scenarios in Oslo Harbour

The Norwegian Maritime Directorate has a database with ship incidents[2] as described in [18]. The following data includes all types of vessels except vessels used for leisure. The number of reported accidents per year for the period 2003 – 2014 shows that incidents are relatively frequent in Norway:

- Impacts to quay, bridge etc. (Dominant scenario is ferry impact to quay): 37 incidents per year
- Collisions: 20 incidents per year
- Fire/explosions: 19 incidents per year

[2] *Sjøfartsdirektoratets ulykkesdatabase*

Table 9.1: Scenario analysis with plots from [8]

Sjursøya escalated oil fire scenario. Wind conditions will affect the extent of this scenario.	
Bjørvika oil fire at sea scenario. This is a scenario with fuel leak from a tanker (ship) to the sea which is ignited. The wind and current conditions are important for the accident consequences. Note: A similar scenario could occur south of Sjursøya, near the planned CO_2 facilities.	
Cavern storage accident scenario.	This scenario is assessed to have primarily consequences local to the facilities.

9.2.3 Risk picture Oslo Harbour – prior to CO_2 facilities

Several risk analyses have been performed for the activities and installations in the Oslo Harbour area. Scenarios identified include leak of flammable liquids with possible fire, tank explosion, train – vehicle collision and crane accidents. Risk contours for "Sjursøya oljehavn" were established in a risk analysis by Scandpower in 2007 as presented in Figure 9-2.

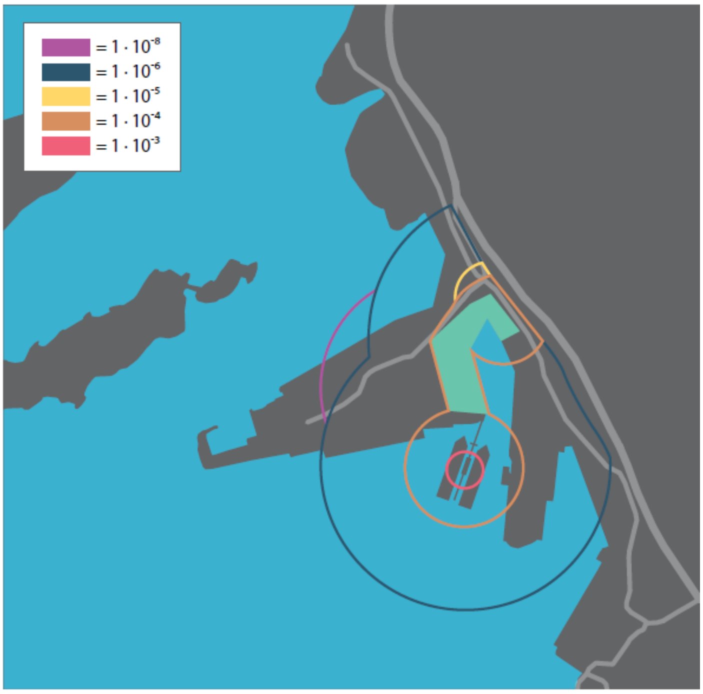


Figure 9-2: Risk Contours – individual risk for petroleum related accidents in "Sjursøya oljehavn"

9.3 Risk assessment, CO_2 facilities

9.3.1 CO2 leak scenario from truck/hose at Oslo Harbour.

These hose leak scenarios are essentially the same as for truck loading at Klemetsrud. The frequencies are summarised in Table 9.2.

Table 9.2: Leak frequencies for hose load transfer operations – Oslo Harbour

Leak hole diameter (mm)	Frequency (per operation)	Leak rate (kg/s)	Number of operations at Klemetsrud and Oslo Harbour	Leak frequency at Oslo Harbour (per year)
15	$2.8 \cdot 10^{-6}$	7	16 000	0.044
25	$2.0 \cdot 10^{-7}$	17		0.0031
Full rupture	$4.9 \cdot 10^{-8}$	250		0.00076

A potential BLEVE scenario in the truck were discussed in chapter 6.5. The frequency for this scenario is proposed the same as at Klemetsrud; $1 \cdot 10^{-7}$ per year. There will however not be scenarios related to overfilling of the truck.

9.3.2 CO_2 leak scenario from storage tanks at Oslo Harbour

The piping and valve arrangement out of the storage tanks are assumed equal as the intermediate storage tanks at Klemetsrud (see chapter 6.4). An alternative with larger storage tanks was found to result in longer hazardous distances. Also, the effect of introducing local physical barriers has been studied. No such barrier has been assumed in this risk analysis. These sensitivities are documented in Appendix E.

The leak frequencies are based on HSE data; both for piping and pressure vessels. Basis for the frequencies in Table 6.4 can be found in Appendix A. Lengths and number of storage tanks that has been used as basis when calculating the frequencies are summarised in Table 9.3.

Table 9.3: Lengths and number of storage tanks used as basis for frequency calculations at Oslo Harbour

Leak source	No./ m
Storage tanks	16
Piping length	64

A scenario of 650 kg/s, corresponding to a rupture of a 6" piping, is considered as the as the worst credible scenario when establishing the restricted area zones. A hole size of 50mm will (approximately) correspond to 20% of the cross section of a 6" pipe.

The applied frequencies are based on the same basis as on Klemetsrud and is shown in Table 9.4.

Table 9.4: Leak rates and durations for the intermediate storage

Hole size	10 mm	25 mm	50 mm	Rupture
Leak rate [kg/s]	3	17	120	650
Leak frequency per year	6.4E-05	4.5E-05	4.2E-05	1.4E-05

9.3.2.1 Simulation results

Dispersion simulations for 600 kg/s releases at Sjursøya, have been simulated for the FEED phase. In the previous phase. This corresponds to rupture of a 6" pipe. In the previous phase, leaks of 1270 kg/s (10" pipe rupture) and 254 kg/s were simulated. The storage tanks were substantially larger than the current configuration, and the worst-case gas dispersion scenario had a large footprint compared to the current solution.

The storage will use 6" pipework (150 mm). Rupture of 6" pipework will result in a leak rate more than 600 kg/s initially. Figure 9-3 and Figure 9-5 shows the dispersion for the four cases. The plots show the gas cloud 8 minutes after the leak starts, when the leak ends. The scenario is that one tank emptied at constant rate.

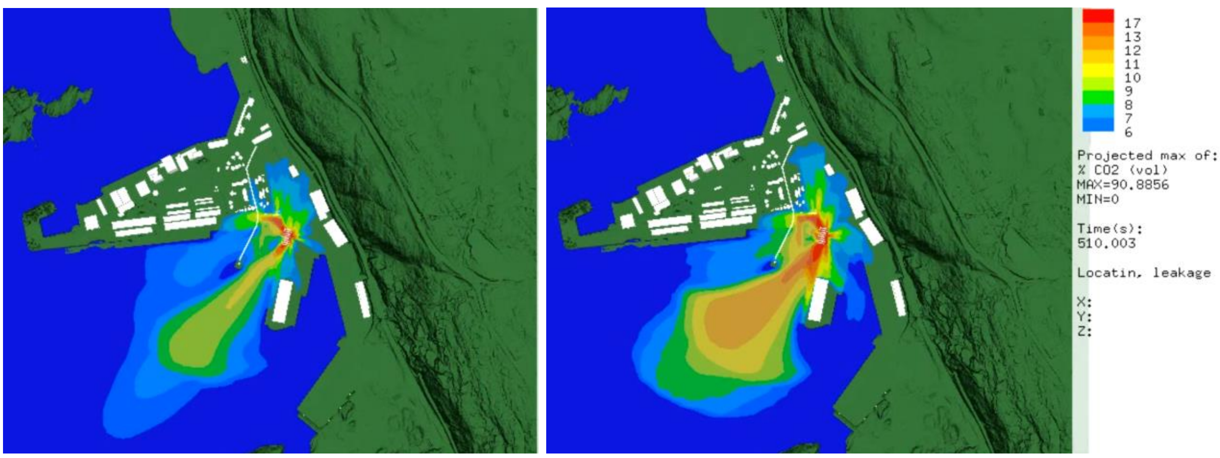


Figure 9-3: 620 kg/s, case 11 and 12, 2-phase jet down, wind from North and South Z = 12m and 3m

Figure 9-4 shows case 11 and case 12 at 2 and 4 minutes after the end of the leak, respectively. Within 10 minutes, these gas clouds are diluted to non-hazardous concentrations.

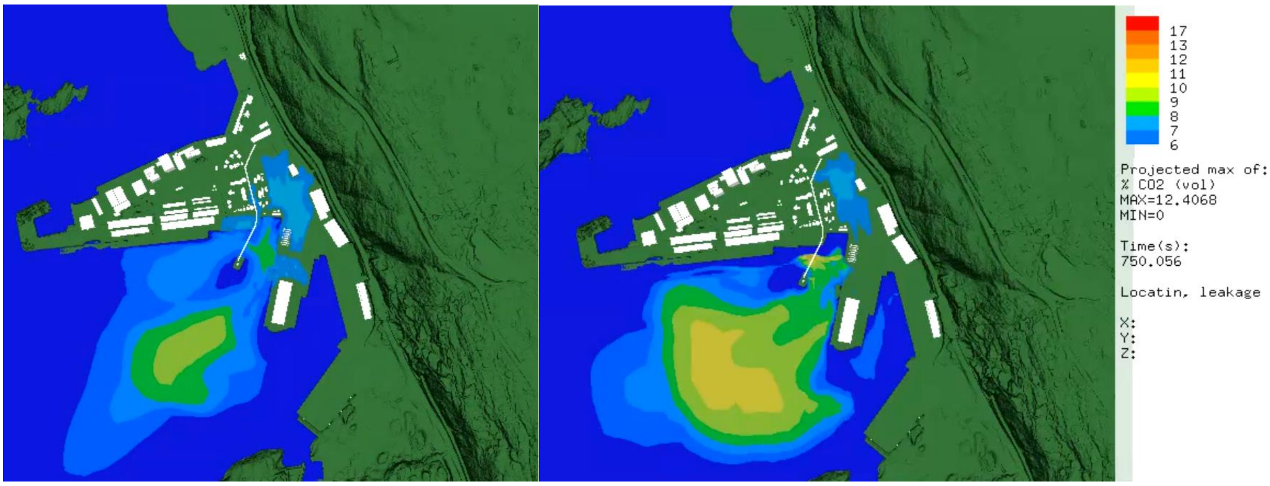


Figure 9-4: Case 11 2 minutes after end of leak and case 12 4 minutes after end of the leak

As for Klemetsrud it is seen that the horizontal releases can lead to smaller gas clouds, in particular if the release is unobstructed. Still, the horizontal jet directed west (over the sea surface) has a quite long hazardous distance. For these cases, the gas will be diluted to non-hazardous concentrations even faster than for case 11 and 12. For all the tank rupture scenarios, exposure to toxic levels of gas will rarely exceed 15 minutes.

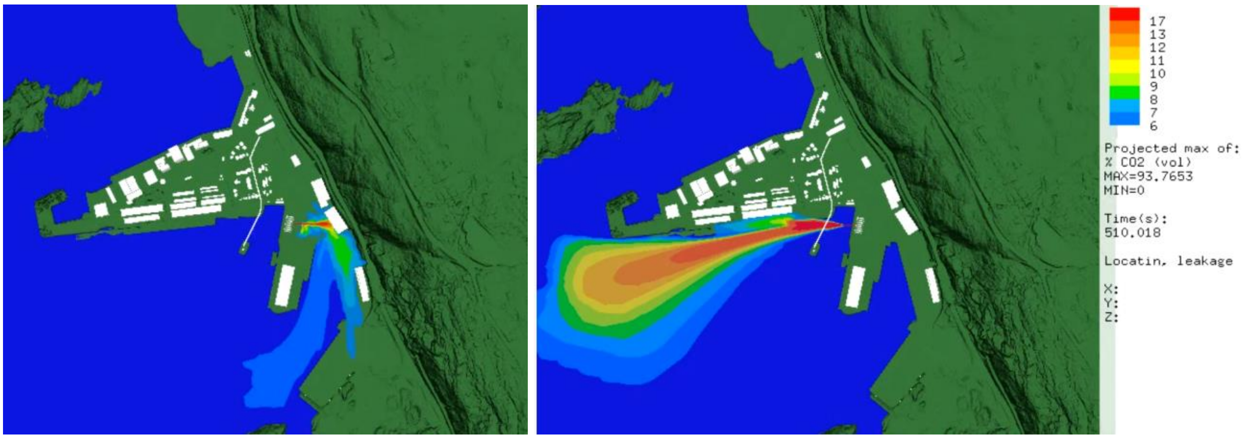


Figure 9-5: 600 kg/s, case 13 and 14, 2-phase jet east and west, wind from South, Z = 12m and 3m

Note that all the plots above show projected maximum in z-direction; that is, for each (x, y)-coordinate in the domain the maximum gas concentration in z-direction is plotted. In this way, the maximum extent of gas exposure is found. The CFD simulations show that the gas cloud is limited to a few meters above ground or sea level. This means that physical barriers could affect the spreading of CO_2 and that elevated areas and buildings may effectively prevent exposure of individuals

9.3.3 CO_2 leak scenario from offloading to ship

During loading operations to ship the CO_2 from the storage tanks is routed through a about 300m 6" pipeline. CO_2 leak scenarios from offloading operations hence includes leaks from pumps, piping, connections and loading arm.

Assuming about 75 offloading operations to ship per year and 300m piping, the frequencies for this operation can be estimated as shown in Table 9.5.

Table 9.5: Leak frequency per year for loading operations to ship

	Hole size		
	15 mm	50 mm	Rupture
Leak rate (kg/s)	6.5	72	650
Leak duration after isolation (minutes)	14.5	1.3	0.1
Leak frequency from 300m piping	2.1E-04	1.2E-04	1.5E-04
Leak frequency from loading arm (75 operations)	4.5E-02		4.0E-03
Leak frequency per year (sum)	**4.5E-02**	**1.2E-04**	**4.7E-03**

It is expected that safety barriers such as break-away coupling are in place such that the possible leak inventory will be limited. The leak durations in Table 9.5 is based on 5600 kg pipe inventory. In addition, there will be a delay before the pipe inventory is isolated.

Hazardous distances

For the smallest hole size category, consequences are local and hazardous distances have not been assessed for the iso-risk contour calculations. For the 50mm hole scenario and the rupture scenario, hazardous distances can be significant. Because the inventory is modest, this rupture scenario will result in a smaller gas cloud as compared to the storage tank scenarios with similar leak rate.

The dominating leak scenario is related to the loading arm and not the pipeline from the storage to the ship. The maximum hazardous distance is set to 150 meters. The scenario is governing for the 10^{-5} iso-risk contour in the south-east sector, see Figure 10-2.

9.4 Risk contribution from CO_2 transport ship while in Oslo Harbour

9.4.1 General

Storage at Oslo Harbour is required for efficient offloading to ship, and the storage capacity is four days production. The ship introduces some additional accident scenarios including tank rupture and BLEVE for the CO_2 storage tanks onboard. The ship will primarily use LNG for propulsion but will also have a battery pack for electric propulsion and operation. There will be no LNG bunkering in Oslo Harbour, but there will be battery charging.

Fire and explosion risks for the ship includes scenarios from LNG tanks and the battery pack. This analysis has not quantified risk from the CO_2 transport ship. These risks will be additional to the risk picture presented in this report.

9.4.2 Risk contribution from the CO_2 transport ship

General

An interface request was raised by FOV to Equinor and the Northern Lights project (at Øygarden, west in Norway) [19] regarding the risk contribution (dimensioning accidents) from the CO_2 transport ship.

The response to the request (from Equinor) is that: The ship will be designed according to the IGC code and relevant class rules. CO_2 is classified as a non-flammable gas under pressure, and the CO_2 carrier will be designed based on the relevant rules for this classification. For standard ship design, a quantitative risk analysis is not considered necessary, and therefore not carried out. Safety is assumed to be implemented in design and safety barriers will be implemented according to the standards and normal approval processes for ship design. Detailed design of the CO_2 carrier will take place after 2021.

The ship equipment approximate sizes are as follows:

- Liquid CO_2 cargo tanks: 7 500m^3 (est. 2 x 3 563m^3 @max 95% capacity)
- Marine diesel oil (MDO) tanks incl. settling and day tanks, ca. 770m^3
- LNG fuel tank 580 m^3 (est. 2 x 290m^3)

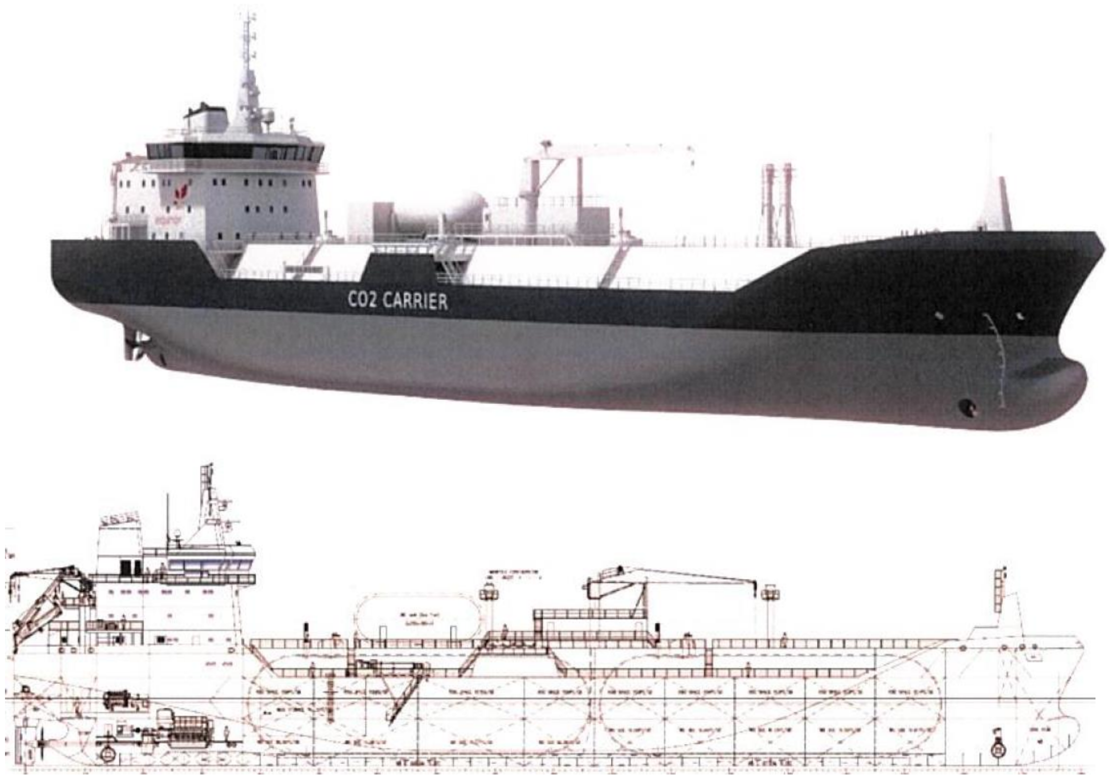


Figure 9-6: LCO_2 carrier with CO_2 tanks in hull and LNG tank on deck [9]

The jetty and the harbour area are shown in Figure 2-10. The CO_2 carrier will be present at Oslo harbour about 8 hours 75 times a year, which is about 7% of time.

Risk contribution from collision incidents

The ship collision analysis [9] which is a part of the Northern Lights project's total risk analysis has been made available by Equinor. The collision frequency is quantified to $2.4 \cdot 10^{-7}$ per arrival. It is further assumed that 10% of collisions will damage a loading arm and 1% of collisions lead to damage to the double hull and a CO_2 release. The frequency for LNG release is set equal to the frequency for CO_2 release. For LNG releases, ignition probability is set to 50%. The consequence assessments for these scenarios have not been available for review.

With 75 offloading operations per year and using the same assessments as in [9], the following accident frequencies result:

a) Annual frequency for collision upon arrival: $75 \cdot 2.4 \cdot 10^{-7} = 1.8 \cdot 10^{-5}$
b) Annual frequency for collision upon arrival with CO_2 tank failure: $1.8 \cdot 10^{-5} \cdot 1\% = 1.8 \cdot 10^{-7}$
c) Annual frequency for collision upon arrival with LNG fire: $1.8 \cdot 10^{-5} \cdot 1\% \cdot 50\% = 9.0 \cdot 10^{-8}$

[9] does not explicitly say whether scenario b) and c) occur simultaneously.

The frequency for an LNG BLEVE scenario is considered low with reference to standard design and requirements and assessed not to contribute to the risk contours for Øygarden.

The main risk for ship collision at the jetty is at arrival. In consistence with the assessments for Øygarden, the ship collision scenario with release from CO_2 tank is set to $1.8 \cdot 10^{-7}$ per year for Oslo Harbour (see above). In contrast to the CO_2 carrier arriving at Øygarden, the ship is expected to, in most cases, only to carry small CO_2 quantities upon arrival. This will significantly reduce the risk for major accidents from collisions upon arrival at Oslo Harbour.

There is a collision risk related to other large vessels manoeuvring in Oslo Harbour in near vicinity of the CO2 facilities and the CO_2 carrier during loading operation. This could potentially threaten the CO_2 and LNG tanks at the CO_2 carrier while in harbour. There is also collision risk while manoeuvring the CO_2 carrier from the harbour.

LNG tank rupture and BLEVE while at the jetty

There is a potential risk for LNG and BLEVE scenarios from the CO_2 carrier while in harbour. The generic frequency for a catastrophic failure of an LNG tank rupture is very low and quantified to $5 \cdot 10^{-8}$ per year in (see Appendix A for details). With the ship present 7% of time, the frequency for a catastrophic failure of the LNG tank while in harbour is negligible in the sense that the restricted area zones will be unaffected ($7 \cdot 10^{-9}$ per year for the two fuel tanks combined).

CO_2 tank rupture and BLEVE while at the jetty

In addition to collision scenarios, there is a potential for CO_2 tank rupture while the ship is in harbour. The scenarios are generally the same as for the storage tanks evaluated in chapter 7. The main difference is that the tank volume is 10 times larger for the ship as compared to the intermediate storage tanks. The dispersion distance for a gas release could be longer and the worst case BLEVE scenario will have about twice the hazardous distances compared to the storage tanks, and the scaled hazardous distances are shown in Table 9.6. This is based on the methodology used in chapter 7.4.

Table 9.6: Hazardous distances from CO2 carrier tank BLEVE (3500 t CO_2)

Distance	Fatal probability for blast	Fatal probability, gas	Fatal prob, total (assuming $P_{blast} = 0.5$)
107	100 %	100 %	100.0 %
213	75 %	50 %	68.8 %
320	30 %	10 %	23.5 %
427	5 %	3 %	5.4 %
640	0.1 %	1 %	1.0 %
854	-	0.1 %	0.1 %

The frequency for catastrophic accident scenario at the CO_2 carrier is found to be low. Most collision scenarios will be with empty or near empty ship. The ship will be present about 7% of time, but failure frequency during loading operations are judged to be higher than during sailing. For the purpose of this QRA, the frequency of catastrophic failure of a full CO2 tank at the ship is set to 10^{-7} per year with corresponding hazardous distances as shown in Table 9.6. The effect on the risk contours is small, and this is basically the case when the frequency for this scenario is less than $5 \cdot 10^{-7}$ per year. With higher frequencies than this, the 10^{-7} risk contour is moved significantly further south. Plots in Appendix C shows the contribution from the different scenarios and can be used to assess the robustness of the restricted area zones considering uncertainties in frequency and consequence modelling.

Fire and explosion scenarios from the battery pack

The CO_2 carrier is equipped with a battery pack to operate as a hybrid with LNG/electric propulsion. While at the jetty, there will be battery charging. Experience has shown that introducing batteries involves risk of overheating. Perhaps the most serious case to date is the resent fire and subsequent explosion at MF Ytterøyningen October 10^{th} and 11^{th} 2019. For the CO_2 carrier ship, the main concern related to the battery pack is the risk for escalation to either CO_2 or LNG tanks, or causing damages to the hull.

10 Risk contours

The calculation of iso-risk contours for individual risk is documented in Appendix C and the methodology is explained in chapter 3.6. The relation between the iso-risk contours and the restricted area zones are shown in Figure 2-12.

The calculated risk contours for Klemetsrud are shown in Figure 10-1. It is seen that the 10^{-5} contour is at the site, while the 10^{-6} and 10^{-7} contours extend outside the fence. The contours (10^{-6} and 10^{-7}) will follow the terrain and dense gas will reach the highway. The residential areas are up in the hill and will therefore be outside the contours.

Based on a review of a risk analysis for the WtE plant [20], it is assessed that the WtE plant will not affect the risk contours except at the site.

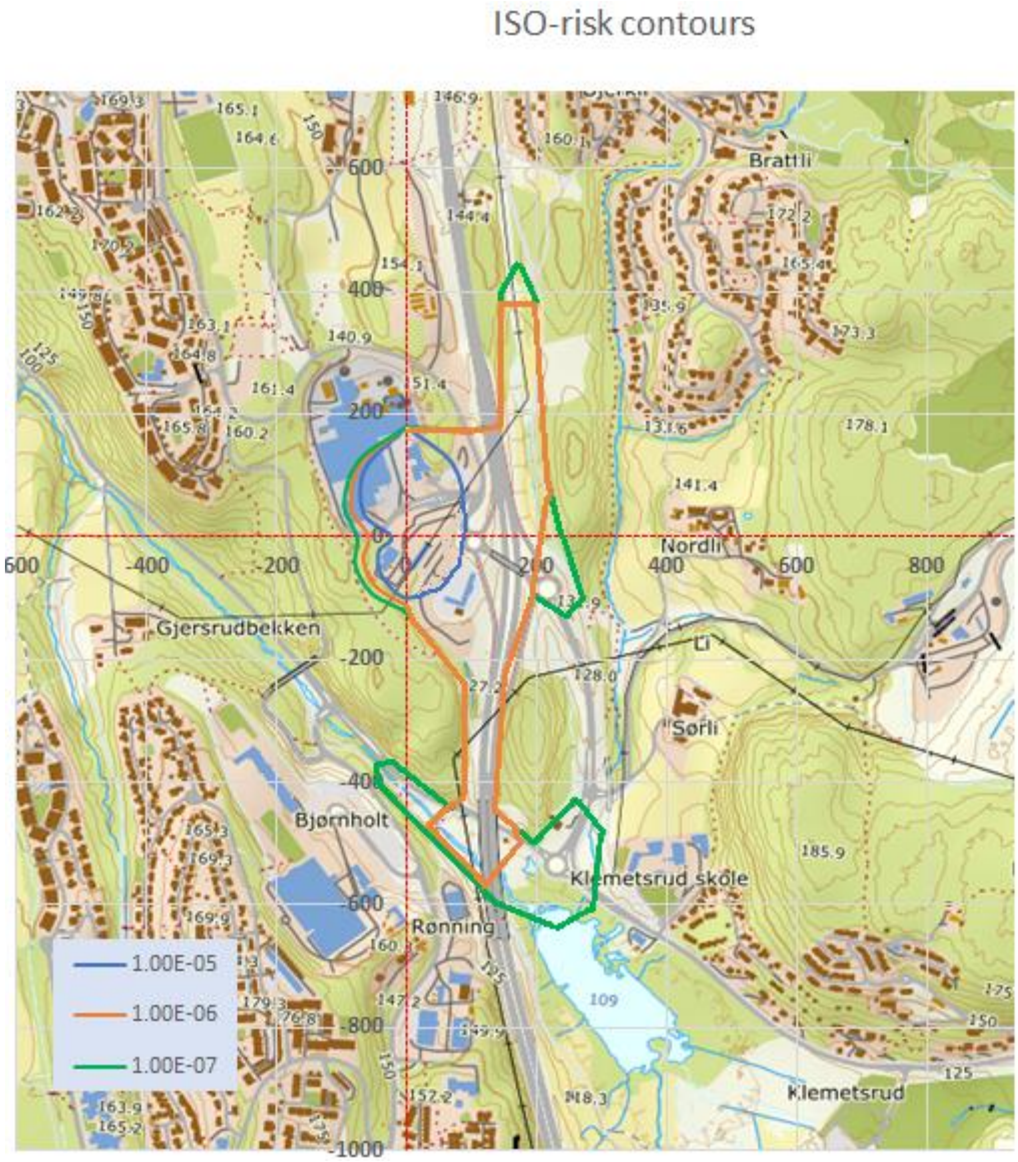


Figure 10-1: Risk contours for Klemetsrud

Risk contours for Sjursøya are shown in Figure 10-2. These risk contours include and is to some extent dominated by the existing risk picture as presented in [8]. The 10^{-5} per year iso-risk contour would be smaller to the north if existing risk picture from the petroleum handling and storage was not included (see Figure

10-3). The 10^{-6} and 10^{-7} risk contours are dominated by the CCS facilities, but do not extend much beyond the risk contours from existing facilities and related activities as shown in Figure 9-2.

Offloading to CO_2 carrier ship is included in the SoW for this risk analysis and in the iso-risk contours. Major accidents at the ship is considered outside SoW and only coarsely assessed as described in chapter 9.4.2. To reduce the uncertainty in restricted area zones and better understand the risk from major accident scenarios at the CO_2 carrier, a more detailed risk analysis for the CO_2 carrier is recommended.

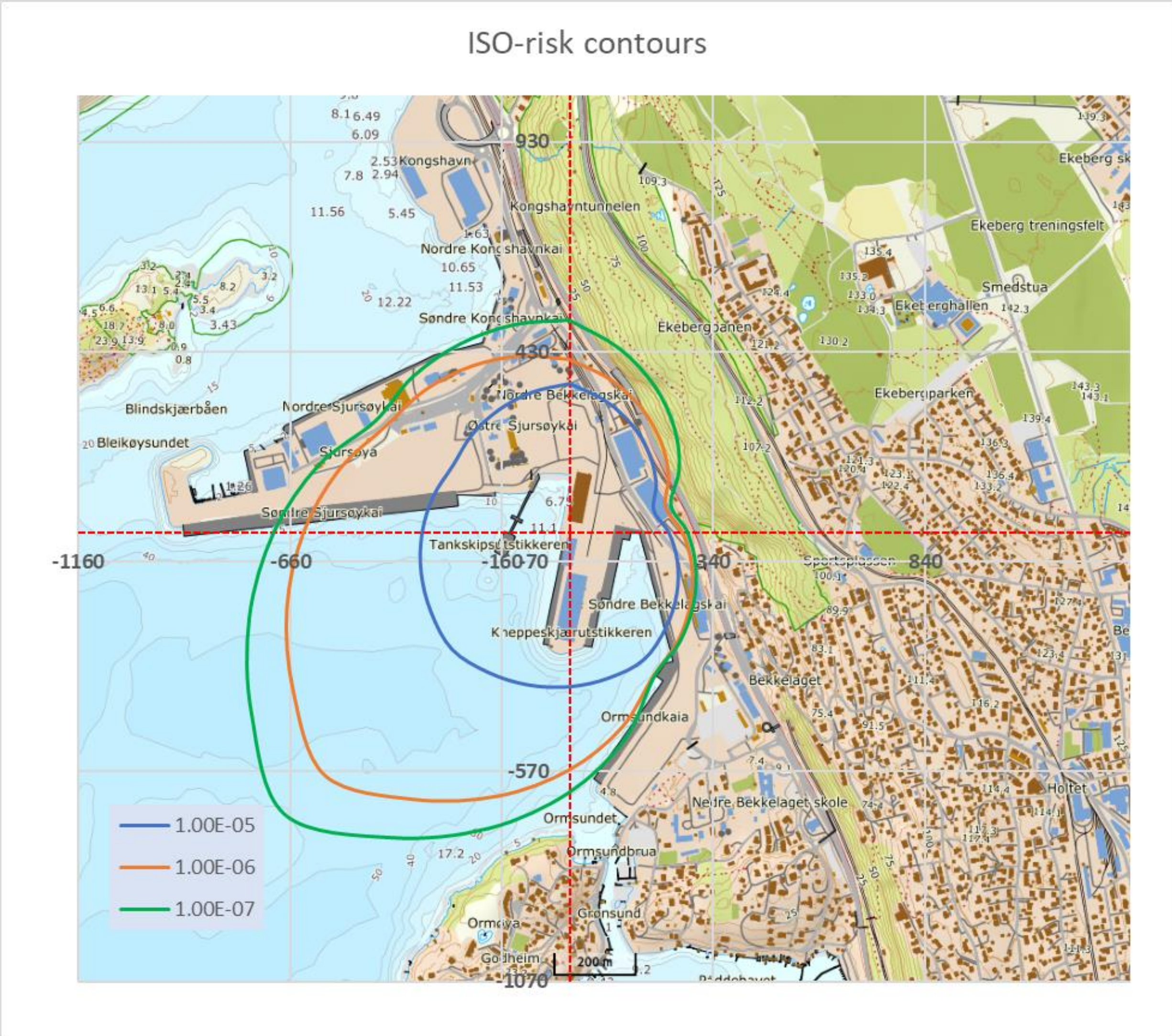


Figure 10-2: Risk contours for Oslo Harbour/Sjursøya (including existing risk picture)

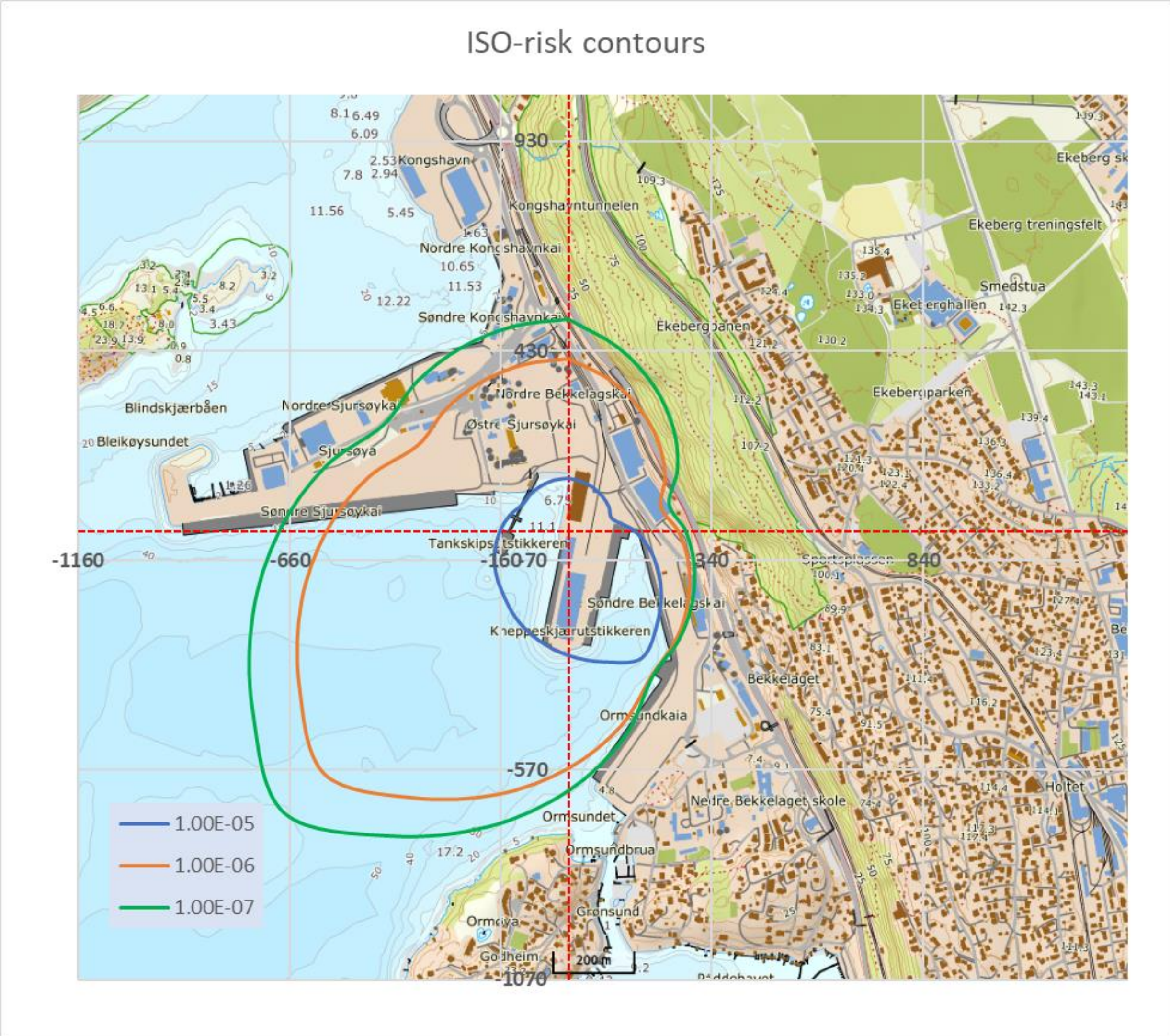


Figure 10-3: Risk contours for Oslo Harbour/Sjursøya (not including existing risk picture)

11 Risk summary

Several accident scenarios have been evaluated in order to investigate the risk for personnel at the carbon capture facilities and 3rd party. The scenarios that have been identified and investigated further are summarised in Table 11.1 and Table 11.2 for Klemetsrud and Sjursøya respectively.

Table 11.1: Overview of the Klemetsrud risk assessment

Case	Leak rate (kg/s)	Frequency (per year)	Comment	Primary data source	Consequence assessment
Storage tank BLEVE	NA	1.0E-07	Includes catastrophic failure of tanks, excl. fault developing in service.	HSE data, failure rate for vessels (catastrophic scenarios)	Blast loads from BLEVE and coarse assessment of gas cloud size included in chapter 7.
CO_2 leak scenario from tank/piping	600	3.6E-06	Catastrophic scenarios developing in service + rupture (hole size = 150mm) of piping connected to tank (between ESV and tank), 2m, upstream and downstream tank	HSE data, failure rate for piping	Gas dispersion simulation cases 01, 02, 02a, 03 and 04. The results are presented and discussed in 6.4. Note: Pressure drop from blowdown and leak will contribute to make the leak transient and with reduced leak duration (See chapter 3.4.2 discussion)
CO_2 leak scenario from tank/piping	120	1.0E-05	Leak in piping connected to tank + connection point (hole size = 50 mm)	HSE data, failure rate for piping + vessel (hole size = 50 mm)	
CO_2 leak from Klemetsrud CC plant	17	7.0E-05	Leak in piping	HSE data, failure rate for piping.	Gas dispersion simulation cases 06, 07, and 08. The results are presented and discussed in 6.1.
	50	2.0E-05	Leak in piping	HSE data, failure rate for piping.	
Tank rupture/ BLEVE truck	NA	1.0E-07	This could for example be an overpressure scenario while loading.	HSE data for road tankers.	Blast loads from BLEVE and coarse assessment of gas cloud size included in 6.5.2.
Hose rupture (truck loading)	250	7.6E-04		*Hose and Coupling Failure Rates and the Role of Human Error* [4]	Gas dispersion simulation cases 09 and 10. The results are presented and discussed in 6.5. Note: The resulting gas cloud size will depend on the quantity released, which is a function of the time to isolate the leak.

Table 11.2: Overview of the Oslo Harbour risk assessment

Case	Leak rate (kg/s)	Frequency (per year)	Comment	Primary data source	Consequence assessment
Background - Existing	NA	NA	Include existing risk picture for 10^{-5}, 10^{-6} and 10^{-7} risk level in the iso-risk presentation.	DSB report [2]	These are primarily risks related to handling petroleum products. Risk at storage facilities and jetty dominate the risk picture. In some cases, the CO_2 interim storage can be affected. Existing risk picture on Oslo Harbour is presented in chapter 9.2.
Storage tank BLEVE	NA	2.0E-07	Includes catastrophic failure of tanks, excl. fault developing in service.	HSE data, failure rate for vessels (catastrophic scenarios)	Blast loads from BLEVE and coarse assessment of gas cloud size included in chapter 7.
CO_2 leak scenario from tank/piping	600	1.4E-05	Catastrophic scenarios developing in service + rupture (hole size = 150mm) of piping connected to tank (between ESV and tank), 2m, upstream and downstream tank	HSE data, failure rate for piping	Gas dispersion simulation cases 11, 12, 13 and 14, and simulations performed in the concept phase. The results are presented and discussed in chapter 9.3.2. Note: Pressure drop from blowdown and leak will contribute to make the leak transient and with reduced leak duration (See chapter 3.4.2 discussion)
CO_2 leak scenario from tank/piping	120	4.2E-05	Leak in piping connected to tank + connection point (hole size = 50 mm)	HSE data, failure rate for piping + vessel (hole size = 50 mm)	
Tank rupture/ BLEVE truck	NA	1.0E-07	This could for example be an overpressure scenario while loading	HSE data for road tankers.	Blast loads from BLEVE and coarse assessment of gas cloud size included in chapter 9.3.1.
Hose rupture (truck loading)	250	7.6E-04		*Hose and Coupling Failure Rates and the Role of Human Error* [4]	Gas dispersion simulation cases 09 and 10 (at Klemetsrud) are relevant. The results are presented and discussed in 6.5. Note: The resulting gas cloud size will depend on the quantity released, which is a function of the time to isolate the leak.
Offloading to ship	600	4.7E-03	Rupture scenario. This includes 300m 6" piping from storage, metering station and loading arm.	TNO, Purple book (loading arm) + HSE data (piping)	Scenario is discussed in 9.3.3.
CO2 tank rupture/BLEVE at ship	NA	1.0E-07	Includes ship collision with full tank, catastrophic tank rupture and BLEVE	Collision risk analysis for Nothern Lights and generic data, see Appendix A	As for storage tank rupture, but scaled for distances, see chapter 9.4.2.

The assessment of risks at the carbon capture plant concludes that the individual risk for personnel at the plant will be low. There are several gas release scenarios that are toxic or could cause asphyxiation, but as long as the leak sources are outdoors, the risk is found low. For indoor areas (compressor house s may be an example) the risk related to these scenarios must be focused.

The major accident risks that have been identified are liquid CO_2 releases from storage tanks. The liquid leaks are likely to result in dense gas dispersion that can expose large areas to hazardous gas concentrations. Risk contours have been established and is presented in chapter 10. Comparing the results against the DSB acceptance criteria the risk picture is acceptable both for Klemetsrud and for Oslo Harbour. From CFD simulation plots in chapter 6.4 it is seen that for large releases dense gas reaches out of the facility area on Klemetsrud and down to the highway. These releases are governing for the 10^{-6} and 10^{-7} risk contours, but according to DSB criteria it is acceptable with roads inside the 10^{-6} contour. At Oslo Harbour large liquid leaks from the storage tanks is also dominating the 10^{-6} and 10^{-7} contours, but existing risk from petroleum handling and storage at the harbour has also a significant contribution.

As for other process plants, occupational risk is an issue. This includes risks such as falling objects, fall from height, confined space entry and high voltage equipment. This risk contribution has not been quantified in this analysis and no specific scenario has been identified as a particularly high-risk scenario.

The CO_2 will be transported from Klemetsrud to Oslo Harbour by truck. The truck transport includes some risks worth being mentioned. The high number of manual loading and offloading operations means that there is risk for operation or equipment failure during such operations. In addition, there is risk for traffic accidents. The potential loss of lives from these operations is however found low.

From storage tanks at Oslo Harbour the CO_2 is loaded to ship. Risk assessment of scenarios on the ship has not been part of scope for this analysis. Nevertheless, a very coarse analysis of the scenarios has been included in 9.4.2. The ship will introduce some additional accident scenarios such as tank rupture and BLEVE for the CO_2 storage tanks and LNG onboard. The risk associated with the loading operation (via 300 m piping and loading arms) has been considered but due to modest inventory the leak duration and hence the extent of the gas cloud will be limited.

