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REPORT

Consequence analysis for hydrogen fueling station

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Consequence analysis for hydrogen fueling station

Extract

This report documents a consequence analysis for potential hydrogen release scenarios related to vehicle fueling stations being considered for implementation in Sweden.

Project Info

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1 Introduction

This report documents a consequence analysis for potential hydrogen release scenarios related to vehicle fueling stations being considered for implementation in Sweden. The release scenarios have been identified in a HAZID study performed by Energigas Sverige, and the objective of the work has been to simulate and visualize potential consequences, and to estimate hazardous distances with respect to:

- Flammable gas at concentrations down to 50 % LFL
- Heat radiation at levels down to 4 kW/m^2
- Overpressure levels down to 30 mbarg

The focus of this report has been to document the performed simulations, and summarize the obtained hazardous distances, as well as main features displayed by the simulation results. A presentation containing videos visualizing a larger number of the simulations has been provided as Appendix A.

1.1 Abbreviations and definitions

LFL	Lower Flammability Limit
UFL	Upper Flammability Limit
CFD	Computational Fluid Dynamics
MEGC	Multiple Element Gas Container
ACH	Air Changes per Hour

2 FLACS

The CFD simulations documented in this report have been carried out by FLACS (Flame Acceleration Simulator). FLACS is a software developed and validated by Gexcon for ventilation, dispersion and explosion simulations in complex geometries. In FLACS the flow equations are solved in a 3D model, allowing effects from obstructions such as walls and equipment to be accounted for.

FLACS is the industry standard for CFD explosion modelling and one of the best validated tools for modelling flammable and toxic releases in the technical safety context. It is used extensively in the oil and gas and process industries, in facilities with dust explosion potential, and many other fields.

Figure 2-1: Explosion test for validation of FLACS (above to the left), explosion simulation with FLACS (above to the right), LNG dispersion simulation with FLACS (below to the left), and fire simulation with FLACS (below to the right).

3 Geometry

3.1 Fueling station layout

A FLACS geometry model representing a generic hydrogen fueling station has been prepared by Gexcon using existing models from Gexcon's geometry library. The fueling station consists of two MEGCs, a compressor container, a permanent storage tank, and a dispenser for fuelling of vehicles. The layout of the fueling station, with walls separating the containers from the storage tank and dispenser, was chosen based on discussions with the client, and the model was shown to the client for approval before starting the simulations.

The geometry model is shown in Figure 3-1. Distances between the different components are indicated in Figure 3-2, where the geometry model is seen from above.

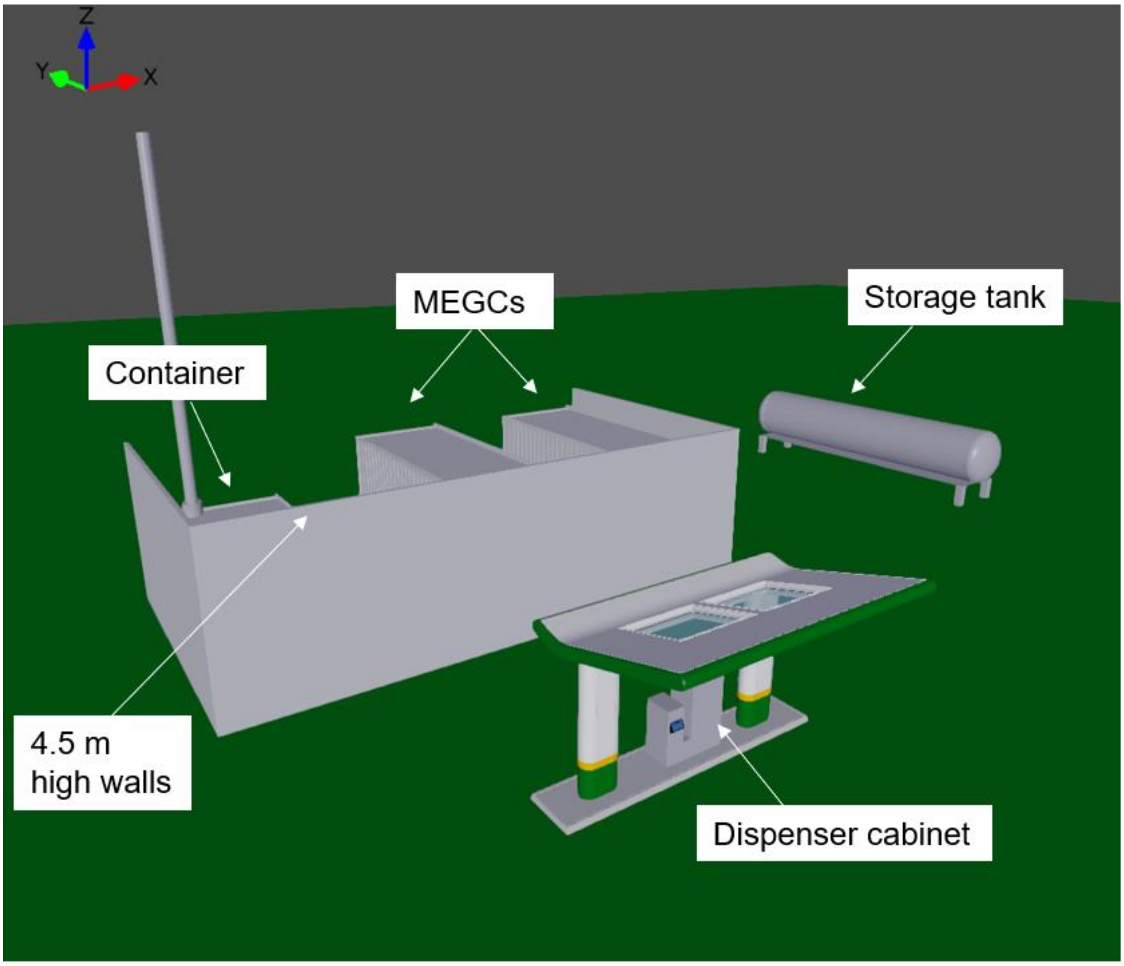

Figure 3-1: FLACS geometry model of generic hydrogen fueling station built by Gexcon.

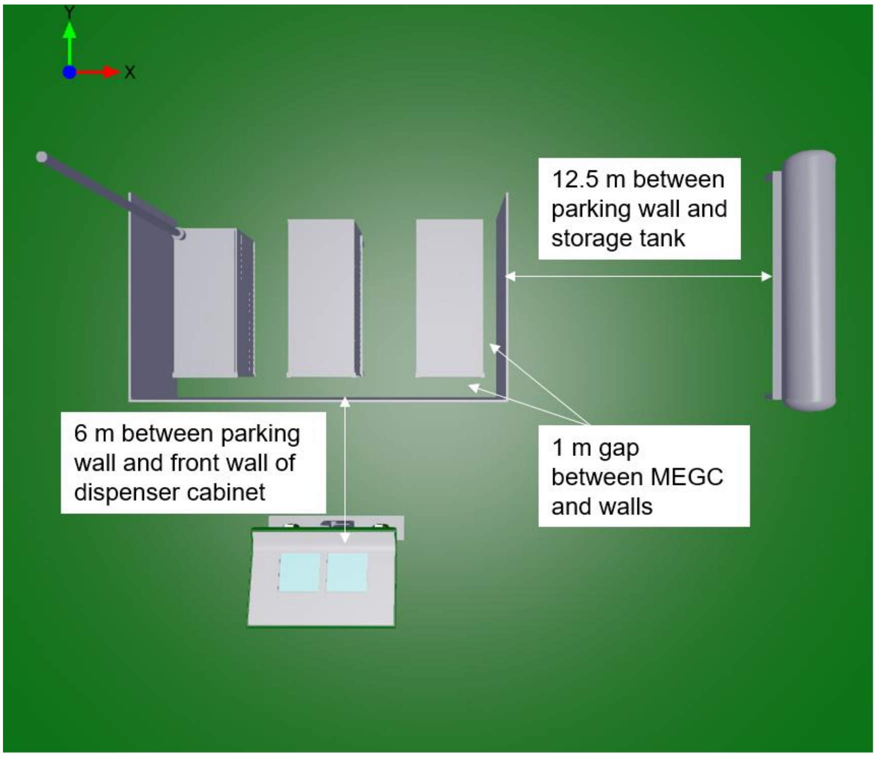

Figure 3-2: FLACS geometry model seen from above.

3.2 Compressor container

The dimensions of the compressor container have been based on a standard 20 ft storage container, adjusted to 6 m x 2.5 m x 2.5 m for being compatible with 10 cm and 25 cm grid cells. Based on input from the client, the container has been filled with generic equipment/structures, to obtain an overall volume porosity of 50 %. This is seen in Figure 3-3, where the rightmost picture shows the container with one wall removed.

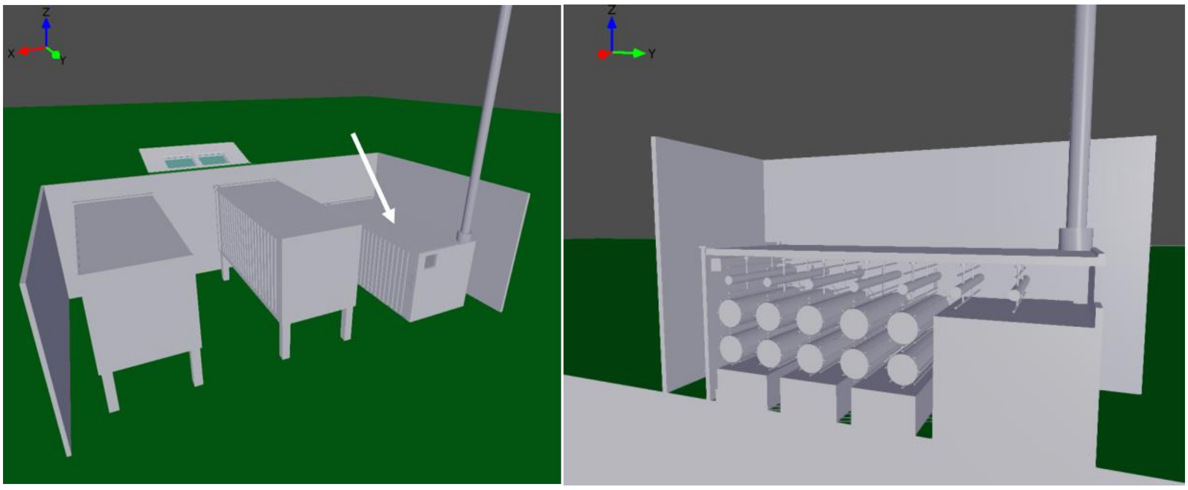

Figure 3-3: Compressor container indicated by white arrow (left). Compressor container with one wall removed (right).

3.3 Dispenser cabinet

The dimensions of the dispenser cabinet have been specified by the client to 0.8 m x 0.6 m x 2 m. As indicated by the rightmost picture in Figure 3-4, the cabinet has also been filled with generic equipment/structures, to obtain an overall volume porosity of 50 %.

***Figure 3-4:* Dispenser cabinet indicated by white arrow (left). Dispenser cabinet with front wall removed (right).**

4 Simulated scenarios

4.1 Simulation matrix

The simulation matrix specified by the client is presented in Table 4-1. Further details concerning the weather and ventilation conditions, source term modelling, leak locations and directions are given in the following subsections.

Table 4-1: Simulation matrix specified by the client.

Location	Scenario	Type of analysis	Ventilation	Leakage	Pressure (bar)	Hole (mm²)	Location and direction of leakage	Weather conditions
Inside compressor container	Small leakage	Dispersion	Mechanical ventilation: Normal: 30 ACH Emergency: 60 ACH	Steady state	1000	0.5	0.5m above floor, 0.5m from longitudinal wall, 2 m from transverse wall. Horizontal inwards, transversal to longitudinal wall.	5D (5 m/s wind, Pasquill stability class D) and 2F (2 m/s wind, Pasquill stability class F) (if relevant)
		Jet fire						
		Explosion						
	Medium leakage	Dispersion				4.7		
		Jet fire						
		Explosion						
	Large leakage	Dispersion				28.3		
		Jet fire						
		Explosion						
Inside dispenser cabinet	Small leakage	Explosion	Natural ventilation: 10 ACH	Steady state	1000	0.5	0.5 m above floor, horizontal	5D and 2F (if relevant)
Outdoors	Small leakage	Dispersion	Outdoors	Steady state	1000	0.5	0.5 m above ground, horizontal in along wind direction	5D and 2F (if relevant)
		Jet fire						
		Explosion						
	Medium hose leakage	Dispersion			700	5.1		
		Jet fire						
		Explosion						
	Large hose leakage	Dispersion			700	32.2		
		Jet fire						
		Explosion						
	Large pipe leakage	Dispersion			1000	28.3		
		Jet fire						
		Explosion						
	PRD release	Dispersion		Time limited - 10 seconds	4000 kg/h		12 m above ground, vertical upwards	
		Jet fire						
		Explosion						
At MEGC parking	Small leakage	Dispersion	Outdoors	Steady state	500	0.5	1.5 m above ground parallel to transverse wall	5D and 2F (if relevant)
		Jet fire						
		Explosion						
	Medium hose leakage	Dispersion			500	5.1		
		Jet fire						
		Explosion						
	Large hose leakage	Dispersion			500	32.2		
		Jet fire						
		Explosion						

4.2 Wind and ventilation

A wind direction from the MEGC parking towards the dispenser (i.e. in negative y-direction with respect to the geometry model) has been applied for all base case scenarios, as indicated in Figure 4-1. (For the compressor container, two additional dispersion simulations have been run with opposite wind direction.)

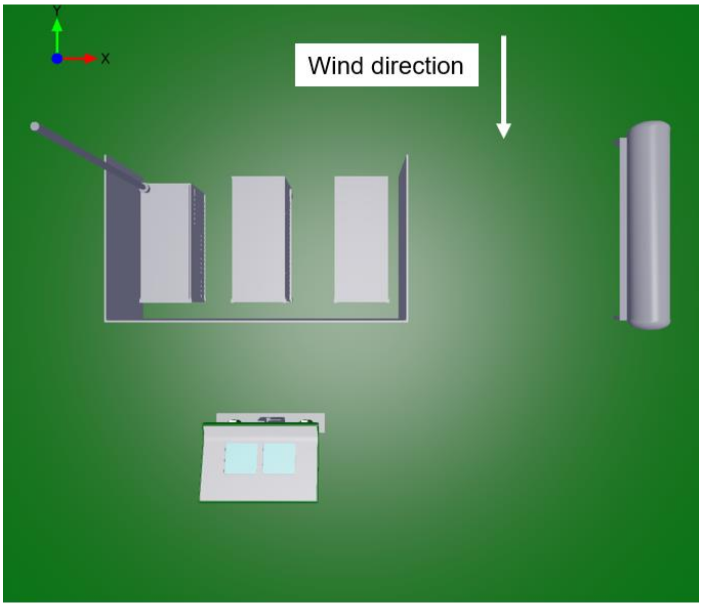

Figure 4-1: Wind direction applied for base case scenarios.

The compressor container is assumed to be mechanically ventilated, with diagonally located ventilation openings, as indicated in Figure 4-2. The dimensions of the ventilation openings are 0.25 m x 0.25 m. The ventilation rate is assumed to be 30 ACH during normal operation, and 60 ACH during emergency ventilation.

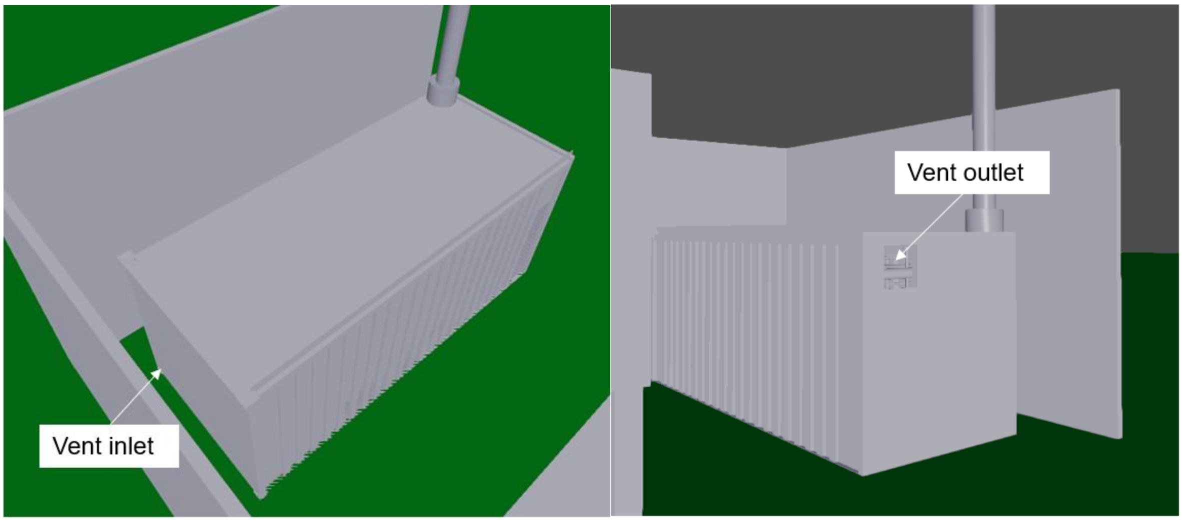

Figure 4-2: Location of ventilation inlet (left) and outlet (right) on compressor container.

The dispenser cabinet is assumed to be naturally ventilated, with 10 ACH. As shown in Figure 4-3, the ventilation openings are assumed to be diagonally located, with dimensions of 0.6 m x 0.1 m.

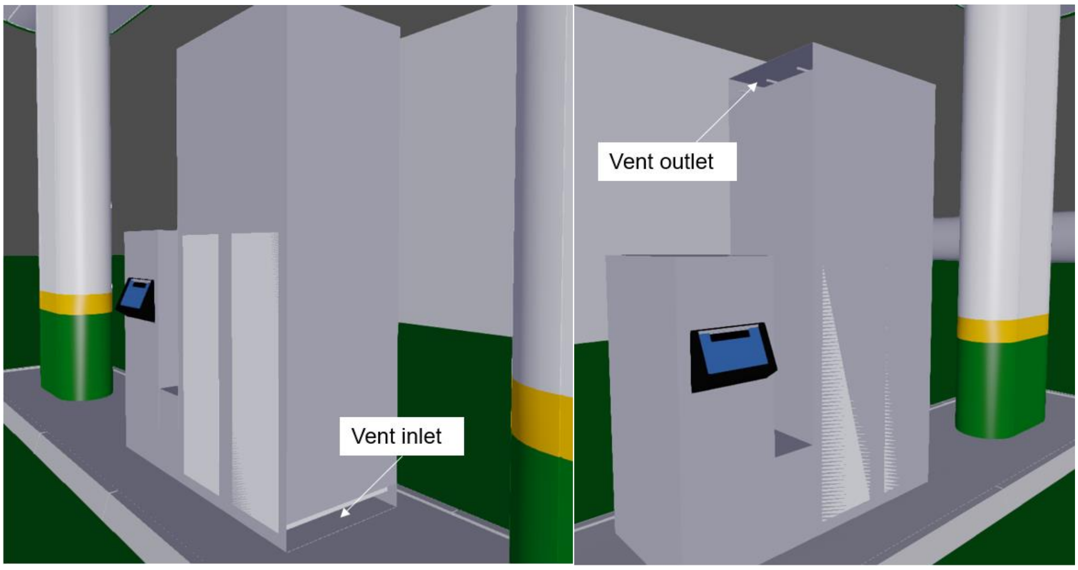

Figure 4-3: Location of ventilation inlet (left) and outlet (right) on dispenser cabinet.

4.3 Release locations and directions

Release locations and directions are indicated in Figure 4-4 to Figure 4-8 for the various hydrogen leak scenarios. It should be noted that, for the compressor container leaks, the height has been increased from 0.5 m (specified in Table 4-1) to 0.65 m to be compatible with the geometry model.

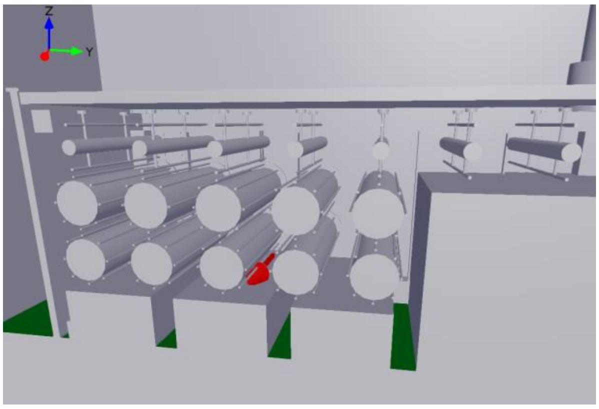

Figure 4-4: Leak inside compressor container: 0.65 m above floor, 2 m from transversal wall, 0.5 m from longitudinal wall, with horizontal direction towards opposite wall.

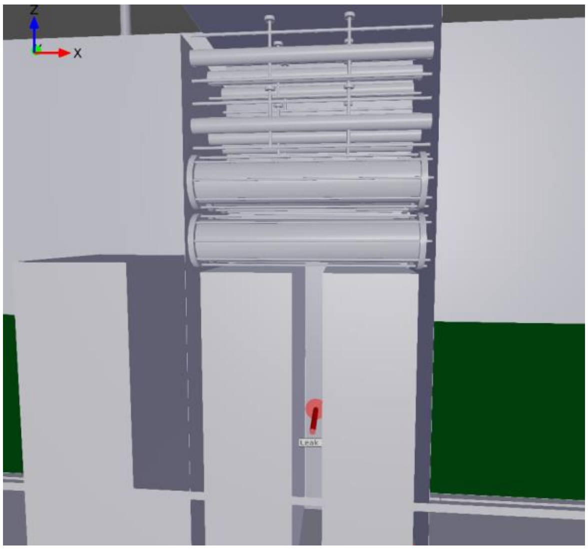

Figure 4-5: Leak inside dispenser cabinet: 0.5 m above floor, with horizontal direction.

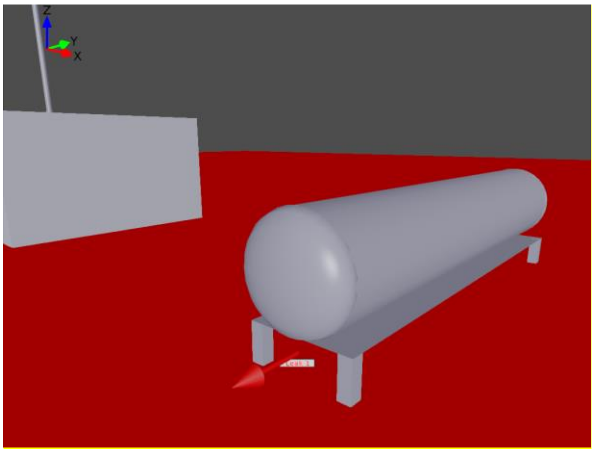

Figure 4-6: Leak outdoors, by permanent storage tank: 0.5 m above ground, with horizontal direction parallel to tank.

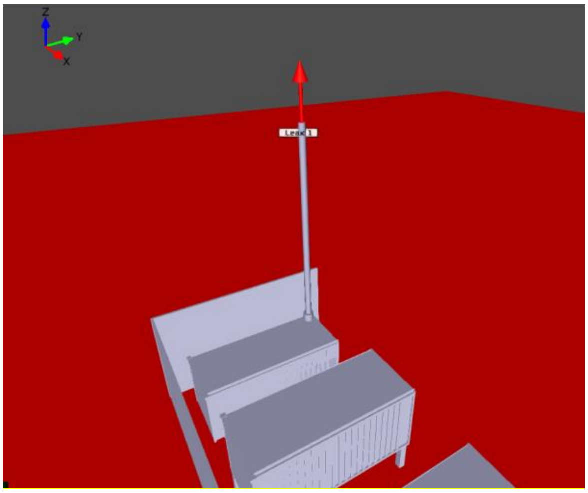

Figure 4-7: Leak outdoors, vent release: 12 m above ground, directed upwards.