12 Recommendations

To the extent safety critical task is involved in safe operation of the tank farm, tank failure will be affected by the reliability of operators carrying out such tasks. External impact from operation of cranes and vehicles are possible failures related to manually operated equipment. In relation to overpressure incidents, manual closure of a valve in the safety relief system contributed to one of the CO_2 BLEVE accidents, and in different ways human error can contribute to either overpressure or too low temperature and brittle fracture. Inspection and maintenance are other manual operations that are critical to the safe operation of the facility. A systematic analysis to identify safety critical tasks (manual operations) that could cause overpressure or otherwise lead to tank failure is recommended.

This QRA and the related gas dispersion analysis assumes constant release rate based on initial storage tank conditions. The actual development of the scenario will be more complex. Pressure drop will lead to temperature drop and could result in phase transition and possibly very low temperatures. It is recommended that the possible consequences for the tank (and the leak scenario) from large leaks, possibly in combination with pressure relief is assessed in more detail.

A detailed ESD hierarchy with automatic and manual responses to process disturbances and the fire and gas systems should be developed.

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Appendix A

CO_2 risk modelling and loss of containment frequencies

Table of contents:

A1 Introduction

This appendix describes data and methods for risk modelling from scenarios where large quantities of CO_2 are released. These large leaks result from storage and handling of liquid CO_2.

Several data sources for quantitative risk assessments are available. DSB has recently distributed a guidance for QRA for facilities that are handling hazardous substances [1], and that report has been consulted as part of this study.

This appendix gives an overview of relevant data sources for generic loss of containment frequencies, focusing on large or "catastrophic" incidents.

A2 Leak rate calculation

Liquid leaks

The challenge with calculating leak rates for liquid CO_2 is that the phase transitions involved (liquid transformed to gas and solids). Using simple models for liquid flow is expected to give conservative results, but comparison with Phast and other models shows that the model for liquid leak is accurate.

Liquid leak rate calculation: $m_l = c_d \cdot \frac{\pi \cdot d^2 \cdot \rho_l}{4} \cdot \sqrt{\left(\frac{2 \cdot (p_0 - p_e)}{\rho_l} + 2 \cdot g \cdot H\right)}$

In this equation, pressures are in Pa, density in kg/m^3 and hole diameter in mm. C_d = 0.6 (or 0.62) are commonly applied for leak rate calculations.

Oslo CCS storage conditions:

- Pressure: 16 bara = $1.6 \cdot 10^6$ Pa
- Temperature: -26°C
- Density: 1064 kg/m^3

The resulting leak rate from a 1" hole for liquid CO2 is 17.8 kg/s

Gas leaks

A general equation for leak rate calculation is given as follows (m is in kg/s provided SI units are used):

$$m = C_d \cdot A \cdot \Psi \cdot \sqrt{2 \cdot \rho_0 \cdot P_0}$$

Here, A is the cross section of the hole and C_d is the discharge coefficient. From gas leak equations, we have:

For choked flow : $\Psi = \frac{1}{\sqrt{2}} \sqrt{k \left(\frac{2}{k+1}\right)^{k+1/_{k-1}}}$

For subsonic flow: $\Psi = \sqrt{\frac{k}{k-1}\left[\left(\frac{P_{amb}}{P_0}\right)^{\frac{2}{k}} - \left(\frac{P_{amb}}{P_0}\right)^{\frac{k+1}{k}}\right]}$

For CO_2 at reasonably low pressure and temperature, the specific heat ratio for CO_2 is about 1.3 ($k = C_p/C_v = 1.3$).

Choked flow is when $P_0 > P_{amb} \cdot \left(\frac{k+1}{2}\right)^{k/k-1}$, which means $P_0 > P_{amb} \cdot 1.8$

A3 Dispersion modelling

Source modelling
Dispersion modelling results will depend on the source modelling, the grid and other parameters applied in the simulator. Specifically, for CO_2 releases, the mix of gas and solids and the temperature of the release is of interest. This must be performed using thermodynamic models and should be aligned between the projects.

Modelling topology
Topology should be modelled since terrain is critical for dense gas dispersion.

Measuring and reporting gas concentrations
Gas concentration should be measured 1m above ground. In this risk analysis, the projected maximum gas concentration for any height above ground has been applied for consequence assessments.

Grid (calculation mesh)
Grid is important for the simulation results, but also for computing time. Sensitivity studies can be performed to demonstrate that the grid is sufficiently fine to produce consistent results. This may be related to height for concentrations to be measured.

A4 CO_2 toxicity and probit function

Dangerous toxic load (DTL) describes the airborne concentration and duration of exposure, which would produce a particular level of toxicity in the general population [2]. The toxicity expressed by a given substance in the air is influenced by two factors, the concentration in the air (c) and the duration of exposure (t). A general relation applied is the following:

$$DTL = c^n \cdot t$$

A DTL relating to the mortality of 50% of an exposed population is known as the SLOD (significant likelihood of death) DTL. Note that concentrations are measured as ppm and exposure time in minutes.

According to the HSE, data available for carbon dioxide indicate that it does not meet the criteria for classification as a dangerous substance [3]. Nevertheless, releases of CO_2 have the potential to cause fatalities either due to short time exposure at high concentrations or due to long time exposure to more moderate concentrations.

For CO_2, the SLOD DTL [2] is $1.5 \cdot 10^{41}$, with $n = 8$.

The correlation between CO_2 exposure time and concentration giving 50% probability of death is;

$$c = \left(\frac{1.5 \cdot 10^{41}}{t}\right)^{\frac{1}{8}}$$

Where c is CO_2 concentration (ppm) and t is exposure time (minutes). Example: 5 minutes exposure gives a concentration of 11.5%. Exposure of a person to this load gives him only 50% chance to survive.

A probit function for CO_2 mortality is found in [4]. The probit is defined as follows:

$$Pr = A + B\ln(C^n \cdot t)$$

For CO_2, A = -90.8 and B = 1.01 and n = 8

The resulting mortality as function of gas concentration and duration of exposure is shown in Figure A 4-1.

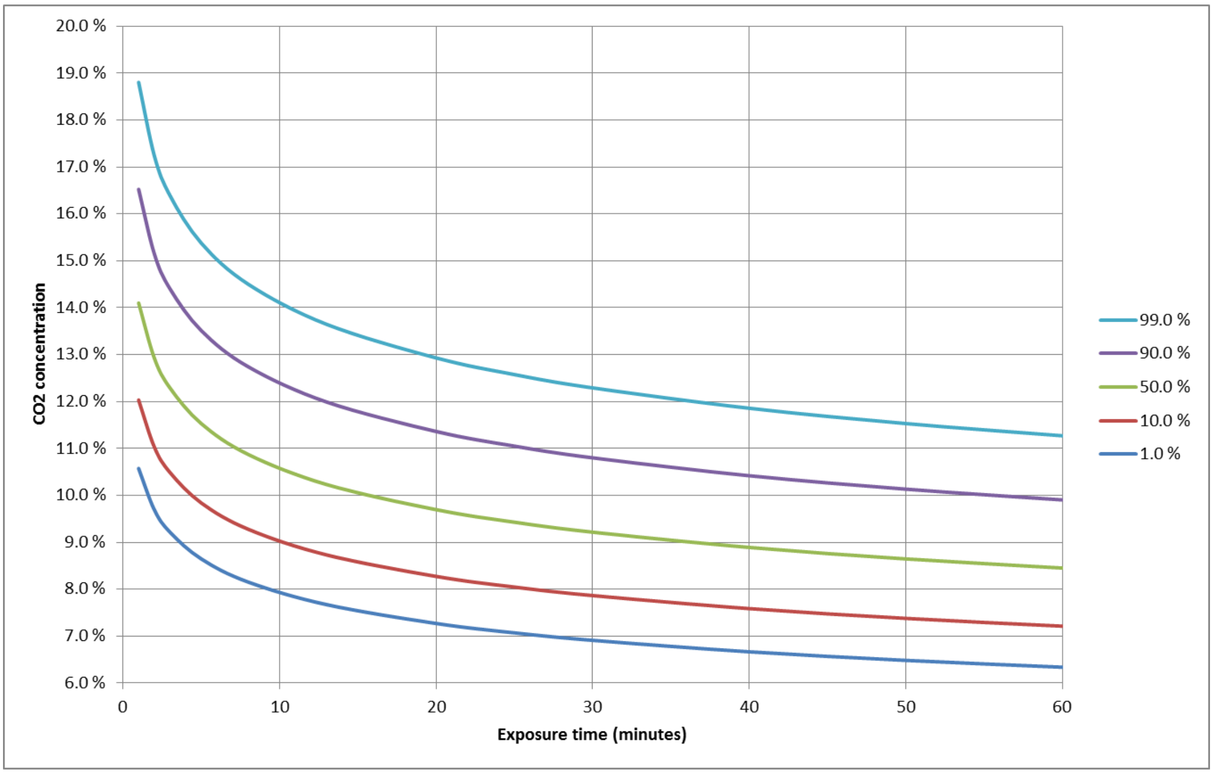

Figure A 4-1: Curves for 1% mortality to 99% mortality for CO_2 exposure

An alternative presentation of the same probit function is shown in Figure A 4-2.

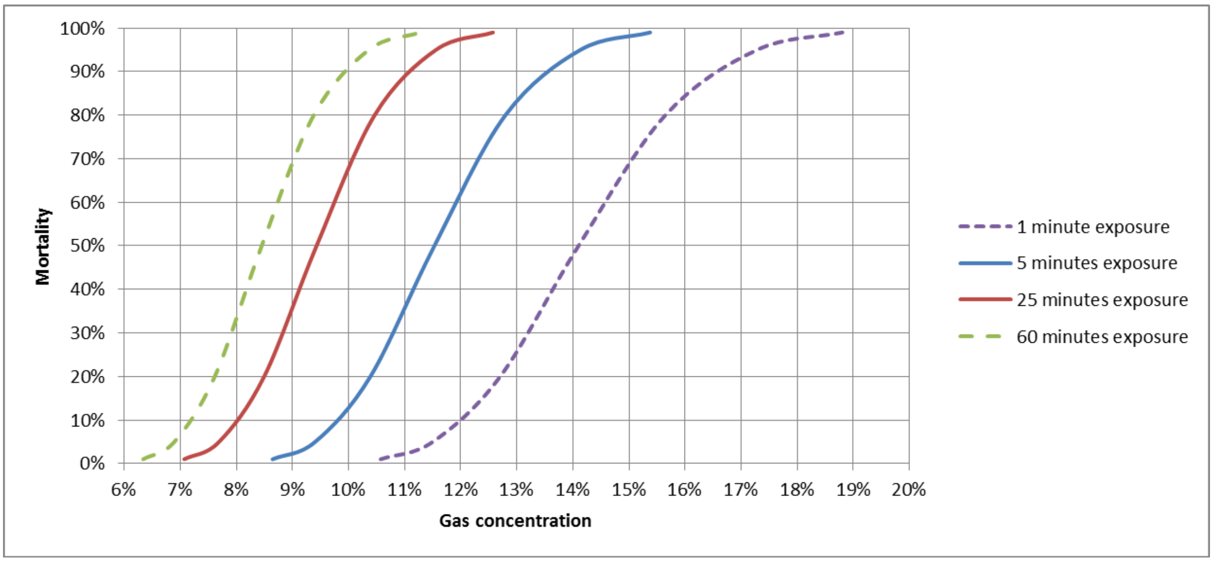

Figure A 4-2: Mortality curves for CO_2 exposure for different exposure times

The concentration limit known as IDLH (immediately dangerous to life or health) as defined by NIOSH is set to 40000 ppm (4%). From Figure A 4-1 and Figure A 4-2 it is seen that exposure to 4% CO_2 concentration for 1 hour has a mortality way below 1%. For exposure time one hour or less, 6% CO_2 concentration is used as the lower concentration that could pose risk for fatal accidents. This is also used as the lower concentration in the plots from CFD simulations.

A5 Exposure time, escape and evacuation

The accident scenarios identified give different dispersion distances and exposure periods. Provided a fast responding detection and alarm (PA) system, site personnel and third-party personnel will start evacuating. At the CC plant, personnel will be trained to evacuate to mustering areas which should be located where CO_2 exposure risk is negligible. Evacuation speed (walking speed) is normally set to 1 m/s which means it takes approx. 5 minutes to cover 300 meters.

Evacuation of 3rd party personnel is more unpredictable since alarms and contingency plans are not established and because drills are not easily undertaken for persons in residential areas or for the public in general. For the input to the restricted area zones evaluation, 1 hour exposure time is proposed, unless the exposure time is judged to be shorter because the leak has short duration. This is judged to be a conservative approach, as it is believed that exposure times exceeding 30 minutes will be rare in most occasions. Using a conservative approach on this subject is in line with the DSB guidance for risk analysis, which does not recommend to credit escape and evacuation in relation to exposure time.

A6 Data sources for loss of containment frequencies

A6.1 Purple book and RIVM

The Purple book, [5] is a reference that is commonly accepted source for generic accident frequencies for risk analysis work. The RIVM [6] apply leak frequencies from the Purple book for many of the scenarios applied in this concept risk analysis.

It is important to realize that the accident frequencies in the Purple book (and therefore also RIVM) to a large degree are based on expert judgement, and that the source documents and studies referred in most cases are older than 1980. This means that technological improvements over time are not reflected in the data. For some scenarios, it is believed that using the RIVM or Purple book data can lead to a conservative risk picture, in particular for a new-built facility. Also, the basis for the frequencies in the Purple book is now in some cases unknown.

The wide-spread use of the Purple book and RIVM for onshore risk analysis is a good argument for using these sources, as this contributes to more consistency in risk quantification.

A6.2 PLOFAM

In the offshore oil and gas industry, generic leak frequencies have been derived through several projects based on reported leaks at the Norwegian and UK continental shelves and population data. The latest model developed in Norway is the PLOFAM(2) model [7]. The developed models seek to give a realistic and unbiased prediction of hydrocarbon process leaks and ignitions for an average facility on the NCS.

The PLOFAM requires detailed equipment count where possible leak points are identified and is thus less applicable in for early phase risk quantification when few details are available. The basis for PLOFAM is mainly complex facilities with a variety of failure modes that could potentially result in loss of containment. The counting of equipment is considered a reasonable way to quantify the plant complexity. Even if the leak picture is comprised of leaks from different types of equipment (flanges, valves, etc.), the equipment count serves as an indicator for leaks related to maintenance and operation in addition to equipment failures. Therefore, when applying leak frequencies from PLOFAM to a simple system such as a storage tank with connected piping, the loss of containment frequencies may be conservative.

A6.3 EGIG

The EGIG database [8] is a database of pipeline and incident data. Pipeline data and incident data of natural gas transmission pipelines are in the database since 1970. The data are from onshore steel pipelines.

Seventeen gas transmission system operators in Europe now collect incident data on more than 143,000 km of pipelines every year. The total exposure, which expresses the length of a pipeline and its period of operation, is 3.98 million km·year.

A6.4 Dow's Chemical Exposure Index Guide

Dow's chemical exposure index guide [9] is not a data source in the sense that it presents generic frequencies for leak scenarios. It is rather a method to determine hazardous distances based on consequence assessment. The guide is used extensively internationally and referenced in some countries' regulations including the USA and Netherlands. For the purpose of this concept risk analysis, it is of particular interest what scenarios the guide recommends applying as basis for hazardous distance evaluations. These scenarios can be read as the design or worst credible scenarios to be applied as basis for design.

A6.5 HSE failure rates and event data

HSE has established a set of generic failure rates that are intended for use on land use planning cases in [10].

A7 Experienced catastrophic rupture of CO_2 storage tanks

There are at least three known incidents with catastrophic failure of refrigerated and pressurised CO_2 storage tanks (storing CO_2 as a liquid). For all these cases, it seems that operational errors caused the explosions. If a refrigerated CO_2 storage tank is sealed off, and the inventory allowed to be heated, pressure will increase, and it is likely the tank will eventually fail from overpressure. The pressure drop following rupture can result in violent boiling of the liquid and a BLEVE or BLEVE-like scenario. These mechanisms are further described in [11], but it seems the conditions for an explosion to occur are still not fully understood.

All the described accidents are very serious events with significant damages and casualties. With possible exception for the incident in Haltern, it seems conditions were outside design limits due to operational and/or technical failures.

Repcelak, Hungary, January 2nd 1969 [11]
Two vessels containing liquid CO_2 (15 bar, -30°C) in a CO_2 production and filling plant exploded in rapid succession. The explosion destroyed the tank yard of four liquid CO_2 storage vessels. During filling, the first vessel exploded. The probable cause of the accident was overfilling the first tank due to a level indicator failure. Some minutes later, another close-by vessel exploded. The second vessel probably failed because of impact from a fragment from the first vessel. The explosions tore a third vessel off its foundation bolts which was shot like a rocket due to liquid CO_2 rapid expansion through a hole on the bottom.

Fukushima, Japan, March 1st 1969 [12]
A 8m^3 tank with operating pressure up to 23.5 barg and a design pressure at 25 barg failed during a maintenance operation. The pressure relief valves were closed (considered an operational error), and it seems the inventory was heated. The vessel failed due to high pressure, and there was an explosion causing 3 fatalities and 38 injuries. Debris was found up to 60 meters away, and windows were damaged within a 500m radius.

Haltern, Germany, September 2nd 1976 [11]
A rail car carrying 231 000 kg of CO_2 exploded in Haltern, Germany. The tank's contents was at minus -15°C. Prior to the explosion the car was observed to be releasing plumes of CO_2 from the safety valve. It then exploded, and parts of the tank were thrown up to 360 m. One person was killed in the explosion. [11] concludes that brittle metal fracture caused this BLEVE type incident.

Worms, Germany, November 21st 1988 [13]
There was a catastrophic failure of a vessel containing liquid carbon dioxide at Proctor and Gamble's citrus facility in Worms, Germany. The vessel over-pressurised leading to loss of containment. The force of the explosion propelled the majority of the vessel into the river Rhine approximately 300 m away. The incident resulted in three fatalities, eight employees hospitalised with serious injuries, three months' lost production and 20 million dollars' worth of property damage.

The tank had a nominal capacity of 30 te CO_2 and was designed for -50°C and 20 bar. During a 17 hour general power failure, tank pressure was increasing. Pressure may have been 1.75 to 2.5 times the design pressure when the vessel eventually failed. An important cause for this incident was that the relief valve failed to open, possibly due to ice/freezing.

Yuhang, Hangzhou, China, November 13th 2008 [14] **and** [11]
A transport ship carrying 130 cu. meter (95% full) of CO_2 exploded. The storage conditions were minus 15°C and 23 bara. The ship was in the dock where the explosion destroyed the CO_2 ship and sank two nearby ships. Two workers on the CO_2 ship lost their lives instantly and 3 were injured due to projectiles. Windows shattered in residential buildings 500 meters away. The cause of this accident is believed to be overloading and brittle failure of the CO_2 tank. The tank was designed for on-shore use but was modified for ship transportation. To lower the transportation cost, the company modified the level indicator, locked the relief valve, and overloaded the tank (95% filling level).

A8 Leak frequencies for equipment handling large quantities of liquid CO_2

A8.1 Leak frequencies for pressurized storage tanks

Liquefied CO_2 is stored in pressurised tanks both at KEA and at the harbour. Release of liquid CO_2 could be either from connecting lines and flanges or from a crack or rupture of the tank itself. Various data sources give different leak frequencies from pressurised tanks. In the following is a summary of frequencies.

A8.1.1 Frequencies from various data sources

OGP – Oil and Gas Producers; "Risk Assessment Data Directory"
Leak frequencies for pressurised tanks are given in Table A 8-1. Note that "Small containers" do not apply as they are defined for volumes less than 2 m^3. The frequencies apply to the vessel with nozzles and associated equipment like instrumentation as well as the man-hole. Connection points are included up to the first flange but not the flange itself. One of the accidents used as basis for the frequency data was rupture of a CO_2 tank in Germany (1988). Most of the accidents referred to are from F.P. Lees [15]. The risk assessment data directory is basically meant for use on offshore installations.

Table A 8-1: Leak frequencies for pressurised storage tanks (OGP)

Hole Diameter		Leak Frequency (per vessel year)	
Range	Nominal	Storage Vessels	Small Containers
1-3 mm	2 mm	2.3×10^{-5}	4.4×10^{-7}
3-10 mm	5 mm	1.2×10^{-5}	4.6×10^{-7}
10–50 mm	25 mm	7.1×10^{-6}	
50-150 mm	100 mm*	4.3×10^{-6}	
>150 mm	Catastrophic	4.7×10^{-7}	1.0×10^{-7}
TOTAL		4.7×10^{-5}	1.0×10^{-6}

*Or diameter of largest pipe connection if this is smaller

TNO – Purple Book

Leak frequencies for pressurised tanks are given in Table A 8-2. By "instantaneous" is meant release of the total content instantaneously. By "continuous-10 min" is meant a steady state release which will empty the tank content in ten minutes. The corresponding leak hole diameter is therefore determined by the content of the tank. By "continuous-Ø10 mm" is meant a release rate corresponding to an effective leak hole diameter of 10 mm. As for OGP data the frequencies do only apply to the vessel with nozzles and associated equipment like instrumentation as well as the man-hole.

Table A 8-2: Leak frequencies for pressurised storage tanks (TNO)

Installation (part)	G.1 Instantaneous	G.2 Continuous, 10 min	G.3 Continuous, D = 10 mm
Pressure vessel	$5\cdot10^{-7}$ per year	$5\cdot10^{-7}$ per year	$1\cdot10^{-5}$ per year

In relation to this table, TNO Purple book includes the following statement: *A lower failure frequency can be used if a tank or vessel has special provisions additional to the standard provisions, e.g. according to the design code, which have an indisputable failure-reducing effect. However, the frequency at which the complete inventory is released (i.e. the sum of the frequencies of the LOCs, G.1 and G.2) should never be less than 1 × 10^{-7} per year.*

The failure frequencies in Purple book excludes failures like corrosion, fatigue, operating errors and external impacts. If these failures cannot be excluded, Purple book suggests an extra failure frequency of $5\cdot10^{-6}$ should be added to G1 and G2 in Table A 8-2.

HSE (UK)

In [10], HSE has performed an extensive review for major failures of high pressure storage vessels and has established failure frequencies for pressure vessels such as chlorine pressure vessels, LPG pressure vessels and spherical storage vessels. The frequencies do not differ much for the three different types.

Table A 8-3: Leak frequencies for pressurised storage tanks (HSE)

Installation (part)	Hole diameter [mm]				
	Catastrophic	50	25	13	6
Pressure vessel	$2\cdot10^{-6}$	$5\cdot10^{-6}$	$5\cdot10^{-6}$	$1\cdot10^{-5}$	$4\cdot10^{-5}$

The HSE recommended frequencies for catastrophic failure is $2\cdot10^{-6}$ per year, split equally on external factors and overpressurisation and defects. HSE states that "*the values above take the effects of external hazards into account at a rate of* $1\cdot10^{-6}$ *per vessel year for catastrophic failures. If site specific conditions are known to result in a higher external hazard rate then the overall failure rate used should be adjusted as necessary".*

A report by Nussey (2006) compares HSE recommended failure frequencies to the figures recommended by TNO [16]. A comparison between Purple Book frequencies and HSE frequencies for pressure vessels is shown in Table A 8-3. Purple book frequencies (PB99) is given both including and excluding operating errors, external impact etc. Denoted in table as "complete" and "default", respectively.

Table A 8-4: Comparison of HSE and PB99 failure frequencies for pressure vessels

Type of failure	PB99 default	PB99 "complete"	HSE
Catastrophic	$5 \cdot 10^{-7}$	$5.5 \cdot 10^{-6}$	$2 \cdot 10^{-6}$ - $6 \cdot 10^{-6}$
Large hole	$5 \cdot 10^{-7}$	$5.5 \cdot 10^{-6}$	$5 \cdot 10^{-6}$
Small hole	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$5.5 \cdot 10^{-5}$
All types	$1.1 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$	$6.2 \cdot 10^{-5}$ - $6.6 \cdot 10^{-5}$

Considering catastrophic failures and large hole sizes it can be seen that the two references do not differ much. But for small hole sizes (6, 13 and 25 mm) the HSE aggregated failure frequency is 5 times the PB99 value for 10mm holes. A factor of 5 can significantly influence the location of the inner planning zone; the magnitude of the effect will depend on the choice of hole sizes and the corresponding failure frequencies.

For LPG storage vessels > 6.6 te capacity, [16] refers a study by O'Donnel et al (2004) concluding that there were no "cold catastrophic failures" in 3.36 million vessel years. This corresponds to $2 \cdot 10^{-7}$ failures per vessel year (50% confidence).

The HSE report also proposes failure rates for refrigerated ambient pressure vessels, including LNG vessels. Failure rates are given for both single- and double walled vessels. In the report it is argued that due to no record of failure of LNG vessels generic figures should be reduced for double walled LNG vessels.

Table A 8-5: Failure rates for refrigerated vessels

Release	Vessel		
	Single walled	Double walled	LNG
Catastrophic	$4 \cdot 10^{-5}$	$5 \cdot 10^{-7}$	$5 \cdot 10^{-8}$
Major failure	$1 \cdot 10^{-4}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-6}$
Minor failure	$8 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$3 \cdot 10^{-6}$
Failure with a release of vapour only	$2 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$4 \cdot 10^{-5}$

Table A 8-6: Release sizes for refrigerated vessels

Category	Hole diameters for different tank volumes		
	450-4000 m^3	4000-12000 m^3	> 12000 m^3
Major	500 mm	750 mm	1000 mm
Minor	150 mm	225 mm	300 mm

<u>AIChE – DOW's Chemical Exposure Index Guide</u>
This guide does not provide accident frequencies but rather specify the size of leaks which shall be used for determination of hazard distances.

All releases shall be assumed to last for minimum 5 minutes. If a leak rate is found to last for less than 5 minutes, the rate to be used shall be adjusted to the rate calculated by dividing the total inventory by 5 minutes.

A8.1.2 Conclusions – establishing frequency for pressure vessel loss of containment

[16] includes a simplified fault tree as basis for discussing generic tank failure frequencies. A somewhat modified fault tree for intermediate CO_2 storage is shown in Figure A 8-1.

- Generic (cold) catastrophic failures relates to the branch “defects developing in service”. Based on available sources reviewed and assessed in [16], the frequency for this branch could be in the range $1 \cdot 10^{-7}$ to $1 \cdot 10^{-6}$ per year. Note that this frequency may be affected by impurities in the stored product.
- For a liquid CO_2 storage tank, operational errors resulting in overpressure should not include all types of operational and technical failures that could result in overpressure in the tank. This failure mode should be analysed for the tank considered.
- The branch “external damage” should include all external threats identified. Examples are shown in Figure A 8-1.

Refrigerated and pressurised storage of liquid CO_2 requires that operational conditions are under control and implemented overpressure protection systems are reliable. Experienced accidents demonstrate the importance of such measures. In the known cases, pressure was gradually building up over time, and the pressure build-up was undetected. Although population data for refrigerated CO_2 storage facilities are unavailable, it can be concluded that the generic frequency for catastrophic tank failure from operational causes is higher than the frequencies for external damage or defects developing in service.

Failure scenarios for pressurized storage were found to have very low frequency when external causes (impact, fire, etc.) and operational causes (overpressure) are excluded. There are hardly any incidents recorded, and the order of magnitude for storage rupture is 10^{-7} per year.

While still rare, rupture due to overpressure are more frequently observed. Three examples of CO_2 storage vessel explosion have been recorded, at least two of these with fatal consequences. These are BLEVE scenarios with severe consequences caused by overpressure as the tank inventory is heated well above the storage temperature. The frequency for such incidents depends on the reliability of the safety barriers for overpressure protection. No similar accidents have been identified for LNG storage facilities, and this is an indication that the risk for overpressure can be effectively controlled. Quantification of the frequency for overpressure should include a reliability analysis or assessment of these barriers. The reliability requirements to safety systems must be strict since storage tank rupture consequences will be severe.

External loads such as fire, vehicle impact, earthquake or landslide can impact the storage facilities and cause single or multiple storage tank failure. Design measures must be implemented to ensure that the risk for storage tank damage from external loads is negligible.

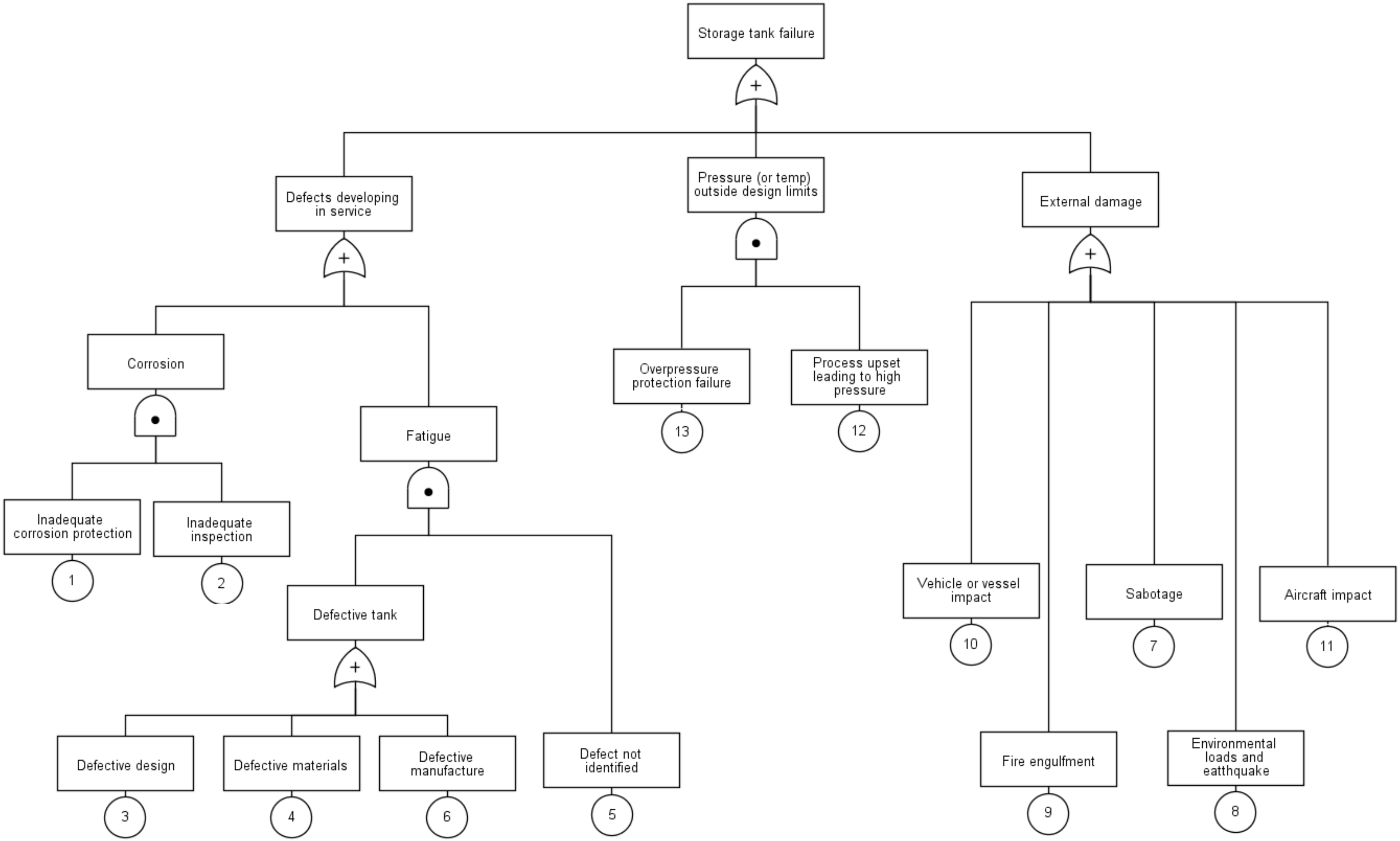

Figure A 8-1: Simplified fault tree for storage vessel failure

A8.1.3 Applied frequencies in QRA– pressurised storage tanks

When establishing loss of containment frequencies to be used for storage tanks at KEA and Oslo harbour, two scenarios are considered:

- CO_2 leaks from storage tanks
- Storage tank rupture/BLEVE scenarios

Relating these scenarios to the fault three shown in Figure A 8-1, “pressure outside design limits” and “external damage” are considered causes to storage tank rupture and BLEVE scenarios, while “defects developing in service” are considered causes for leaks in connection point between vessel and piping.

With several storage tanks at the facility, in particular at the harbour, it is a question whether the frequency should be multiplied with number of tanks. Some failures are likely to affect all tanks simultaneously, e.g. external failures, and the frequency should therefore not be dependent on number of tanks. Failures developing in service however, is type of failures that potentially could happen to “any of the tanks” and number of tanks will therefore be relevant in this matter.

<u>CO_2 leaks from storage tanks</u>

With new designed tanks and double walls with monitored annulus, the frequency for *failures developing in service* are considered low. In the HSE data frequencies for refrigerated ambient pressure vessels, including LNG vessels, have been established ($5 \cdot 10^{-7}$ and $5 \cdot 10^{-8}$ per year, respectively). Frequencies for pressurised vessels have also been established ($1 \cdot 10^{-6}$ per year – external effects negligible). No frequencies have been established for refrigerated pressurised vessels. As basis for this analysis a frequency of $1 \cdot 10^{-7}$ per year due to failures developing in service is chosen.

The frequency to be used for worst credible scenario from storage tanks will hence be calculated as follows:

$$f_{\text{failures developing in service}} \cdot n + f_{\text{piping rupture}}$$

where “n” is number of storage tanks. Frequency for pipe rupture is based on HSE data (see chapter A8.2)

HSE data has, in addition to catastrophic failures suggested failure rates for different hole sizes for process vessels. A hole size of 50mm will (approximately) correspond to 20% of the cross section of a 6” pipe. HSE data uses a failure rate of 5.0E-06 per vessel year for a 50mm diameter hole in process vessels. As for catastrophic failures, it is considered reasonable to reduce the frequency some. A frequency of 1.0E-06 will hence be used for this hole size.

The frequency for 20% cross section of a 6” pipe (approximately 50 mm) will hence be calculated as:

$$1 \cdot 10^{-6} \cdot n + f_{\text{piping with hole size 50mm}}$$

where “n” is number of storage tanks. Frequency for pipe leaks is based on HSE data (see chapter A8.2)

Storage tank rupture/BLEVE scenarios

Historically it has been seen that icing and blockage of relief valves have caused accidents with quite violent explosions (BLEVE) with fatal consequences and material damages (historical incidents have been described in chapter A7). For the Oslo CCS storage, there will be a minimum back-pressure in the relief system that will prevent formation of solids. In addition, there will be frequent inspection and maintenance of valves and instrumented safety barriers. The resulting frequency for overpressure scenarios with BLEVE is considered low; $1 \cdot 10^{-7}$ per year for each tank cluster is proposed for this analysis.

The frequency for tank rupture/BLEVE scenarios will be calculated as:

$$f_{\text{tank rupture}} = f_{\text{pressure outside design limits}} + f_{\text{external damage}}$$

Considering failures during service or failures as a result of pressure/temperature above design limits, these failure frequencies are considered equal for Klemetsrud and Oslo harbor (although number of storage tanks will be different). External impacts may be somewhat different on the two locations and is hence discussed separately. External impacts frequency and resulting frequencies for storage tank failure at Klemetsrud and Oslo harbour is discussed separately in the main report.

A8.2 Leak frequencies for process piping and connections

A summary of presented piping leak frequencies in various data sources is given in the following.

A8.2.1 Frequencies from various data sources

TNO – Purple Book

Leak frequencies for piping are given in Table A 8-7. The frequencies include flanged connections.

Table A 8-7: Leak frequencies for piping with flanged connections

Installation (part)	G.1 Full bore rupture	G.2 Leak (10% of diameter)
Pipeline, nominal diameter < 75 mm	$1 \cdot 10^{-6}$ per m · year	$5 \cdot 10^{-6}$ per m · year
Pipeline, nominal diameter 75 mm to 150 mm	$3 \cdot 10^{-7}$ per m · year	$2 \cdot 10^{-6}$ per m · year
Pipeline, nominal diameter > 150 mm	$1 \cdot 10^{-7}$ per m · year	$5 \cdot 10^{-7}$ per m · year

The following apply for these data;

- "Full bore rupture" implies that full outflow from both ends shall be used.
- "Leak" implies the use of a leak diameter equal to 10 mm with a maximum of 50 mm.
- Length of a pipe shall be set to minimum 10 meters since the frequency data includes flanges.

HSE data

Leak frequencies for pipework according to HSE data is shown in Table A 8-8. Leaks from valves are included in the pipework failure rates, but failure on demand is given separately for valves.

Table A 8-8: Failure rates for pipework, HSE data

Hole size (diameter)	Failure rates (per m per y) for pipework diameter			
	50mm to 149mm	150mm – 299mm	300mm – 499mm	500mm-1000mm
	2” to 5”	6” to 11”	12” to 20”	21” to 40”
4 mm*	$2{\cdot}10^{-6}$	$1{\cdot}10^{-6}$	$8{\cdot}10^{-7}$	$7{\cdot}10^{-7}$
25 mm	$1{\cdot}10^{-6}$	$7{\cdot}10^{-7}$	$5{\cdot}10^{-7}$	$4{\cdot}10^{-7}$
1/3 pipework	-	$4{\cdot}10^{-7}$	$2{\cdot}10^{-7}$	$1{\cdot}10^{-7}$
Rupture	$5{\cdot}10^{-7}$	$2{\cdot}10^{-7}$	$7{\cdot}10^{-8}$	$4{\cdot}10^{-8}$

* For pipwork 50mm to 149mm the hole size for this category is 3mm

Dow’s chemical exposure index guide

Dow’s chemical index guide [9] recommends using piping dimension as basis for hazardous distance calculations follows:

- < 2” pipe – full bore rupture
- 2”-4” pipe – rupture equal to that of a 2” diameter pipe
- >4” pipe – rupture area equal to 20% of pipe cross section area

PLOFAM

Leak frequencies from PLOFAM are shown in chapter A8.5. Leak frequencies depend on the piping dimension and are split with contributions from flanges and piping. Leak frequencies are similar to those reported in the Purple book.

A8.2.2 Applied frequencies in QRA – piping

In the QRA, data from HSE have been applied (ref. Table A 8-8).

A8.3 Leak frequencies for pumps

A summary of presented pump leak frequencies in various data sources is given in the following.

A8.3.1 Frequencies from various data sources

TNO – Purple Book

Leak frequencies for pumps are given in Table A 8-9.

Table A 8-9: TNO Leak frequencies for pumps

Installation (part)	G.1 Full bore rupture	G.2 Leak
Pumps without additional provisions	$1{\cdot}10^{-4}$ per year	$5{\cdot}10^{-4}$ per year

The following apply for these data;

- “Full bore rupture” implies rupture of the largest connecting pipe.
- “Leak” implies the use of a leak diameter equal to 10 mm with a maximum of 50 mm.

HSE

Table A 8-10 lists recommended leak frequencies from the HSE [10].

Table A 8-10: HSE leak frequencies for pumps

Type of event	Item	Frequency [per year per pump]
Failure of casing	Pumps	$3 \cdot 10^{-5}$
Spray release	Pumps single seal	$5 \cdot 10^{-4}$
	Pumps double seal	$5 \cdot 10^{-5}$

<u>PLOFAM</u>
PLOFAM leak frequencies for pumps are shown in chapter A8.5. Leak frequencies from PLOFAM are dependent on equipment size (piping dimension). The PLOFAM data represents offshore experience, and the frequencies are well below those recommended by HSE and TNO's Purple Book. The majority of pumps in the PLOFAM data set are relatively large pumps.

A8.3.2 Applied frequencies in the QRA – pumps

The QRA did not explicitly apply leak frequencies for pumps.

A8.4 Leak frequencies for heat exchangers

A summary of presented heat exchanger leak frequencies in various data sources is given in the following.

A8.4.1 Frequencies from various data sources

<u>TNO – Purple Book</u>
Leak frequencies for pumps are given in Table A 8-11.

Table A 8-11: Leak frequencies for heat exchangers

Installation (part)	G.1 Instantaneous	G.2 Continuous, 10 min	G.3 Continuous, ∅10 mm
heat exchanger, dangerous substance outside pipes	5×10^{-5} y^{-1}	5×10^{-5} y^{-1}	1×10^{-3} y^{-1}
Installation (part)	**G.4 Rupture, 10 pipes**	**G.5 Rupture, 1 pipe**	**G.6 Leak**
heat exchanger, dangerous substance inside pipes, design pressure outer shell less than pressure of dangerous substance	1×10^{-5} y^{-1}	1×10^{-3} y^{-1}	1×10^{-2} y^{-1}
heat exchanger, dangerous substance inside pipes, design pressure outer shell more than pressure of dangerous substance	1×10^{-6} y^{-1}		

For simplicity, and due to lack of equipment information, we will assume that all heat exchangers contain the fluid of concern on the shell side.

<u>PLOFAM</u>
PLOFAM leak frequencies for heat exchangers are shown in chapter A8.5. Leak frequencies from PLOFAM are dependent on equipment size (piping dimension). The PLOFAM LoC frequencies are well below those recommended by HSE and TNO's Purple Book except for the case with "dangerous substance inside pipes" in Table A 8-11.

A8.4.2 Applied frequencies for KEA – heat exchangers

The QRA did not explicitly apply leak frequencies for heat exchangers.

A8.5 Leak frequency quantification using PLOFAM

The following leak frequencies are quantified using PLOFAM with the following assumptions:

- Equipment size is 10"
- Leak rate is scaled with hole size based on 13 kg/s for a 1" diameter hole (see chapter A2).