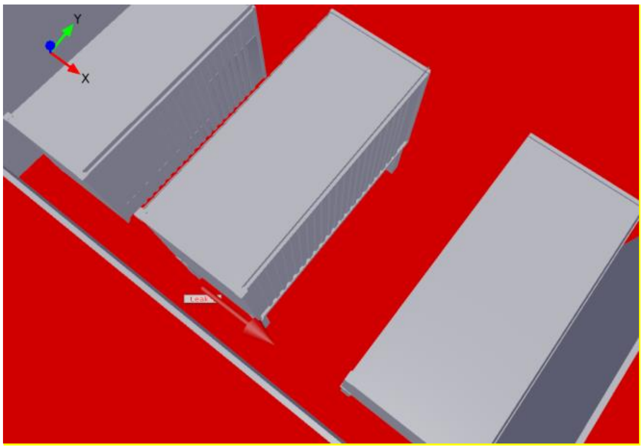

Figure 4-8: Leak at MEGC parking: 1.5 m above ground, with horizontal direction parallel to wall.

4.4 Source term modelling

Source terms representing the leaks have been calculated using the Jet tool incorporated in FLACS, according to the following assumptions:

- Process pressure and hole area as indicated in Table 4-1
- Process temperature and ambient temperature of 15 deg C
- Discharge coefficient of 1
- Constant release rate (given by initial release rate), thus not accounting for effects from limited inventory and/or process shutdown
- No reduction in release rate from friction in pipes/hoses (as dimensions are not known)

Calculated release rates for the different leak scenarios are given in Table 4-2. In view of the above assumptions, the release rates are considered to be on the conservative side. This especially applies to the large leakages, where effects due to limited inventory, process shutdown, and pipe/hose friction are expected to be significant.

Table 4-2: Applied release rates for the various leak scenarios.

Location	Scenario	Leakage	Pressure (bar)	Hole area (mm^2)	Release rate (kg/s)
Inside compressor container	Small leakage	Steady state	1000	0.5	0.0280
	Medium leakage			4.7	0.262
	Large leakage			28.3	1.57
Inside dispenser	Small leakage	Steady state	1000	0.5	0.0280
Outdoors	Small leakage	Steady state	1000	0.5	0.0280
	Medium hose leakage		700	5.1	0.206
	Large hose leakage		700	32.2	1.29
	Large pipe leakage		1000	28.3	1.57
	PRD release	Time limited - 10 seconds	4000 kg/h		1.11

At MEGC parking	Small leakage	Steady state	500	0.5	0.0148
	Medium hose leakage		500	5.1	0.150
	Large hose leakage		500	32.2	0.947

4.5 Simulation set-up

4.5.1 Ventilation simulations

Before simulating the hydrogen releases, ventilation simulations have been performed, in order to establish a representative flow field for the different wind and ventilation conditions. The ventilation of the container and dispenser has been obtained by applying air leaks at the ventilation inlets providing the proper flowrate (30/60 ACH for the container and 10 ACH for the dispenser cabinet.)

Computational domains and grids applied for the ventilation simulations are shown in Figure 4-9 to Figure 4-11 for the different leak locations. The grids are orthogonal with relatively small cells in the core domains (0.02 m for the leaks inside the dispenser cabinet and 0.25 m for the other leak locations). Outside the core domains, the grid cells are stretched to a maximum size of 2 m.

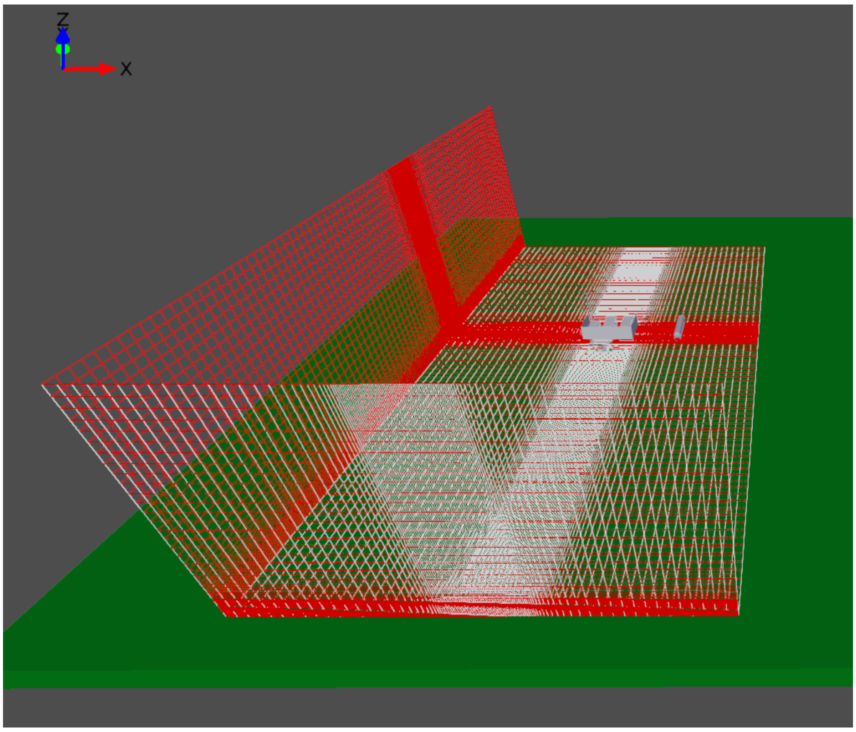

Figure 4-9: Computational domain and grid used for ventilation simulations for leaks inside compressor container.

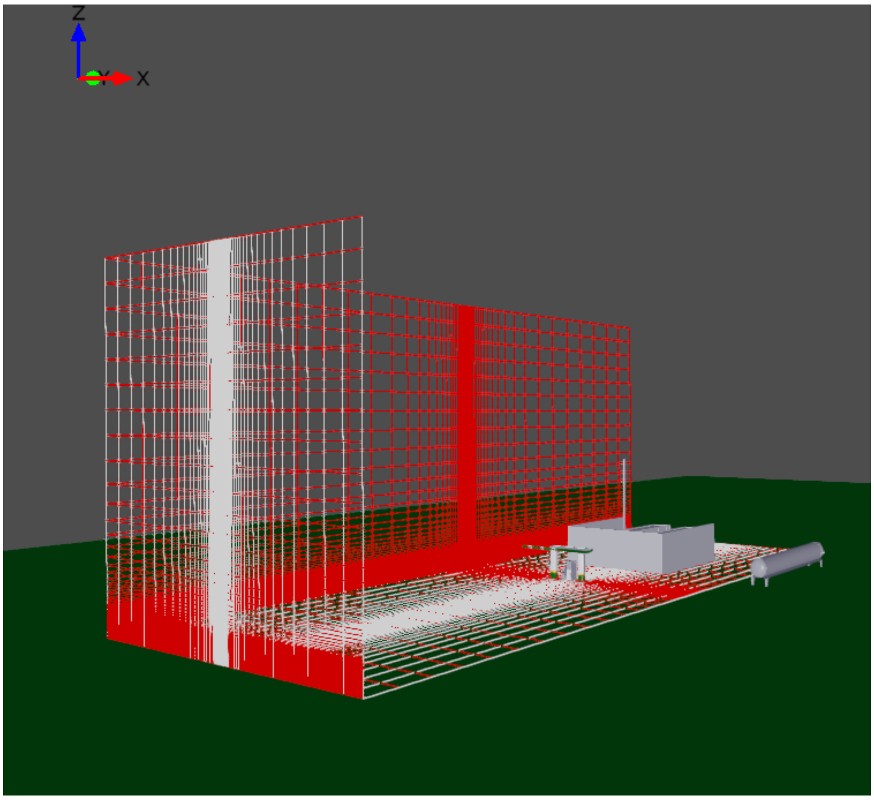

***Figure 4-10:** Computational domain and grid used for ventilation simulations for leaks inside dispenser cabinet.*

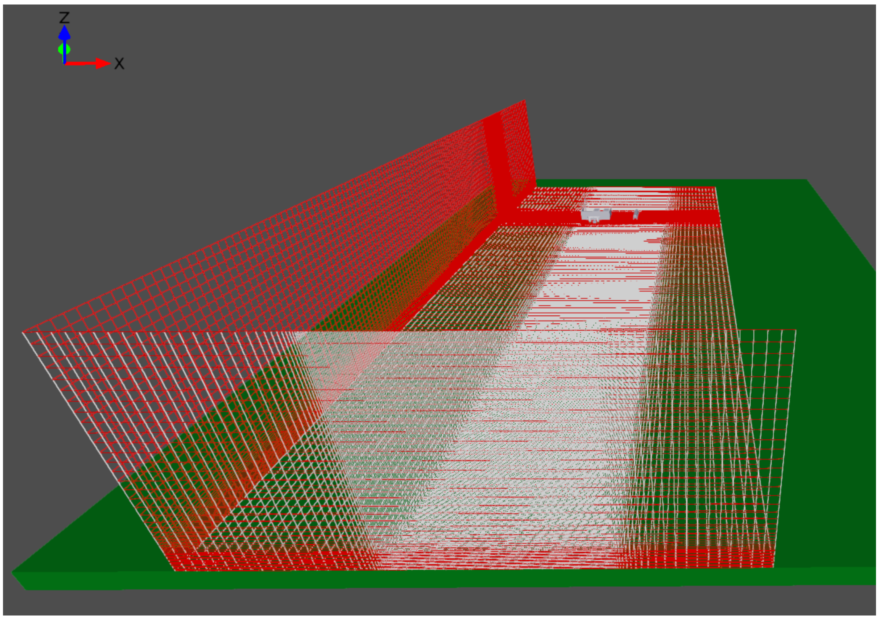

***Figure 4-11:** Computational domain and grid used for ventilation simulations for leaks outdoors (by permanent storage tank) and at MEGC parking.*

4.5.2 Dispersion simulations

For the dispersion simulations, the computational domains have been optimized for limiting computation time, while ensuring that hydrogen concentration levels down to 50 % of LFL are covered. The grids are customized for each leak scenario listed in Table 4-1, but are in general refined close to the leak source, and stretched to a maximum cell size of 2 m outside the core domains. Examples of computational domains and grids used for the dispersion simulations are shown in Figure 4-12 and Figure 4-13.

For the leaks outdoors (by the permanent storage tank) and at the MEGC parking, a ground roughness of 0.005 m has been applied to the entire domain. This is representative for a flat ground surface without vegetation or obstacles. This is a conservative approach, as vegetation and/or obstacles would dilute the gas more and typically lead to shorter hazardous distances with respect to flammable gas exposure.

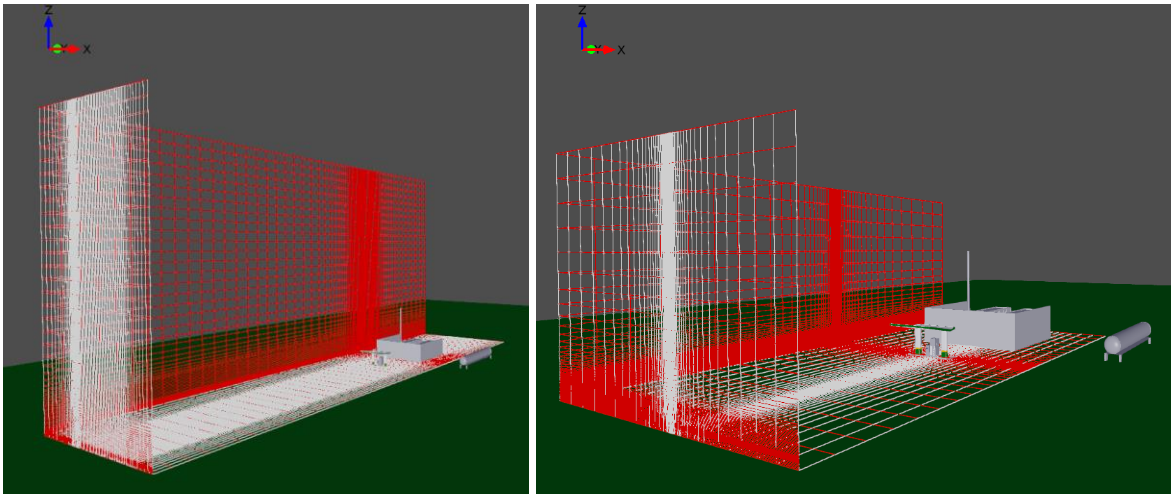

Figure 4-12: Computational domain and grid used for medium leakage inside compressor container (left) and small leakage inside dispenser cabinet (right).