Table A 8-12: Summary of PLOFAM leak frequencies (liquid leaks, 10" equipment)

	Leak rate (kg/s)								
	1 - 10	10 - 16	16 - 32	32 - 64	64 - 128	128 - 256	256 - 512	512 - 1024	> 1024
Standard flange	2.6E-06	2.7E-07	3.0E-07	2.2E-07	1.6E-07	1.1E-07	8.1E-08	5.9E-08	2.9E-07
Compact flange	4.3E-08	2.2E-09	2.0E-09	1.1E-09	5.8E-10	3.1E-10	1.7E-10	9.3E-11	9.2E-10
Valve	9.6E-06	7.8E-07	8.1E-07	5.3E-07	3.4E-07	2.3E-07	1.5E-07	9.7E-08	3.4E-07
Pump	6.8E-05	3.2E-06	2.7E-06	1.4E-06	7.3E-07	3.8E-07	2.0E-07	1.0E-07	1.1E-07
Heat exchanger	3.9E-05	4.2E-06	4.9E-06	3.6E-06	2.7E-06	2.0E-06	1.5E-06	1.1E-06	3.2E-06
Piping (per m)	5.0E-07	3.2E-08	3.1E-08	1.9E-08	1.1E-08	6.6E-09	3.9E-09	2.3E-09	2.9E-08
Process vessel	3.1E-05	2.4E-06	2.4E-06	1.5E-06	9.7E-07	6.2E-07	3.9E-07	2.5E-07	4.4E-07

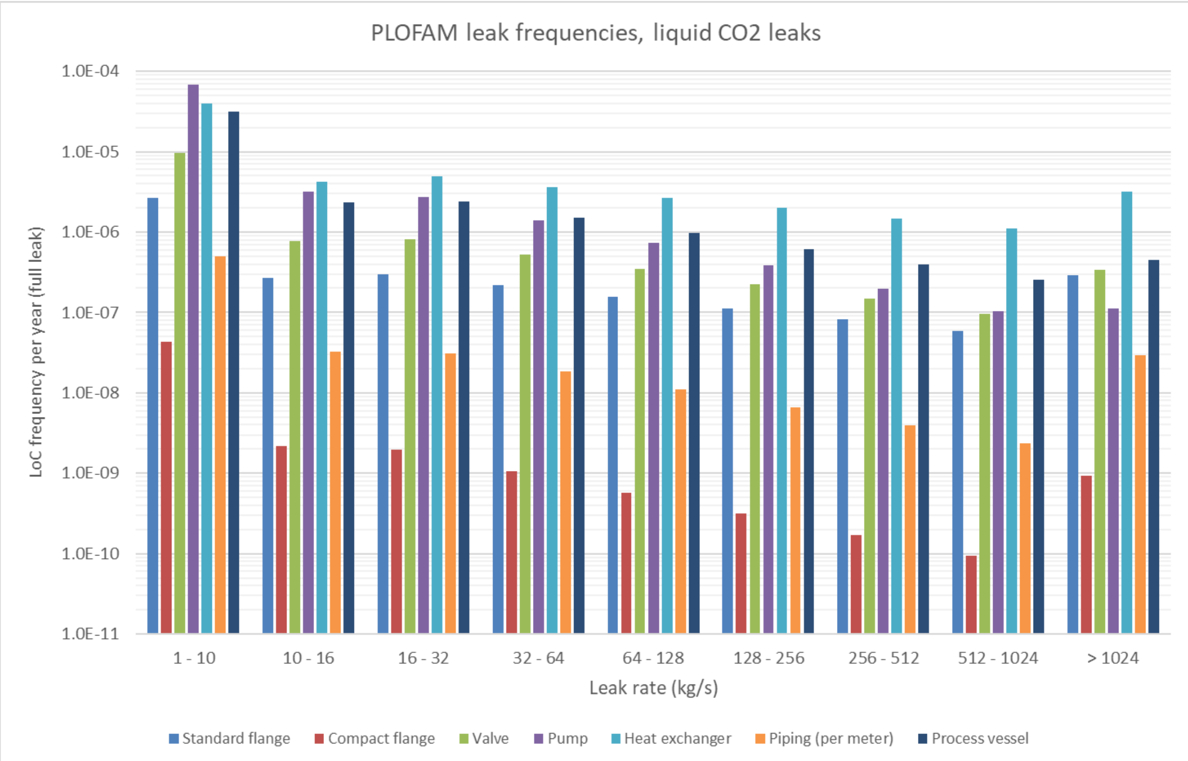

Figure A 8-2: Summary of PLOFAM leak frequencies (for 10" equipment)

A9 Leak frequencies for other equipment

A9.1 Leak frequencies for pressurised process vessels

<u>TNO – Purple Book</u>
Leak frequencies for piping are given in Table A 9-1.

Table A 9-1: Leak frequencies for pressurized process vessels

Installation (part)	G.1 Instantaneous	G.2 Continuous, 10 min	G.3 Continuous, D = 10 mm
Process vessel	$5 \cdot 10^{-6}$ per year	$5 \cdot 10^{-6}$ per year	$1 \cdot 10^{-4}$ per year

Dow's chemical index guide [9] recommends using the maximum connected piping dimension as basis for hazardous distance calculations (as for process pipes and associated connections):

- < 2" pipe – full bore rupture
- 2"-4" pipe – rupture equal to that of a 2" diameter pipe
- >4" pipe – rupture area equal to 20% of pipe cross section area

A9.2 Leak frequencies for compressors

TNO – Purple Book

Leak frequencies for compressors are not given in the Purple Book.

HSE

Leak frequencies for centrifugal compressors from [10] are given in Table A 9-2.

Table A 9-2: Loss of containment frequencies for compressors [10]

Failure category	Failure rate	
	Centrifugal	Reciprocating
Rupture (> 110mm diameter)	$2.9 \cdot 10^{-6}$	$1.4 \cdot 10^{-5}$
Large hole (75-110 mm diameter)	$2.9 \cdot 10^{-6}$	$1.4 \cdot 10^{-5}$
Small hole (25 – 75 mm diameter)	$2.7 \cdot 10^{-4}$	$3.3 \cdot 10^{-3}$
Pinhole (< 25 mm diameter)	$1.2 \cdot 10^{-2}$	$8.6 \cdot 10^{-2}$

PLOFAM

PLOFAM documents leak frequencies for offshore compressors. The frequency for a hole size exceeding 110mm is about $2 \cdot 10^{-5}$ per year, which is higher than the failure frequency recommended by HSE.

A9.3 Leak frequency for loading hose operations

The preliminary DSB guideline for QRA [1] refers to [17] as a relevant source for loading operations. Leak frequencies from this source are addressing full bore loss of containment incidents during the transfer of chlorine from road tanker to storage. The frequency for this scenario is $4.9 \cdot 10^{-8}$ per operation. The contribution from intermediate events is pullaway (24%), hose burst (49%) and coupling failure (27%). Note that the methodology used in this report is a fault three analysis and not experienced faults.

Loading and offloading operations at KEA and Oslo Harbour will have multiple safety systems, and the following leak frequencies from ref. [17] are applied:

Table A 9-3: Leak frequencies for hose load transfer operations

Leak hole diameter (mm)	Frequency (per operation)
15	$2.8 \cdot 10^{-6}$
25	$2.0 \cdot 10^{-7}$
Full rupture	$4.9 \cdot 10^{-8}$

Dow's chemical index guide [9] recommends using full bore rupture as basis for hazardous distance calculations for hoses.

A9.4 Leak frequencies for loading arms

TNO Purple book [5] proposes leak frequencies for loading arms. Frequencies for loss of containment scenarios from loading arms on ships in an establishment is shown in Table A 9-4.

Table A 9-4: Leak frequencies for loading arms

Ship	Frequencies for loading-/unloading arm [per transhipment]	
	Full bore rupture	Leak, diameter = 10 % of nominal diameter (max 50 mm)
Single walled liquid tanker	$6.0 \cdot 10^{-5}$	$6.0 \cdot 10^{-4}$
Double walled liquid tanker	$6.0 \cdot 10^{-5}$	$6.0 \cdot 10^{-4}$
Gas tanker, semi gas tanker	$6.0 \cdot 10^{-5}$	$6.0 \cdot 10^{-4}$

External impact on ships in an establishment, causing large or small spills can also be found in Purple book.

A9.5 Leak frequencies for road tankers

Failure rates for serious accident rates for road tankers can be found in the HSE data [10].

Table A 9-5: Failure rate for road tankers ([10])

Failure category	Failure rate [per km]
Serious accident rate	$2.2 \cdot 10^{-7}$

According to the reference report these rates are collected from, "a serious accident" was defined as one for which the cost of repair was at least £10,000.

In the QRA the possibility for a BLEVE scenario from the truck is considered. Typically causes to BLEVE scenario can be exposure of external fires and overfilling (at Klemetsrud). The driving distance on the facility areas is limited. Also, as the trucks will be purposed-built it is assumed robust tanks and systems for preventing overfilling. It can hence be argued that the frequency for this scenario is low; 1.0E-07 is proposed in this QRA.

A9.6 Pipeline leak frequencies

EGIG [8] has collected gas pipeline leaks and ruptures incidents from several gas transmission system operators in Europe. The EGIG database is a database of pipeline and incident data. Pipeline data and incident data since 1970 for natural gas transmission pipelines are in the database. The database is restricted to onshore steel pipelines with operating pressure higher than 15 bar. The data base is therefore considered appropriate to use for the future pipeline from Klemetsrud to the harbour, see Table A 9-6.

In this data set, a "hole" has a diameter exceeding 20 mm and rupture is at least the full cross section of the pipe.

Table A 9-6: Generic leak frequencies for gas pipelines (1970-2013)

Nominal diameter	System exposure · 10^6 km·yr	Primary failure frequency per 1000 km · yr			
		Unknown	Pinhole/crack	Hole	Rupture
diameter < 5"	0.436	0.005	0.445	0.268	0.133
5" ≤ diameter < 11"	1.066	0.008	0.28	0.197	0.064
11" ≤ diameter < 17"	0.714	0.004	0.127	0.098	0.041
17" ≤ diameter < 23"	0.442	0.005	0.102	0.05	0.034
23" ≤ diameter < 29"	0.401	0	0.085	0.027	0.012
29" ≤ diameter < 35"	0.214	0	0.023	0.005	0.014
35" ≤ diameter < 41"	0.389	0	0.023	0.008	0.003
41" ≤ diameter < 47"	0.146	0	0.007	0	0
diameter ≥ 47"	0.17	0	0.006	0.006	0.006
Total (average)	**3.978**	**0.004**	**0.171**	**0.109**	**0.045**

The data of interest is for pipeline diameters in the range 5-11 inches. For the period 1970 to 2013, the overall primary failure frequency has fallen from about 0.9 failures per 1000 km·yr to less than 0.2 failures per km·yr. For the period 2004-2013 the average primary failure frequency is 52% lower than for the period 1970 to 2013. Falling leak frequency applies for all leak sizes, and the relative reduction in holes and ruptures exceed that for pinholes and cracks.

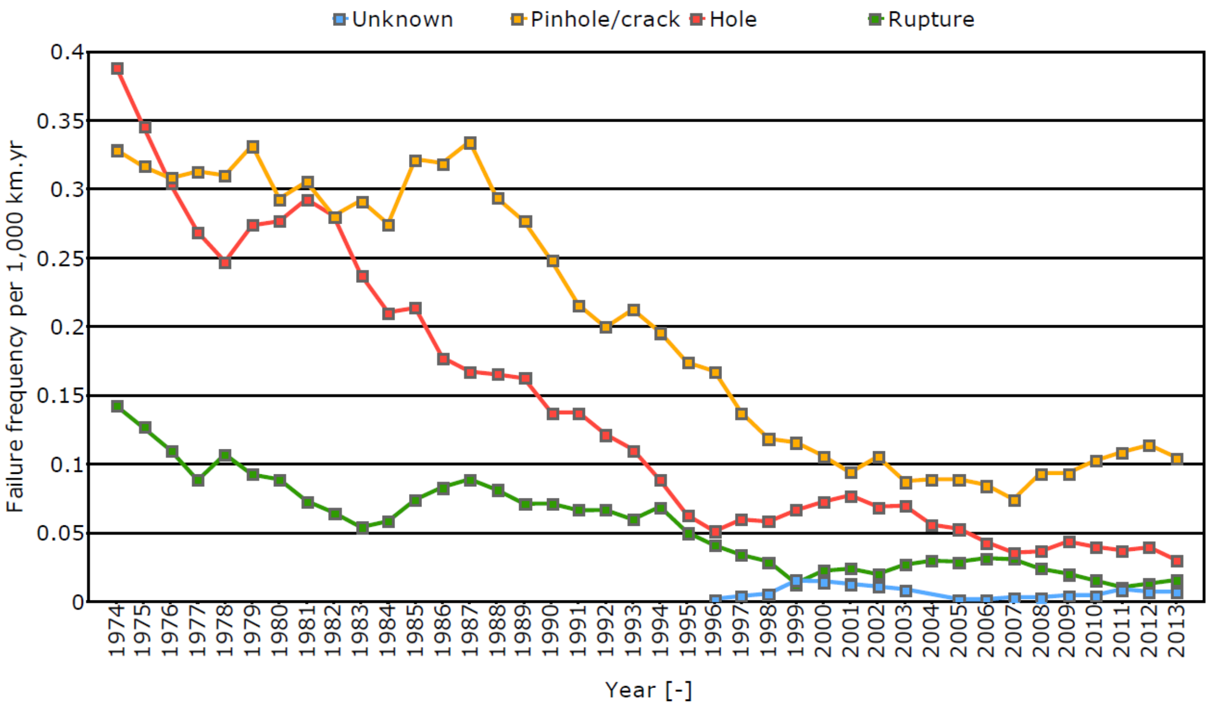

Figure A 9-1: Trend in pipeline failure frequencies

Over the last 10 years, the overall rupture frequency is about 0.025 per 1000 km · year, while the frequency for “hole” is about 0.04 per 1000 km · year. For the category 5” to 11”, the rupture frequency is a factor 1.4 higher than for the average pipe, while for holes this factor is 1.8 (from Table A 9-6). The following leak frequencies per km · year are concluded applicable:

- Hole: $f = 0.040 \cdot 10^{-3} \cdot 1.8 = 7.2 \cdot 10^{-5}$ (per km · yr)
- Rupture: $f = 0.025 \cdot 10^{-3} \cdot 1.4 = 3.5 \cdot 10^{-5}$ (per km · yr)

The distribution of reported causes is shown in Figure A 9-2. Note that external interference represents a significant contribution.

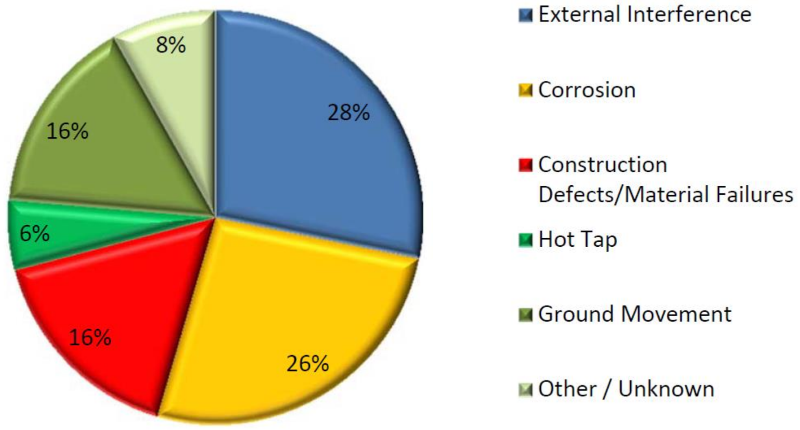

Figure A 9-2: Distribution of incidents (2009-2013)

A10 References

[1] *Retningslinjer for kvantitative risikovurderinger for anlegg som håndterer farlig stoff*, Rapport til: Direktoratet for samfunnssikkerhet og beredskap (DSB), Lloyd's Register Consulting Report 106535/R1. Rev: Eksternt høringsutkast 12. april 2017.

[2] *Toxicity levels of chemicals*, HSE, http://www.hse.gov.uk/chemicals/haztox.htm.

[3] *Toxicity levels of chemicals, footnote*, HSE, http://www.hse.gov.uk/chemicals/haztox.htm#footnote1.

[4] *Comparison of risks from carbon dioxide and natural gas pipelines*, HSE, research report RR749, 2009, http://www.hse.gov.uk/research/rrpdf/rr749.pdf.

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[6] *Reference Manual Bevi Risk Assessment*, National Institute of Public Health and the Environment (RIVM) in Netherland.

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[9] *Dow's chemical exposure index guide*, American Institute of Chemical Engineers, AIChE technical manual, 1994.

[10] Failure rate and event data for use within risk assessments. HSE (UK) 28.06.2012..

[11] Revisiting the Conditions for a CO2 Tank Explosion. Air Products. 9th global congress on process safety, 2013.

[12] Failure knowledge database; http://www.shippai.org/fkd/en/cfen/CC1000038.html.

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[17] *Hose and Coupling Failure Rates and the Role of Human Error*, M. Trainor, J. Gould and M. Anderson, Health and Safety Laboratory Report HSL/2000/09.

Appendix B

Regulatory requirements (in Norwegian)

Table of contents:

B1 Forskrift om systematisk helse-, miljø- og sikkerhetsarbeid i virksomheter

Denne forskriften kalles internkontrollforskriften, og har definert formålet slik: Gjennom krav om systematisk gjennomføring av tiltak, skal denne forskrift fremme et forbedringsarbeid i virksomhetene innen

- arbeidsmiljø og sikkerhet
- forebygging av helseskade eller miljøforstyrrelser fra produkter eller forbrukertjenester
- vern av det ytre miljø mot forurensning og en bedre behandling av avfall slik at målene i helse-, miljø- og sikkerhetslovgivningen oppnås.

B2 Forskrift om håndtering av farlig stoff

FOR-2009-06-08-602: Forskriften har som formål å verne liv, helse, miljø og materielle verdier mot uhell og ulykker med farlig stoff.

Forskriften regulerer håndtering av farlig stoff og utstyr og anlegg, herunder rørledninger med tilhørende systemer, som benyttes ved håndtering av farlig stoff. Forskriften regulerer prosjektering, konstruksjon, produksjon, omsetning, installasjon, drift, endring, reparasjon, vedlikehold og kontroll av utstyr og anlegg som benyttes ved håndtering av farlig stoff.

§16 i forskrift om håndtering av farlig stoff sier at *Det skal opprettes arealmessige begrensninger rundt utstyr og anlegg der dette er nødvendig etter § 14 for å sikre omgivelsene på en tilfredsstillende måte*. §14 i samme forskrift sier bl.a. at *Virksomheten skal kartlegge farer og problemer med hensyn på håndtering av farlig stoff og på denne bakgrunn vurdere risiko. Vurderingen skal inkludere interne og eksterne forhold samt uønskede tilsiktede handlinger*.

B3 Forskrift om trykkpåkjent utstyr

FOR-1999-06-09-721: Forskriften skal sikre at trykkpåkjent utstyr og enheter ved første gangs idriftsettelse er i forsvarlig stand for derved å forebygge skade på liv, helse og materielle verdier.

B4 Forskrift om utførelse av arbeid, bruk av arbeidsutstyr og tilhørende tekniske krav

FOR-2011-12-06-1357: Formålet med forskriften er å sikre at utførelse av arbeid og bruk av arbeidsutstyr blir gjennomført på en forsvarlig måte, slik at arbeidstakerne er vernet mot skader på liv eller helse.

B5 Havne- og farvannsloven og regler som er spesifikke for havneområder

Lover og regelverk som gjelder spesifikt for havneområder er godt beskrevet i [1]. Havne- og farvannsloven (Lov 17. april 2009 nr. 19 om havner og farvann) hjemler forskrifter som inkluderer både terrorsikring: Forskrift 29. mai 2013 nr. 538 om sikring av havneanlegg. og Forskrift 29. mai 2013 nr. 539 om sikring av havner.

B6 References

[1] *Sydhavna (Sjursøya) - et område med forhøyet risiko,* DSB, Februar 2014.

Appendix C

Calculation of restricted area zones

Table of contents:

C1. Introduction

This appendix shows details of the restricted area zone calculation. These zones are based on iso-contours for individual risk with frequencies 10^{-5}, 10^{-6} and 10^{-7} per year.

C2. Sjursøya

C2.1 Chosen origin and main directions

The chosen origin and five main directions for Sjursøya is shown in Figure C 2-1. The length of each of the green lines are 500 meters. The chosen directions are 0°, 75°, 150°, 225° and 300° relative to the UTM grid (0° is grid north). The zones are calculated in these five directions, and interpolation is used for other directions.

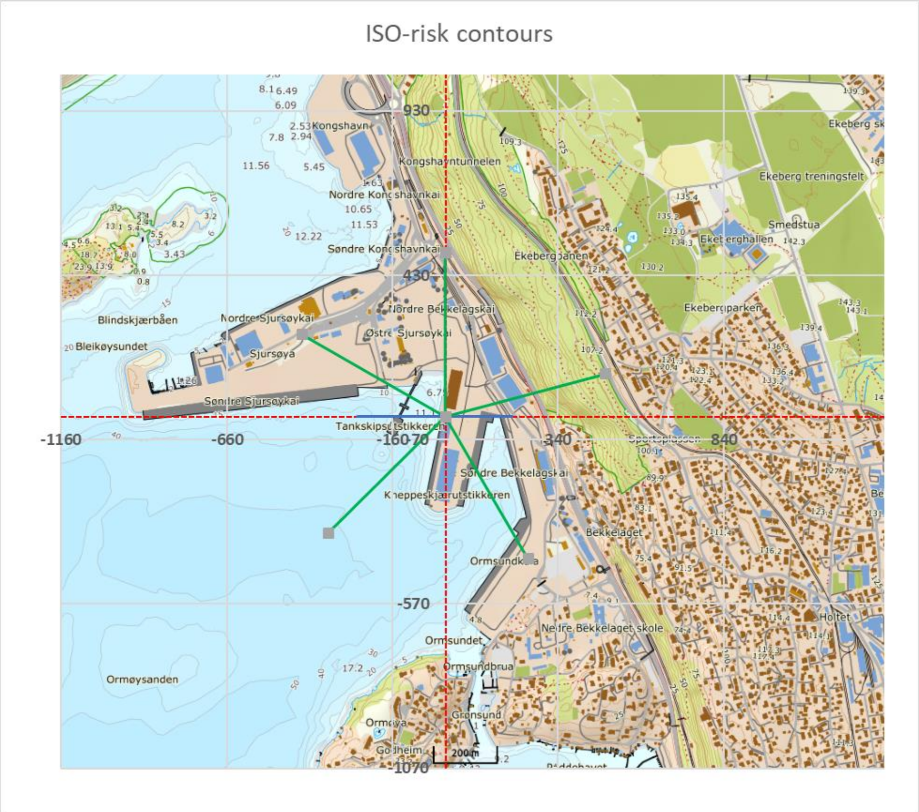

Figure C 2-1: Origin and five main directions used at Sjursøya

For each of the main directions, the relation between distance and lethality is defined as shown in Table C 2-1. Based on this and by using interpolation techniques the sum of all scenarios and distances to the sought iso-contours are calculated. The curves corresponding to Table C 2-1 are shown in Figure C 2-2 with distance to the iso-contours shown with brown bullets. The distances calculated for the main directions are shown in Table C 2-2.

C2.2 Contributing scenarios for each main direction

Table C 2-1: Scenarios with frequencies, distances with corresponding lethality for Sjursøya, 0°

Direction 1, 0°	Frequency	Dist	Prob	Dist	Prob	Dist	Prob	Dist	Prob	Dist	Prob	Dist	Prob	Dist	Prob
Background - existing	1.0E-05	10	1	350	1	375	0.1	400	0.0001						
Tank rupture / BLEVE	2.0E-07	2	1	50	1	100	0.6875	150	0.235	200	5.43E-02	300	0.0105	400	0.001
Pipe rupture (600 kg/s)	1.4E-05	2	1	50	0.9	200	0.5	400	0.1	600	1.00E-03				
Pipe leak (120 kg/s)	4.2E-05	2	1	25	0.75	40	0.5	100	0.10	250	0.001				
Offloading to ship	4.7E-03	2	0.25	50	0.1	100	0.001								
Truck offloading	7.6E-04	2	0.05	10	0.01	75	1E-06								
Truck BLEVE	1.0E-07	2	1	21	1	41	0.69	82	0.054	123	0.01	164	0.001		
Ship BLEVE/tank rup.	1.0E-07	2	0.69	19	0.24	226	0.05	439	0.01	652	0.001				

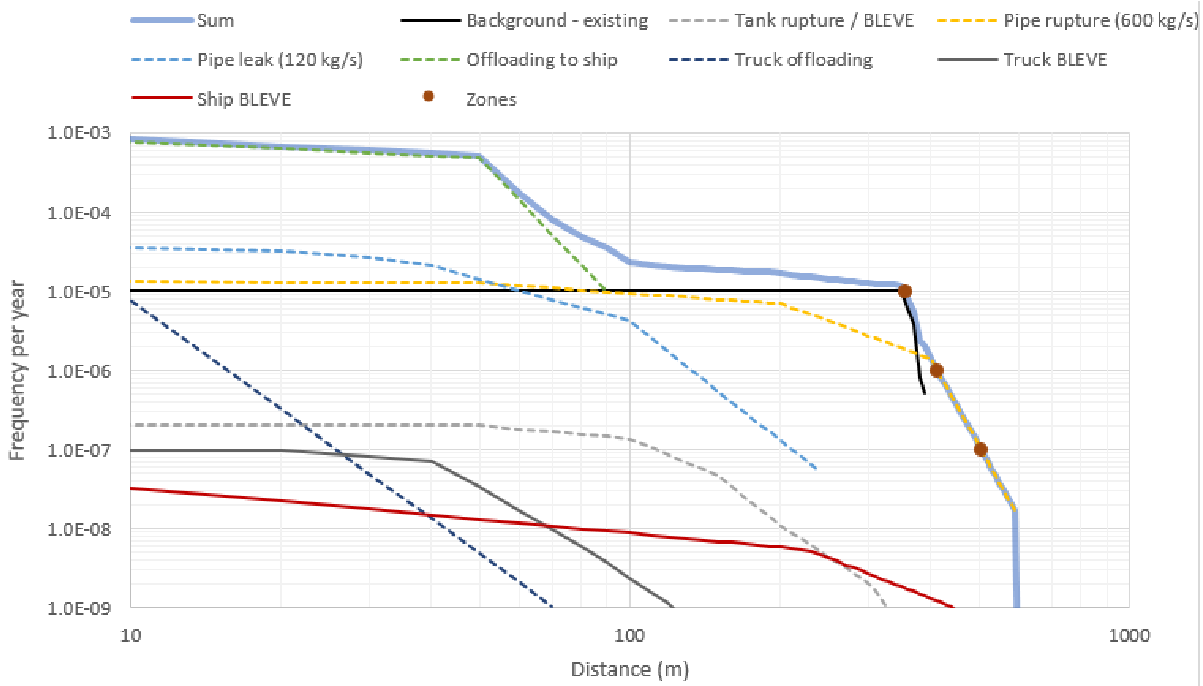

Figure C 2-2: Contributing scenarios; Sjursøya, 0°

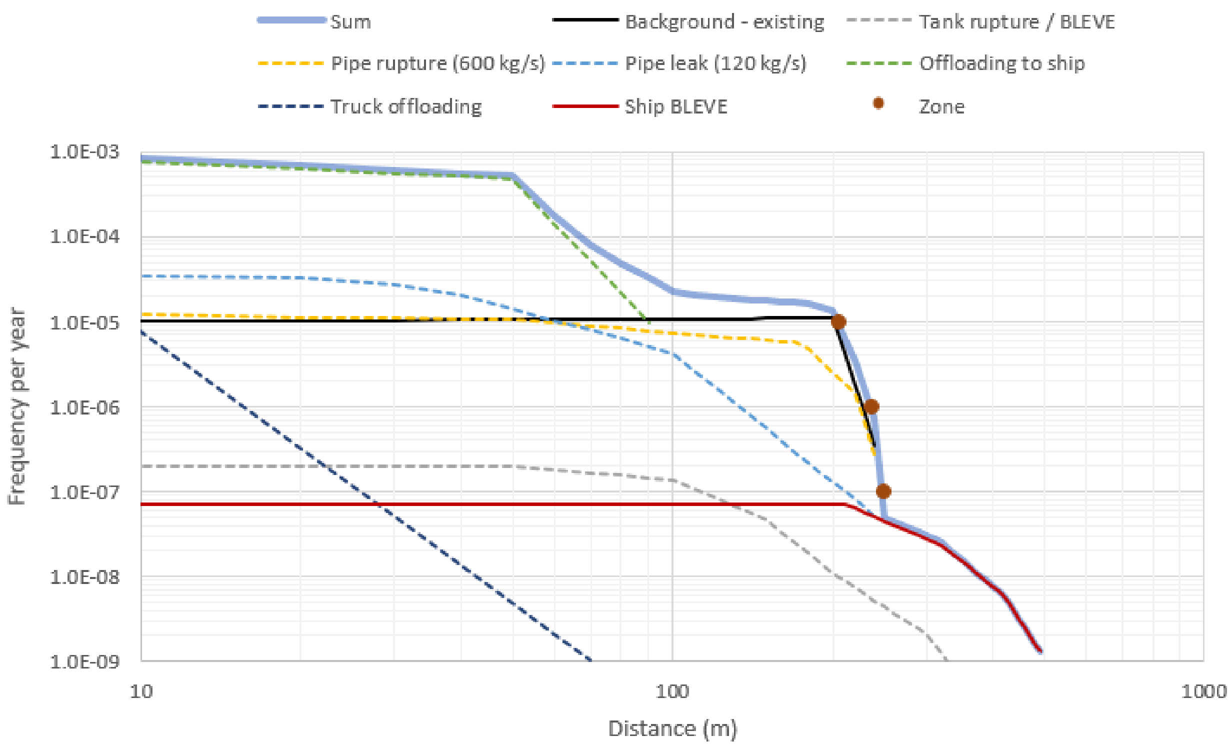

Figure C 2-3: Contributing scenarios; Sjursøya, 75°

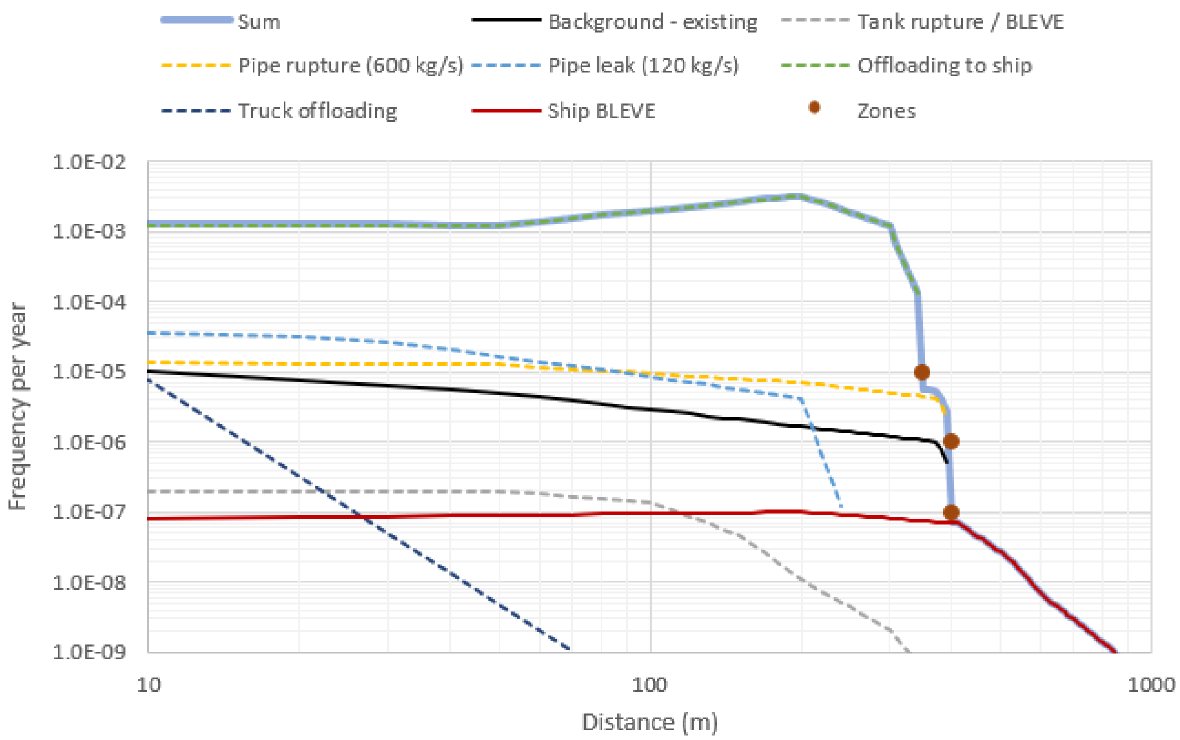

Figure C 2-4: Contributing scenarios; Sjursøya, 150°

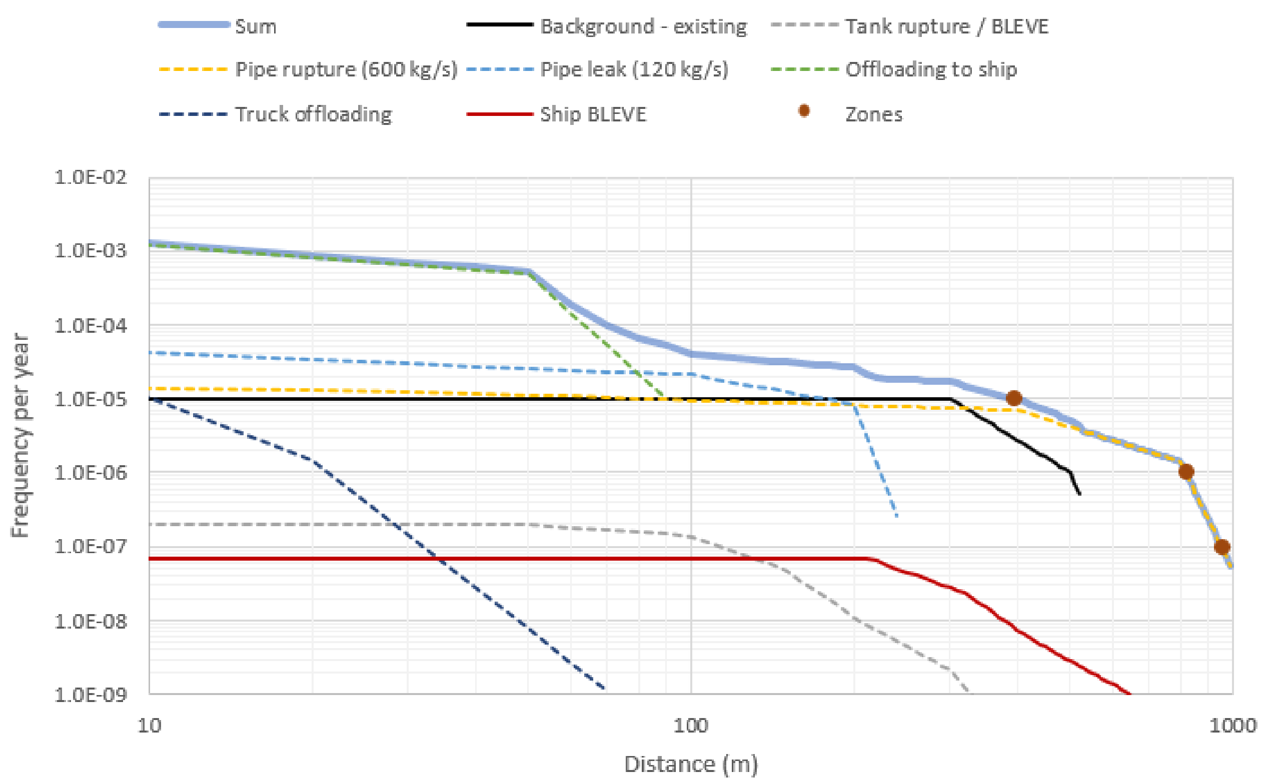

Figure C 2-5: Contributing scenarios; Sjursøya, 225°

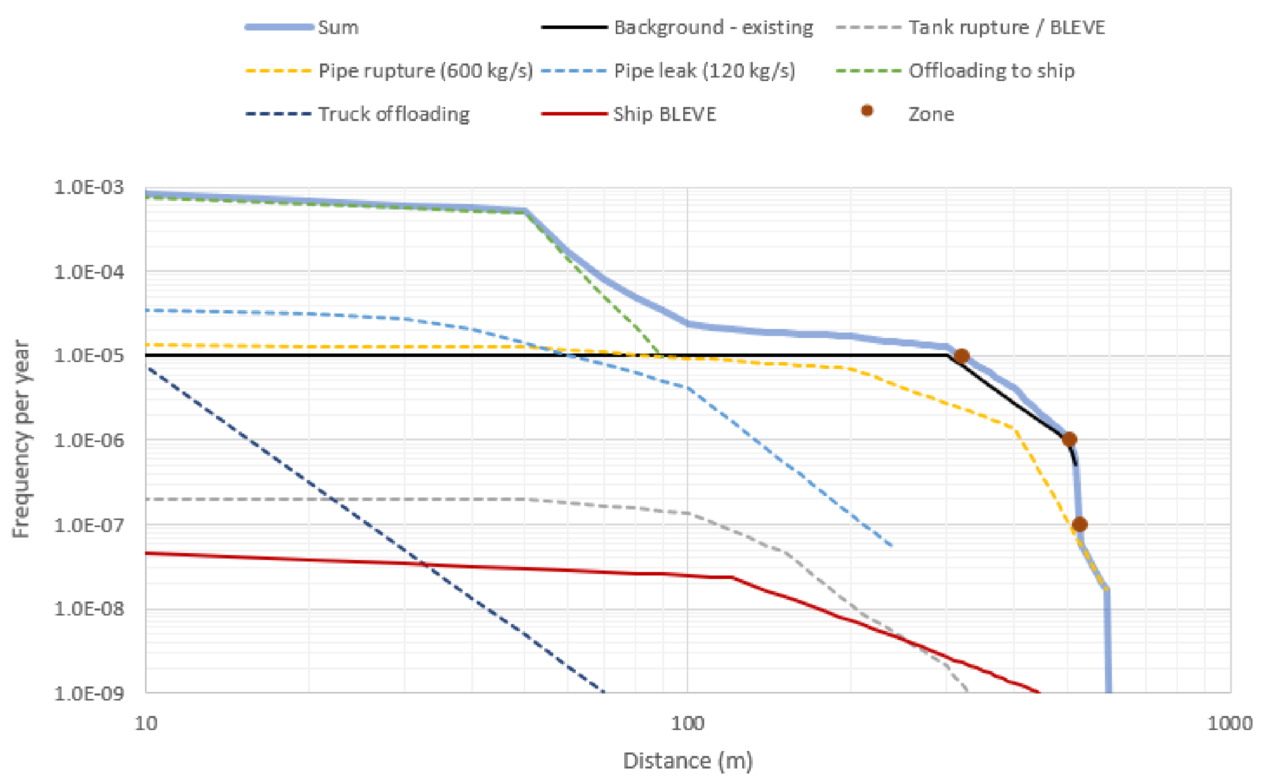

Figure C 2-6: Contributing scenarios; Sjursøya, 300°

C2.3 Restricted area zones - Sjursøya

A summary of the calculated hazardous distances is shown in Table C 2-2. This data set, and linear interpolation is used to establish the iso-risk contours as shown in Figure C 2-7.

Table C 2-2: Distance to restricted area zones (m)

Direction	Inner zone, 10^{-5} per year	Interm. zone, 10^{-6} per year	Outer zone, 10^{-7} per year
0°	355	412	505
75°	205	237	249
150°	350	397	400
225°	393	818	951
300°	319	504	529

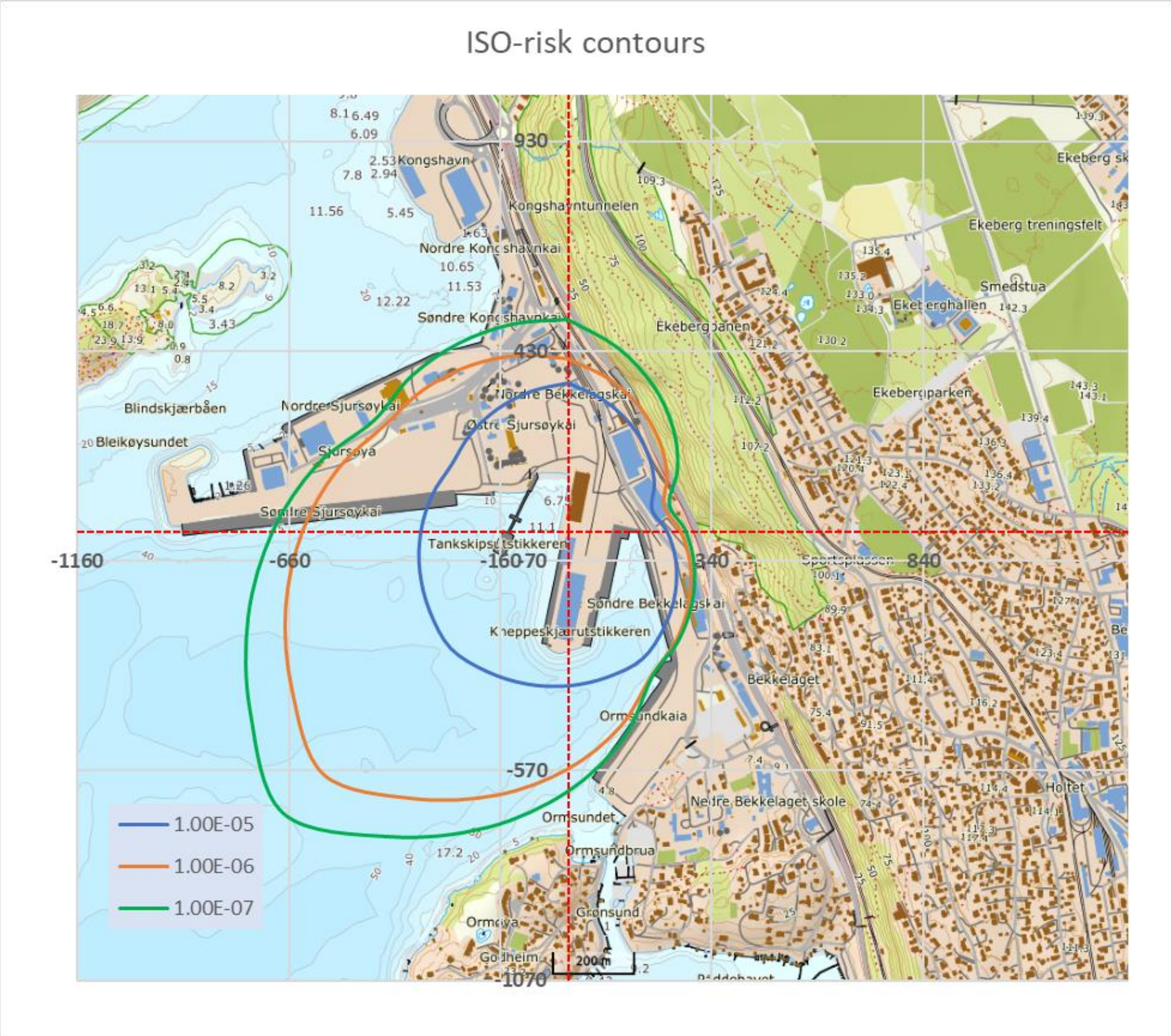

Figure C 2-7: Iso-risk contours for Sjursøya

C3. Klemetsrud

C3.1 Chosen origin and main directions

The chosen origin and main directions for Klemetsrud is shown in Figure C 3-1. The length of each of the green lines is 300 meters. The chosen directions are 0°, 90°, 180° and 270° relative to the UTM grid (0° is grid north). The zones are calculated in these four directions. In addition to the four main grid directions, paths following the terrain has been defined as shown in Figure C 3-2. Hazardous distances are calculated along the defined paths for gas dispersion.