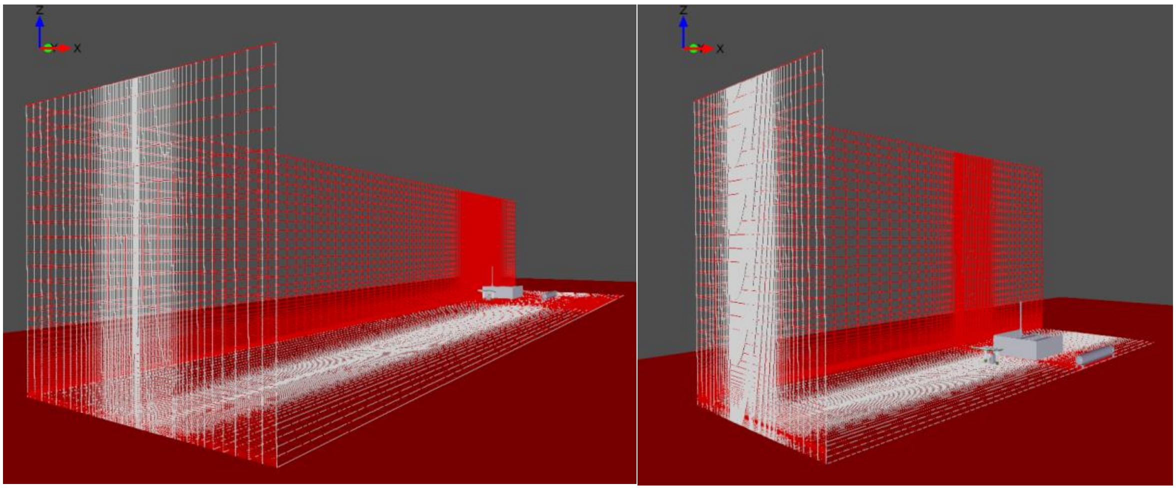

Figure 4-13: Computational domain and grid used for medium hose leakage outdoors (left) and medium hose leakage at MEGC parking (right).

4.5.3 Fire simulations

For the fire simulations the computational domains have been adjusted to cover heat flux levels down to 4 kW/m^2. The grids have been refined close to the leak source in a similar manner as for the dispersion simulations, but the core domains have been expanded where necessary to cover the entire region occupied by the flame. Outside the core domain, the grids have been stretched to a maximum cell size of 2 m. Examples of computational domains and grids used for the fire simulations are shown in Figure 4-14.

The time of ignition has been set to 0.1 s after the start of the leak, at a point of time when the flammable cloud is still relatively small. Hazardous distances with respect to heat loads are thus assumed to be determined by the steady state jet fire (and not by the initial flash fire).

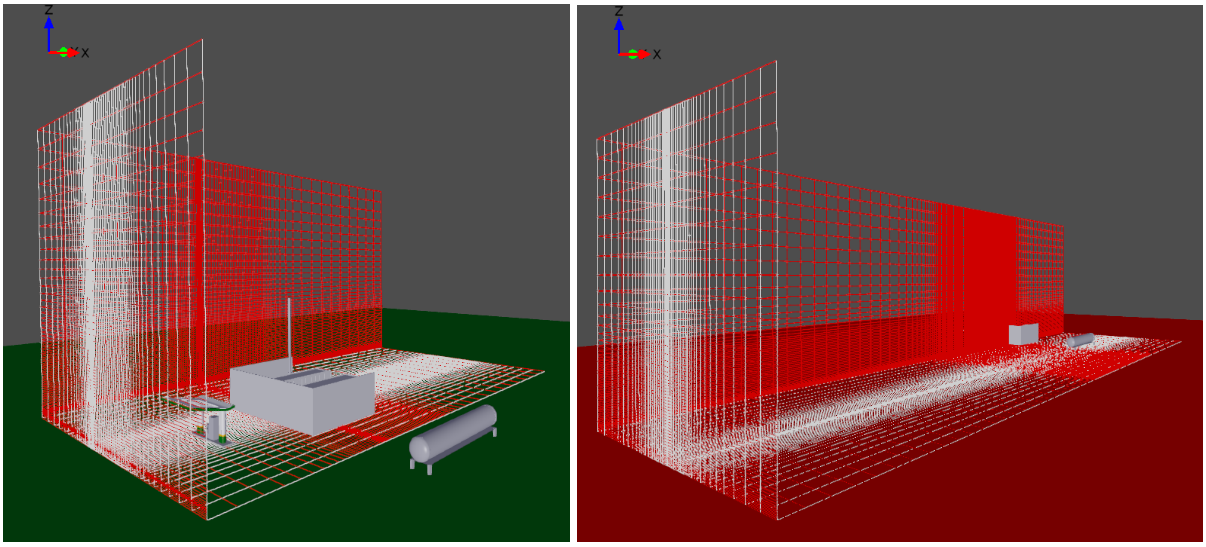

Figure 4-14: Computational domain and grid used for fire from medium leakage inside compressor container (left) and for fire from medium hose leakage outdoors (right).

4.5.4 Explosion simulations

For explosions, the time of ignition is a critical parameter, as the generated overpressure depends strongly on the size and fuel concentration of the flammable cloud. For the indoor releases simulated in this study, the results indicate that the container/cabinet will reach high concentrations of hydrogen relatively fast. However, the highest overpressure levels are expected for hydrogen concentrations close to 29 vol%, which is the stoichiometric concentration of hydrogen when mixed with air. This implies that the worst-case time of ignition (when considering overpressure inside the enclosures) occurs before the flammable gas cloud reaches steady state.

To ensure a conservative approach for the indoor explosion scenarios, the calculated flammable clouds have been dumped at various time steps during the dispersion simulations. Then, explosion simulations have been run based on the dumped clouds assumed to have the largest overpressure potential.

While the simulated clouds typically have hydrogen concentrations with significant variations, the largest overpressures are expected for the “ideal” scenario where a homogeneous stoichiometric cloud filling the entire container/cabinet is ignited. Such scenarios have also been simulated and may be considered as worst-case scenarios with respect to overpressure inside the container/cabinet.

It should be noted that walls/ceilings are modelled as perfectly stiff, and no pressure relief is provided except from the ventilation inlets/outlets. This is conservative when only considering the overpressure obtained inside the container/cabinet.

For the outdoor leak scenarios, explosion simulations have been run based on the steady-state flammable clouds.

Examples of computational domains and grids used for the explosion simulations are shown in Figure 4-15 and Figure 4-16. For the explosion inside the container, the entire container has been resolved by 10 cm grid cells. For the explosion inside the dispenser cabinet, 2 cm cells have been used throughout the cabinet. For the leak by the storage tank, the cloud has been resolved by 25 cm cells, while for the leak at the MEGC parking, 5 cm cells have been used. Outside the core domains, the grids have been stretched to a maximum cell size of 1 m.

A challenge when studying far field pressures using a tool such as FLACS is to prevent smearing of the far field pressure waves. On one hand, the flammable cloud should be resolved by at least 15 grid cells in each direction. On the other hand, stretching of the grid should be avoided in directions where pressure recordings are of interest. Fulfilling these requirements tends to lead to an impractical number of grid cells. This is especially relevant for the large hose leakage at the MEGC parking, where the flammable cloud is large, but narrow, and the distance to the lowest relevant pressure level (30 mbar) is expected to be relatively large.

A limitation of FLACS is that only deflagration is modelled, and not detonation (where the flame front propagates at a supersonic speed). Hydrogen is known to be prone to deflagration-to-detonation transition (DDT), but this is still considered a challenging area within combustion research (1). To assess potential hazardous distances from detonation, calculations have been performed using the TNO Multi-Energy Method (2). These calculations have been based on curve no. 10 (recommended for detonations) and the hydrogen mass of the simulated cloud where the hydrogen concentration is above 8 vol%. Although hydrogen is flammable at concentrations above 4 vol%, experiments have indicated that combustion may not be sustained at concentrations below 8 vol% (3). This means that, in the region between 4 and 8 vol%, local ignition is possible, but the fire may not propagate to richer parts of the cloud.

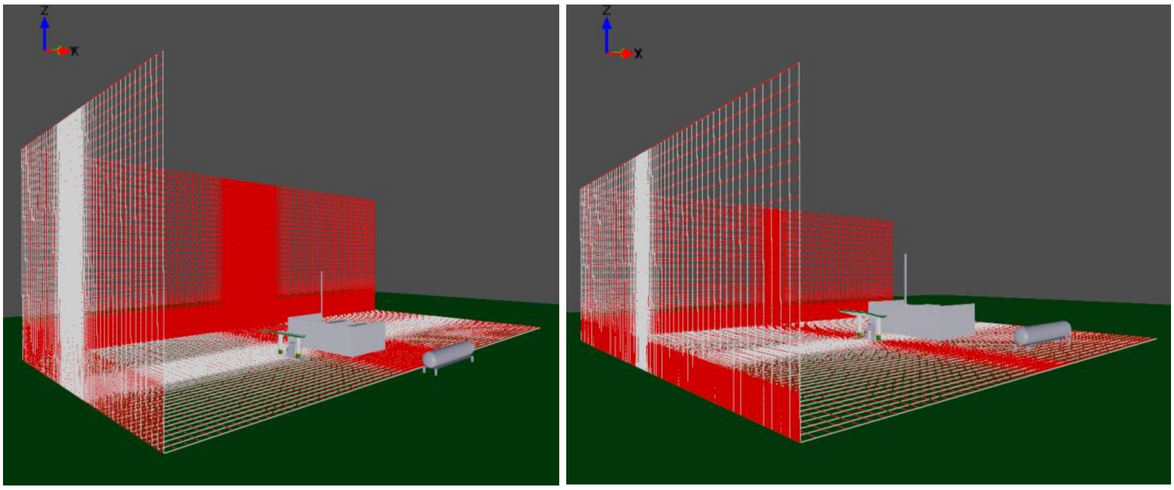

Figure 4-15: Computational domains and grids used for explosion of simulated clouds from small leakage inside container (left) and from small leakage inside dispenser cabinet (right).

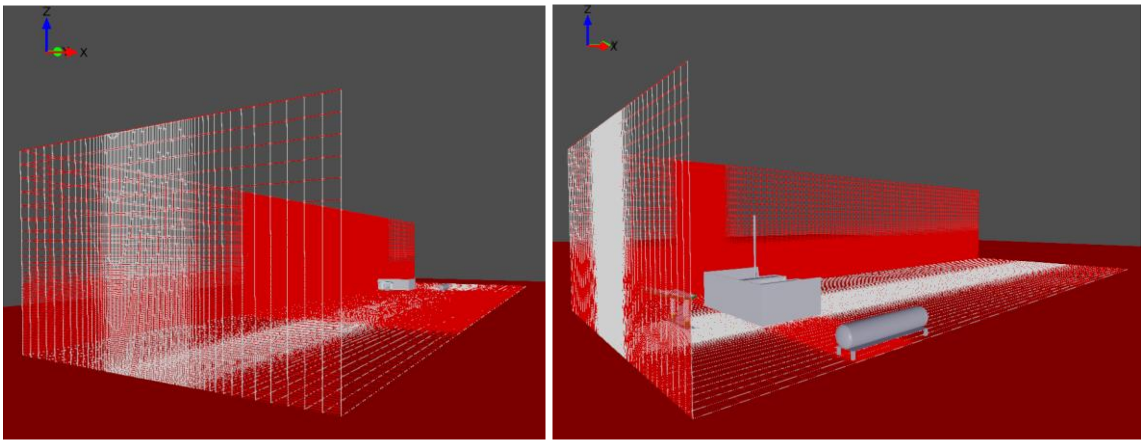

Figure 4-16: Computational domains and grids used for explosion of simulated clouds from large pipe leakage by storage tank (left) and from large hose leakage at MEGC parking (right).

5 Results - dispersion simulations

Results from the dispersion simulations are summarized in the following subsections, mainly focusing on the maximum horizontal distances to hydrogen concentrations of 2 vol% (50 % of LFL), 4 vol% (LFL), and 75 vol% (UFL). A presentation containing videos showing the continual development of the flammable clouds has been provided as Appendix A.

5.1 Leaks inside compressor container

For all the simulated leaks inside the compressor container, the results indicate that the container will eventually be filled with high hydrogen concentrations. The size of the leak and ventilation rate mainly affect how fast the hydrogen concentration rises.

For the base-case wind direction (from the MEGC parking towards the dispenser) the hydrogen gas escapes the container in a direction opposite to the wind and is pushed up and above the container roof. This effect is seen in Figure 5-1, which shows the steady-state cloud from the base-case medium leakage, with normal ventilation and weather condition 2F.

The steady-state cloud for the same leak scenario, but with opposite wind direction, is shown in Figure 5-2. Notably, these plots indicate larger maximum distances to relevant concentrations, as well as exposure to these concentrations closer to the ground.

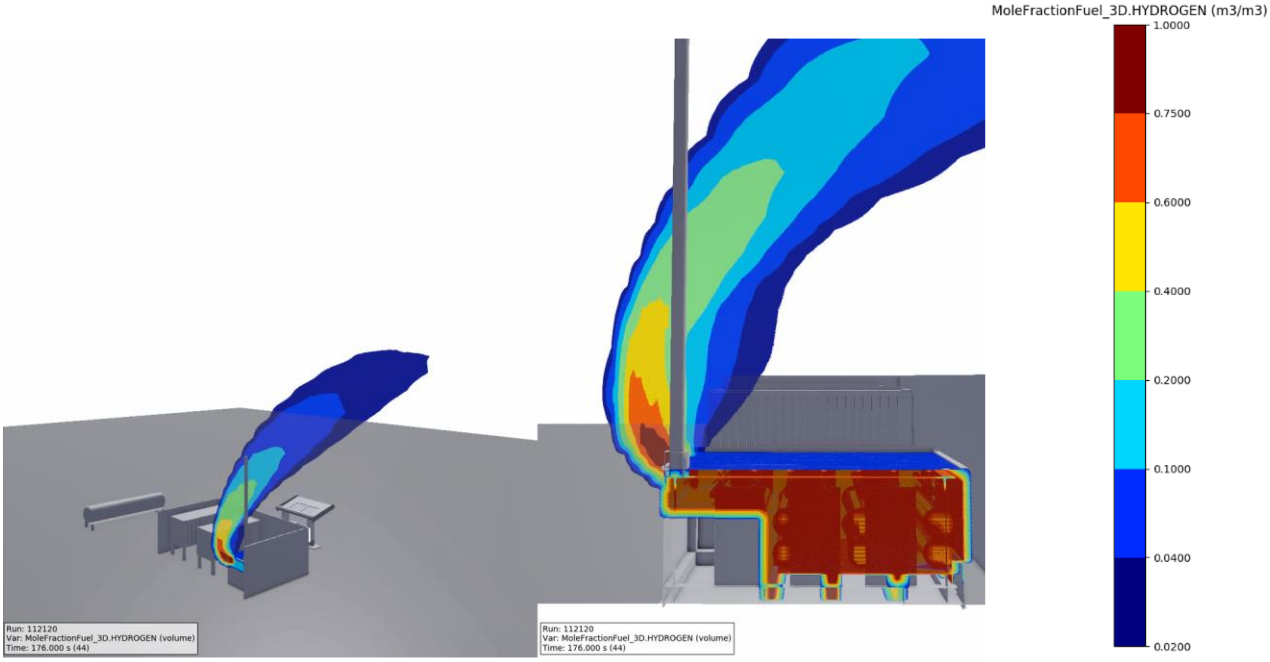

Figure 5-1: ***Plots showing hydrogen concentrations (m^3/m^3) above 50 % LFL for the steady-state cloud from the medium leakage, with normal ventilation and weather condition 2F.***

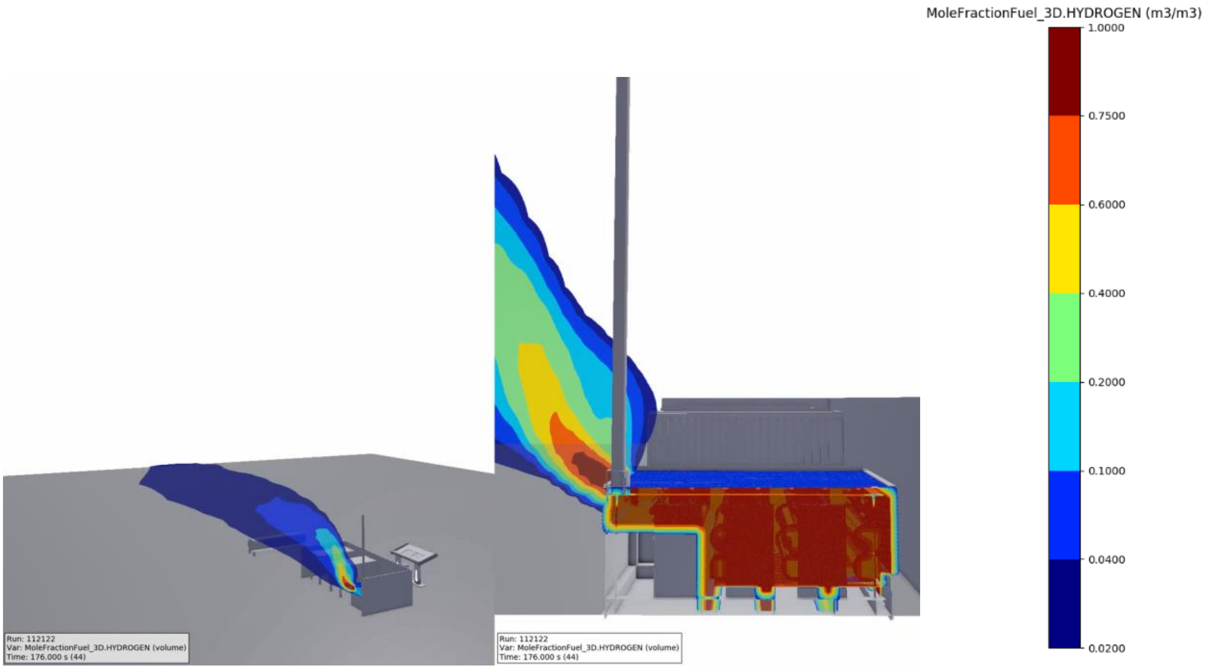

Figure 5-2: ***Plots showing hydrogen concentrations (m³/m³) above 50 % LFL for the steady-state cloud from the medium leakage, with normal ventilation and weather condition 2F, and opposite wind direction.***

Maximum horizontal distances to relevant concentration levels for the simulated base-case scenarios (with wind from the MEGC parking towards the dispenser) are summarized in Table 5-1. Notably, the distances are given with respect to the release point inside the container. The distances from the edge of the container are approx. 2 m shorter.

Table 5-1: ***Hazardous distances with respect to flammable gas dispersion for base-case leaks in compressor container (with wind from MEGC parking towards dispenser).***

Scenario	Release rate (kg/s)	Ventilation	Weather conditions	Maximum horizontal distance (m)		
				50 % LFL (2 vol%)	LFL (4 vol%)	UFL (75 vol%)
Small leakage	0.0280	Normal 30 ACH	2F	5.0	5.0	0.4
		Emergency 60 ACH	2F	5.4	5.3	0.2
Medium leakage	0.262	Normal 30 ACH	2F	33	12	5.3
		Emergency 60 ACH	2F	33	12	5.2
Large leakage	1.57	Normal 30 ACH	2F	81	27	8.7
			5D	79	35	7.3
		Emergency 60 ACH	2F	79	26	8.6

Maximum horizontal distances to relevant concentration levels for the simulated scenarios with opposite wind direction (from the dispenser towards the MEGC parking) are summarized in Table 5-1. Notably, the distances are given with respect to the release point inside the container. The distances from the edge of the container are approx. 4 m shorter.

Table 5-2: Hazardous distances with respect to flammable gas dispersion for leaks in compressor container with opposite wind direction (from dispenser towards MEGC parking).

Scenario	Release rate (kg/s)	Ventilation	Weather conditions	Maximum horizontal distance (m) to 50 % LFL	Height (m) with maximum horizontal distance to 50 % LFL	Maximum horizontal distance (m) to 50 % LFL 0-5 m above ground
Medium leakage	0.262	Normal 30 ACH	2F	40	20	17
			5D	19	5	19

5.2 Leaks inside dispenser cabinet

In line with the simulation matrix provided by the client, the small leakage inside the dispenser cabinet has been simulated merely for evaluating the explosion potential. Figure 5-3 shows hydrogen concentrations 10 seconds after the start of such a release and indicates that the cabinet fills up with hydrogen within short time. This implies that, for this specific leakage, an explosive cloud is present inside the cabinet only for a few seconds before it gets too rich to ignite.

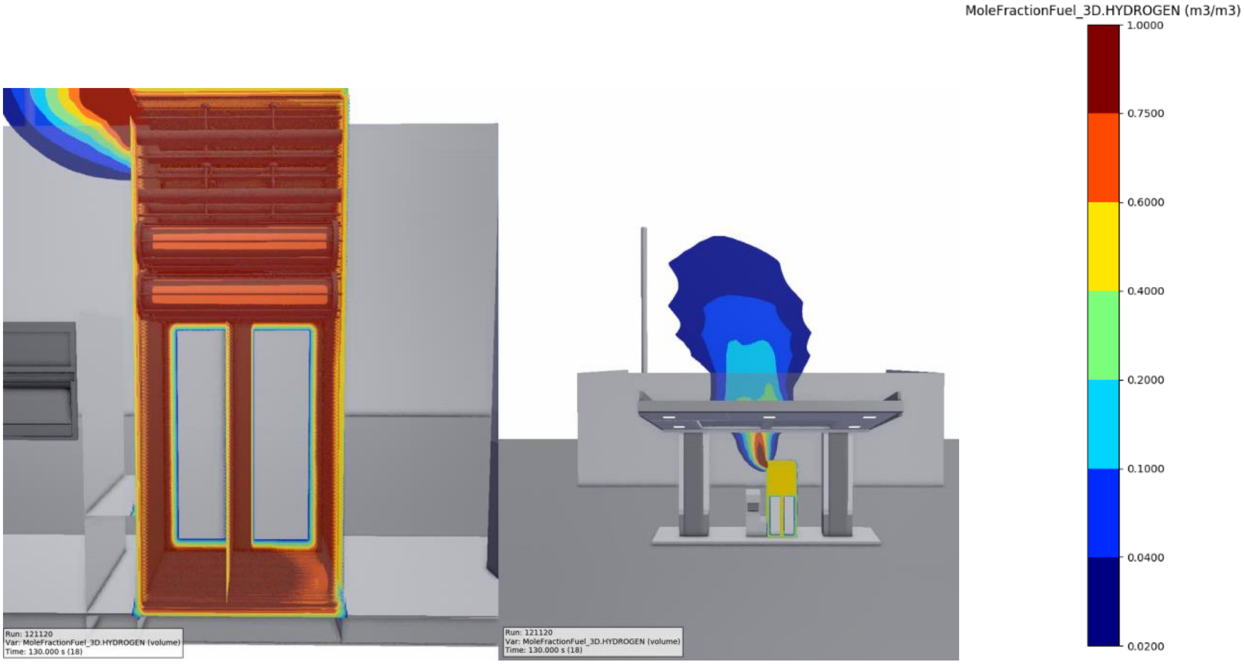

Figure 5-3: Plots showing hydrogen concentrations (m^3/m^3) above 50 % LFL for the small leakage inside the dispenser cabinet, with weather condition 2F, 10 s after the start of the release.

5.3 Leaks outdoors

For the leak scenarios by the permanent storage tank, the results show long and narrow flammable clouds, that spread mainly along the ground, before the gas loses momentum and starts rising towards the sky. The steady-state cloud from the medium hose leakage, with weather condition 2F, is shown in Figure 5-4.