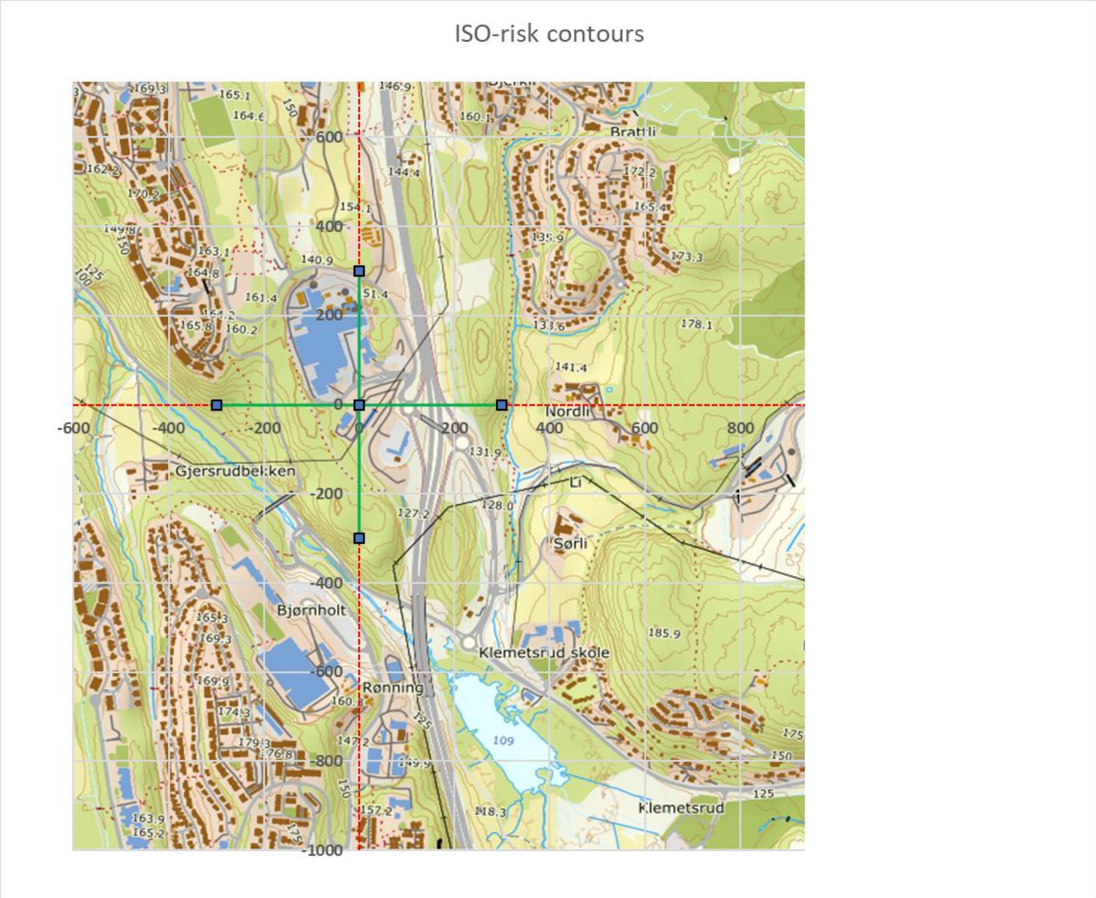

Figure C 3-1: Origin and main directions used at Klemetsrud (300m)

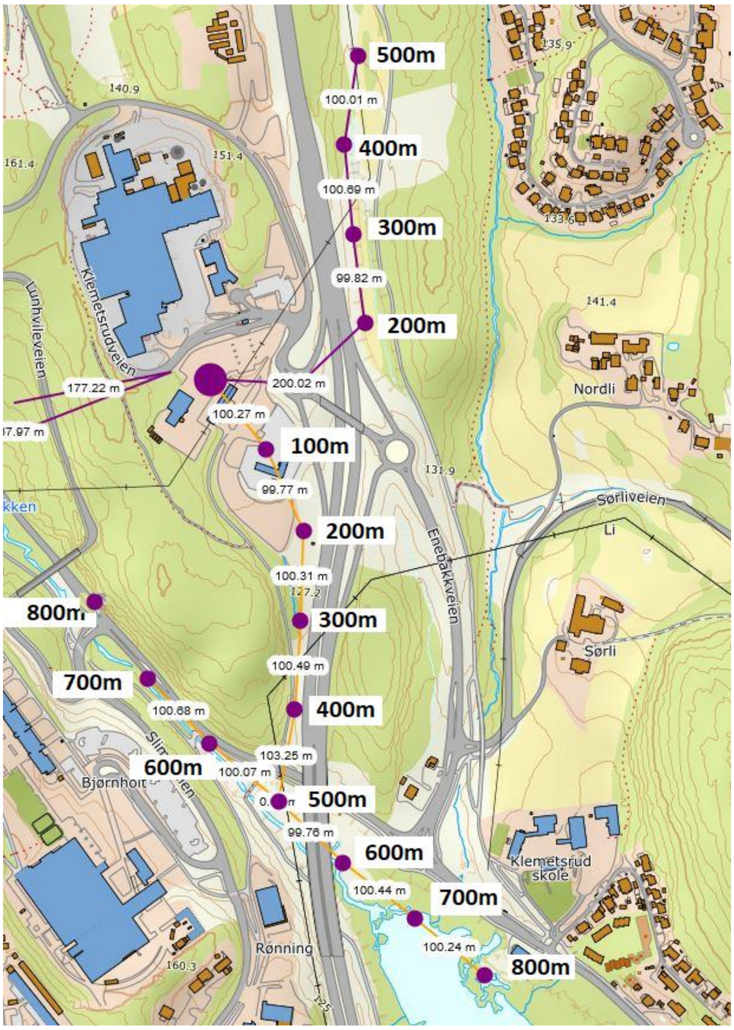

Figure C 3-2: Distances at Klemetsrud when following terrain

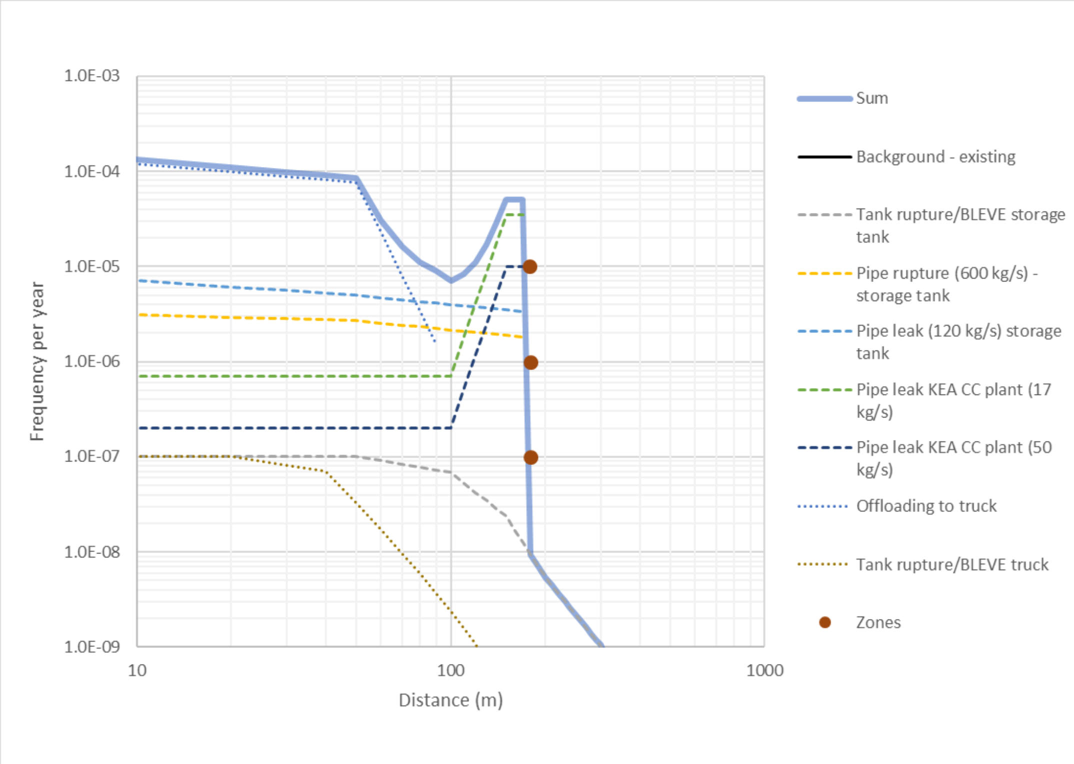

Figure C 3-3: Contributing scenarios; Klemetsrud, 0°

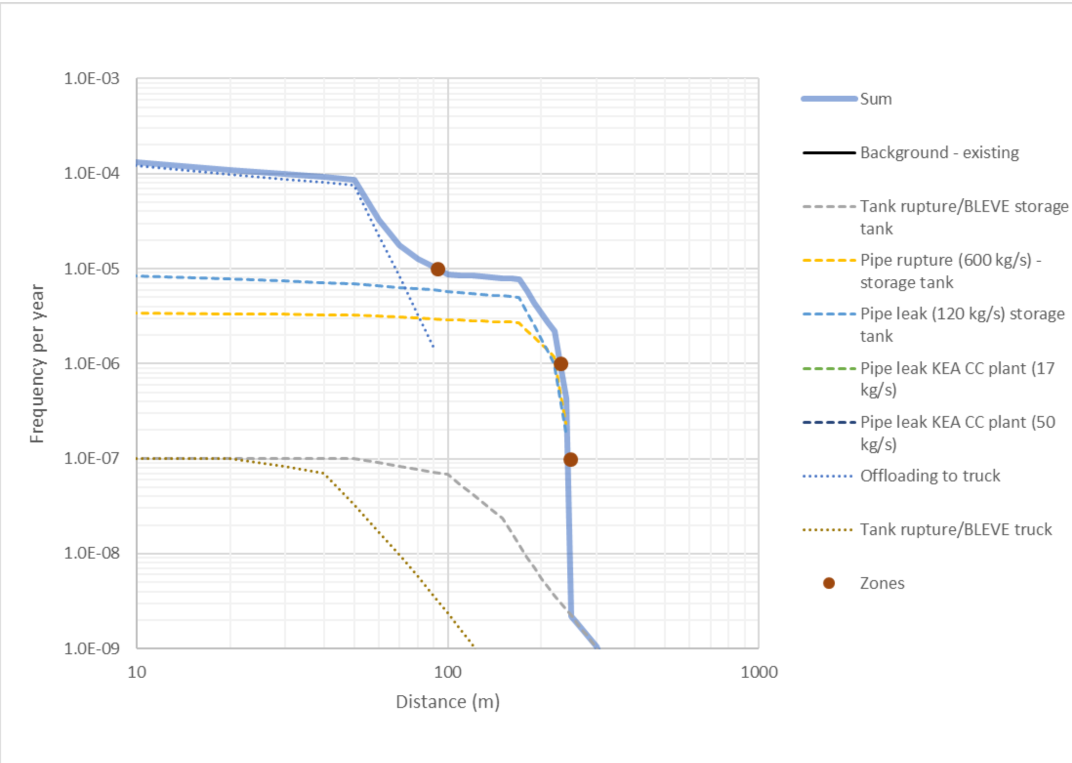

Figure C 3-4: Contributing scenarios; Klemetsrud, 90°

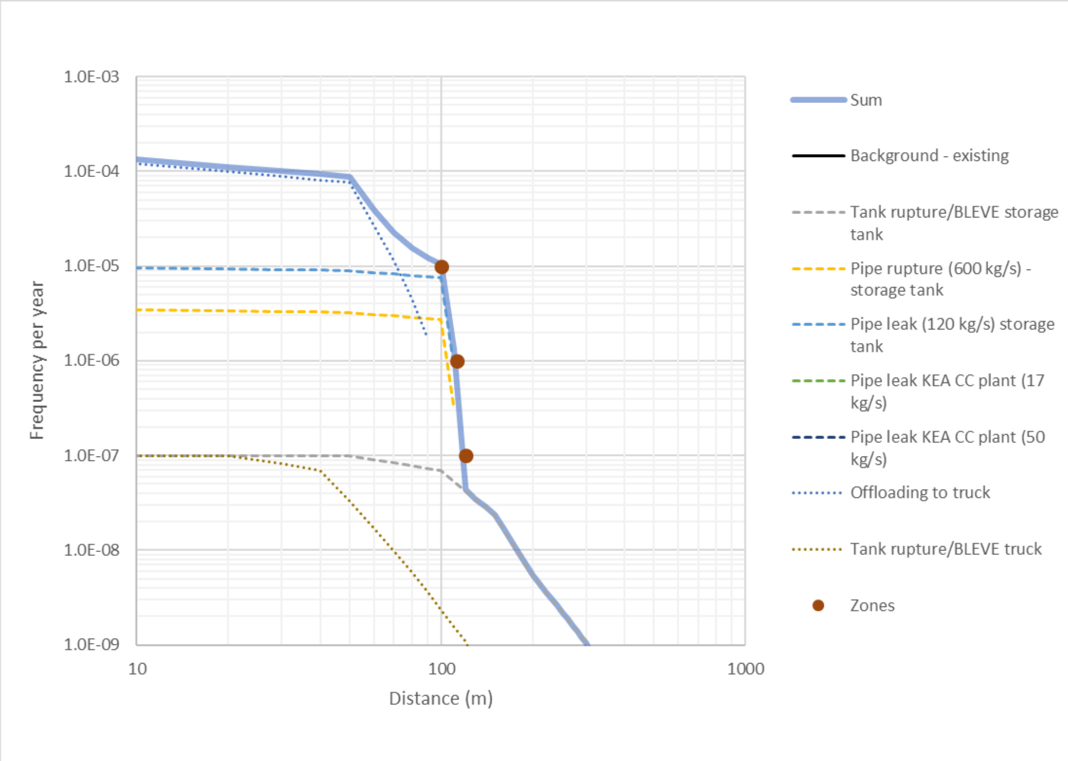

Figure C 3-5: Contributing scenarios; Klemetsrud, 180°

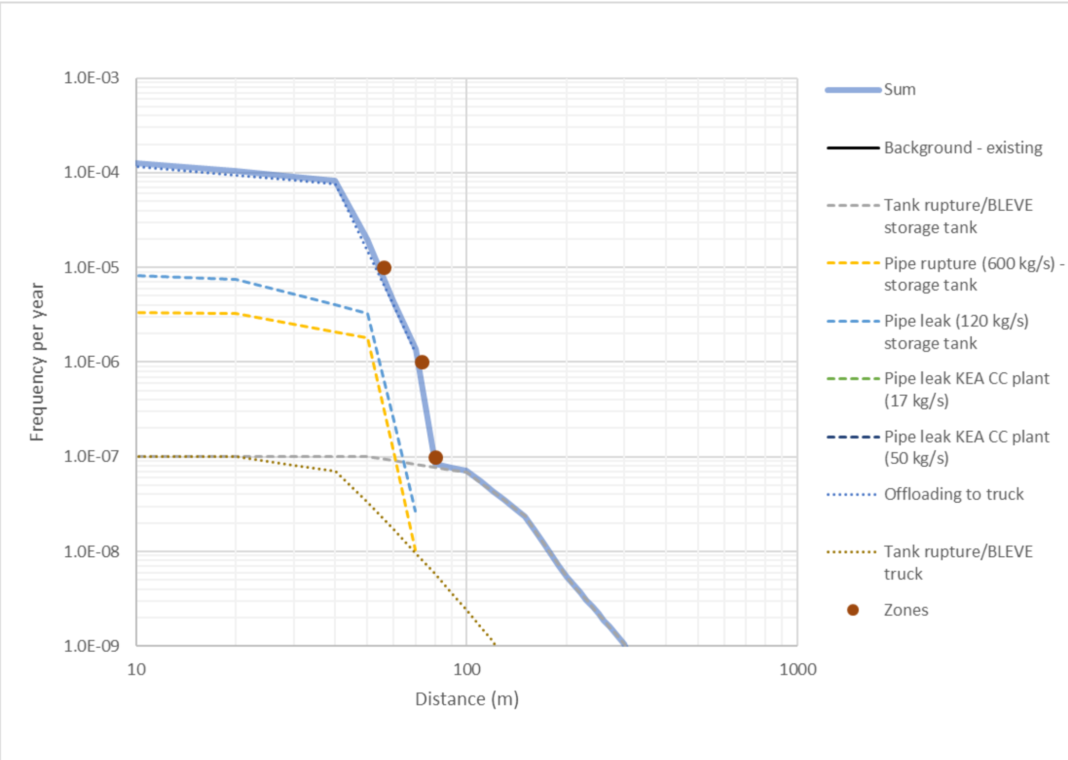

Figure C 3-6: Contributing scenarios; Klemetsrud,270°

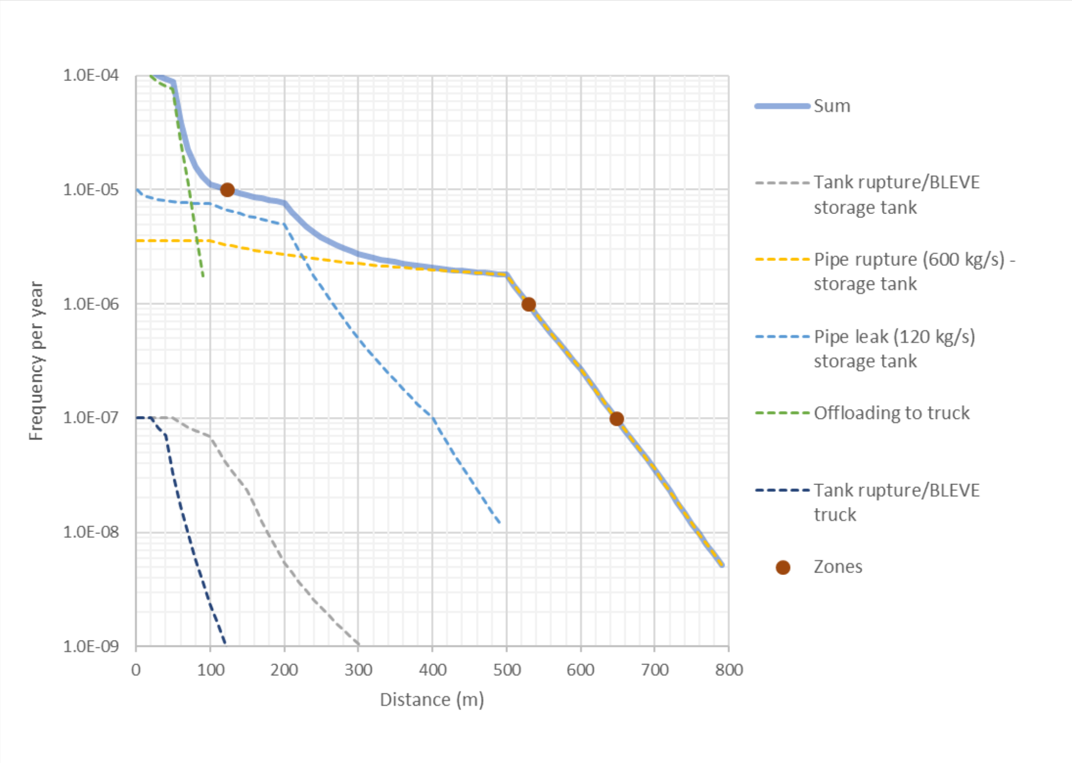

Figure C 3-7: Contributing scenarios; Klemetsrud, dispersion paths - south

C3.2 Restricted area zones - Klemetsrud

Distances to the defined iso-contours are summarised in Table C 3-1. Distances are from a defined point/origin x,y as shown in Figure C 3-8. The shapes for these contours are more complex than for Sjursøya and not readily modelled by use of interpolation. The risk contours are shown in Figure C 3-8.

Table C 3-1: Distance to restricted area zones (m)

Direction	Inner zone, 10^{-5} per year	Interm. zone, 10^{-6} per year	Outer zone, 10^{-7} per year
0°	178	180	180
90°	93	230	248
Path, South	123	529	648
180°	100	113	120
270°	56	73	80

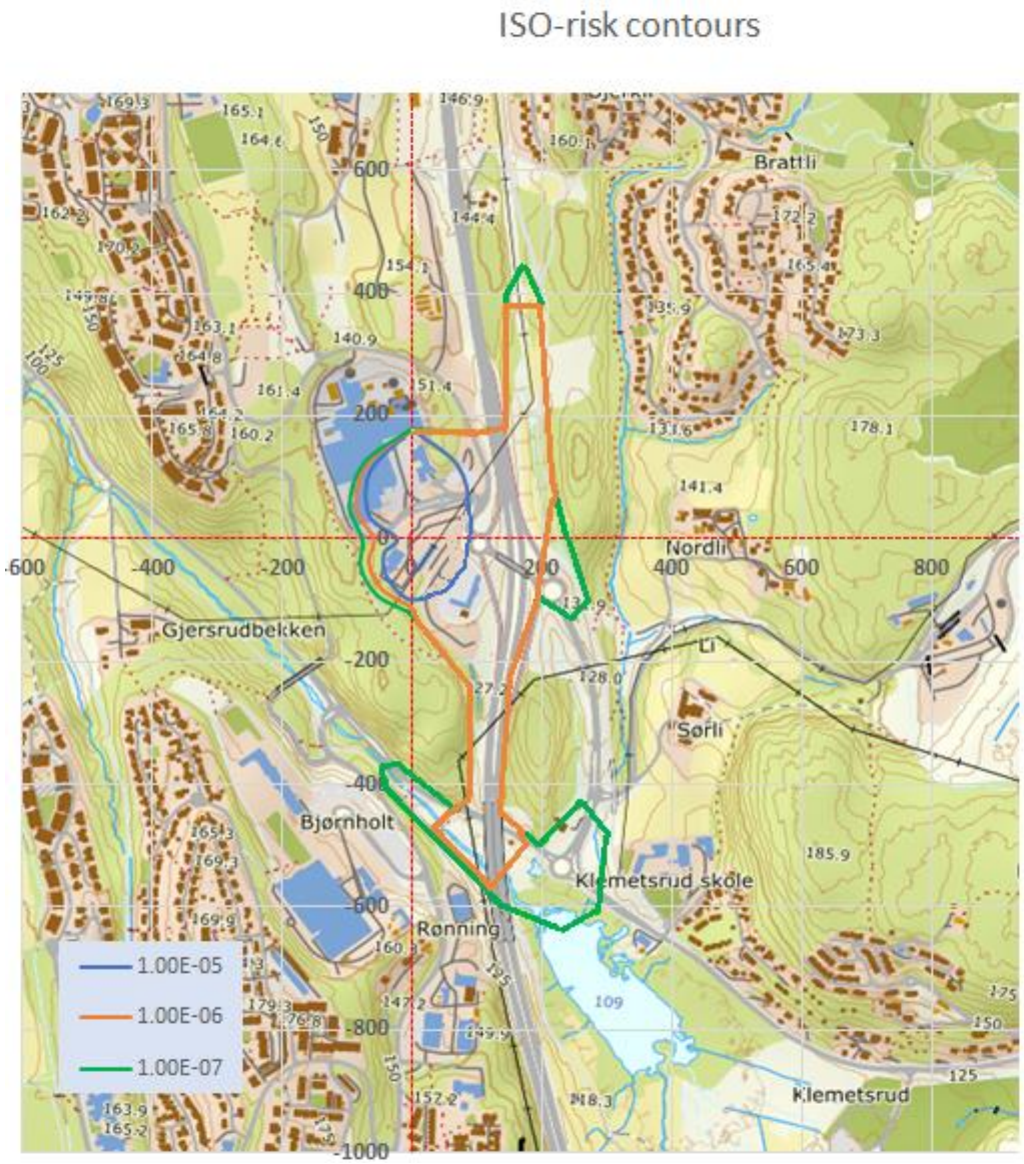

Figure C 3-8: Iso-risk contours for Klemetsrud

Appendix D

Dispersion analysis

KLEMETSRUD CO2 DISPERSION ANALYSIS

CO2 dispersion analysis, Carbon Capture Oslo Project - Draft Report

Fortum Oslo Varme AS

Report No.: R1902 Draft, Rev. 1
Document No.: /Dist/Project/100529/Rapport/R1902_Draft
Date: 2019-05-29

Project name:	Klemetsrud CO2 dispersion analysis	DNV GL Digital Solution
Report title:	CO2 dispersion analysis, Carbon Capture Oslo Project - Draft Report	Plant CFD Solutions
Customer:	Fortum Oslo Varme AS	
Customer contact:	Terje Egeberg	
Date of issue:	2019-05-29	
Project No.:	10154957/100529	
Organisation unit:	Plant CFD Solutions	NO 945 748 931
Report No.:	R1902 Draft, Rev. 1	
Document No.:	/Dist/Project/100529/Rapport/R1902_Draft	

Applicable contract(s) governing the provision of this Report:

Objective:
The objective is to execute KFX™ CO_2 dispersion simulations of leakages from the CO_2 facility at Klemetsrud and the offloading systems at the harbour area at Sjursøya. The scenarios are specified by Lilleaker Consulting AS.

Prepared by:	Verified by:	Approved by:
Petter Aune	Trond Evanger	
[Name] [title]	[Name] [title]	[Name] [title]
Nils Inge Lilleheie		
[Name] [title]	[Name] [title]	
Kjell Erik Rian		
[Name] [title]	[Name] [title]	

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CO2 thermodynamics
Multiphase flow in complex geometries
CFD simulation

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2019-05-14	Draft, first issue			
1	2019-05-29	Draft, second issue			

Table of contents

1 EXECUTIVE SUMMARY

The present work relates to the CO_2-capture and offloading facility planned by Fortum Oslo Varme AS for the waste incinerator at Klemetsrud, Oslo. The work has been performed in collaboration with Lilleaker Consulting AS and the Health, Safety and Environment Office (HSEO) of the Carbon Capture Oslo Project. Lilleaker Consulting AS provided information on CO_2 leakage scenarios to be simulated, and the results from the present CO_2 dispersion simulations will be used as input for the consecutive quantitative risk analysis performed by Lilleaker Consulting AS.

The topographic layout of the eastern area of Oslo has been organized in a KFX™ CAD format which easily generates the topographic information to be used as basis for the KFX™-CO_2 dispersion simulations covering the various relevant areas.

Thirteen different leakage scenarios have been simulated; nine scenarios at the Klemetsrud facility, and four in the Oslo harbour area.

The 3D CO_2 dispersion simulations were performed with a CO_2 version of the advanced industrial CFD tool Kameleon FireEx KFX®. The KFX™-CO_2 simulation technology is capable of predicting CO_2 dispersion at realistic conditions in complex geometries and terrain, including important thermodynamic effects of multiphase CO_2 releases.

Calculated horizontal iso-contour plots of maximum CO_2 volume fraction are presented enabling analyses of the exposure to various levels of CO_2 in the surroundings.

It must be noted that the study covers only a limited number of scenarios. The number of potential leak scenarios at such facilities is infinite. Hence, only a very narrow fraction of the sample space has been investigated. However, the scenarios simulated provide basis to set sound safety distances at this project stage if this element of uncertainty is accounted for. Further analysis in the next phase will enable optimization of design parameters with respect to risk exposure and give basis for more detailed specification of safety zones.

2 INTRODUCTION

2.1 Background

A CO_2-capture facility is planned built at Fortum Oslo Varme's facility at Klemetsrud, Oslo. In relation to the safety assessments of the planned CO_2 facility, DNV GL - Plant CFD Solutions (formerly ComputIT) has been contracted by Fortum Oslo Varme AS to perform KFX™ CO_2 dispersion simulations to be used as basis for the safety studies performed by Lilleaker Consulting AS. Both two-phase (solid-gas) leakages and pure gas phase leakages have been studied.

ComputIT has long and relevant experience in performing CFD studies of all kinds of industrial problems related to gas dispersion, ventilation, explosions, fires and flares on both offshore and onshore installations. The advanced CFD tool Kameleon FireEx KFX® is used for all such simulations. KFX™ is developed by ComputIT/SINTEF/NTNU, and the development has been supported and performed in close cooperation with Equinor, Total, ENI group, ConocoPhillips, Gassco, Engie (former GdF Suez, now GRT Gaz), Sandia National Laboratories and the Research Council of Norway. KFX™ is internationally recognized as a leading industrial simulation tool by major oil and gas companies and by major operators in the risk management industry. Today KFX™ is owned and developed further by DNV GL.

To perform safety assessments of Carbon Capture and Storage (CCS) facilities and infrastructure, a KFX™-CO_2 simulation tool has been developed for reliable, detailed prediction of CO_2 dispersion at realistic conditions in complex environments (Rian et al., 2014). The KFX™-CO_2 simulation tool includes crucial CO_2-specific dispersion features such as a release source model based on comprehensive state-of-the-art CO_2 thermodynamics, a model for multiphase CO_2 dispersion of CO_2 gas and solid CO_2 particles, and a model for sublimation of dry-ice particles, as well as modelling of complex geometries and terrain based on CAD models and electronic maps. The KFX™-CO_2 simulation technology is also extensively validated through various tests and comparisons of simulation results to experimental data from both laboratory tests and large-scale field trials.

The KFX™-CO_2 development project was supported by the Research Council of Norway (CLIMIT Project No. 217114), Equinor and ComputIT.

2.2 Objective

The objective is to execute KFX™ CO_2 dispersion simulations of leakages from the CO_2 facility at Klemetsrud and the offloading systems at the harbour area at Sjursøya. The scenarios are specified by Lilleaker Consulting AS, and the predicted CO_2 concentrations from the dispersion simulations will provide input for the consecutive quantitative risk analysis performed by Lilleaker Consulting AS.

3 SCENARIO AND CASE DESCRIPTION

The scenario and case descriptions are based on input from Lilleaker Consulting AS and related to their quantitative risk analysis work. A full description of the simulated leakage scenarios is found in Table 1: Leakage scenarios.

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
01	KEA-1	TwoPhase	KEA new location for interim storage	3	South	Down	12	480	8	617	-
02	KEA-2	TwoPhase	KEA new location for interim storage	3	South	East	3	480	8	617	Jet/spray unobstructed
03	KEA-3	TwoPhase	KEA new location for interim storage	3	South	Down	12	3000	50	119	-
04	KEA-4	TwoPhase	KEA new location for interim storage	3	North	East	3	3000	50	119	Jet/spray unobstructed
05	Additional	TwoPhase	KEA new location for interim storage	-	-	-	-	-	-	-	-
06	KEA-G1	Gas	KEA CC plant, gas compression	3	South	East	3	600	10	17	Gas Jet unobstruceted
07	KEA-G2	Gas	KEA CC plant, gas compression	3	South	South	3	120	2	30	Gas Jet unobstruceted
08	KEA-G3	Gas	KEA CC plant, gas compression	3	South	Down	3	60	1	50	Gas Jet unobstruceted
09	KEA-L1	TwoPhase	Truck Loading Area	3	West	Down	2	60	1	50	Jet/spray unobstructed
10	KEA-L2	TwoPhase	Truck Loading Area	3	West	Down	2	20	0,33	250	Jet/spray unobstructed
11	S-1	TwoPhase	Sjursøya	3	North	Down	12	480	8	617	Jet/spray unobstructed
12	S-2	TwoPhase	Sjursøya	3	South	Down	3	480	8	617	Jet/spray unobstructed
13	S-3	TwoPhase	Sjursøya	3	South	East	12	480	8	617	Jet/spray unobstructed
14	S-4	TwoPhase	Sjursøya	3	South	West	3	480	8	617	Jet/spray unobstructed

Table 1: Leakage scenarios

3.1 KFX™ CAD model

Due to limited information on the exact layout of the CO_2 facility at Klemetsrud, the major focus has been on the topography, especially because the CO_2 is a heavy gas relative to air.

Topographic tiles of the Oslo east region have been created so that it is easy to put together detailed KFX™ CAD models to be used as basis for the dispersion simulations.

Figure 1 and Figure 2 show the coupling between the tiles and a detailed topography.

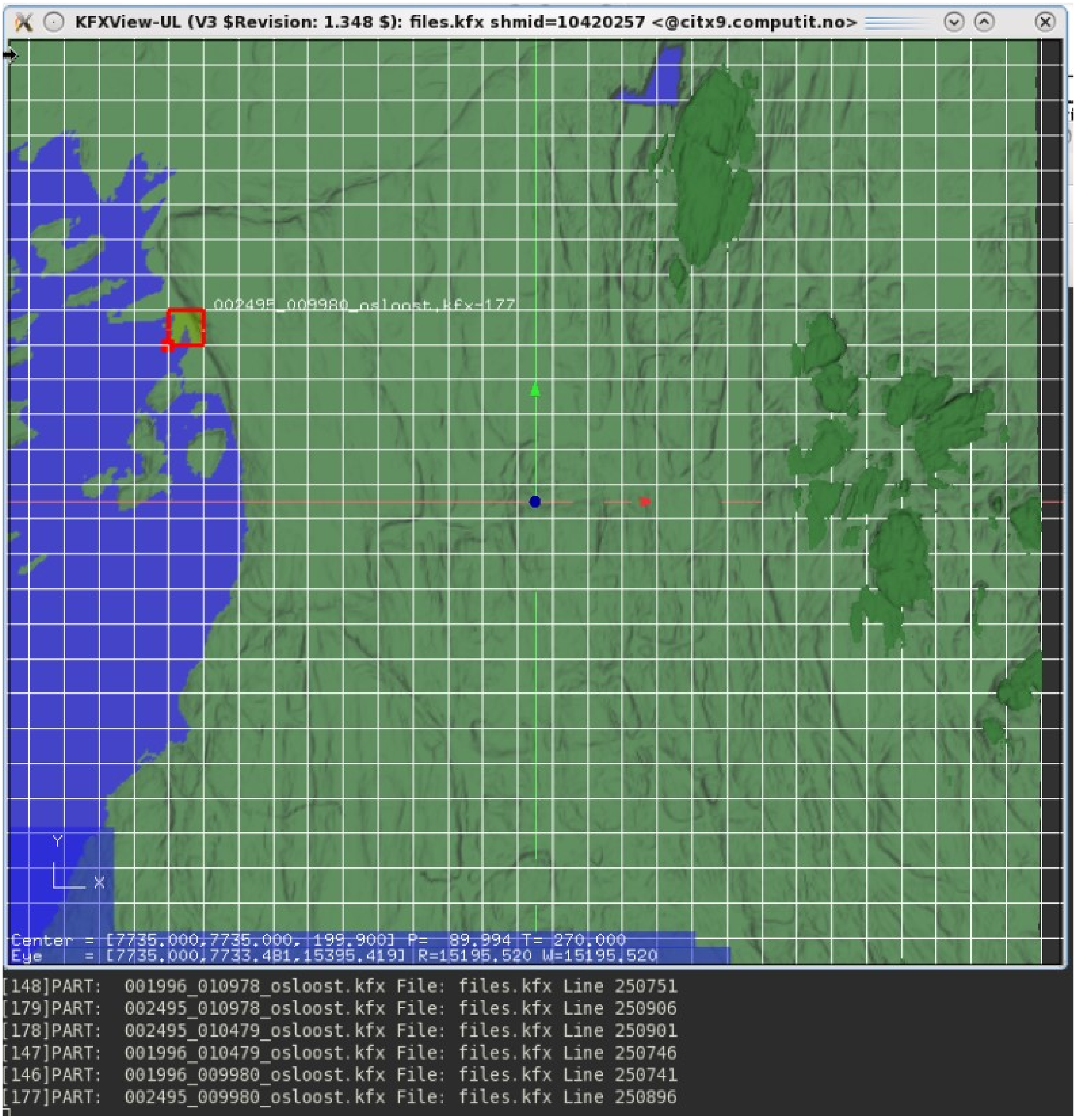

Figure 1: Topographic tiles of Oslo east

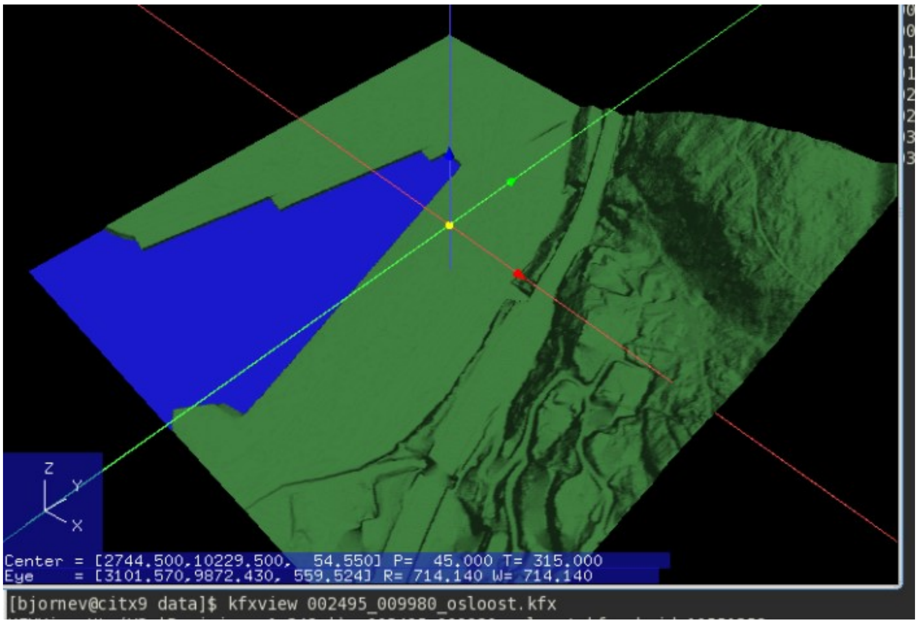

Figure 2: The detailed topography of marked tile in Figure 1: Topographic tiles of Oslo east

3.2 CO_2 release

When liquid CO_2 at 16 bara and 247 K is released into the atmosphere, the CO_2 flow undergoes an expansion process which will result in a very complex high-momentum multiphase flow which includes formation of solid CO_2 particles which disperse, sublimate and possibly deposit downstream the release point. For the CO_2 release source modelling in KFX™, comprehensive state-of-the-art CO_2 thermodynamics is applied to calculate the expansion process resulting in an equivalent two-phase CO_2 release at atmospheric conditions, consisting of a mixture of CO_2 gas and CO_2 solid particles (Rian et al., 2014). Further, the results from the KFX™ CO_2 release source model are used as input conditions for the two-phase CO_2 dispersion simulation in KFX™.

In addition, several scenarios simulating dispersion of pure gas leakages expanded from 46 bara and 303 K to atmospheric conditions has been executed. The expansion process is calculated by the conventional underexpanded jet model in KFX™.

3.3 Wind conditions and surroundings

For the wind profile inlet boundary conditions and domain initial conditions, a logarithmic wind profile based on a reference wind speed of 3 m/s at 10 m above the sea surface has been used. Wind incoming, from south has been used in 9 out of 13 scenarios. Exceptions are Case No. 04 and Case No. 11 with wind from north and Case No. 9 and Case No. 10 with wind from west.

The air temperature of the surroundings was set equal to 10°C, and the atmospheric stability used in KFX™ is neutral.

4 CALCULATION MODEL

4.1 Kameleon FireEx KFX®

- Kameleon FireEx KFX® is a finite-volume CFD code which solves the fundamental conservation equations for three-dimensional time-dependent turbulent flow and combustion using a non-uniform Cartesian grid. KFX™ is specially designed to find reliable solutions to industrial problems related to dispersion of hazardous matter, fire and explosion safety in the oil and gas industry and other process industries.
- The grid system in KFX™ can be generated automatically or manually.
- KFX™-CO_2 includes an Euler-Lagrange model for simulation of multiphase CO_2 dispersion. Dispersion and sublimation of solid CO_2 particles is modeled by the KFX™ Lagrangian spray model which is fully coupled to the Eulerian treatment of the gas phase flow. Flow interactions between the gas and solid phase are accounted for, including mass and heat transfer during sublimation of solid particles of CO_2.
- A KFX™-CO_2 release-source (pseudo-source) model is used to model the very complex expansion process involved in high-pressure releases of CO_2 into the atmosphere. The model is based on comprehensive and accurate state-of-the-art thermodynamics for carbon dioxide in the gas, liquid and solid phase.
- Turbulence is modeled with the k-epsilon model with standard constants and extended for effects of turbulence production due to buoyancy. Wall laws for the turbulent boundary layer are applied to calculate wall shear stress and convective heat transfer coefficients. The wall-law models are represented as source terms in the momentum equations, turbulence equations and energy equation.
- A large number of submodels and special cells have been developed for boundary conditions of practical interest. For instance, KFX™ includes pool spreading models, model for water spray/deluge systems, and special cells for high-pressure gas releases. Wind boundary conditions based on logarithmic wind profiles are used, where effects of ground roughness, neutral and stable wind conditions are included.
- KFX™ includes powerful CAD import capabilities where CAD geometries, including electronic maps of terrain, buildings, modules, process plants, pipelines, etc. are converted automatically into computational cells for solid constructions or surface/volume porosities used by the KFX™ calculation model. In KFX™, solid elements are rigorously treated and the consequences for mass, momentum and energy of the fluid are accounted for according to the physical processes involved. Objects less than the grid spacing are approximated by volume and/or surface porosities which generate for instance restrictions to the flow field and thermal radiation through such volumes, and are included when solving the governing equations. Thermal effects of the porosities are also accounted for.
- KFX™ includes a user interface which is designed to reduce simulation set-up times and possibilities of operator errors.
- Results can be presented in a number of different ways, including visualizations in the CAD geometry.
- Videos can be generated at observation points inside and outside the computational domain.
- KFX™ is interfaced with USFOS for dynamic structural response analyses.
- KFX™ is extensively validated.

More detailed information about the CO_2 dispersion modelling in Kameleon FireEx KFX® and KFX™ validation is found in Rian et al. (2014). More information about Kameleon FireEx KFX® can also be found at www.computit.no.

4.2 Geometry model and computational domain

Appropriate modelling of terrain and complex geometries is essential if reliable CO_2 dispersion predictions for realistic industrial scenarios should be expected. Different tiles of the Oslo east topographic model see Figure 1, have been used to generate detailed topography of the Klemetsrud facility and the harbour area at Sjursøya. The KFX™ CAD model has been imported and automatically converted into a calculation model in KFX™.

The computational domain consisted of 1,100,000 to 1,500,000 computational cells, depending on the scenario.

5 RESULTS

KFX™ simulation results from 13 different scenarios are presented below. The horizontal plots show iso-contours of vertically projected maximum CO_2 concentrations (in vol %) for each CO_2 leakage scenario. This will typically provide a representation of the CO_2 concentrations near the ground in a terrain model.

Furthermore, animations have been made to show the time development of the maximum projected CO_2 gas concentrations for the 13 CO_2 leakage scenarios. These are made as separate deliverables to the Carbon Capture Oslo Project.

5.1 Case 01 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	et Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
01	KEA-1	TwoPhase	KEA new location for interim storage	3	South	Down	12	480	8	617	-

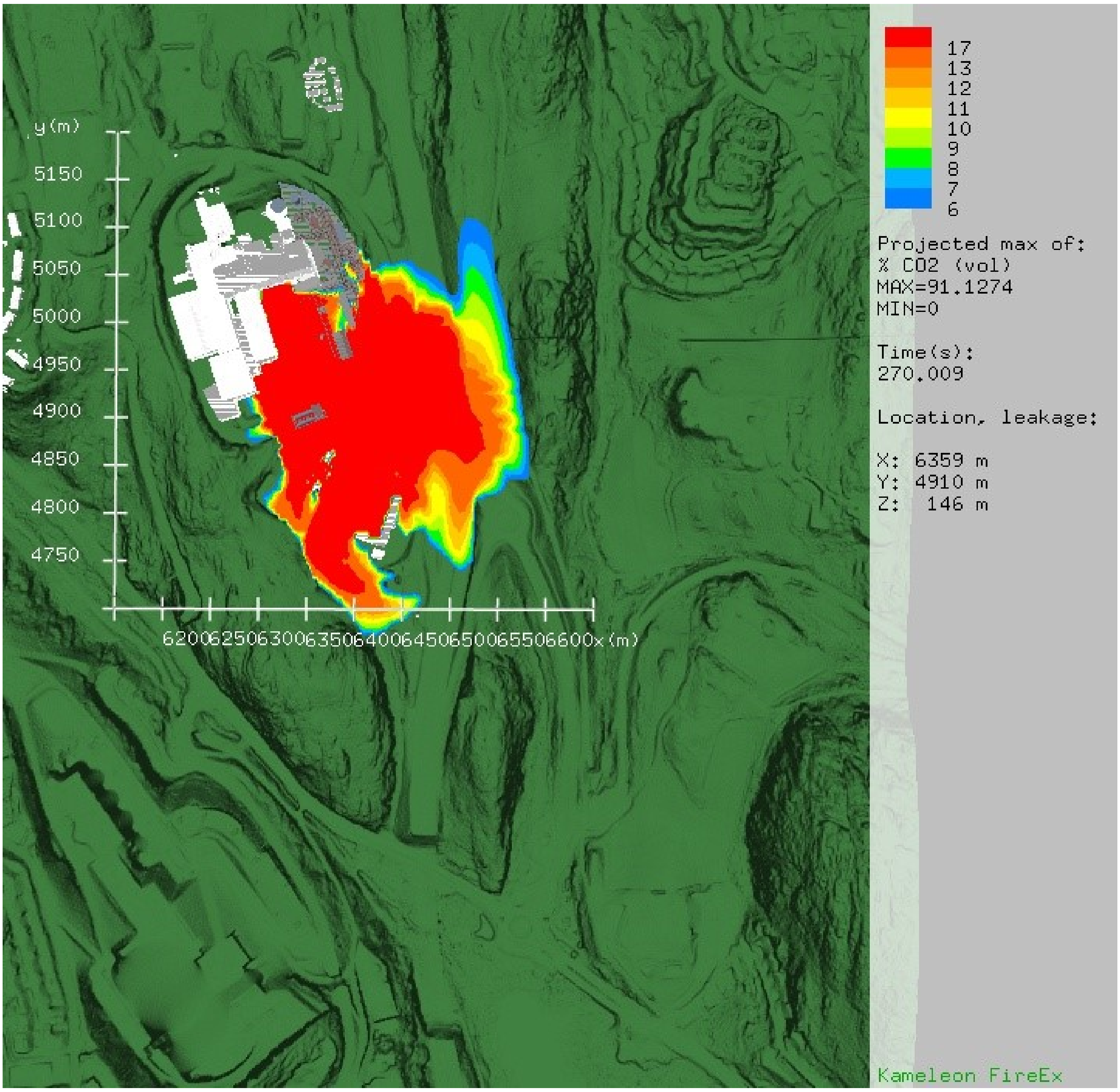

Figure 3: Case 01 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 270 s

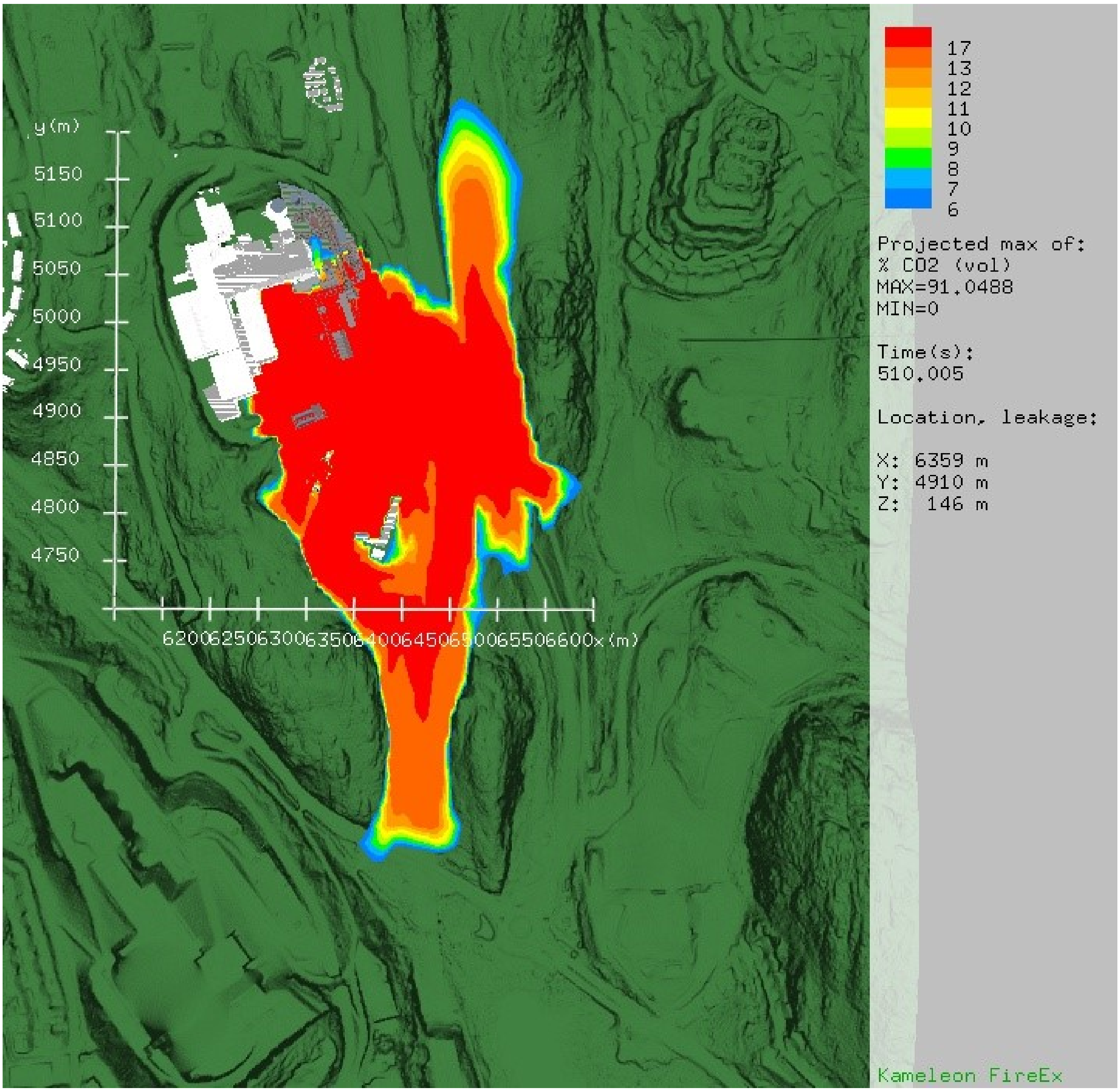

Figure 4: Case 01 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 510 s

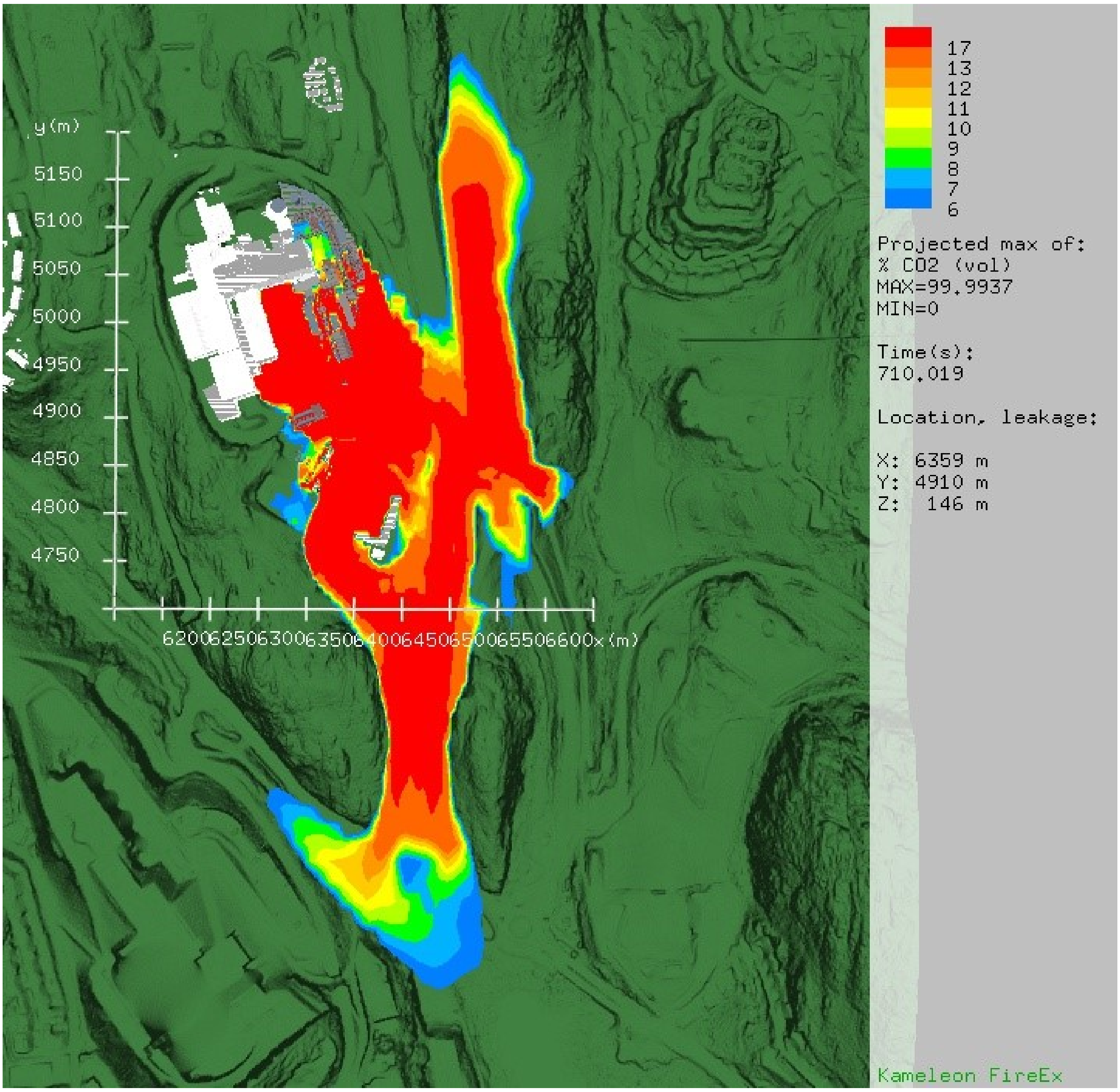

Figure 5: Case 01 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 710 s

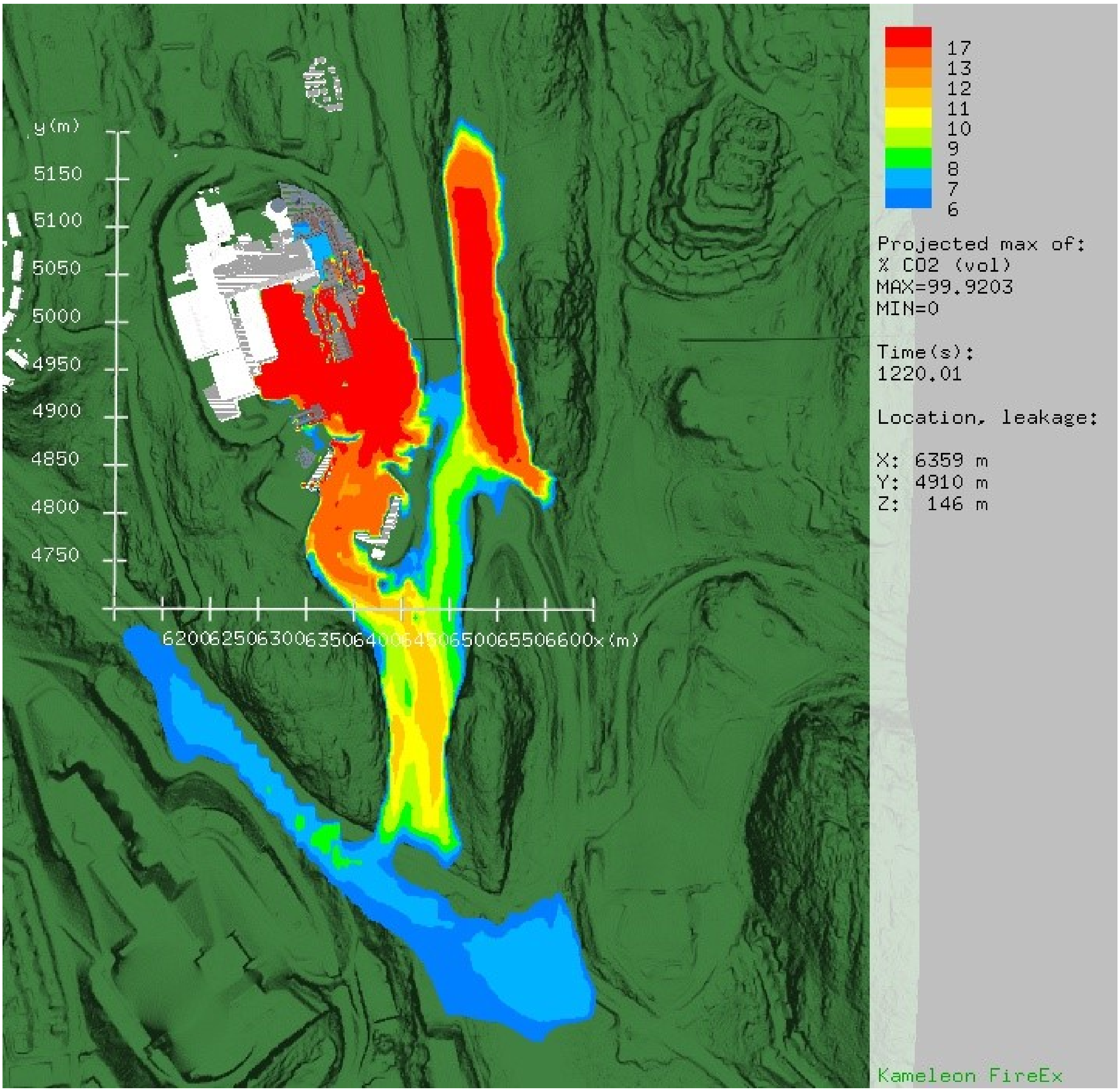

Figure 6: Case 01 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 1220 s

5.2 Case 02 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	et Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
02	KEA-2	TwoPhase	KEA new location for interim storage	3	South	East	3	480	8	617	Jet/spray unobstructed

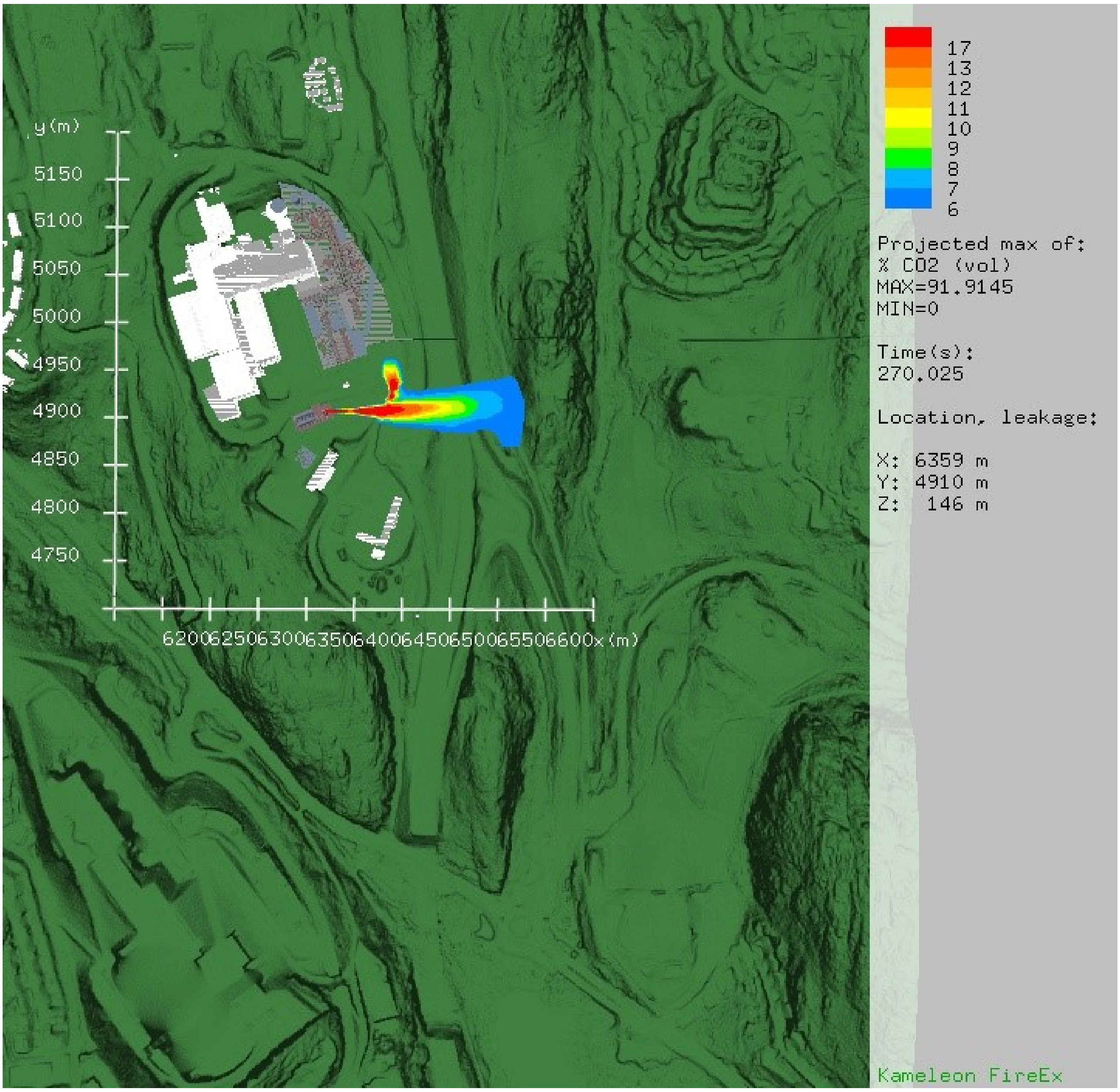

Figure 7: Case 02 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 270 s

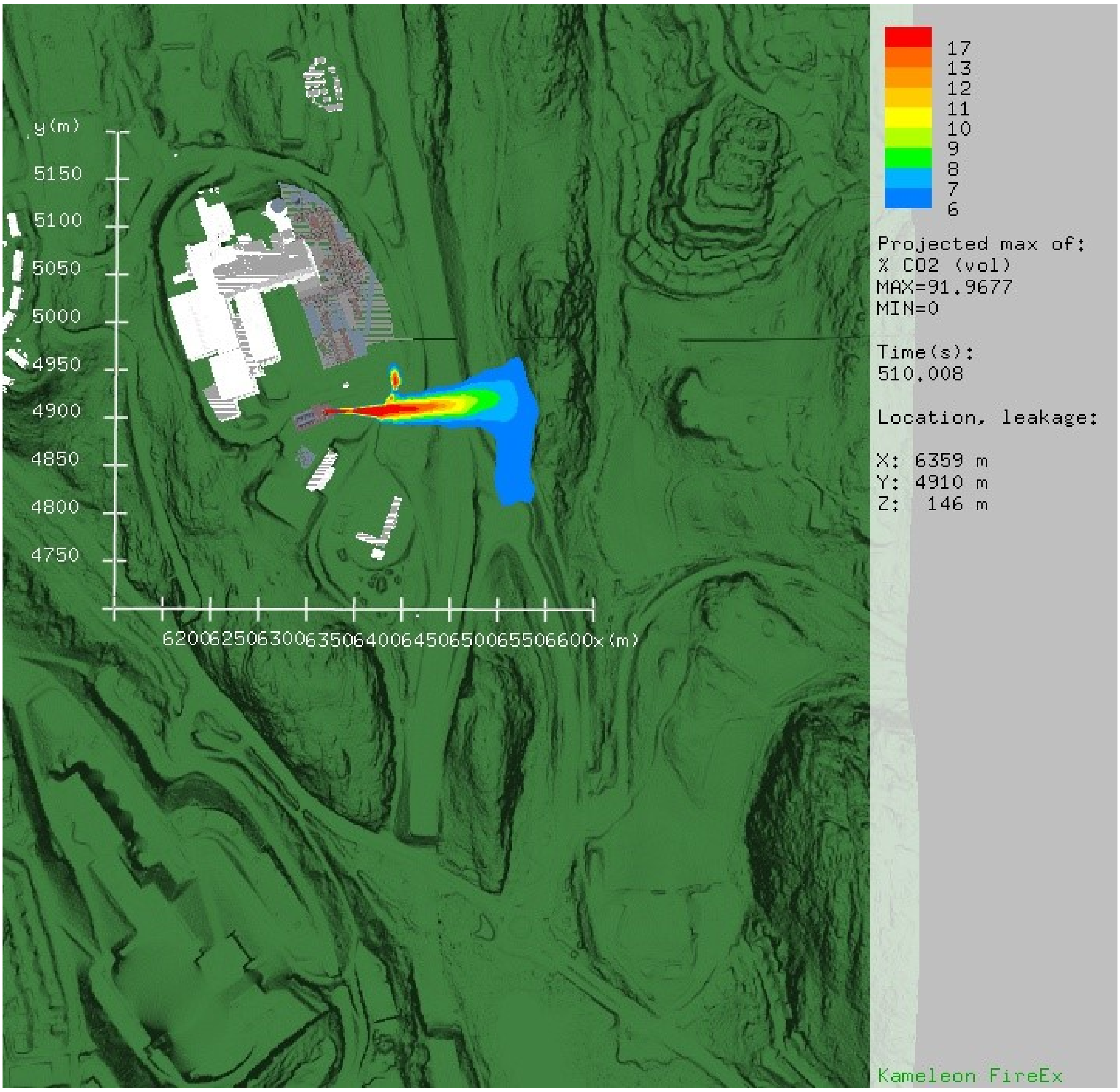

Figure 8: Case 02 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 510 s

5.3 Case 02a - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	et Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
02a	KEA-2	TwoPhase	KEA new location for interim storage	3	South	East	3	480	8	617	Jet/spray **obstructed**

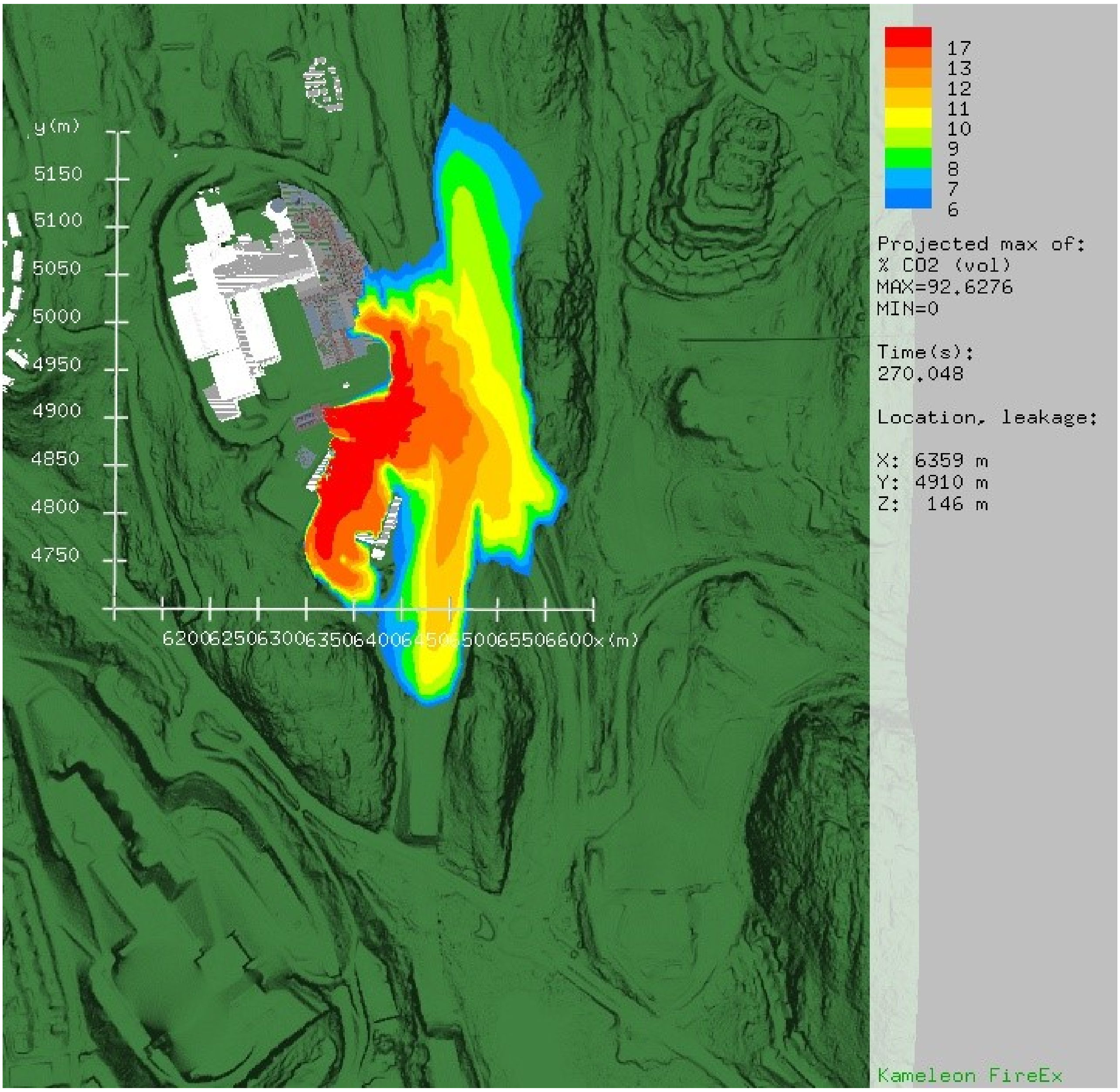

Figure 9: Case 02a - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 270 s

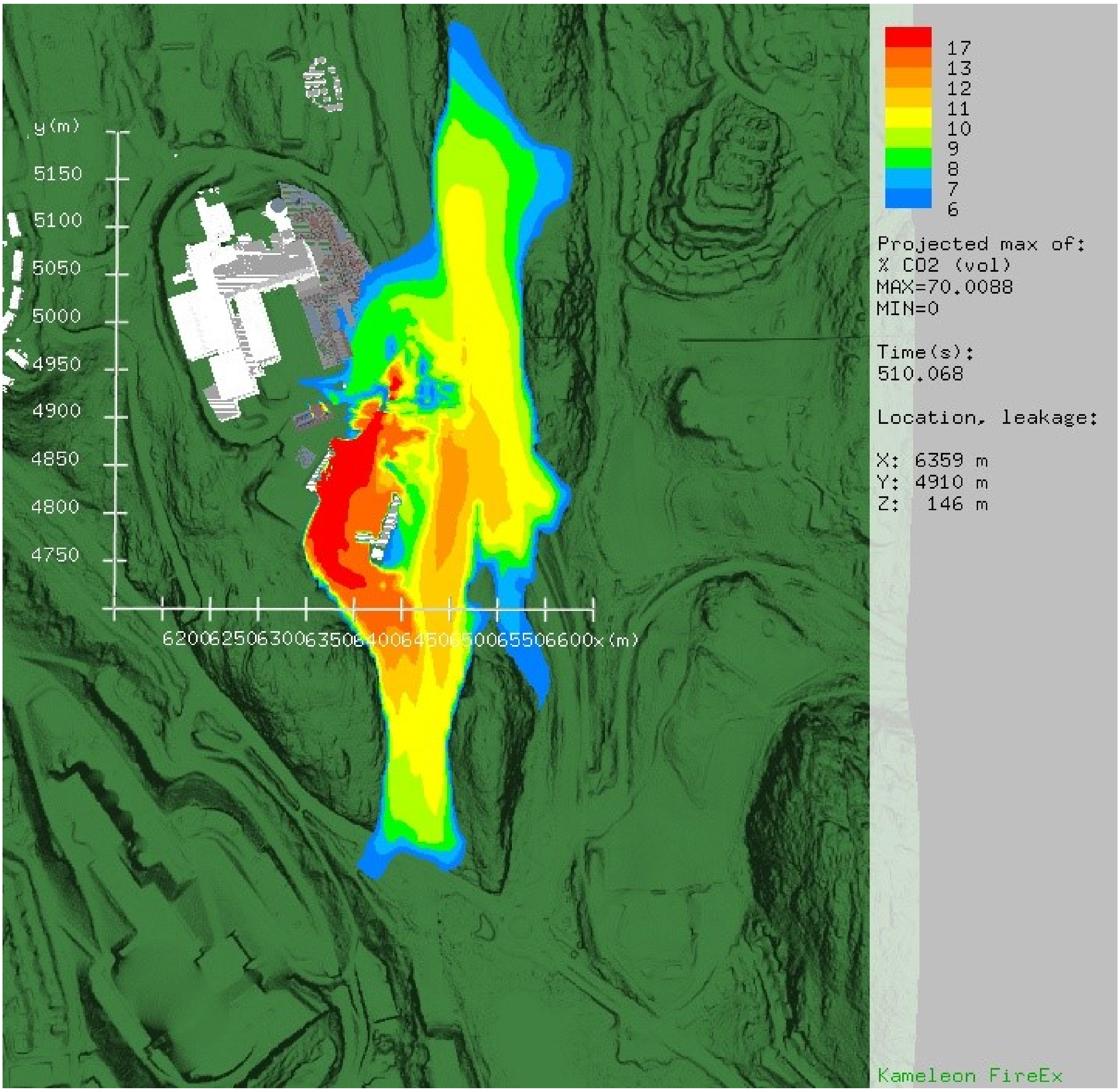

Figure 10: Case 02a - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 510 s

The basic scenario description for Case No.02a is in principle the same as for Case No. 02. However, in Case No. 02 the CO_2 is released without any obstructions in front of the release while in Case No. 02a (present case) the high-pressure CO_2 release is obstructed by surrounding geometries. This case demonstrates how effects of obstructions near the release point can result in very different CO_2 gas cloud characteristics from a high-pressure CO_2 leakage.

5.4 Case 03 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	et Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
03	KEA-3	TwoPhase	KEA new location for interim storage	3	South	Down	12	3000	50	119	-

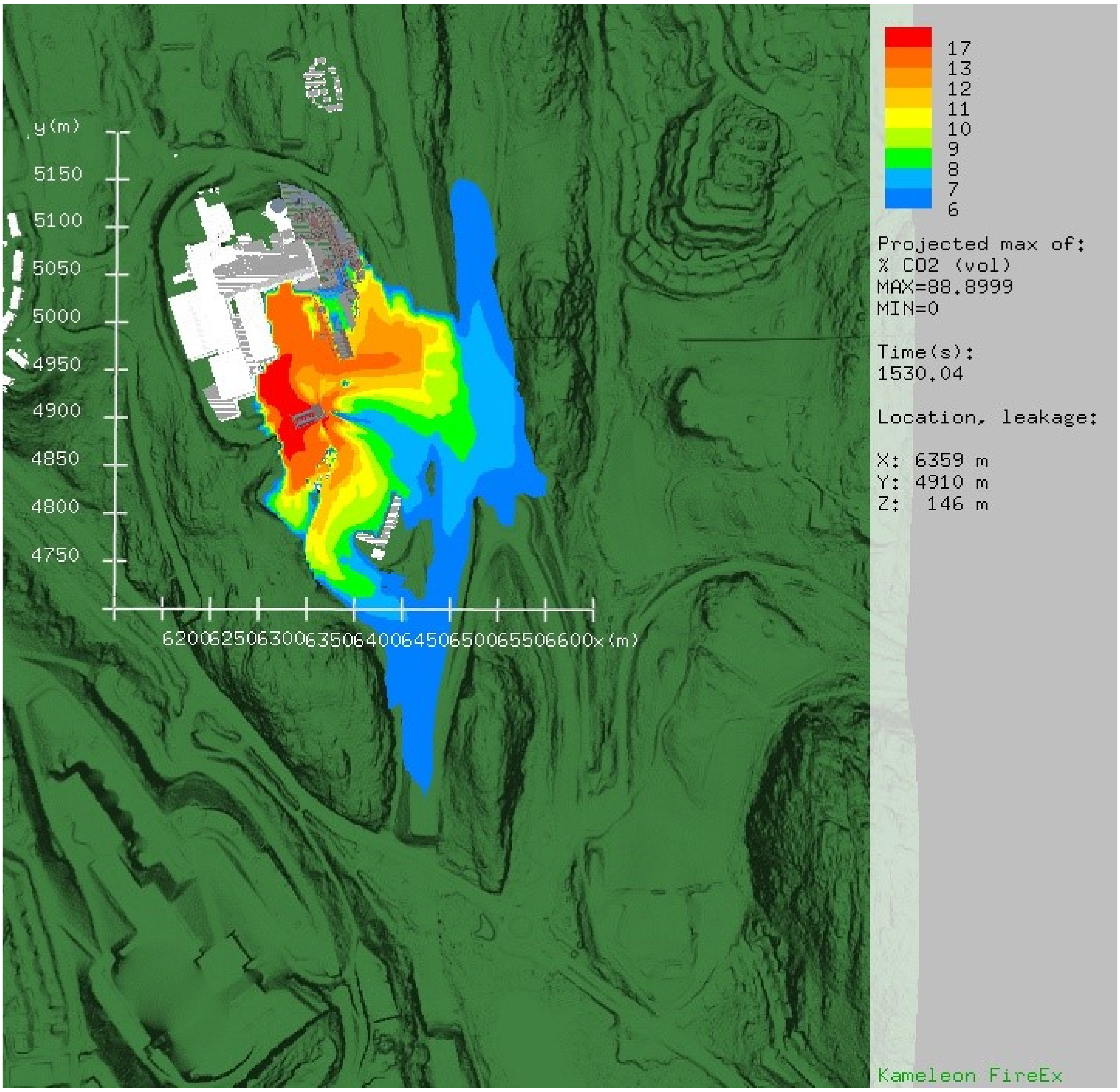

Figure 11: Case 03 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 1530 s

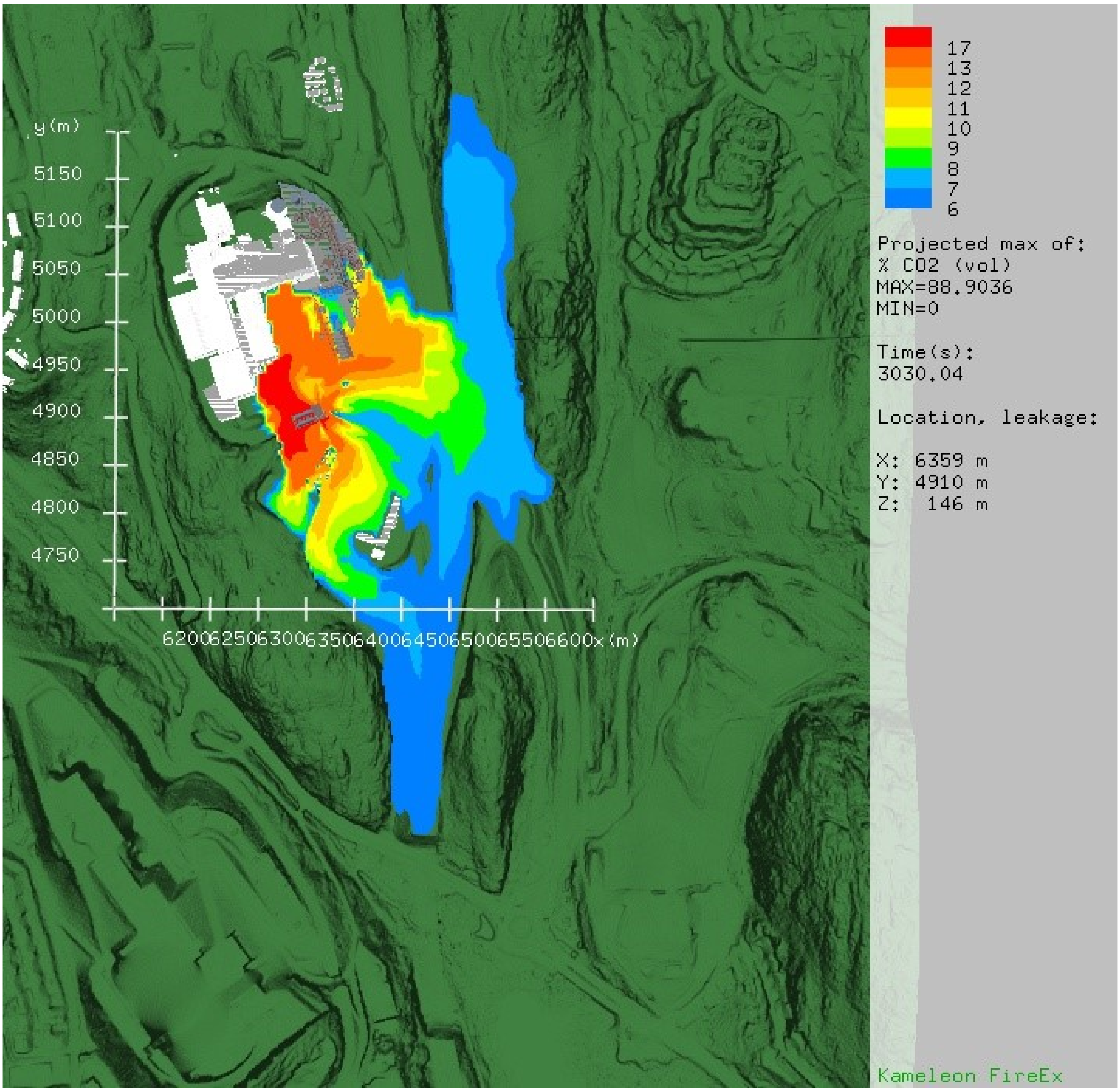

Figure 12: Case 03 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 3030 s

5.5 Case 04 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	et Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
04	KEA-4	TwoPhase	KEA new location for interim storage	3	North	East	3	3000	50	119	Jet/spray unobstructed

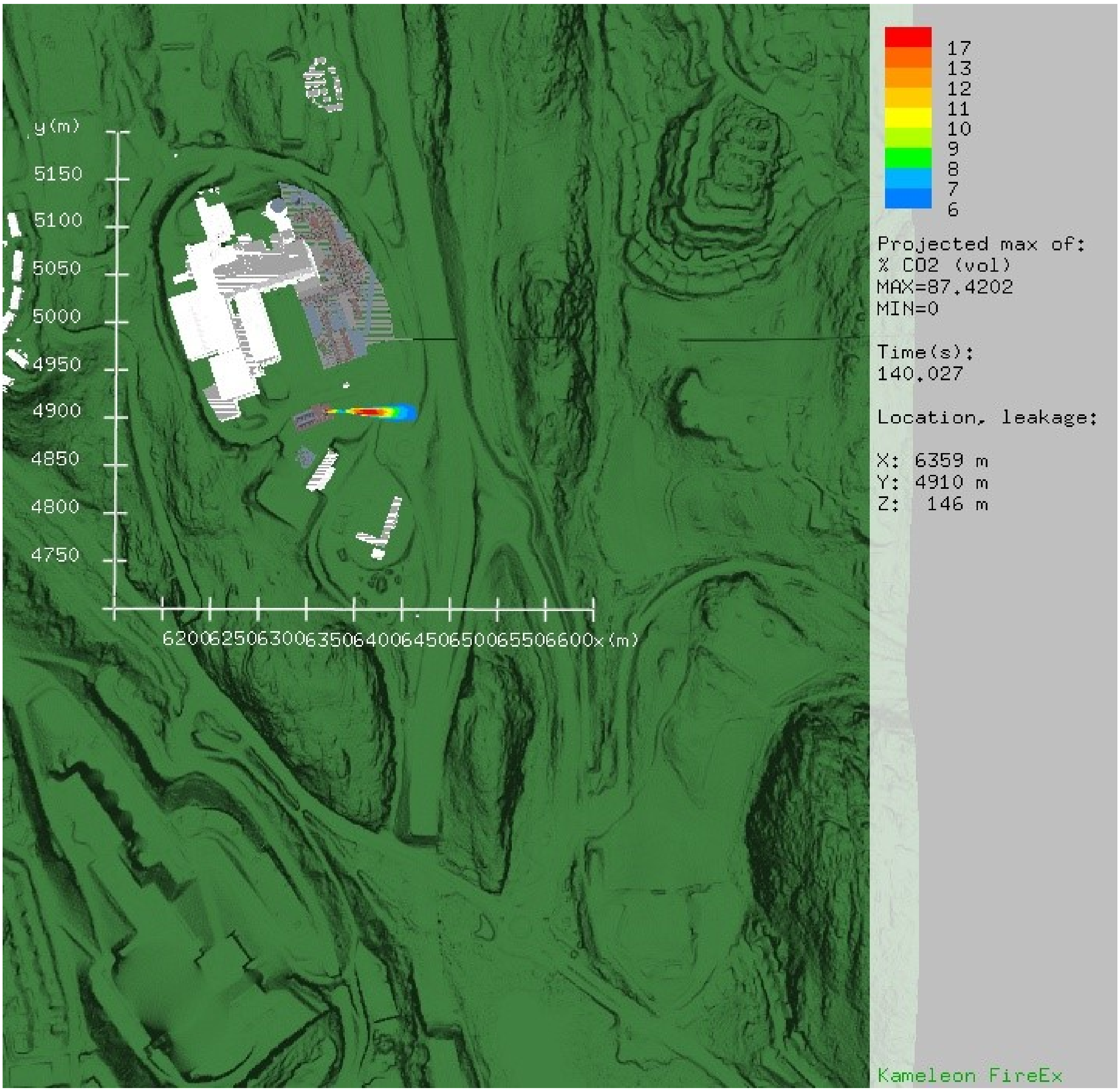

Figure 13: Case 04 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 140 s

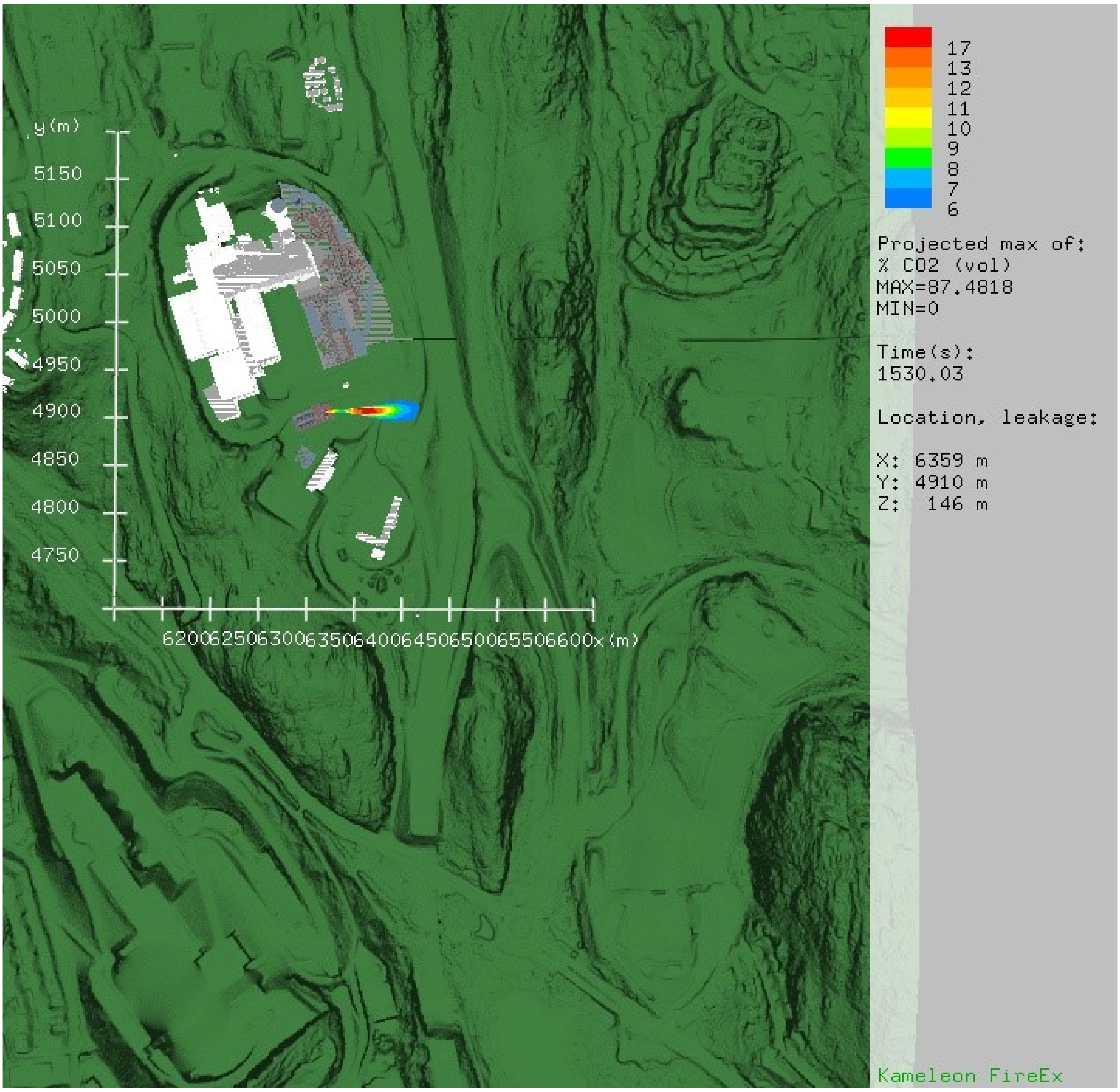

Figure 14: Case 04 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 1530 s

5.6 Case 06 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
06	KEA-G1	Gas	KEA CC plant, gas compression	3	South	East	3	600	10	17	Gas Jet unobstruceted