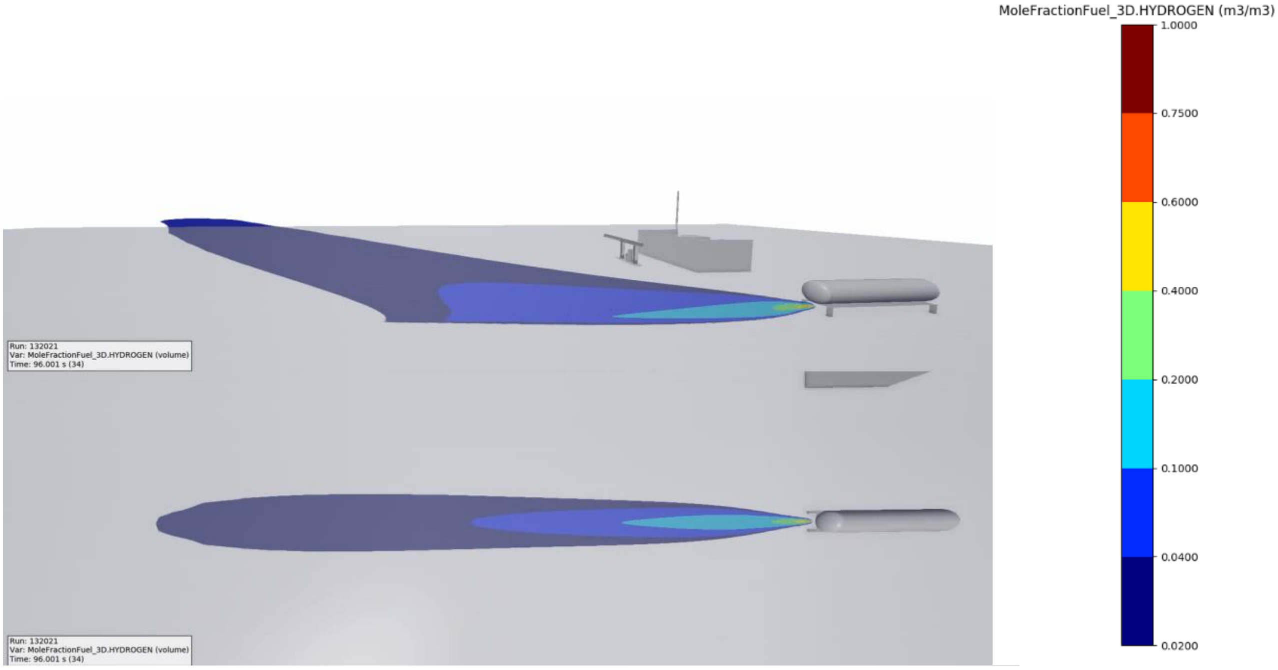

Figure 5-4: ***Plots showing hydrogen concentrations (m³/m³) above 50 % LFL for the steady-state cloud from the medium hose leakage, with weather condition 2F, seen from the side (top) and from above (bottom).***

Maximum horizontal distances to relevant concentration levels for the various scenarios are summarized in Table 5-3. For most cases, larger distances are seen for weather condition 5D than for 2F. The largest distances are obtained for the large pipe leakage with weather condition 5D, with a maximum distance to 50 % LFL of 146 m.

Table 5-3: ***Hazardous distances with respect to flammable gas dispersion for leaks by permanent storage tank.***

Scenario	Release rate (kg/s)	Weather conditions	Maximum horizontal distance (m)		
			50 % LFL (2 vol%)	LFL (4 vol%)	UFL (75 vol%)
Small leakage	0.0280	2F	22	15	0.2
		5D	28	14	0.2
Medium hose leakage	0.206	2F	56	34	0.5
		5D	66	42	0.5
Large hose leakage	1.29	2F	114	70	1.4
		5D	136	88	1.4
Large pipe leakage	1.57	2F	124	76	1.4
		5D	146	94	1.6
PRD release	1.11	2F	65	25	0.3
		5D	73	37	0.1

5.4 Leaks at MEGC parking

For the leak scenarios at the MEGC parking, the results demonstrate that the surrounding walls have a limiting effect on the spreading of flammable gas along the ground. When the hydrogen jet hits the wall, it loses momentum, and the flammable gas dispersion is mainly governed by buoyancy and wind.

This effect is seen in Figure 5-5, which shows the steady-state cloud from the medium hose leakage, with weather condition 2F. Notably, the plots suggest that the spreading of hydrogen along the ground could be even further reduced by extending the lengths of the walls.

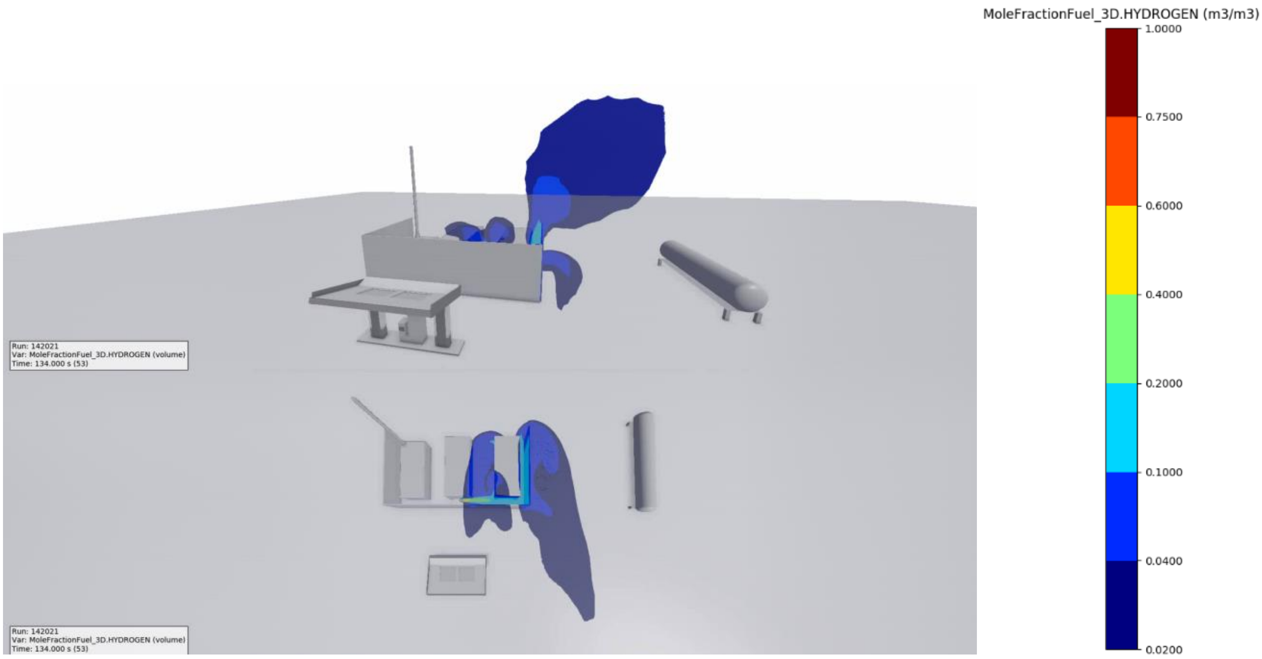

Figure 5-5: Plots showing hydrogen concentrations (m^3/m^3) above 50 % LFL for the steady-state cloud from the medium hose leakage, with weather condition 2F.

Maximum horizontal distances to relevant concentration levels for the simulated scenarios are summarized in Table 5-4. For these scenarios, larger distances are observed for weather condition 2F than for 5D. The largest distances are obtained for the large hose leakage with weather condition 2F, with a maximum distance to 50 % LFL of 42 m.

Table 5-4: Hazardous distances with respect to flammable gas dispersion for leaks at MEGC parking.

Scenario	Release rate (kg/s)	Weather conditions	Maximum horizontal distance (m)		
			50 % LFL (2 vol%)	LFL (4 vol%)	UFL (75 vol%)
Small leakage	0.0148	2F	8.7	7.5	0.1
		5D	7.5	6.4	0.1
Medium hose leakage	0.150	2F	14	13	0.4
		5D	12	9.3	0.4
Large hose leakage	0.95	2F	42	20	1.4
		5D	38	19	1.4

5.5 Distances to 8 vol%

As discussed in Section 4.5.4, experiments have indicated that combustion may not be sustained at hydrogen concentrations in air below 8 vol%. In view of this, maximum horizontal distances to a hydrogen concentration of 8 vol% have been calculated for selected dispersion scenarios. In order to assess the potential effect from shutdown, the distances were measured at the assumed time of leakage isolation for some of the scenarios (after 10 s for the medium leakage inside the container and after 5 s for the medium hose leakages outdoors and at the MEGC parking). Moreover, to reflect that the hazardous distances are most relevant close to the ground, distances were measured only including heights above ground of 0-5 m for some scenarios.

The results are summarized in Table 5-5, and indicate that the distances to 8 vol% are overall significantly shorter than the distances to 4 vol% reported in the previous sections. On the other hand, the results indicate that the effect from shutdown is relatively small, and that the maximum distances to 8 vol% are reached relatively close to the ground.

Table 5-5: Maximum horizontal distances to a hydrogen concentration of 8 vol% for selected scenarios.

Scenario	Release rate (kg/s)	Ventilation	Weather Conditions	Simulation job no.	Time (s) after start of release	Maximum horizontal distance (m) to 8 vol%	Maximum horizontal distance (m) to 8 vol% 0-5 m above ground
Medium leakage inside container	0.262	Normal 30 ACH	2F (base case wind direction)	112120	10	11	11
Medium leakage inside container	0.262	Normal 30 ACH	2F (base case wind direction)	112120	Steady-state	11	11
Medium leakage inside container	0.262	Normal 30 ACH	2F (opposite wind direction)	112122	10	13	13
Medium leakage inside container	0.262	Normal 30 ACH	2F (opposite wind direction)	112122	Steady-state	13	13
Medium hose leakage outdoors	0.206	Outdoors	2F	132021	5	22	22
Medium hose leakage outdoors	0.206	Outdoors	2F	132021	Steady-state	24	24
Medium hose leakage at MEGC parking	0.150	Outdoors	2F	142021	5	11	11
Medium hose leakage at MEGC parking	0.150	Outdoors	2F	142021	Steady-state	12	12
Small leakage inside container	0.0280	Normal 30 ACH	2F	111121	Steady-state	4.9	-
Small leakage inside container	0.0280	Emergency 60 ACH	2F	111221	Steady-state	5.2	-
Small leakage outdoors	0.0280	Outdoors	2F	131021	Steady-state	3.6	-
Small leakage outdoors	0.0280	Outdoors	5D	131051	Steady-state	3.4	-
PRD release outdoors	1.11	Outdoors	2F	135020	Steady-state	9.7	-
PRD release outdoors	1.11	Outdoors	5D	135050	Steady-state	15.4	-
Small leakage at MEGC parking	0.0148	Outdoors	2F	141021	Steady-state	2.6	-
Small leakage at MEGC parking	0.0148	Outdoors	5D	141051	Steady-state	2.4	-

6 Results – fire simulations

Results from the fire simulations are summarized in the following subsections, with the main focus being the maximum horizontal distances to heat radiation levels of 4 kW/m^2, 12.5 kW/m^2, and 37.5 kW/m^2.

A presentation containing videos showing incident heat flux levels on the ground and surfaces throughout the simulations has been provided as Appendix A.

It should be noted that the plots included in this section show incident heat flux levels on the ground and surfaces. For surfaces with low emissivity, the net heat flux will typically be significantly lower than the incident heat flux.

Regarding the presented hazardous distances, these are calculated based on radiation levels throughout the simulation domain. However, shadowing effects from geometry objects are not included, so the distances are assumed to be on the conservative side.

6.1 Leaks inside compressor container

The fire simulations for the leaks inside the compressor container show that, for the smallest leak, the combustion mainly takes place inside the container, and significant heat loads are not observed outside. For the medium and large leaks, the fire inside is to a larger extent ventilation controlled, and after a few seconds combustion primarily takes place outside the container. This is demonstrated in Figure 6-1, which shows incident heat flux levels above 4 kW/m^2 for the steady-state fire from the medium leakage, with weather condition 2F.