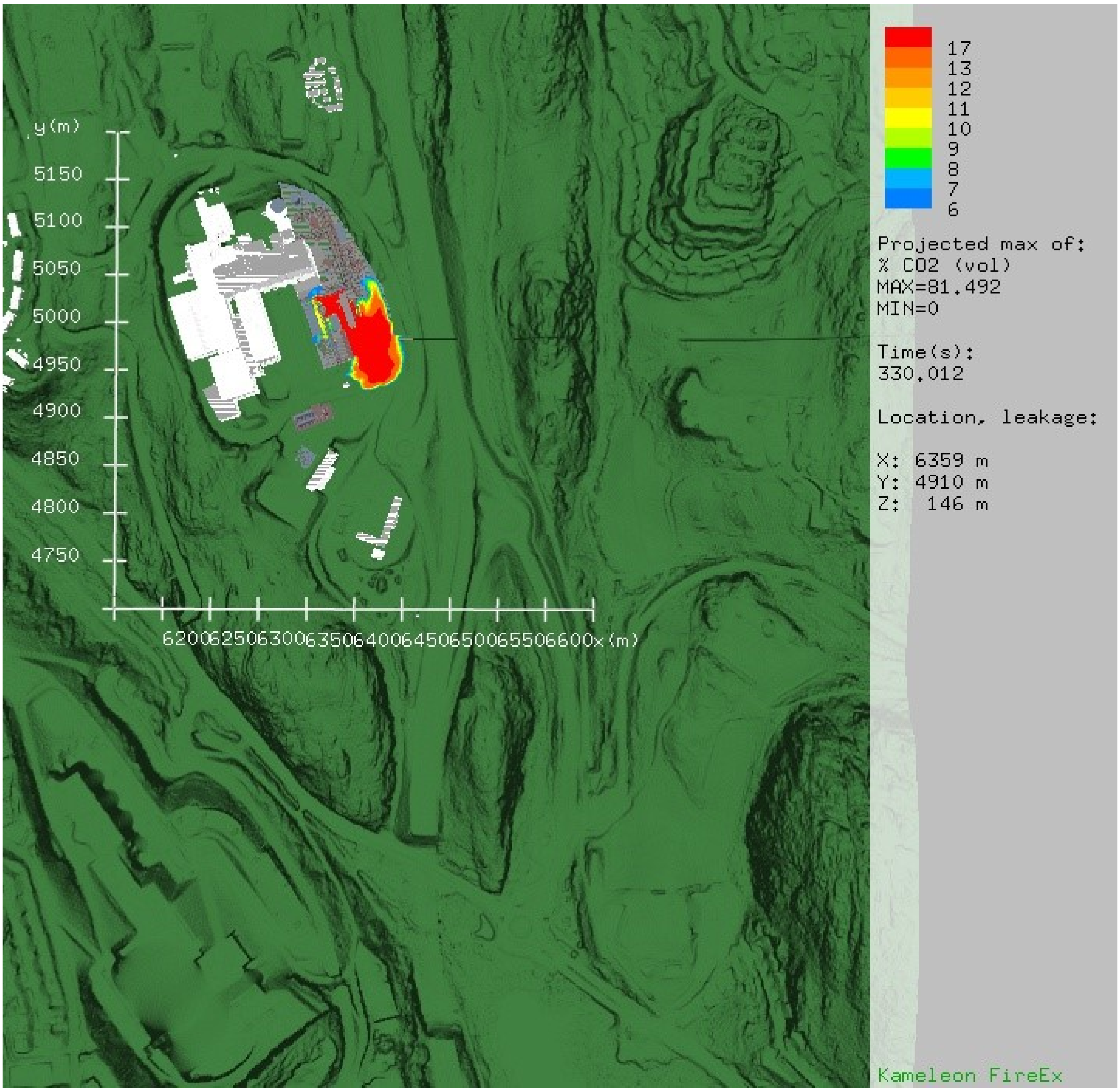

Figure 15: Case 06 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 330 s

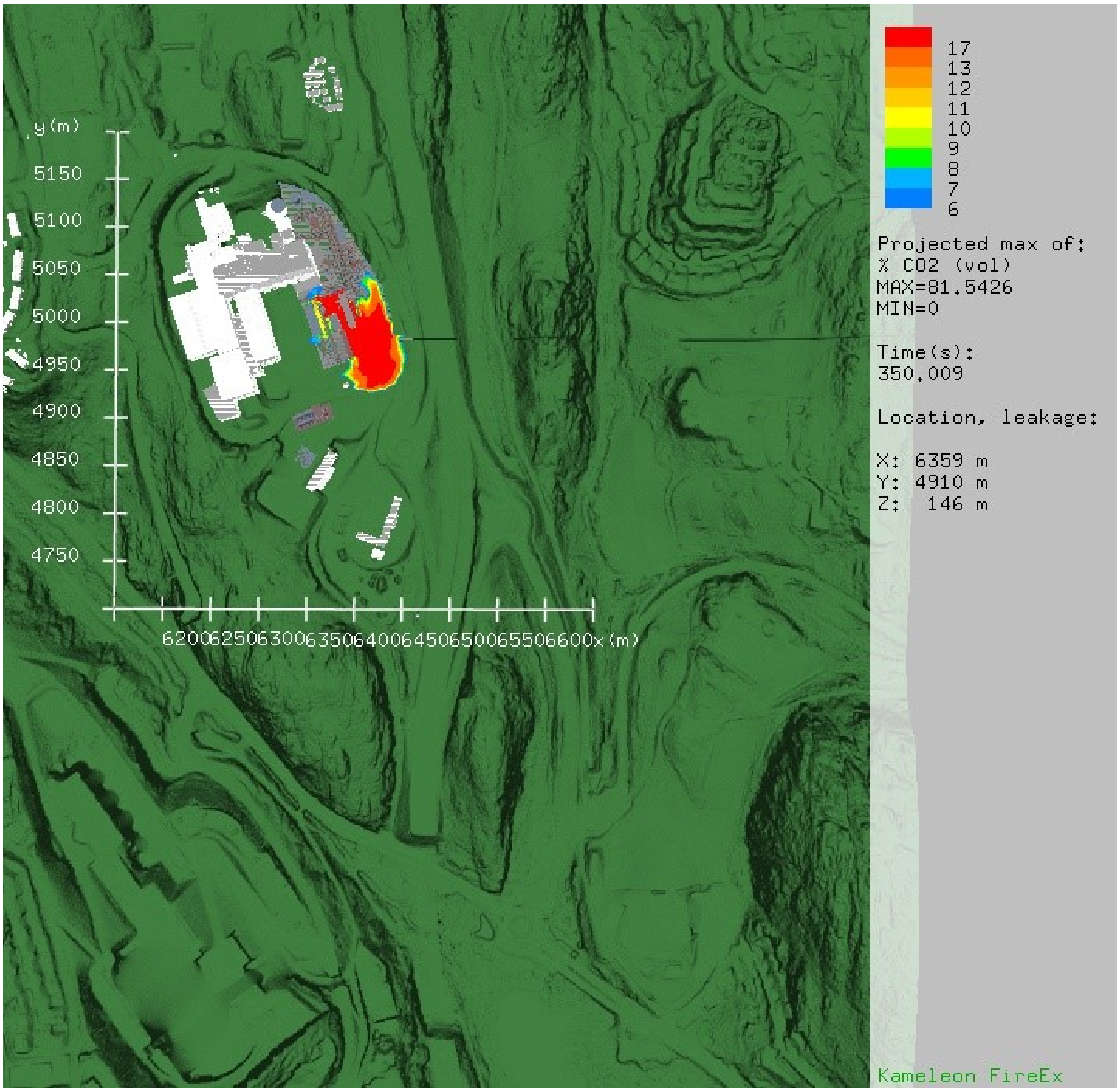

Figure 16: Case 06 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 350 s

5.7 Case 07 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
07	KEA-G2	Gas	KEA CC plant, gas compression	3	South	South	3	120	2	30	Gas Jet unobstruceted

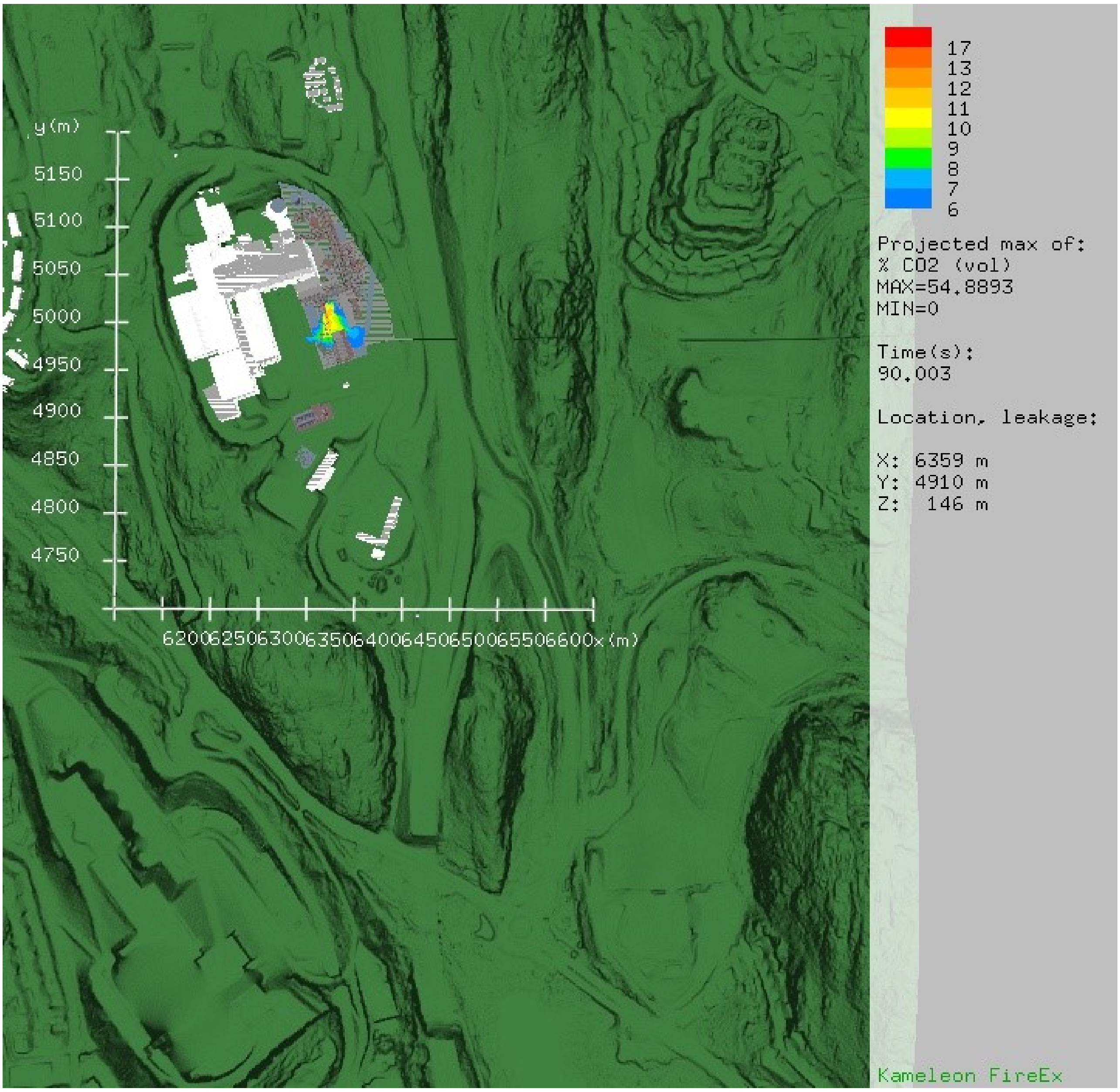

Figure 17: Case 07 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 90 s

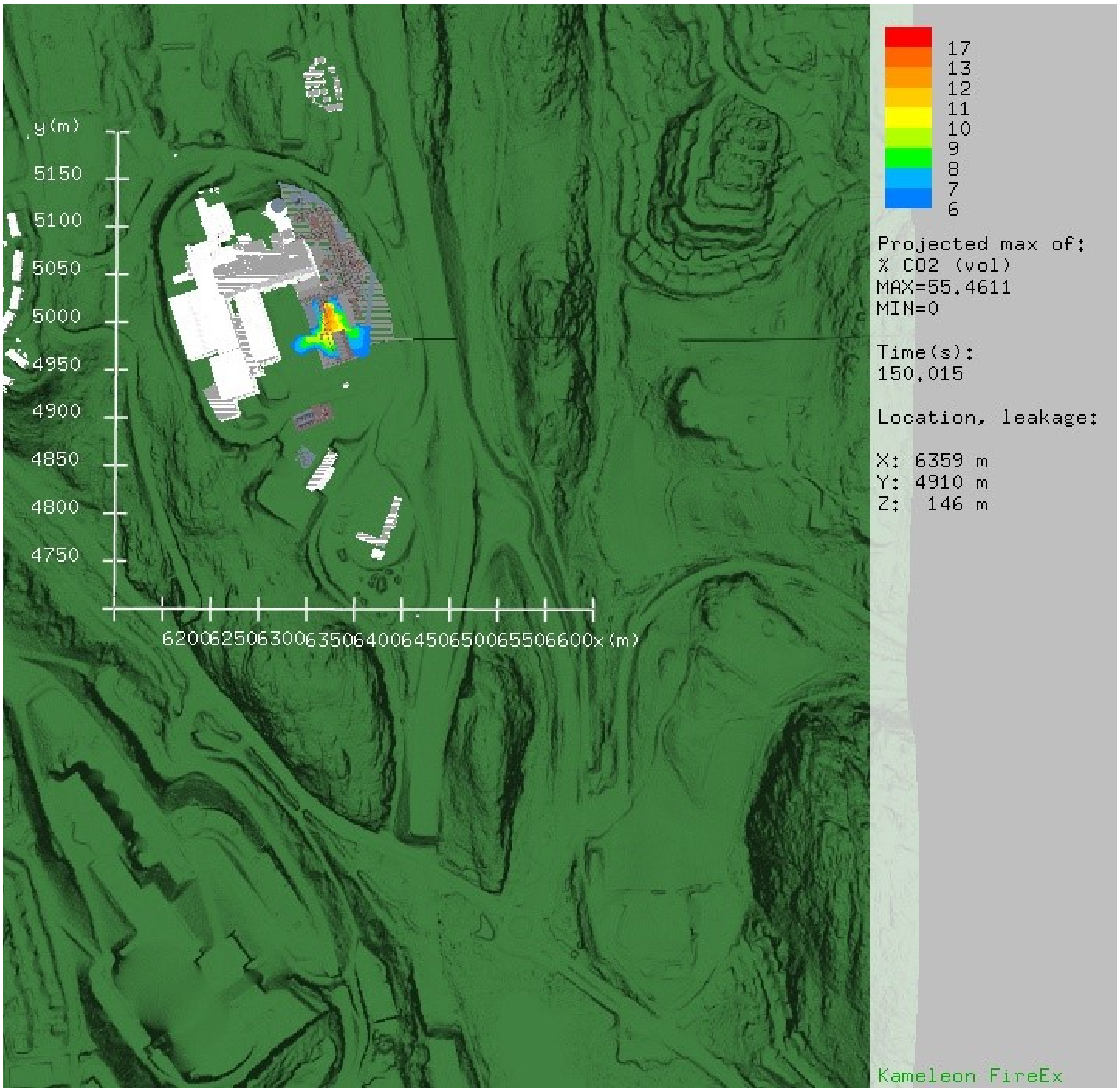

Figure 18: Case 07 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 150 s

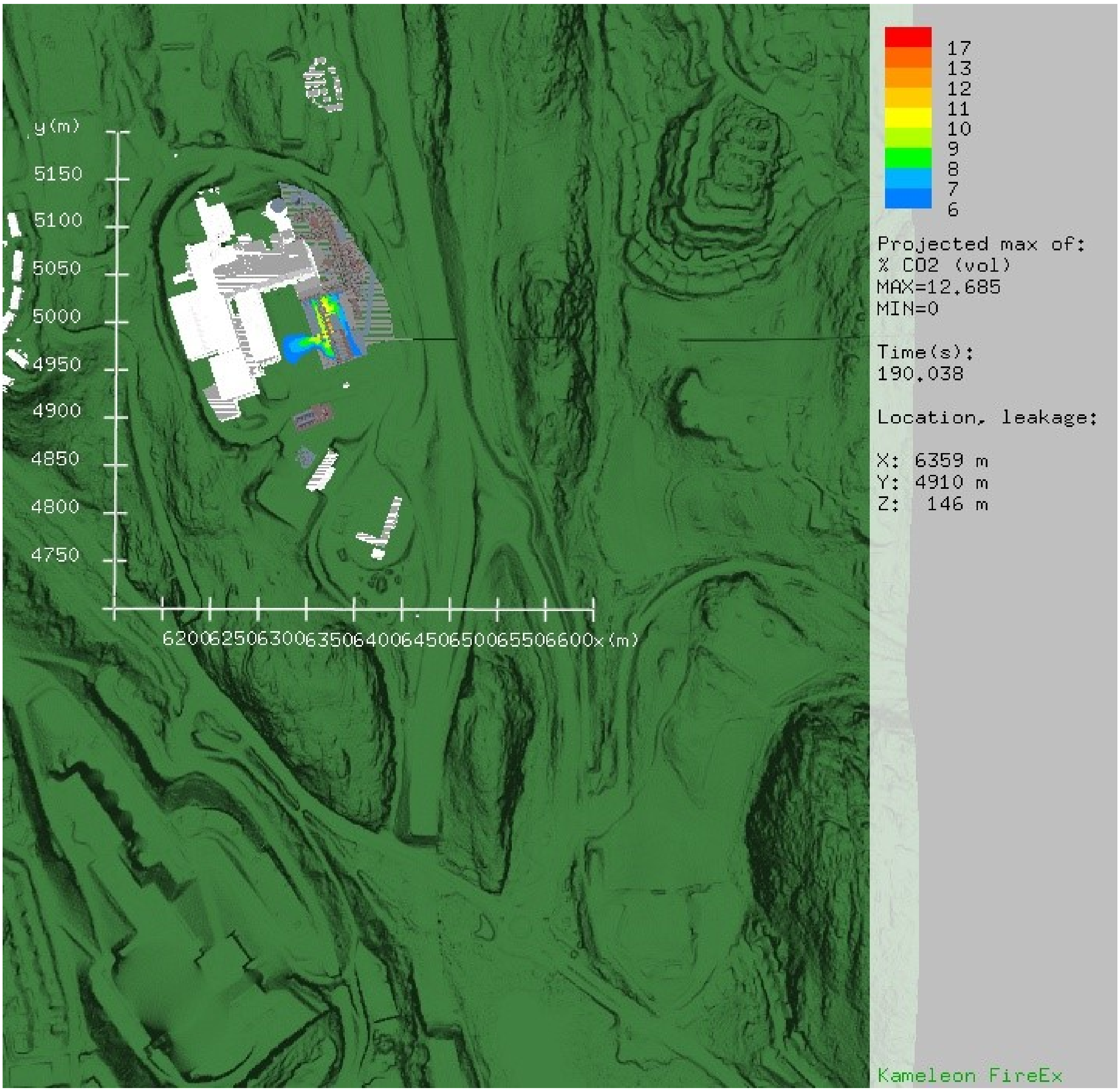

Figure 19: Case 07 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 190 s

5.8 Case 08 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
08	KEA-G3	Gas	KEA CC plant, gas compression	3	South	Down	3	60	1	50	Gas Jet unobstruceted

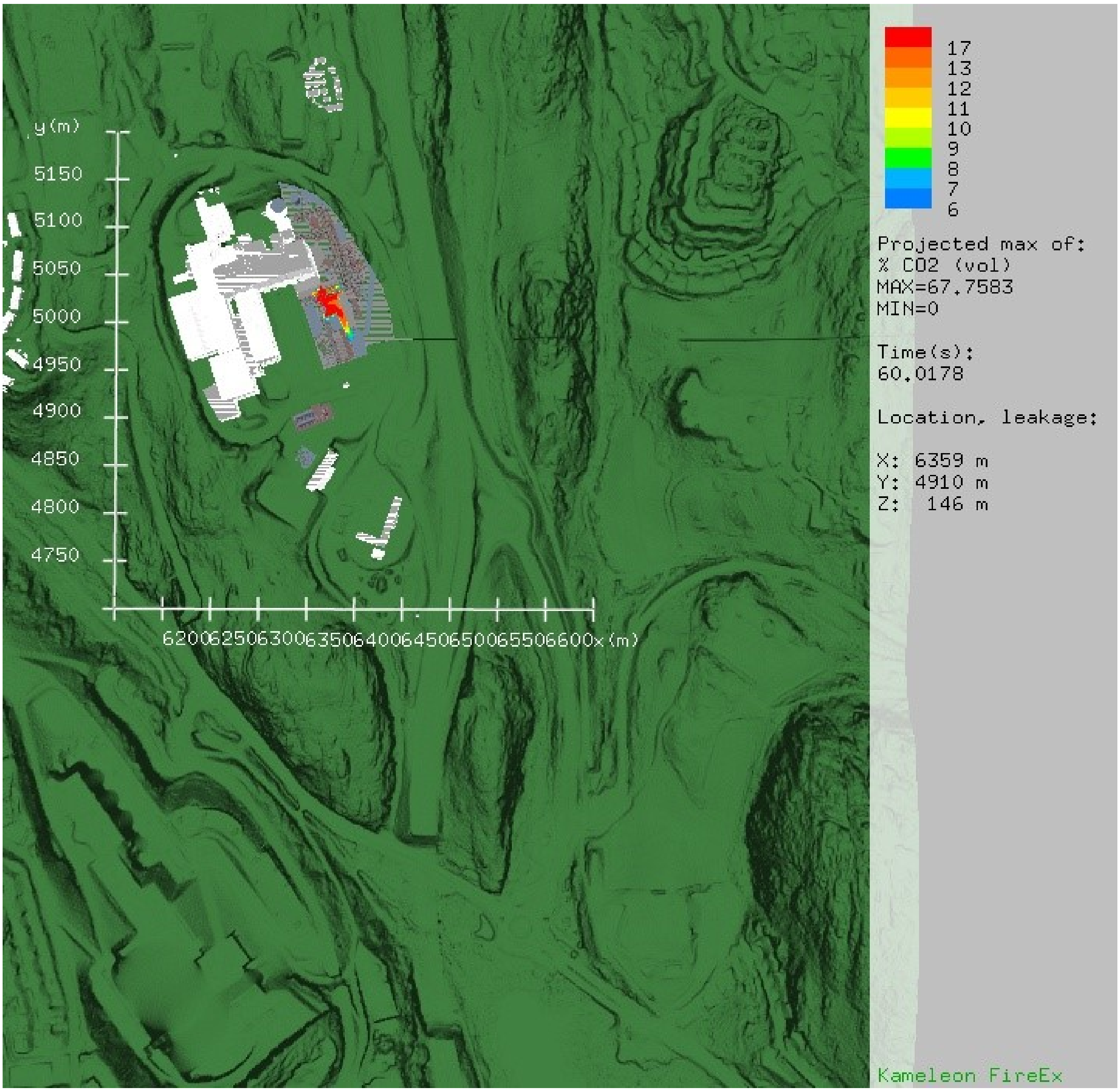

Figure 20: Case 08 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 60 s

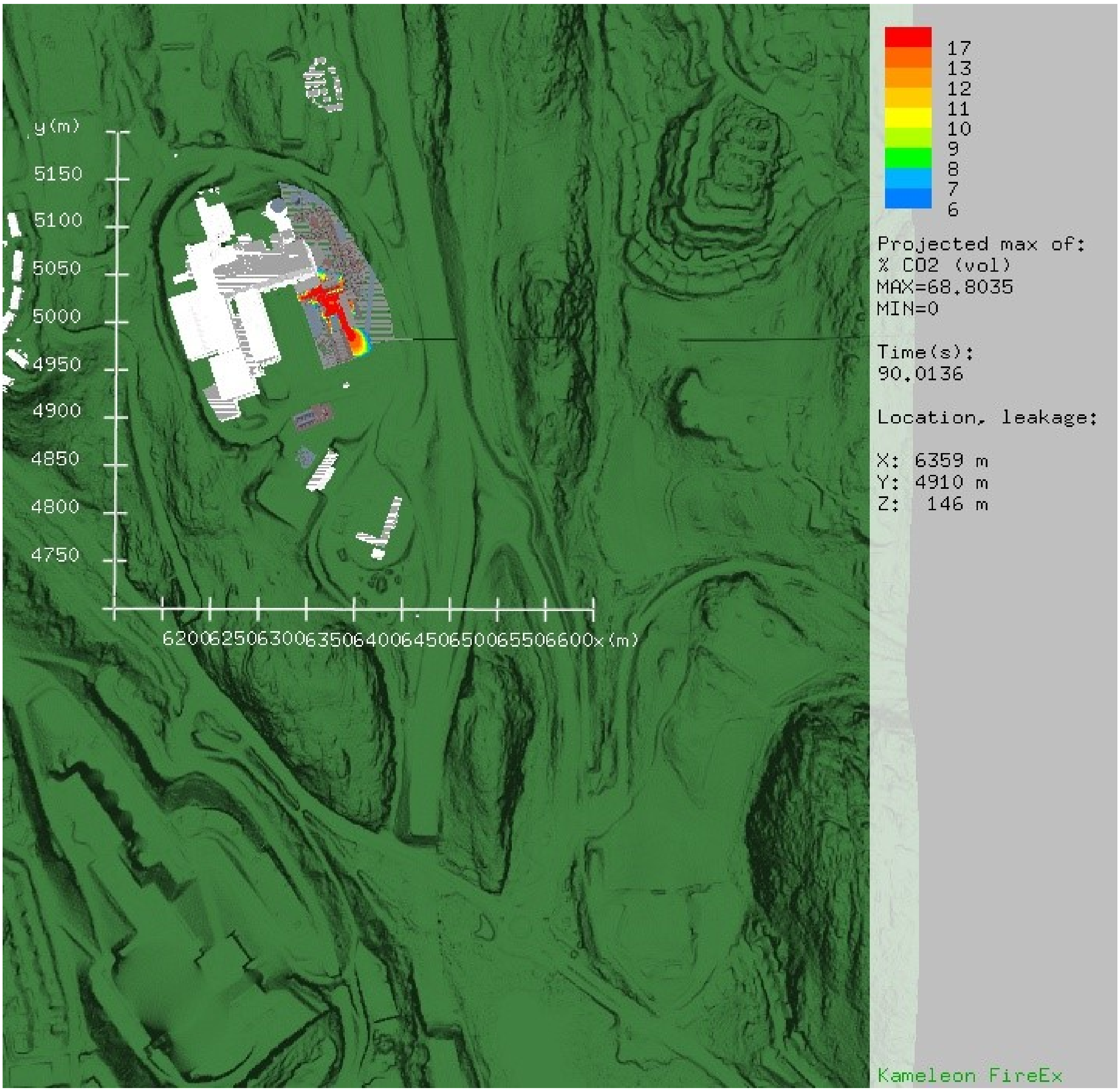

Figure 21: Case 08 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 90 s

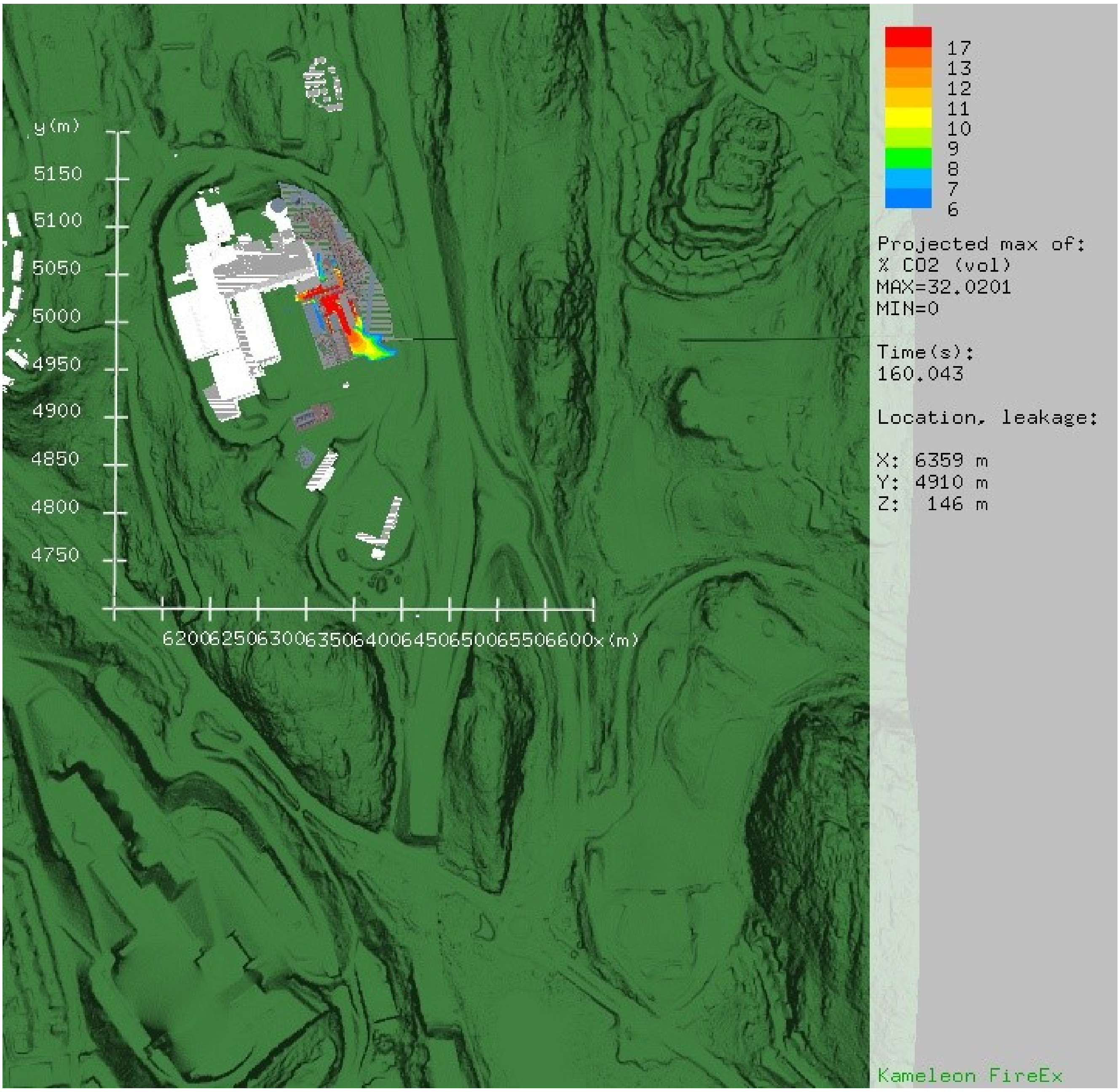

Figure 22: Case 08 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 160 s

5.9 Case 09 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
09	KEA-L1	TwoPhase	Truck Loading Area	3	West	Down	2	60	1	50	Jet/spray unobstructed

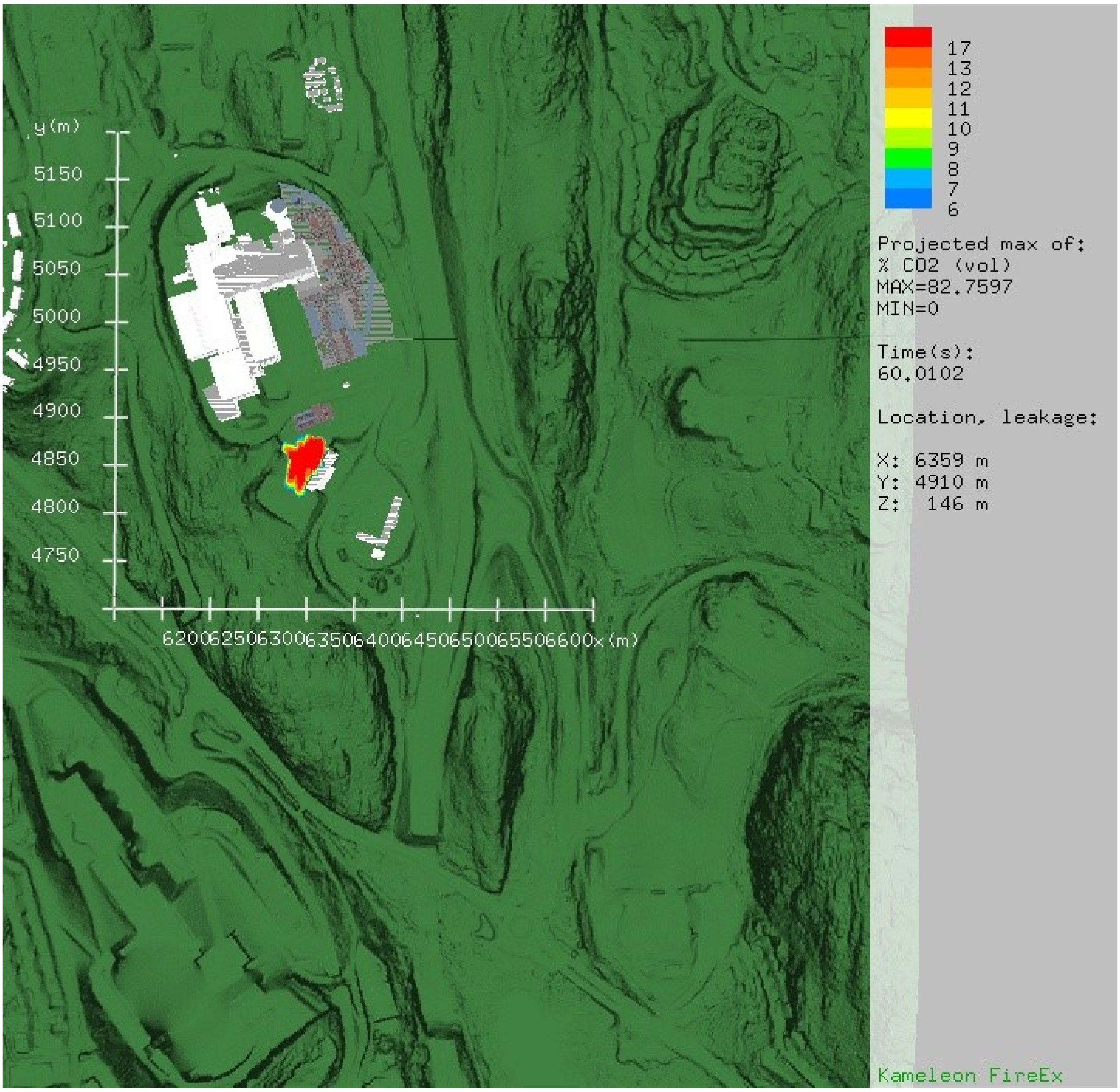

Figure 23: Case 09 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 60 s

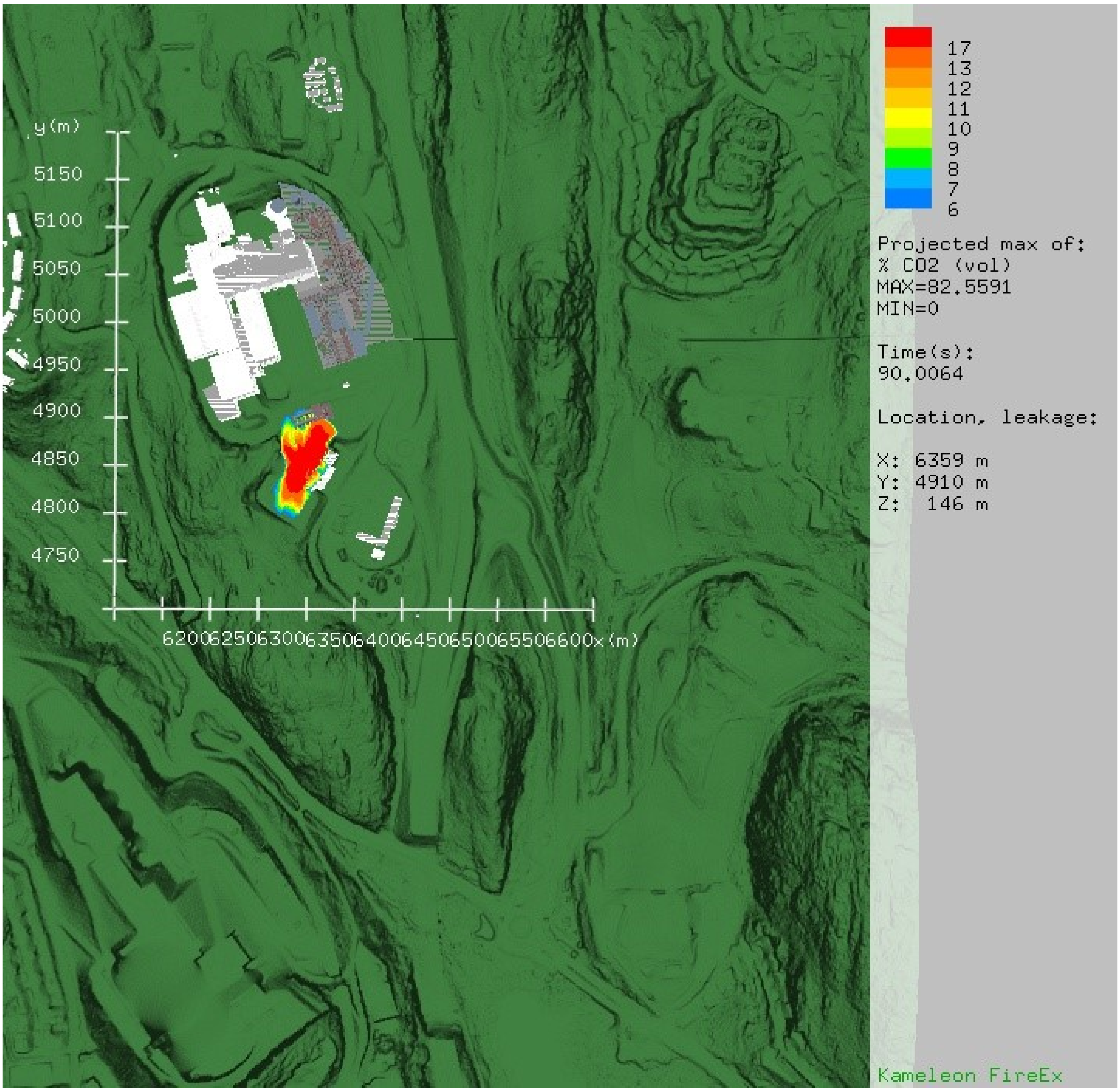

Figure 24: Case 09 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 90 s

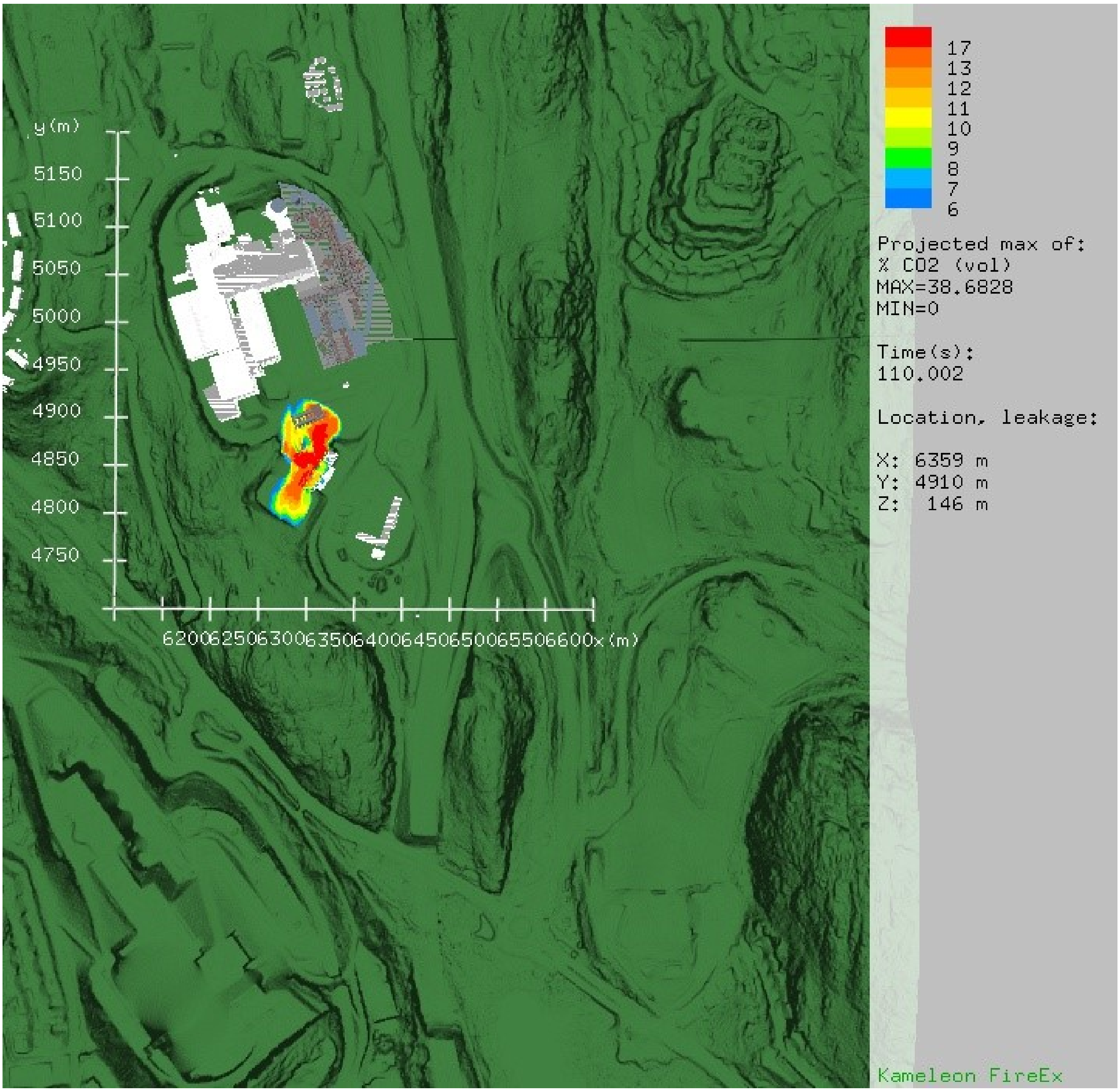

Figure 25: Case 09 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 110 s

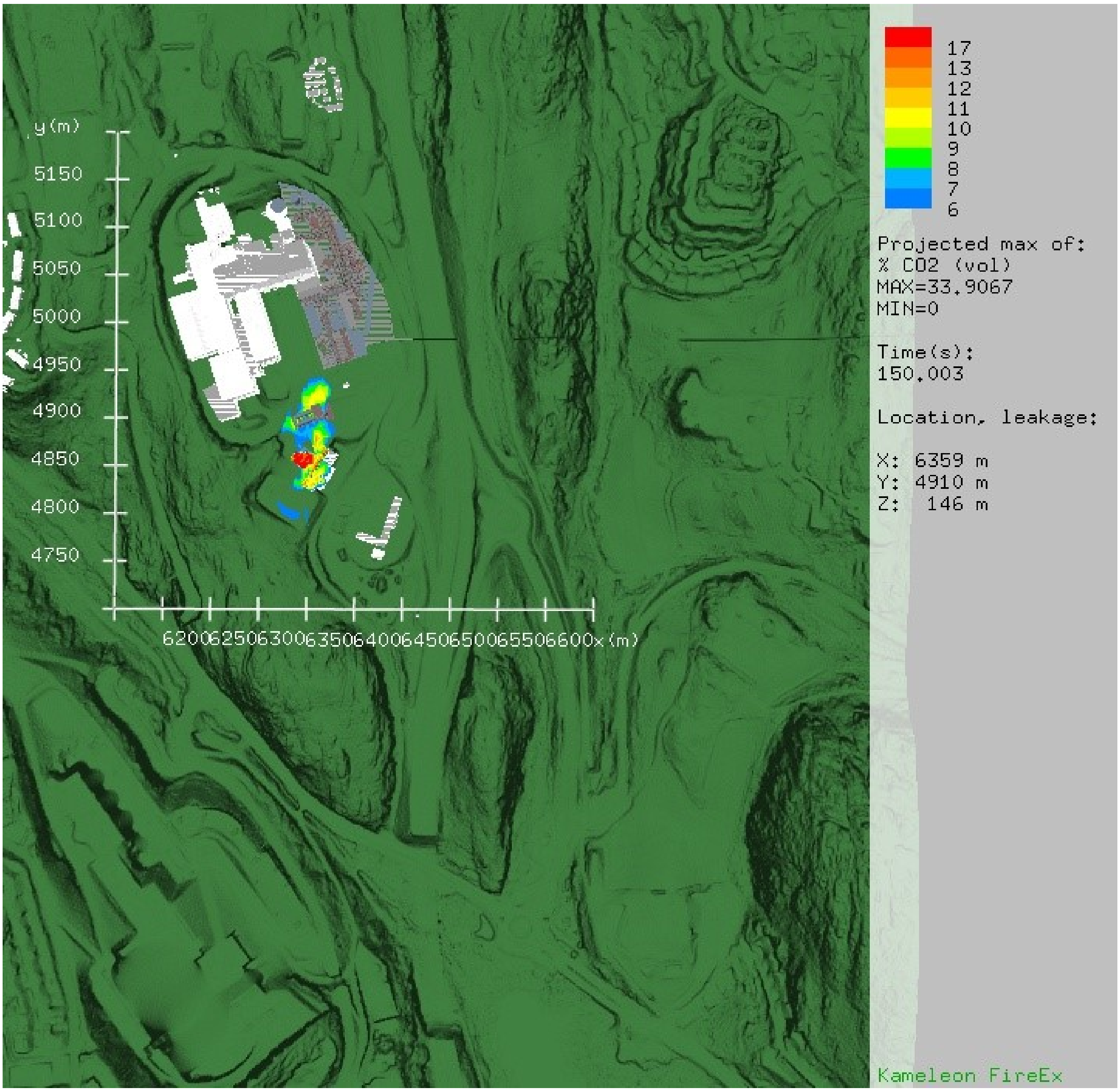

Figure 26: Case 09 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 150 s

5.10 Case 10 - Klemetsrud

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
10	KEA-L2	TwoPhase	Truck Loading Area	3	West	Down	2	20	0,33	250	Jet/spray unobstructed

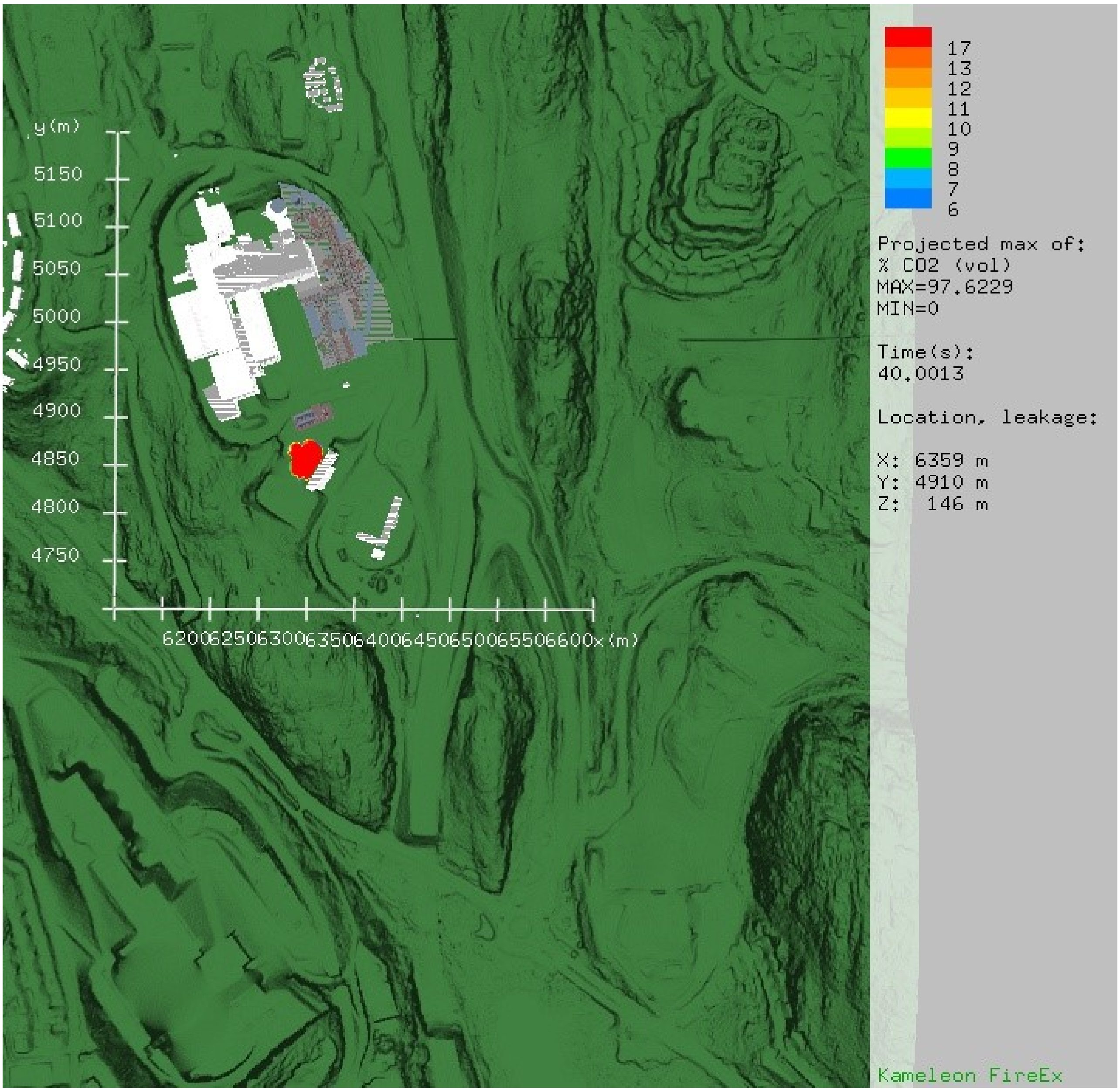

Figure 27: Case 10 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 40 s

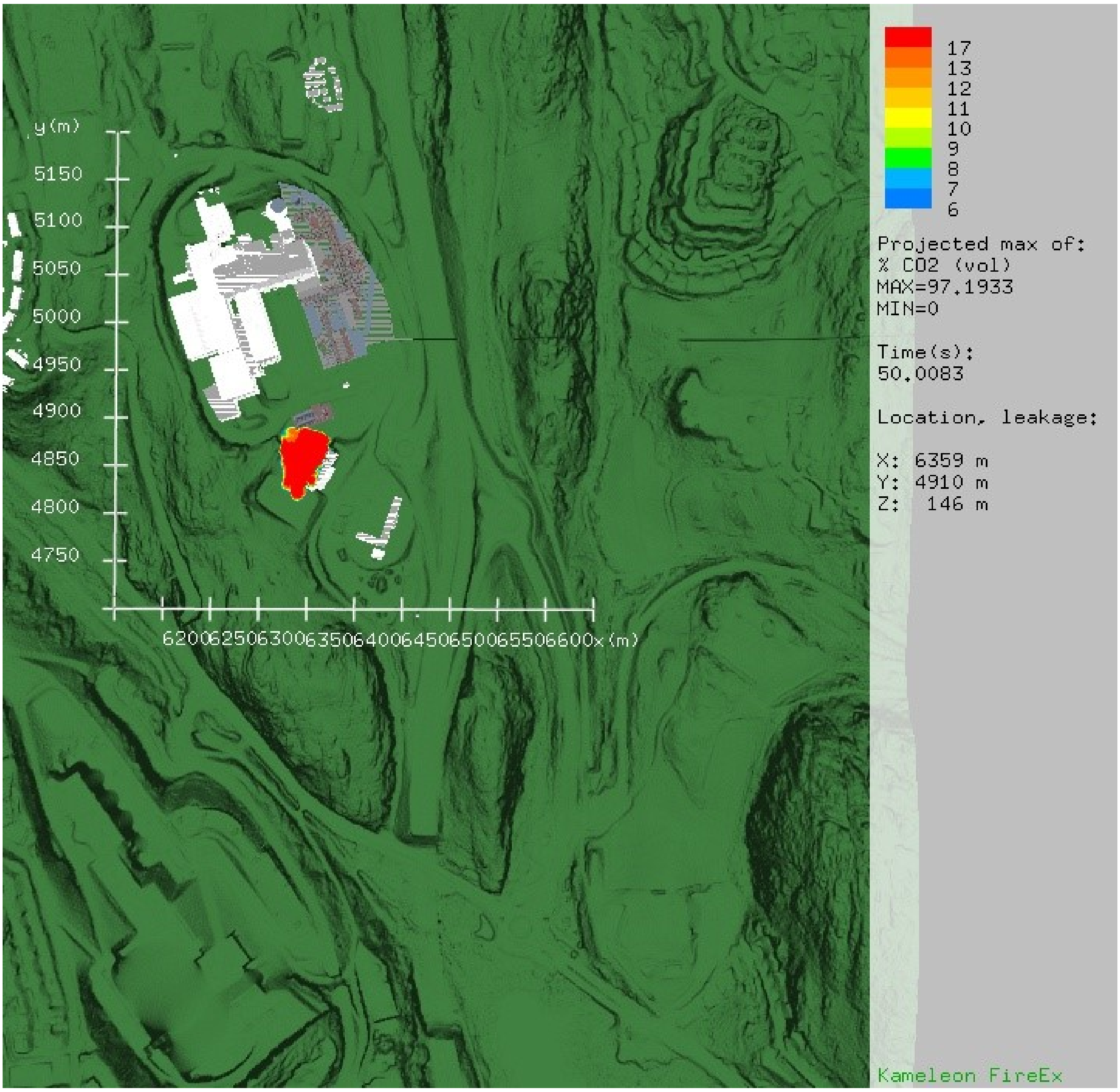

Figure 28: Case 10 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 50 s

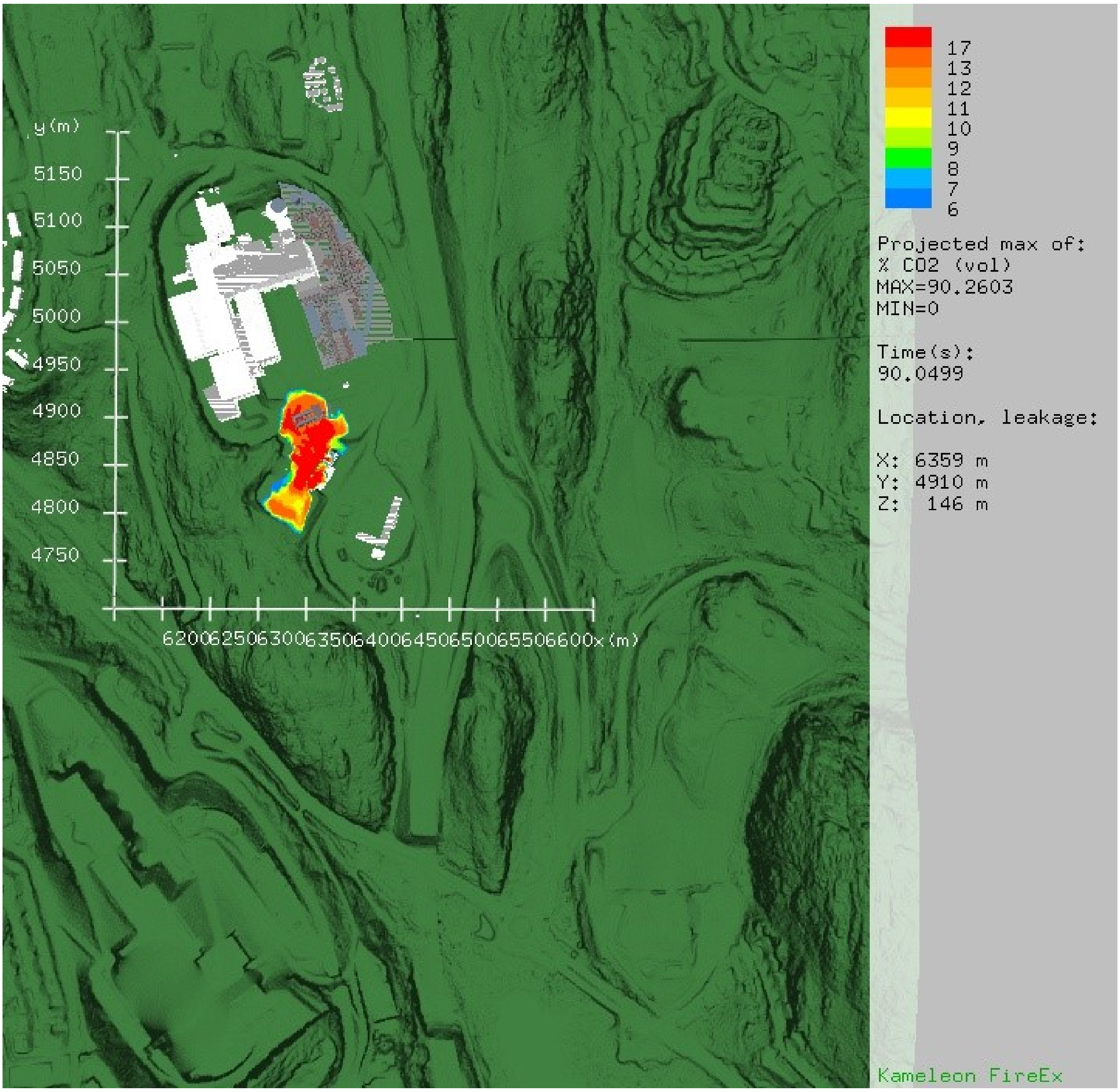

Figure 29: Case 10 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 90 s

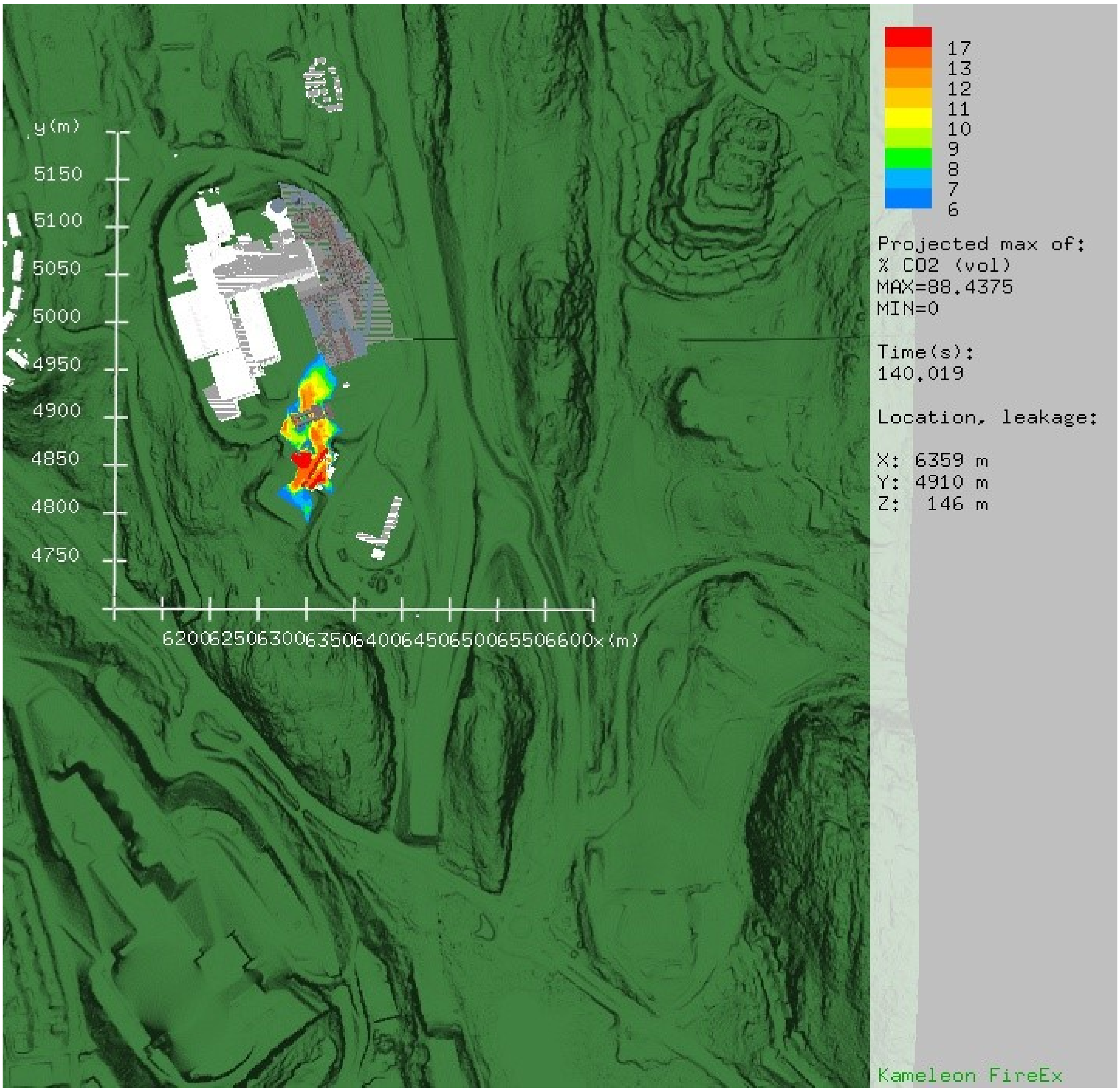

Figure 30: Case 10 - Klemetsrud, horizontal view of CO_2 (vol%) concentrations – time: 140 s

5.11 Case 11 – Sjursøya

Case_No	Case_ID	State	Location	Wind	WindFrom	et Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
11	S-1	TwoPhase	Sjursøya	3	North	Down	12	480	8	617	Jet/spray unobstructed

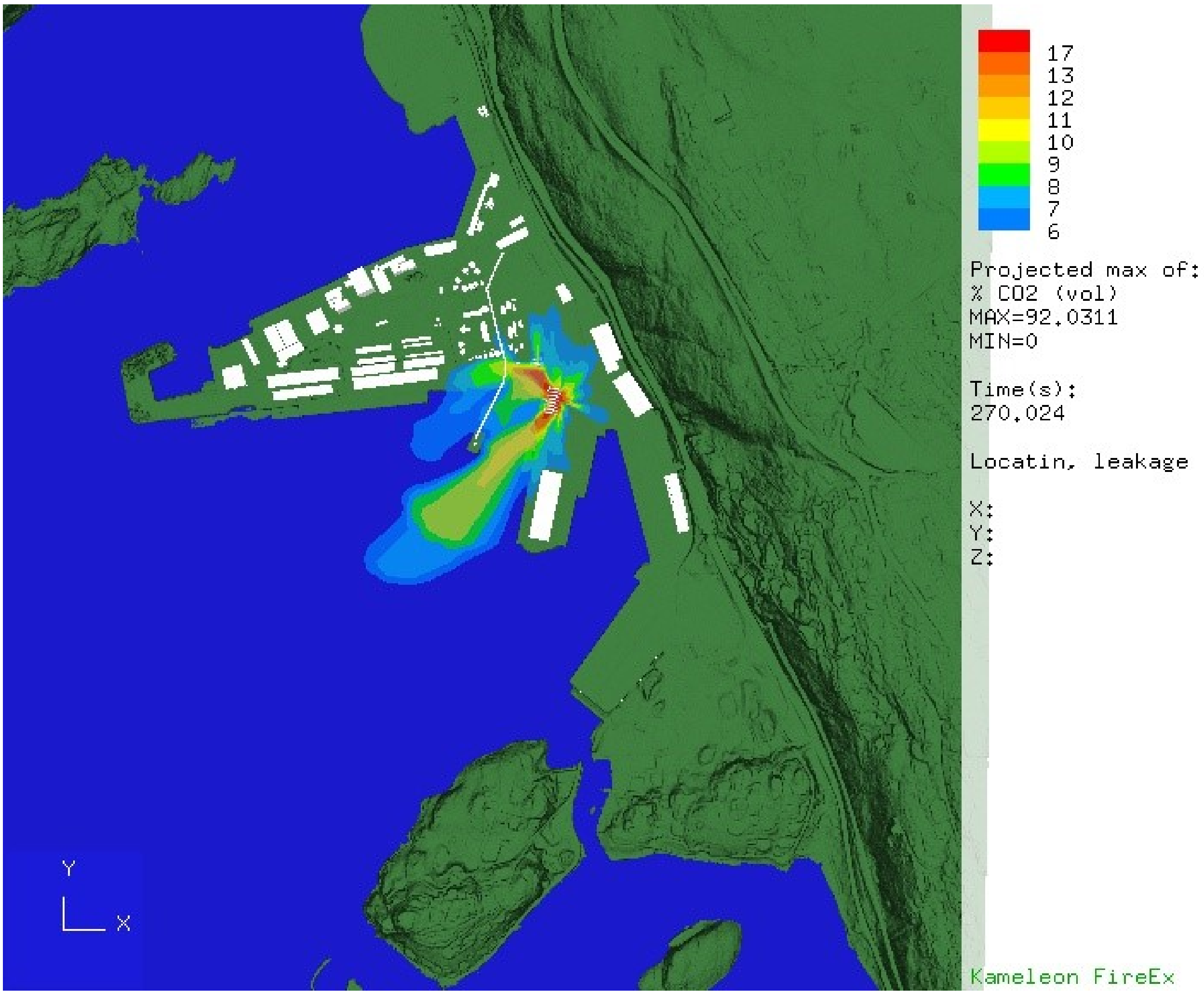

Figure 31: Case 11 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 270 s

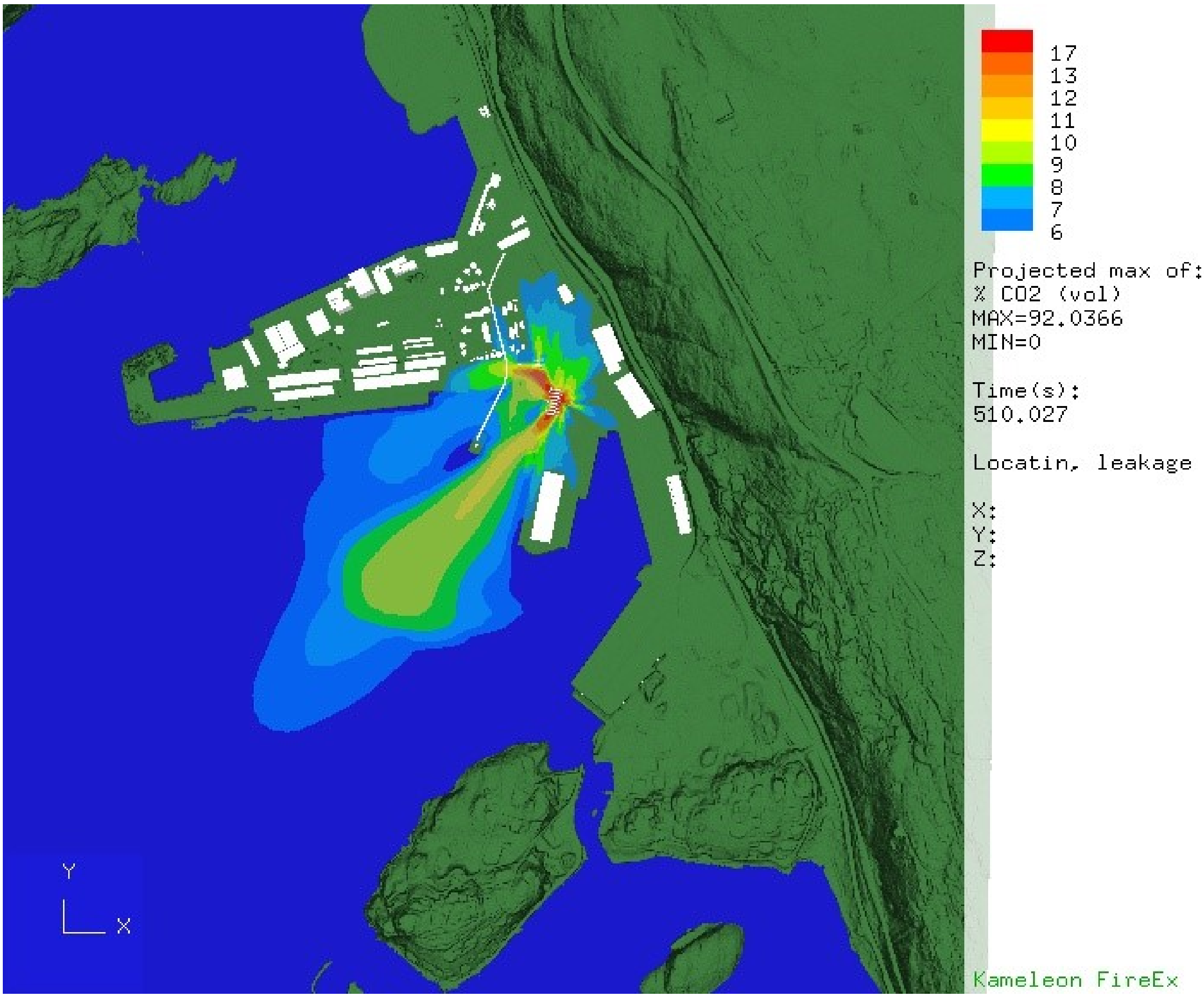

Figure 32: Case 11 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 510 s

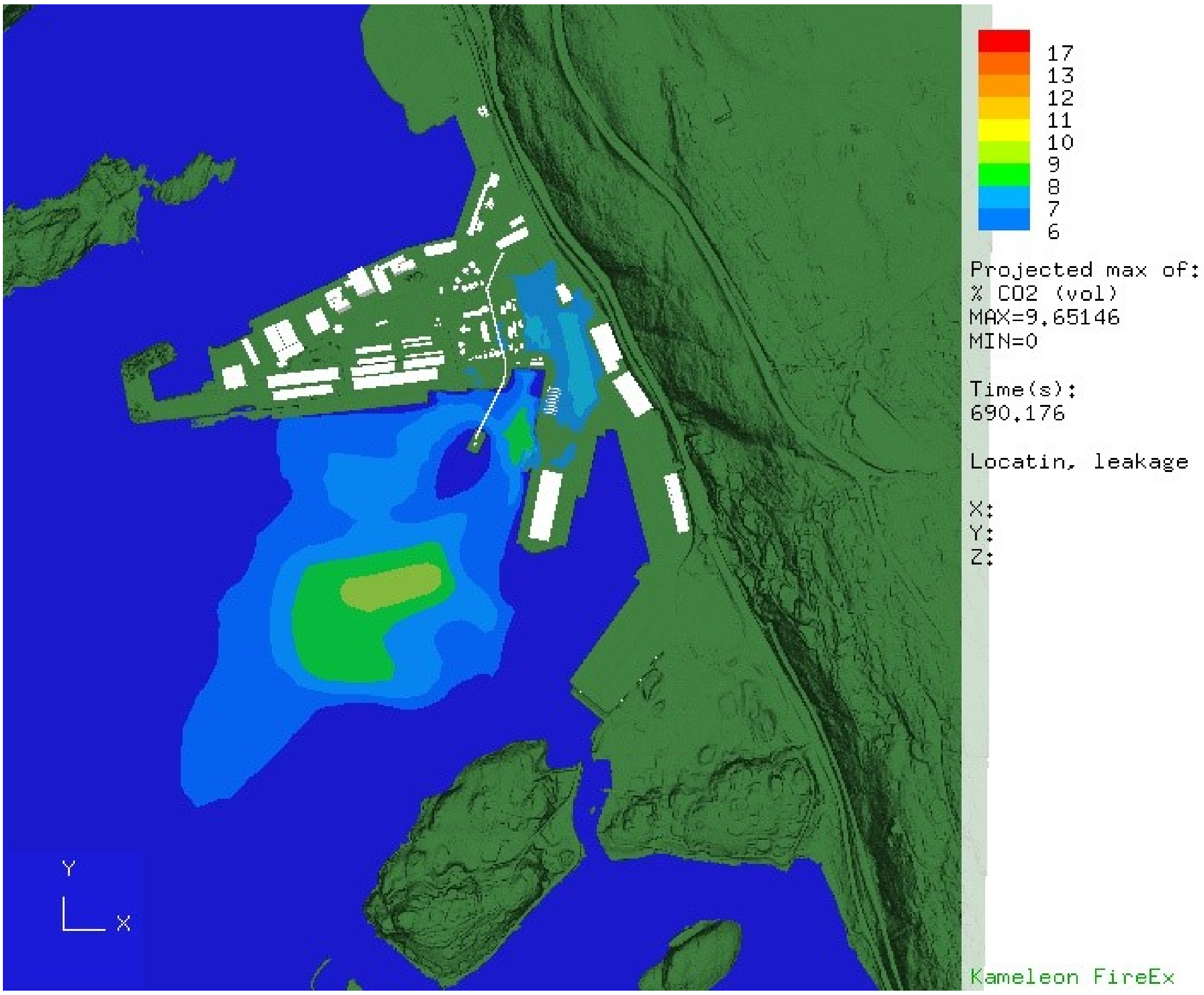

Figure 33: Case 11 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 690 s

5.12 Case 12 – Sjursøya

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Direction	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
12	S-2	TwoPhase	Sjursøya	3	South	Down	3	480	8	617	Jet/spray unobstructed