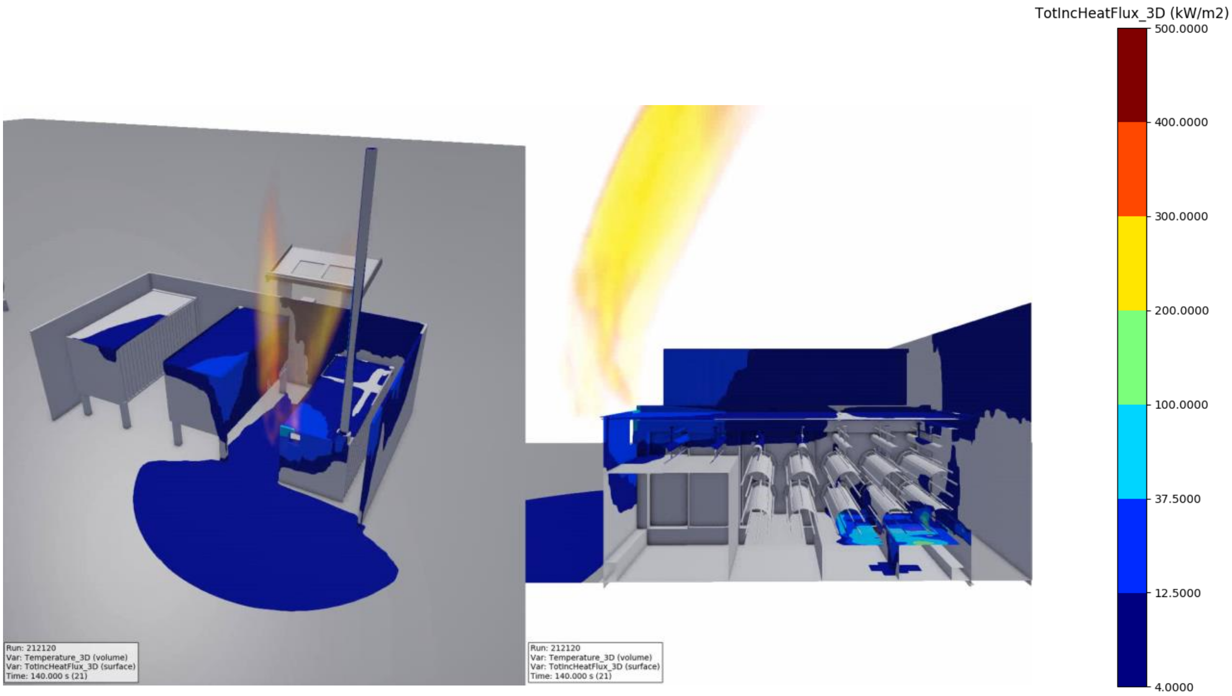

Figure 6-1: ***Incident heat flux (kW/m^2) levels above 4 kW/m^2 on ground and surfaces and visualized flame for steady-state fire from medium leakage inside compressor container, with weather condition 2F.***

Maximum horizontal distances to relevant heat radiation levels for each simulated fire scenario are presented in Table 5-4. Only one scenario has been simulated with weather condition 5D, and this scenario has resulted in shorter distances than the corresponding 2F case. The largest distance to 4 kW/m^2 is obtained for the large leakage with emergency ventilation and weather condition 2F, with a maximum distance of 34 m.

Table 6-1: Hazardous distances with respect to heat radiation exposure for fires from leaks inside compressor container.

Scenario	Release rate (kg/s)	Ventilation	Weather conditions	Maximum horizontal distance (m)		
				4 kW/m^2	12.5 kW/m^2	37.5 kW/m^2
Small leakage	0.0280	Normal 30 ACH	2F	5.4	4.9	4.6
		Emergency 60 ACH	2F	4.5	4.1	3.2
Medium leakage	0.262	Normal 30 ACH	2F	13	8.9	6.5
		Emergency 60 ACH	2F	13	9.3	7.2
Large leakage	1.57	Normal 30 ACH	2F	33	25	18
			5D	23	18	16
		Emergency 60 ACH	2F	34	24	18

6.2 Leaks outdoors

Regarding fires by the permanent storage tank, a typical plot is seen in Figure 6-2, showing incident heat fluxes above 4 kW/m^2 for the steady-state fire from the medium hose leakage, with weather condition 2F.

Maximum horizontal distances to relevant heat radiation levels for each simulated scenario are presented in Table 6-2. The results show overall larger distances for weather condition 5D than for 2F. The largest distances are obtained for the large pipe leakage with weather condition 5D, with a maximum distance to 4 kW/m^2 of 37 m.

For the PRD release, which is located 12 m above ground, the vertical variations in heat radiation are of particular interest. Vertical slice plots of the maximum radiative heat flux are shown in Figure 6-3, and indicate that the 4 kW/m^2 contour extends slightly below the roof of the container, down to a height above ground of approx. 2 m.

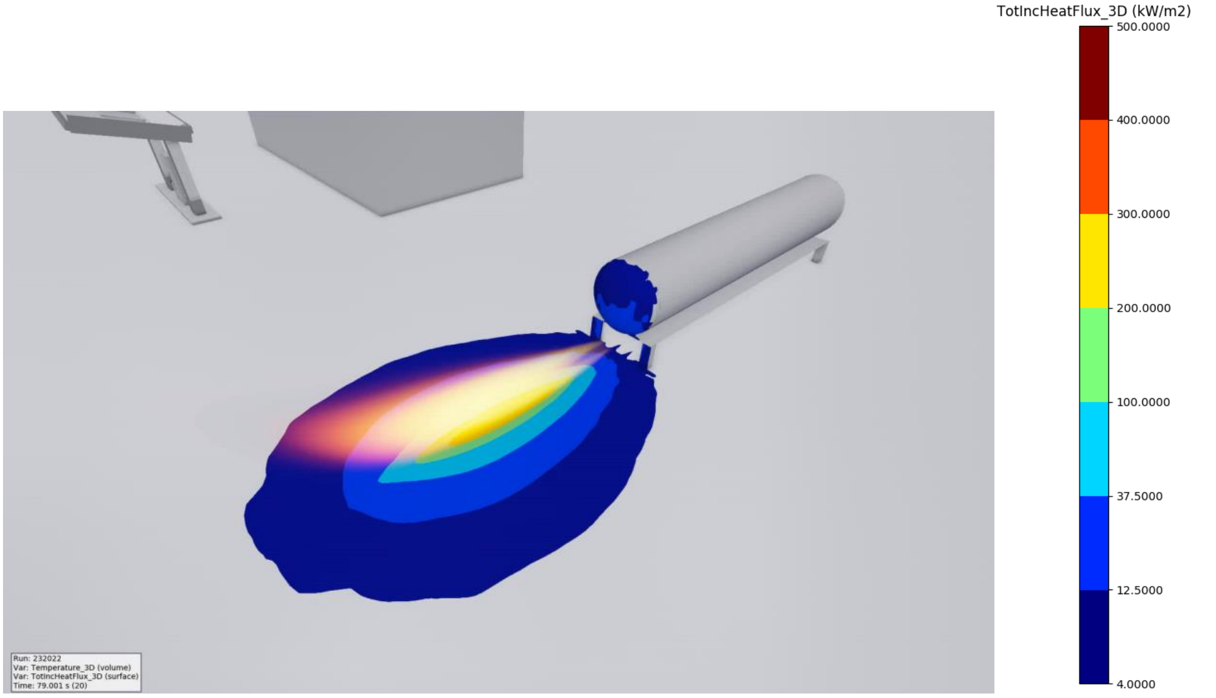

***Figure 6-2:** Incident heat flux (kW/m^2) levels above 4 kW/m^2 on ground and surfaces and visualized flame for steady-state fire from medium hose leakage by permanent storage tank, with weather condition 2F.*

***Table 6-2:** Hazardous distances with respect to heat radiation exposure for fires from leaks by permanent storage tank.*

Scenario	Release rate (kg/s)	Weather conditions	Maximum horizontal distance (m)		
			4 kW/m^2	12.5 kW/m^2	37.5 kW/m^2
Small leakage	0.0280	2F	6.6	6.4	5.6
		5D	7.6	7.4	5.9
Medium hose leakage	0.206	2F	14	12	11
		5D	18	14	12
Large hose leakage	1.29	2F	32	29	26
		5D	35	31	27
Large pipe leakage	1.57	2F	35	30	28
		5D	37	33	31
PRD release	1.11	2F	19	14	14
		5D	29	26	18

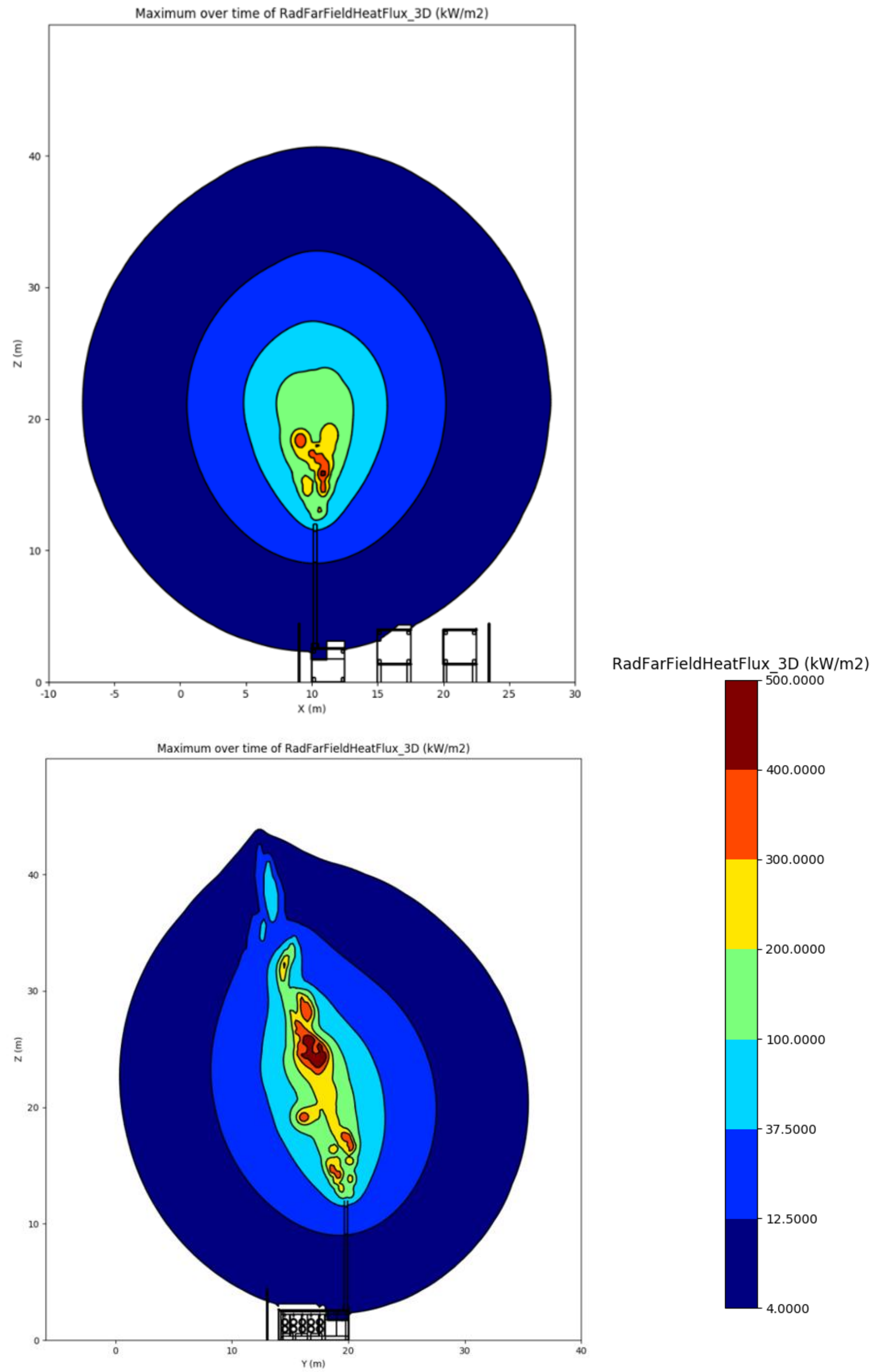

Figure 6-3: Vertical slice plots through release location showing maximum radiative heat flux in XZ plane (top) and YZ plane (bottom) for PRD release, with weather condition 2F.

6.3 Leaks at MEGC parking

For the fire scenarios at the MEGC parking, the results demonstrate that the walls have a preventive effect against fire loads exposing the surrounding area. This is seen in Figure 6-4, which shows incident heat flux levels above 4 kW/m² for the steady-state fire from the medium hose leakage, with weather condition 2F.