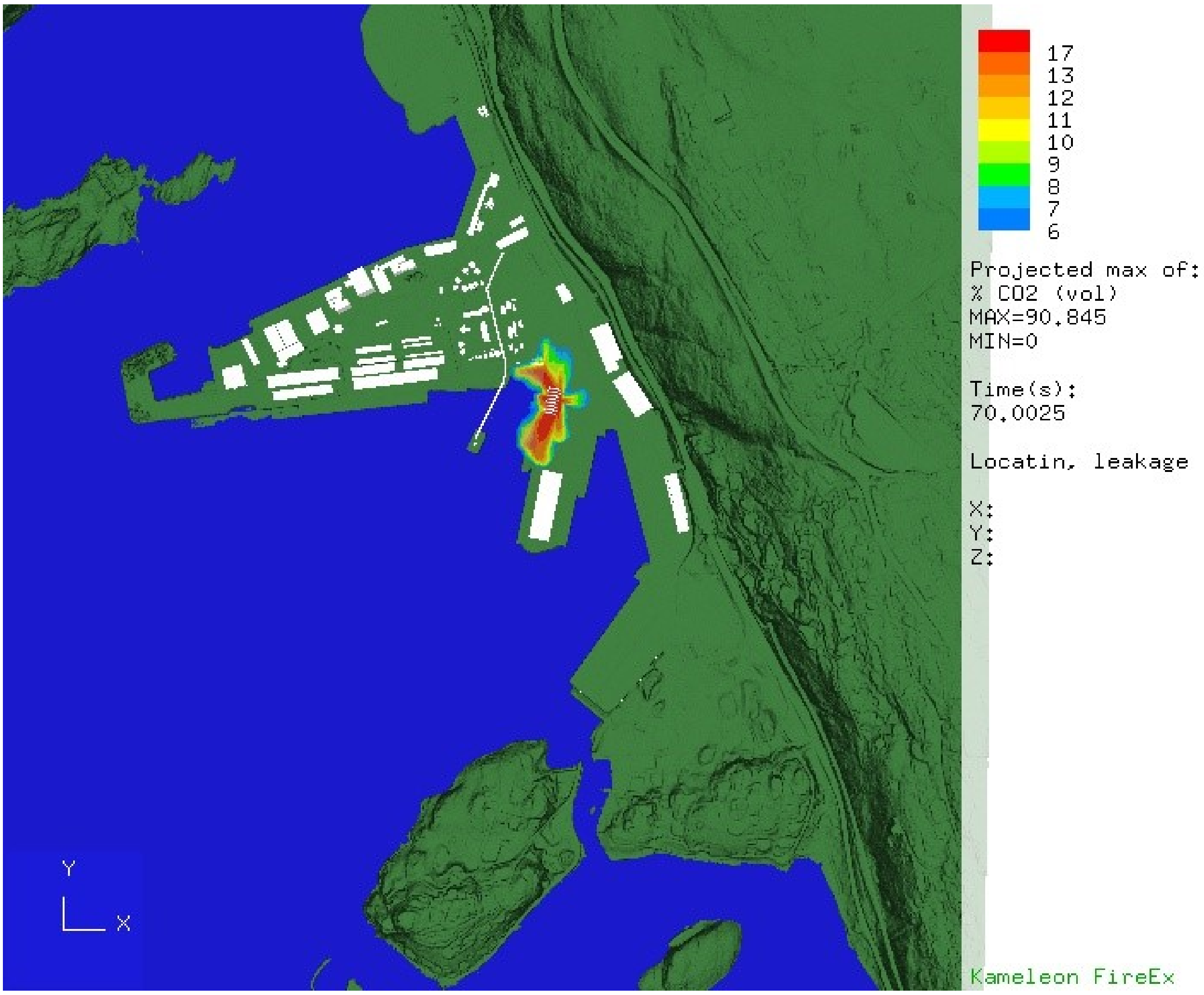

Figure 34: Case 12 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 70 s

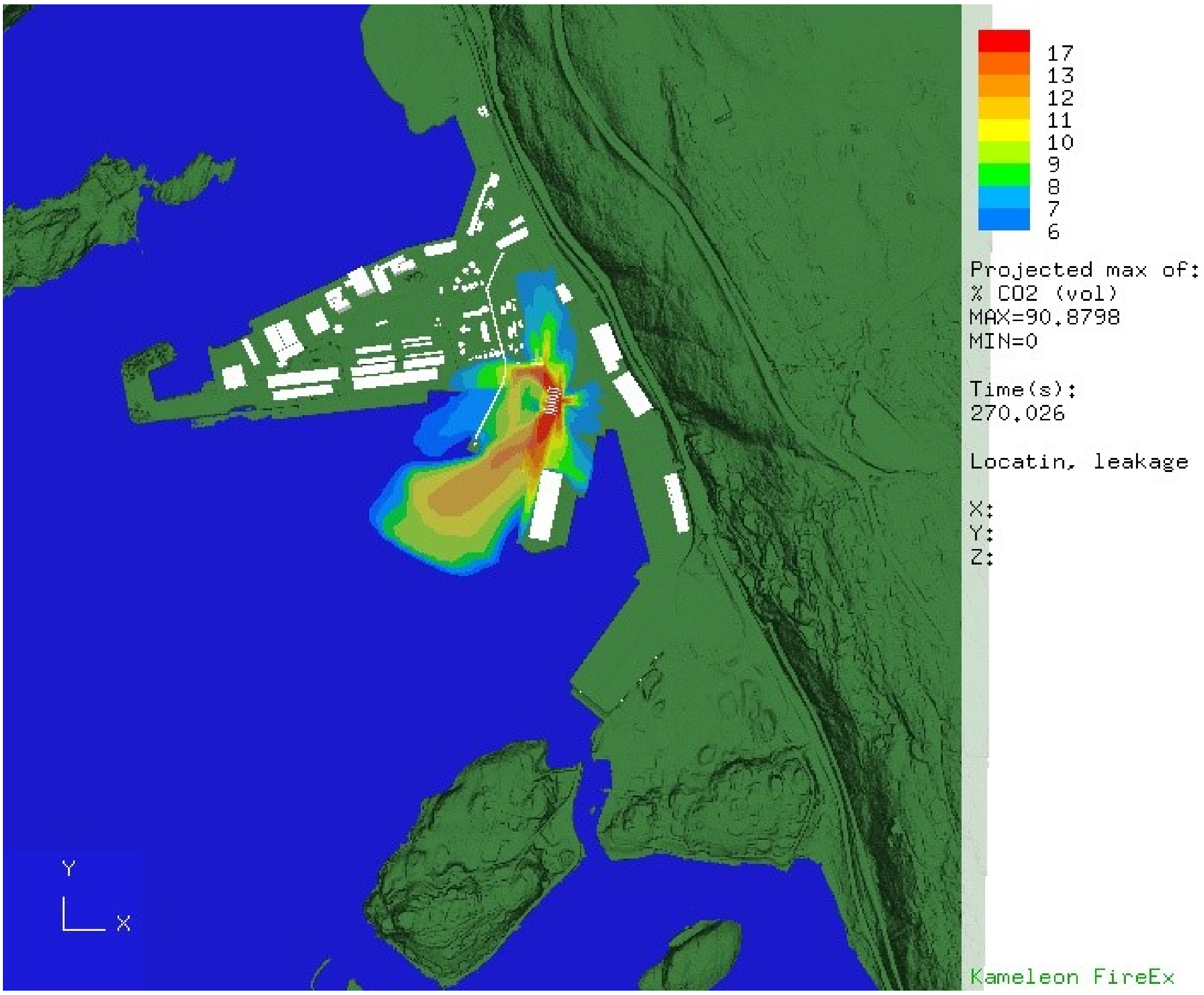

Figure 35: Case 12 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 270 s

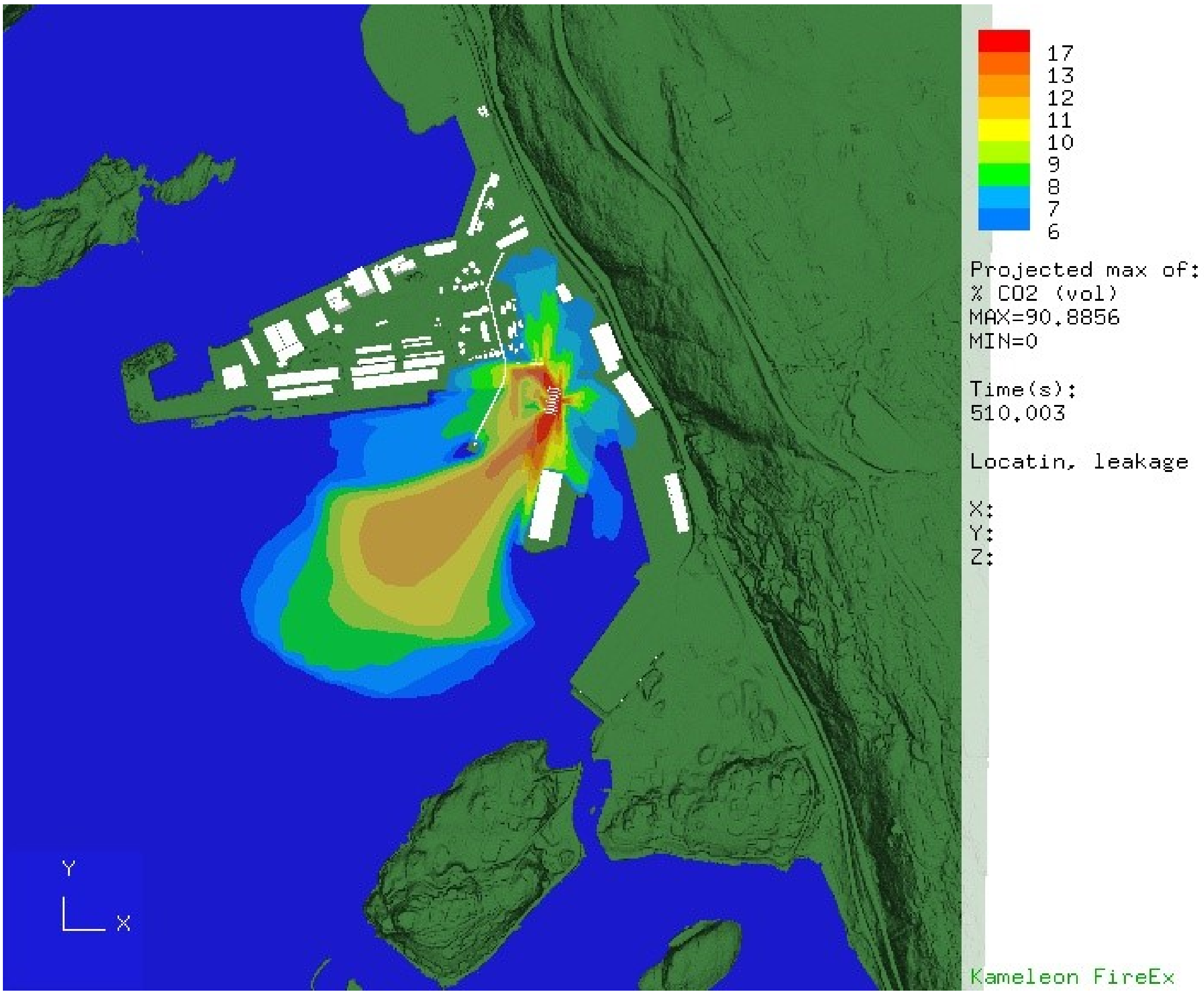

Figure 36: Case 12 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 510 s

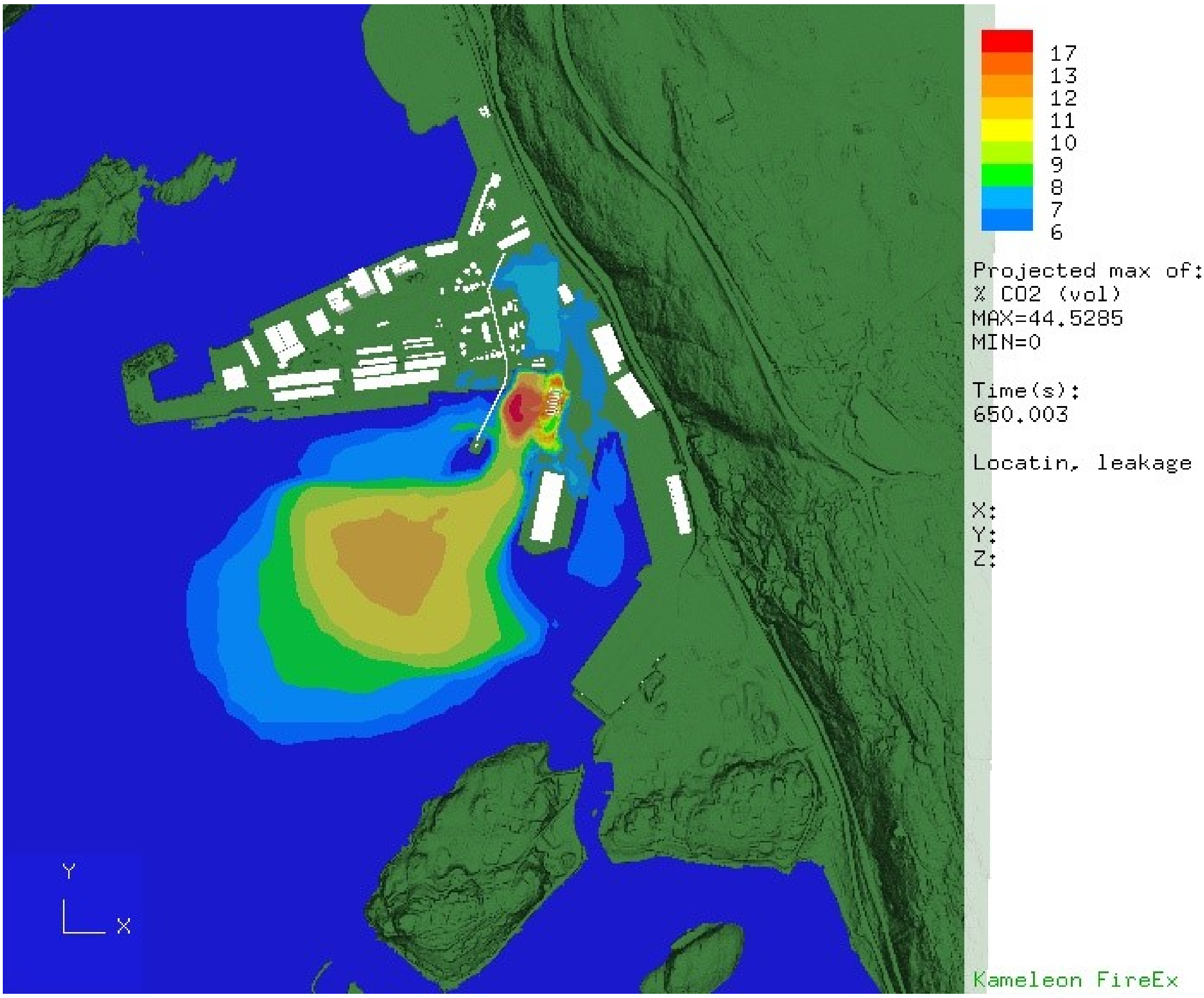

Figure 37: Case 12 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 650 s

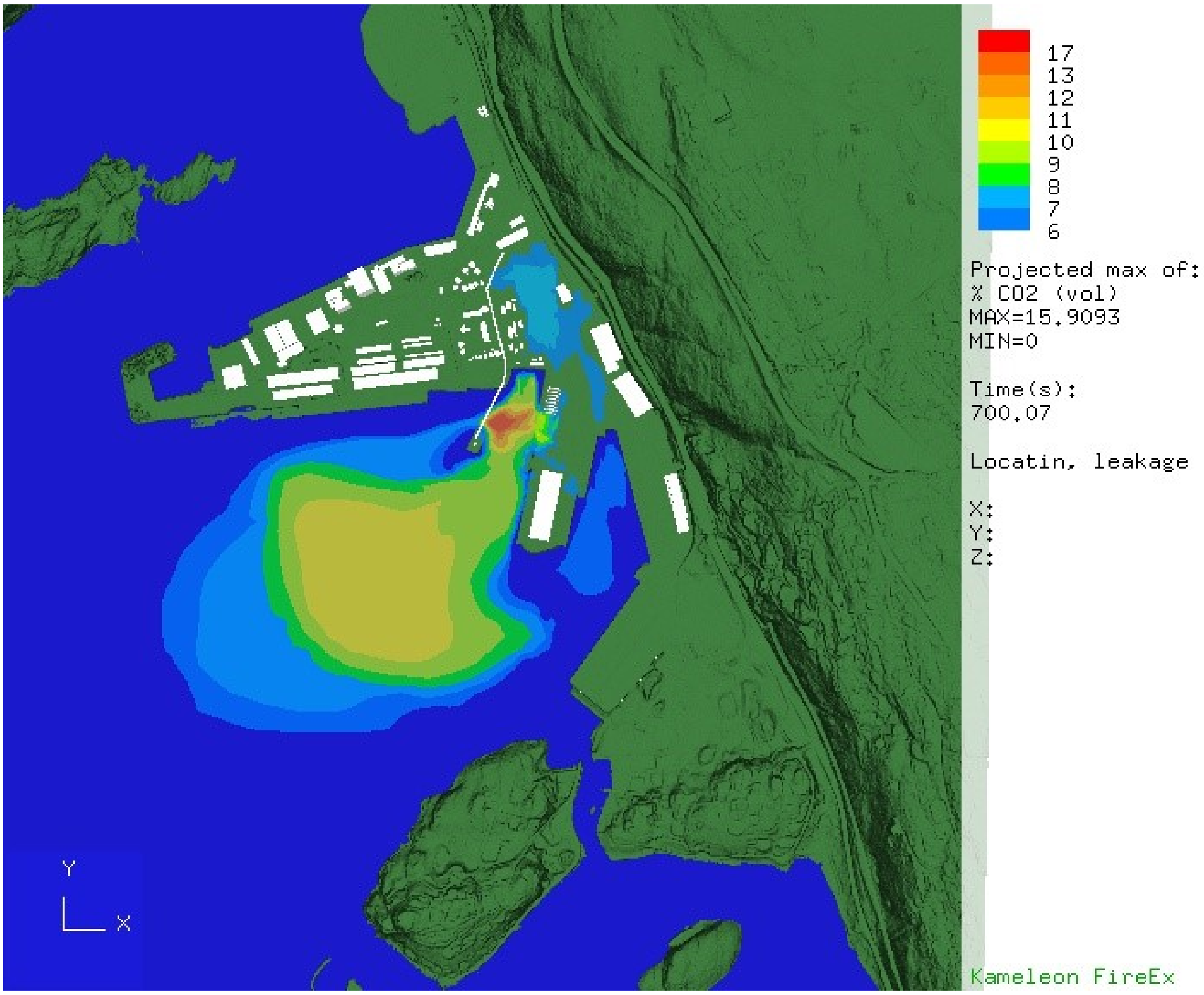

Figure 38: Case 12 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 700 s

5.13 Case 13 – Sjursøya

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
13	S-3	TwoPhase	Sjursøya	3	South	East	12	480	8	617	Jet/spray unobstructed

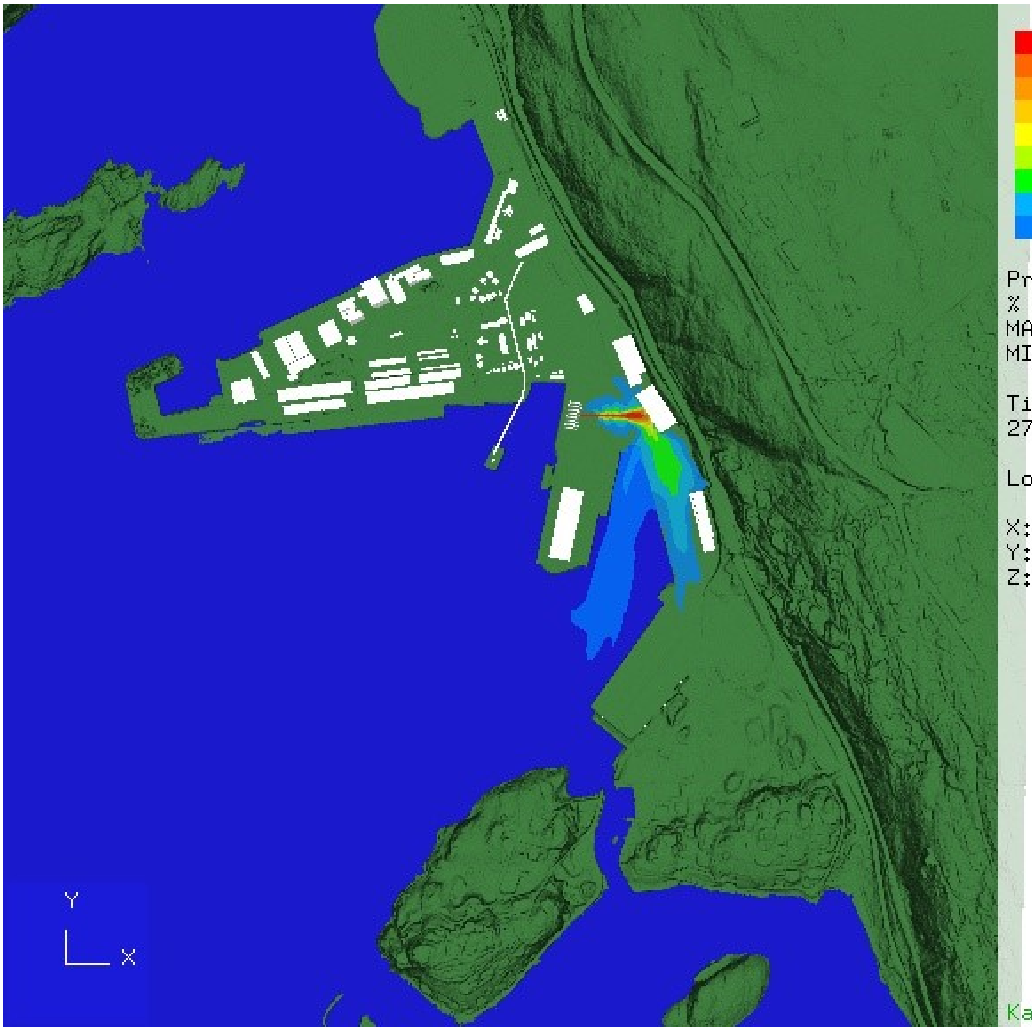

Figure 39: Case 13 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 270 s

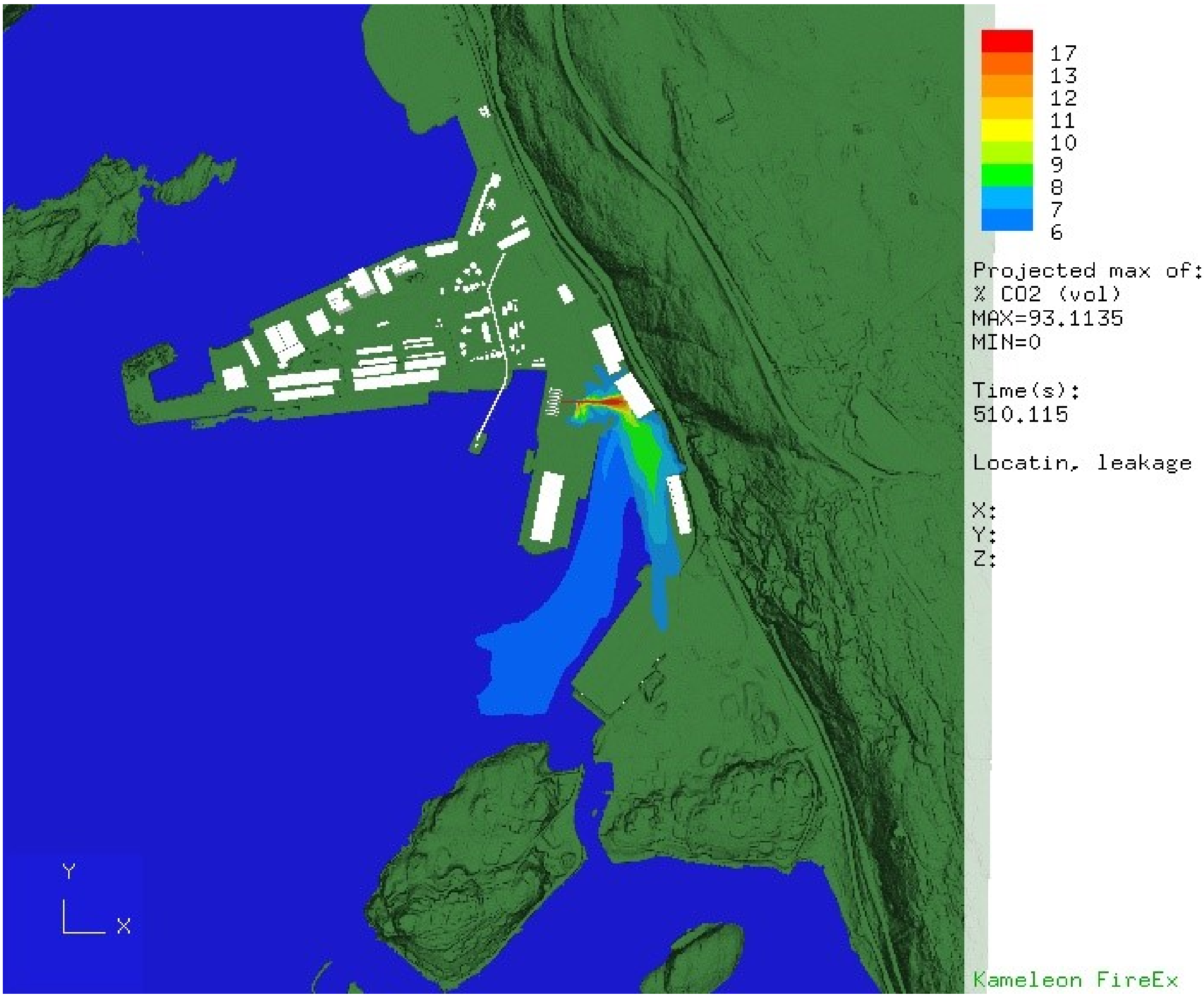

Figure 40: Case 13 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 510 s

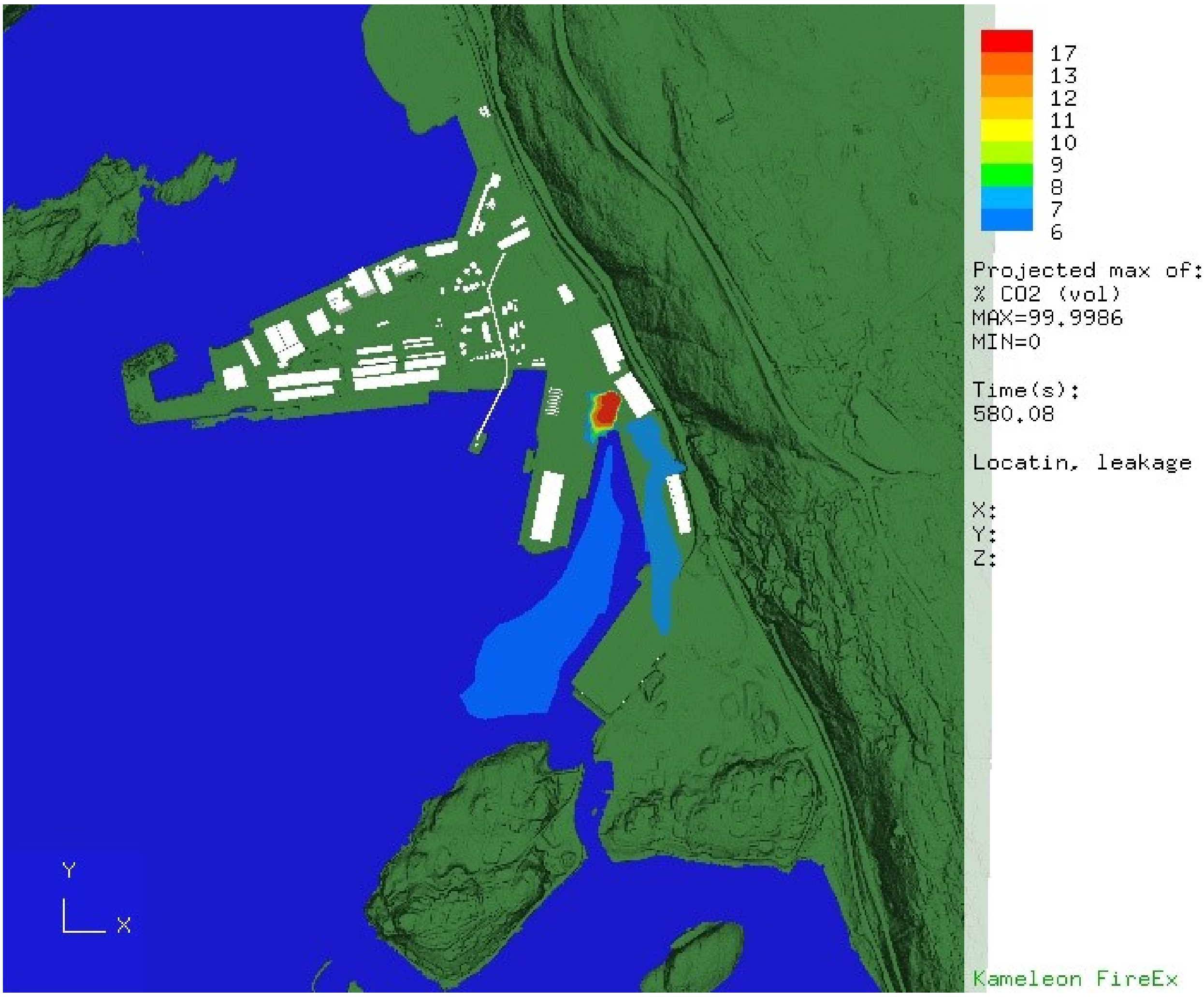

Figure 41: Case 13 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 580 s

5.14 Case 14 – Sjursøya

Case_No	Case_ID	State	Location	Wind	WindFrom	Jet Directio	Jet Z_pos	t_release	t_release	m_rel	Comment
[-]	[-]	[-]	[-]	[m/s]	[-]	[Towards]	[m]	[s]	[min]	[kg/s]	[-]
14	S-4	TwoPhase	Sjursøya	3	South	West	3	480	8	617	Jet/spray unobstructed

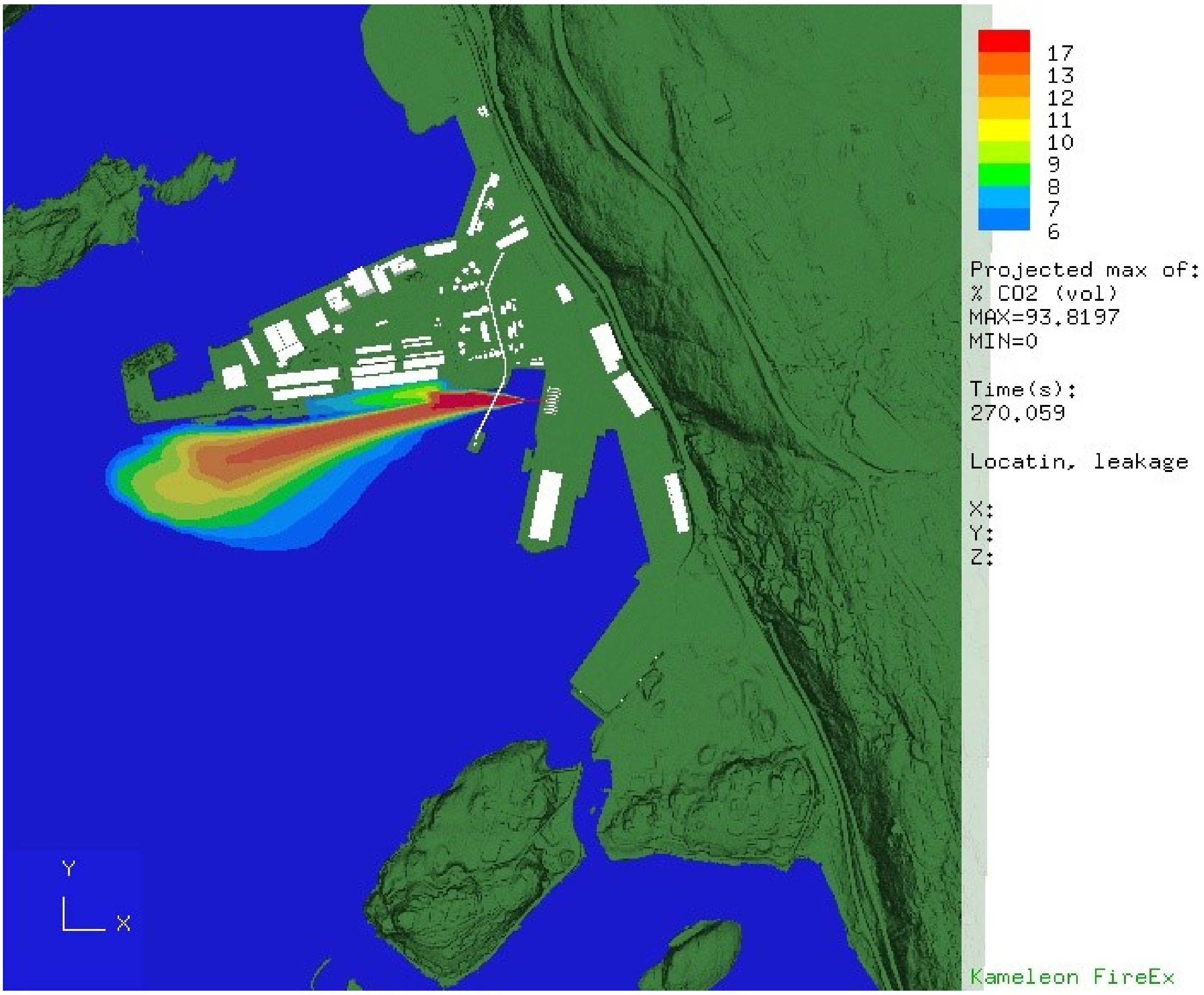

Figure 42: Case 14 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 270 s

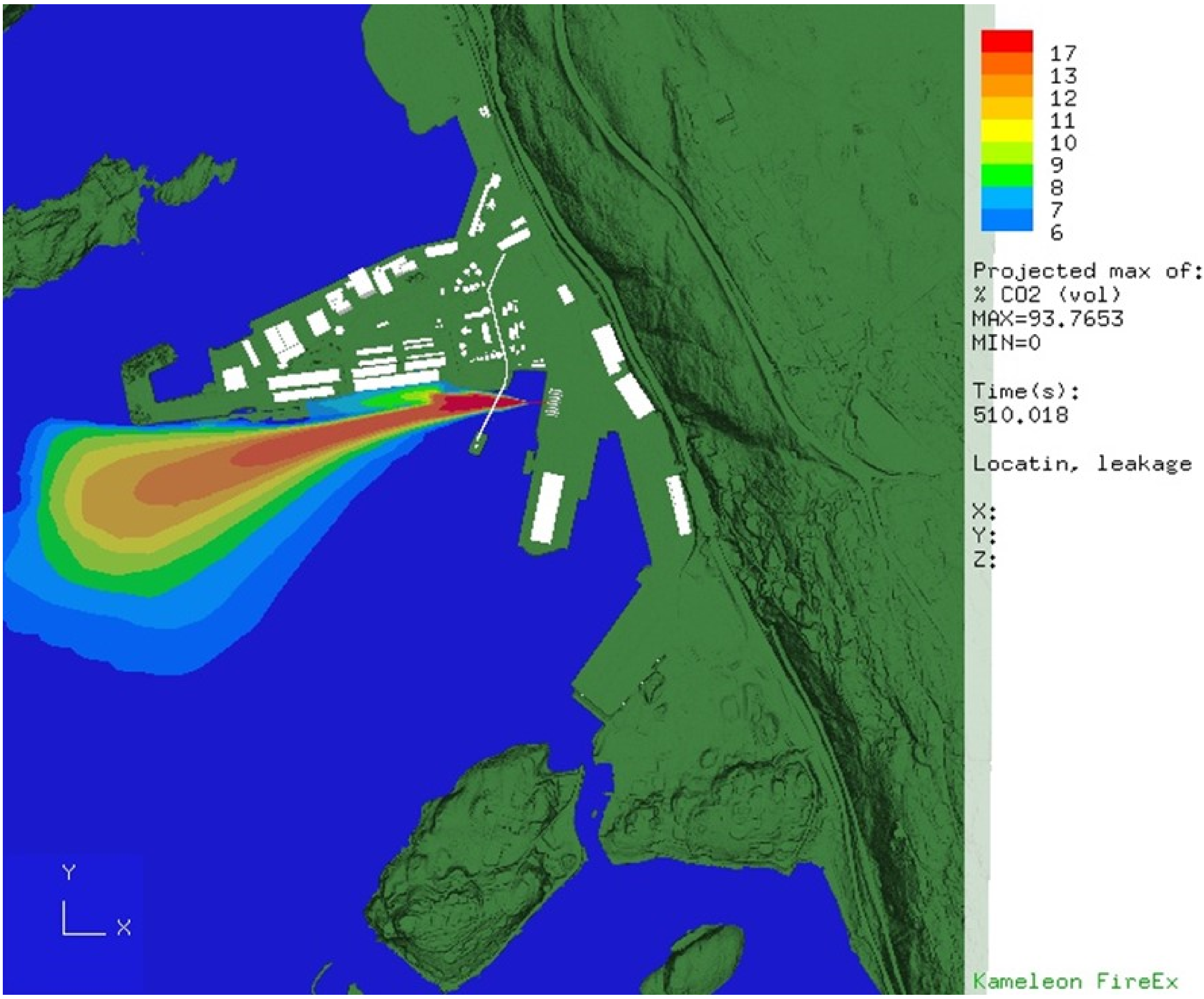

Figure 43: Case 14 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 510 s

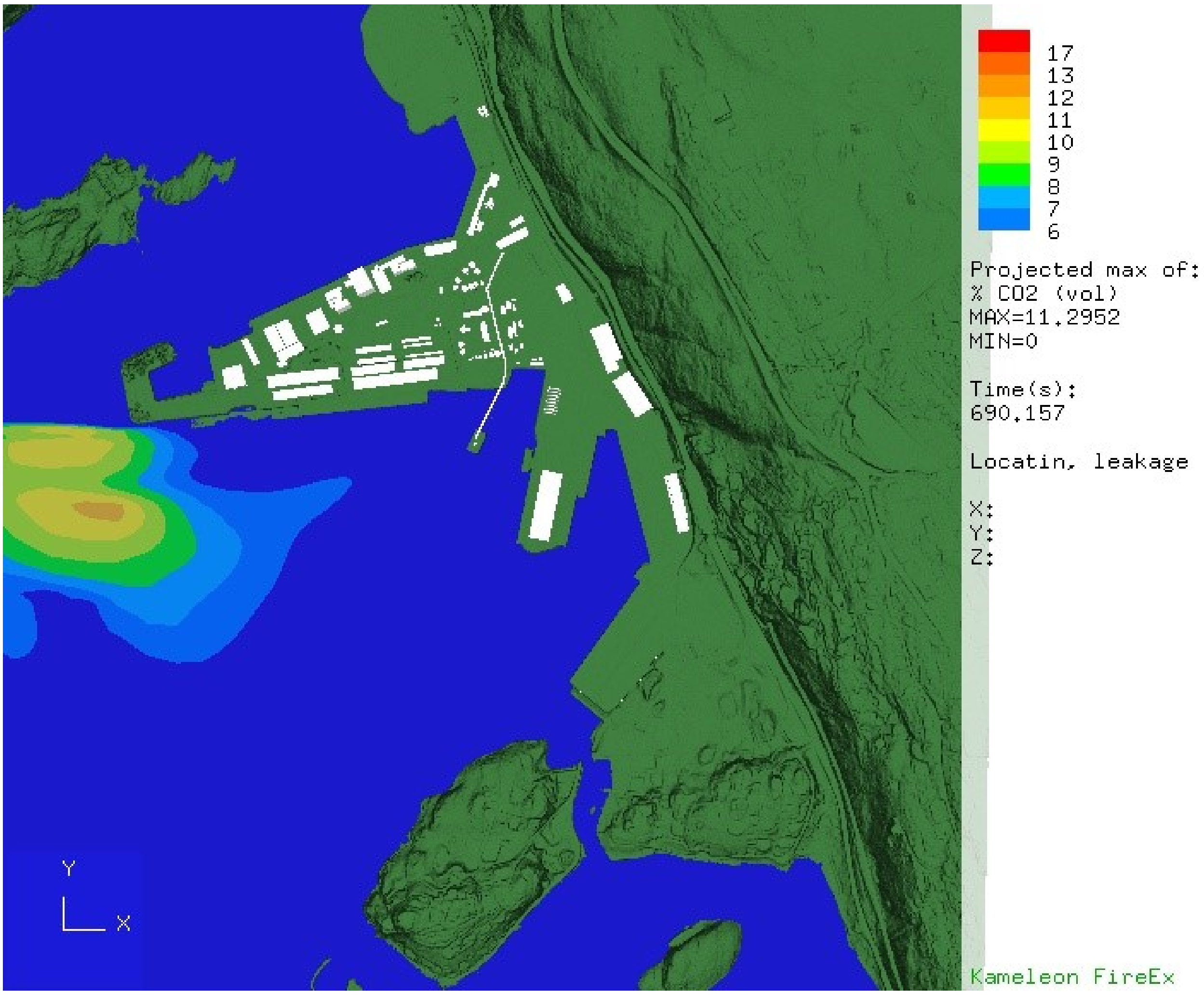

Figure 44: Case 14 – Sjursøya, horizontal view of CO_2 (vol%) concentrations – time: 690 s

6 CONCLUDING REMARKS

KFX™ CAD topography models of Klemetsrud, including the KEA facility and the harbour area at Sjursøya, have been made for CO_2 dispersion analyses using the advanced CFD tool Kameleon FireEx KFX®.

Important effects of CO_2 thermodynamics are included in the dispersion modelling, e.g. effects of formation, dispersion and sublimation of solid CO_2 particles.

Calculated horizontal iso-contour plots of projected maximum CO_2 volume fraction are presented enabling analyses of the exposure to various levels of CO_2 in the surroundings. The results show that for some cases rather high CO_2 concentrations can be observed relatively far outside the CO_2 facilities.

It must be noted that the study covers only a limited number of scenarios. The number of potential leak scenarios at such facilities is infinite. Hence, only a very narrow fraction of the sample space has been investigated.

The present results also demonstrate that one should be very careful about generalizing the results from a specific CO_2 dispersion scenario, as relatively modest alterations of a scenario can result in very different CO_2 gas cloud characteristics.

However, the scenarios simulated provide basis to set sound safety distances at this project stage if this element of uncertainty is accounted for.

The results will be input to the quantitative risk analysis performed by Lilleaker Consulting AS, which will apply the results from these consequence simulations together with the probability of each scenario to calculate risk-based safety distances. Further analysis in the next phase will enable optimization of design parameters with respect to risk exposure and give basis for more detailed specification of safety zones.

REFERENCES

Rian, K.E., Grimsmo, B., Lakså, B., Vembe, B.E., Lilleheie, N.I., Brox, E., and Evanger, T. (2014), Advanced CO_2 dispersion simulation technology for improved CCS safety, *Energy Procedia* 63, 2596-2609.

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Appendix E

Sensitivities and background calculations

Table of contents:

E1 Introduction

This Appendix include some sensitivity work performed as part of project development. This is included for information and background information as part of the risk analysis.

E2 Effect of barriers to control dispersion

ComputIT performed some simulations to investigate the potential effect of walls near the tank farm. The study concluded that the dispersion simulations demonstrate that solid barriers surrounding the storage tanks will be able to guide the dense gas to sea without resulting in major exposure to vicinity of storage on land.

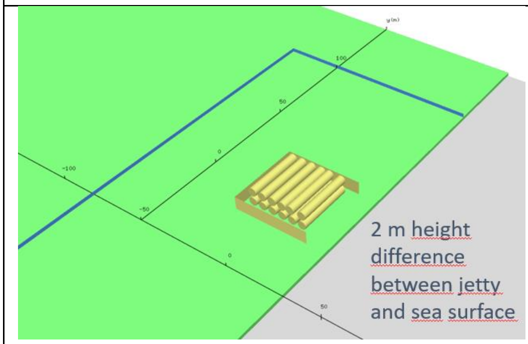
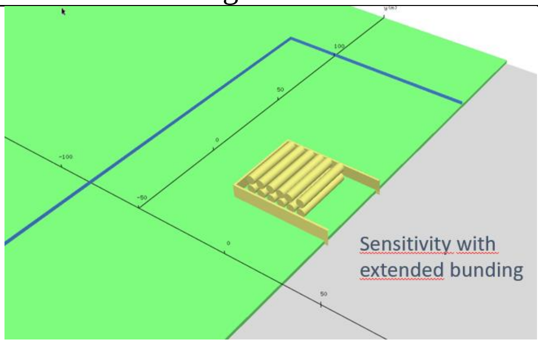
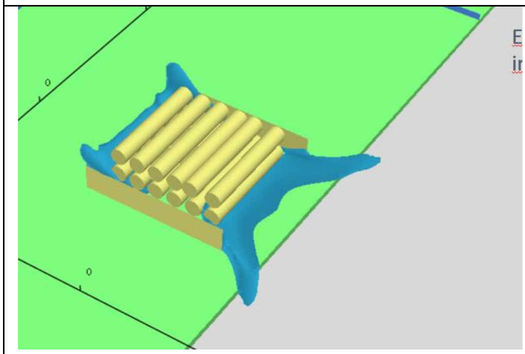
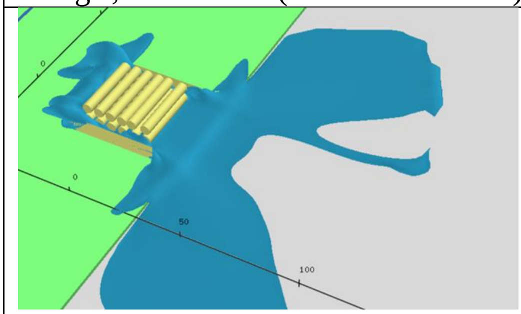
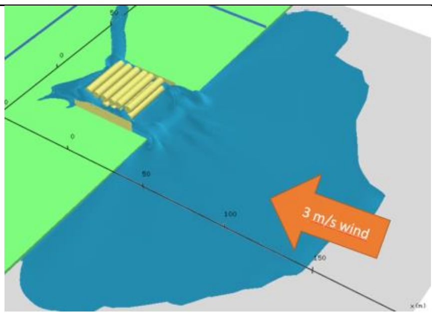
Base case	Extended bunding
	
 51 kg/s, 10 minutes (6% concentration)	
 254 kg/s, 7 minutes (6% concentration)	 254 kg/s, 6 minutes (6% concentration)

Figure E 2-1: Sensitivity – effect of physical barriers

E3 Tank configuration and leak scenarios

E3.1 General

A memo on the "safety aspects of intermediate CO_2 storage alternatives" (LA-2017-N-112, October 2017) evaluates alternative tank configurations. The main content of the memo is included in the following.

E3.1.1 Spherical tank alternative

The two largest hole sizes assumed is 10 inch corresponding to rupture of the largest pipe diameter, and 20% of the full rupture leak area (which in this case equals a 4.5 inch diameter hole). The applied configuration in the CRA was 3 spherical storage tanks with 15 m diameter, including capacity for a future K4 incineration line.

The basis for the frequencies given in Table E 3-1 is two large spherical tanks (diameter 17 meters). For simplicity, the assessment in this memo conservatively assumes full tanks when a leak occurs.

Table E 3-1: Leak rates and durations for the spherical storage tanks

Hole size	20% of cross section for a 10" pipe	Rupture (10")
Leak rate	254 kg/s	1272 kg/s
Duration	3:00 hrs	35 min

E3.1.2 Leak scenarios – bullet tanks

An alternative configuration with 12 vertical 30 meters high bullet tanks has been proposed, each with a storage volume of 500 m^3. The maximum piping diameter would be smaller in this case; 4-inch piping may be sufficient, but 4.5 inch is assumed to simplify the comparison. In this case, the maximum leak rate from a pipe or flange rupture scenario will be similar to the 20% scenario for the spherical tank option considered.

Table E 3-2: Leak rates and durations for the bullet tank option

Hole size	20% of cross section for a 4.5" pipe	Rupture (4.5")
Leak rate	51 kg/s	254 kg/s
Duration	2:45 hrs	32 min

E3.2 Dispersion

A number of dispersion simulations were performed as part of the concept risk analysis. The primary parameters that determine the hazardous distance for a liquid CO_2 release are:

Table E 3-3: Parameters and the effect on gas dispersion

Parameter	Comment
Leak rate	The leak rate is the most important parameter determining hazardous distances, provided the inventory is sufficiently large such that a steady state gas cloud can be formed.
Leak duration	The leak duration is estimated assuming the tank is full and the leak rate constant. The time to establish a steady state gas cloud depends on the cloud size. For a 2700m³ tank and 1270 kg/s release time to steady state is about 35 minutes.
Leak direction	The simulations have assumed a jet release vertically downwards hitting a relatively flat surface. This is a wall-jet scenario with relatively little air entrainment and a good starting point for a heavy gas dispersion scenario with long hazardous distances.
Geometry/terrain	The scenarios simulated are heavy gas scenarios that to a large degree are affected by the terrain.
Wind	Wind is an important factor, in particular at flat surfaces such as the sea. But with moderate wind speeds it is seen that the terrain dominate the dispersion direction rather than the wind.

Dispersion simulations for a 1270 kg/s release have been found to be very much larger than a 254 kg/s scenario, provided the inventory is large. As seen in Figure 3-1, a 500m^3 tank is sufficient to create a large gas cloud with a 10" cross section leak.

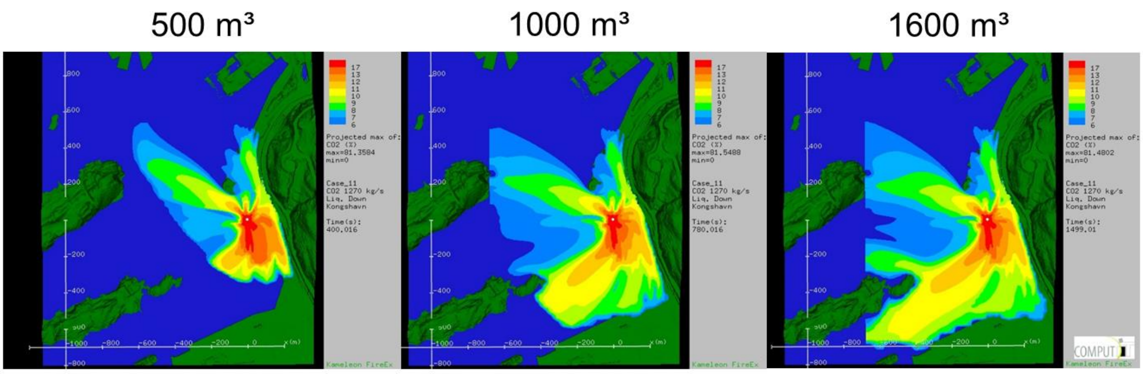


Figure 3-1: Gas cloud sizes for a 1270 kg/s scenario with different leak durations, corresponding to tank volumes in the range 500 m^3 to 1600 m^3.

As seen in Figure 3-2, a leak rate of 254 kg/s would create a much smaller gas cloud. The picture shows a steady state cloud (maximum cloud size) after 25 minutes.

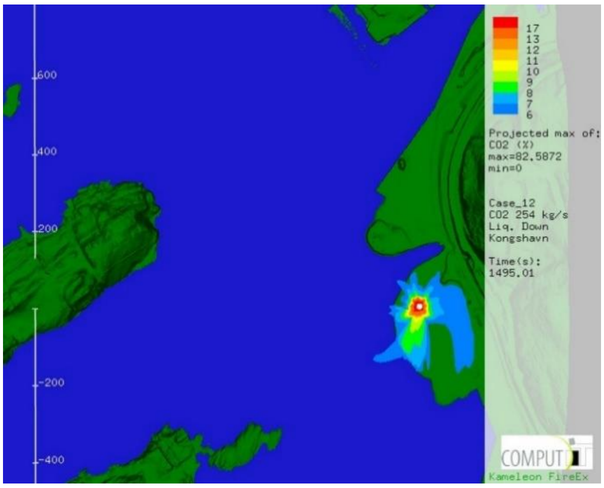


Figure 3-2: 254 kg/s liquid CO_2 leak at Oslo Harbour - Kongshavn

Figure 3-3 shows the crater used to record and measure gas dispersion and compare to dispersion modelling. This study concluded that "the crater shape is clearly the most influent parameter for release direction".

Figure 3-3: Experimental setup for the COSHER experiments

Since the geometry near the potential release point just below or next to the tank can be controlled, it seems a feasible option to reduce hazardous distances could be to implement barriers that would prevent the worst heavy gas dispersion scenarios and possibly also to some extent control the initial leak direction. Barriers to control the dispersion pattern may include wall (or dike) or a trench. There is some uncertainty to what degree of accuracy the effect of such measures can be modelled correct and reliably using simulation tools.

E3.3 Conclusion – tank size and configuration

Third-party risk for a CO_2 intermediate storage at the export terminal could be significant for nearby residential areas. There are different ways to mitigate this risk, including establishing barriers to control leak direction or dilution in order to prevent the worst-case heavy gas dispersion scenarios. Reducing the volume of each storage tank and limit the maximum leak rate by reducing the maximum outlet diameter is an inherently safer alternative. The leak frequency is likely to be higher, but the reduced consequences would be the dominating factor for third party exposure risk. In other words, the 10^{-6} and 10^{-7} iso-risk contours are expected to be reduced by this measure.

To reduce the third-party risk, using smaller tanks with relatively small-bore piping is therefore recommended.

An important premise for this conclusion is that rupture of the largest pipe (or flange) diameter is governing for the hazard zones. The risk level at the facility and possibly also for the neighbouring facilities at the harbour are expected to increase because the leak frequency will be higher for the bullet tank option. Still, since the risk tolerance criteria accepts higher risk levels in these areas, the option with multiple bullet tanks is considered acceptable.