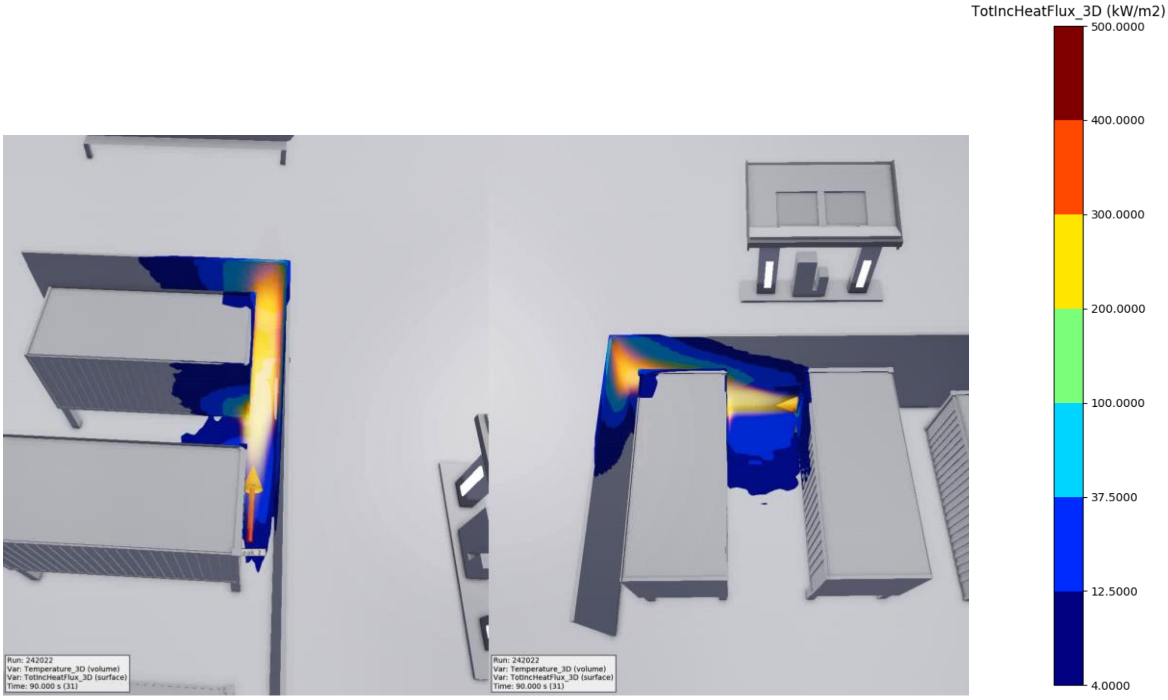

Figure 6-4: ***Incident heat flux (kW/m²) levels above 4 kW/m² on ground and surfaces and visualized flame for steady-state fire from medium hose leakage at MEGC parking, with weather condition 2F.***

Maximum horizontal distances to relevant heat radiation levels for each simulated scenario are presented in Table 6-3. The largest distance to 4 kW/m² is obtained for the large hose leakage with weather condition 5D, with a maximum distance of 26 m.

Table 6-3: ***Hazardous distances with respect to heat radiation exposure for fires from leaks at MEGC parking.***

Scenario	Release rate (kg/s)	Weather conditions	Maximum horizontal distance (m)		
			4 kW/m²	12.5 kW/m²	37.5 kW/m²
Small leakage	0.0148	2F	4.9	3.7	3.1
		5D	4.4	3.2	2.7
Medium hose leakage	0.150	2F	15	11	9.0
		5D	15	11	9.1
Large hose leakage	0.95	2F	25	17	12
		5D	26	20	17

7 Results – explosion simulations

Results from the explosion simulations are summarized in the following subsections. For the enclosed leak scenarios, the main focus has been the internal pressure, i.e. the maximum average pressure acting on walls/ceilings. For the outdoor leak scenarios, the main focus has been the maximum horizontal distances to pressure levels of 30 mbarg, 150 mbarg, and 400 mbarg.

A presentation containing videos visualizing some of the simulated explosions has been provided as Appendix A.

7.1 Leaks inside compressor container

The dispersion simulations indicate that, even for the smallest simulated leak and with emergency ventilation, the container will eventually be filled with high concentrations of hydrogen. As outlined in Section 4.5.4, two explosion simulations have been run for the compressor container:

- Ignition of a homogeneous stoichiometric cloud filling the entire container
- Ignition of the dumped simulated cloud considered to have the largest overpressure potential

While the homogeneous stoichiometric cloud represents a worst-case explosion scenario, the simulated cloud represents a more realistic scenario. The simulated cloud chosen for the explosion simulation (small leakage, emergency ventilation, weather condition 2F, 30 seconds after the start of the release) is shown in Figure 7-1.

Throughout the explosion simulations, the average pressure acting on the container ceiling has been logged by a pressure monitor panel. The results are shown in Figure 7-2 for the stoichiometric cloud (top curve) and the simulated cloud (bottom curve). Both curves indicate maximum average pressures of approx. 7 barg. Notably, also for the simulated cloud, large parts of the cloud display hydrogen concentrations around the stoichiometric level (29 vol%).

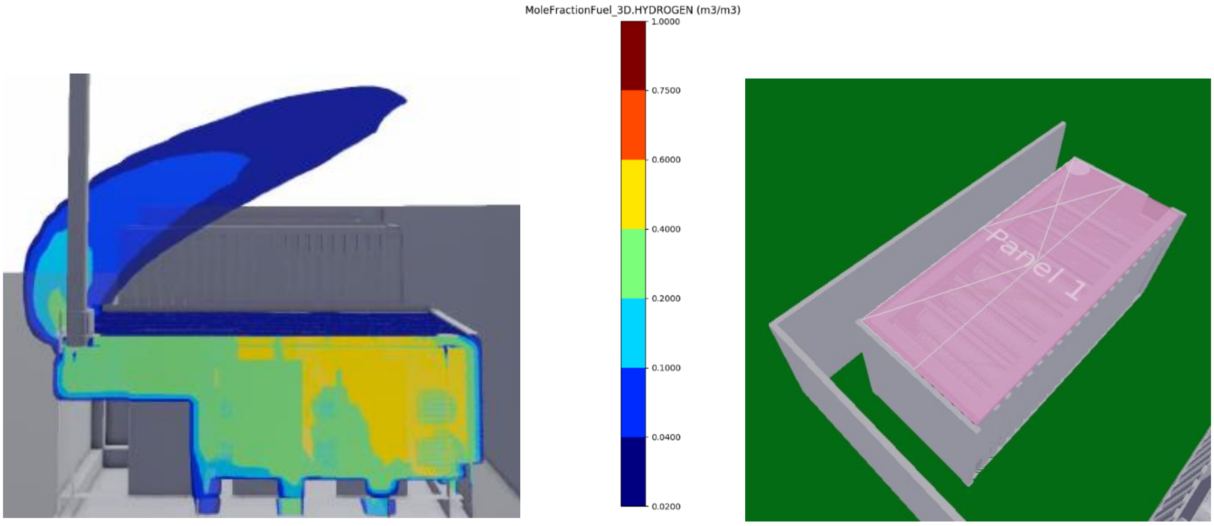

Figure 7-1: Simulated cloud chosen for explosion simulation: small leakage, emergency ventilation, weather condition 2F, 30 s after start of release (left). Pressure monitor panel on ceiling (right).

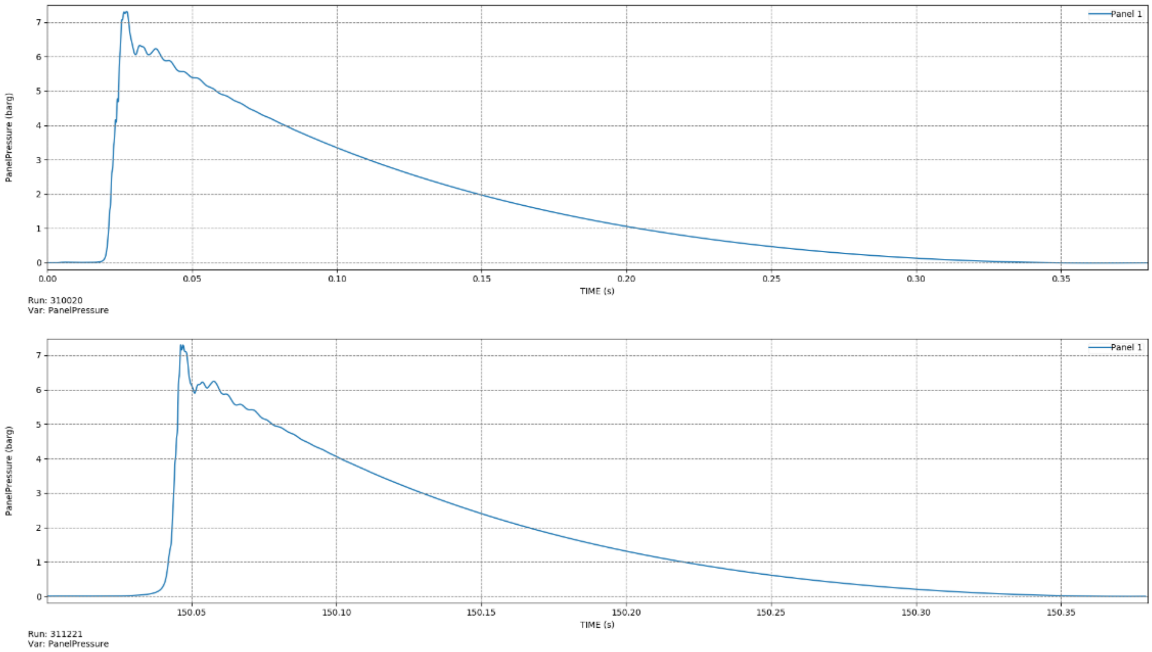

Figure 7-2: ***Curves showing maximum average pressure (barg) measured on the container ceiling throughout the simulation for stoichiometric cloud (top) and simulated cloud (bottom).***

7.2 Leaks inside dispenser cabinet

For the leaks inside the dispenser cabinet, the dispersion simulations indicate that the entire cabinet will be filled with hydrogen gas within a few seconds. Also for the dispenser cabinet, two explosion simulations have been run, where the first represents a worst-case scenario and the second a more realistic scenario:

- Ignition of a homogeneous stoichiometric cloud filling the entire cabinet
- Ignition of the dumped simulated cloud considered to have the largest overpressure potential

The simulated cloud chosen for the explosion simulation (small leakage, weather condition 2F, 0.5 seconds after the start of the release) is shown in Figure 7-3.

Throughout the explosion simulations, the average pressure acting on the cabinet wall and ceiling has been logged by pressure monitor panels. The results are shown in Figure 7-2 for the stoichiometric cloud (top curves) and the simulated cloud (bottom curves). Panel 1 (blue curve) represents the ceiling, while panels 2-5 represent the walls. The curves indicate maximum average pressures of approx. 32 barg for the stoichiometric cloud, and approx. 1.7 barg for the simulated cloud. Notably, the simulated cloud displays large variations in hydrogen concentration.

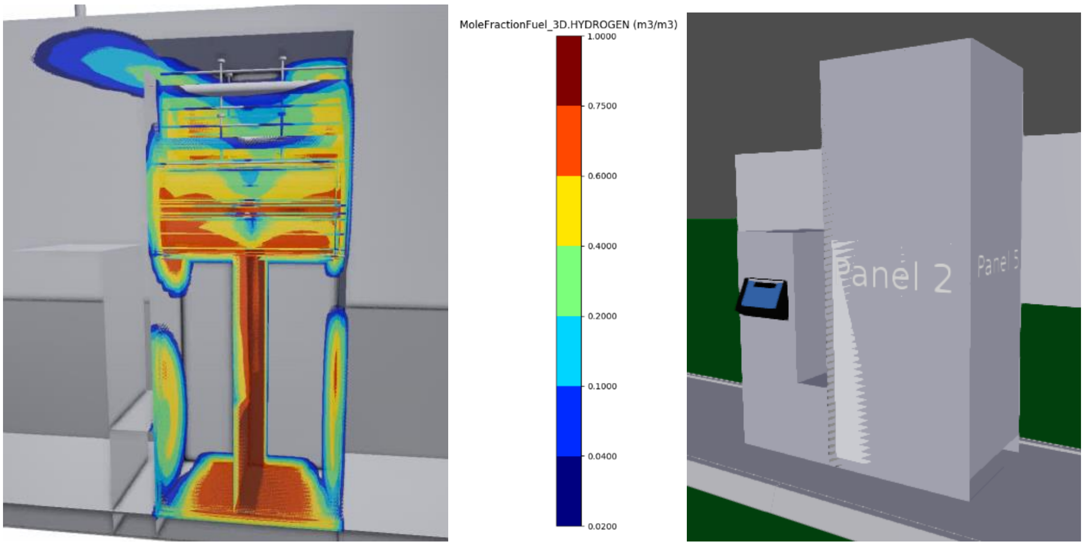

Figure 7-3: Simulated cloud chosen for explosion simulation: small leakage, weather condition 2F, 0.5 s after start of release (left). Pressure monitor panels (right).

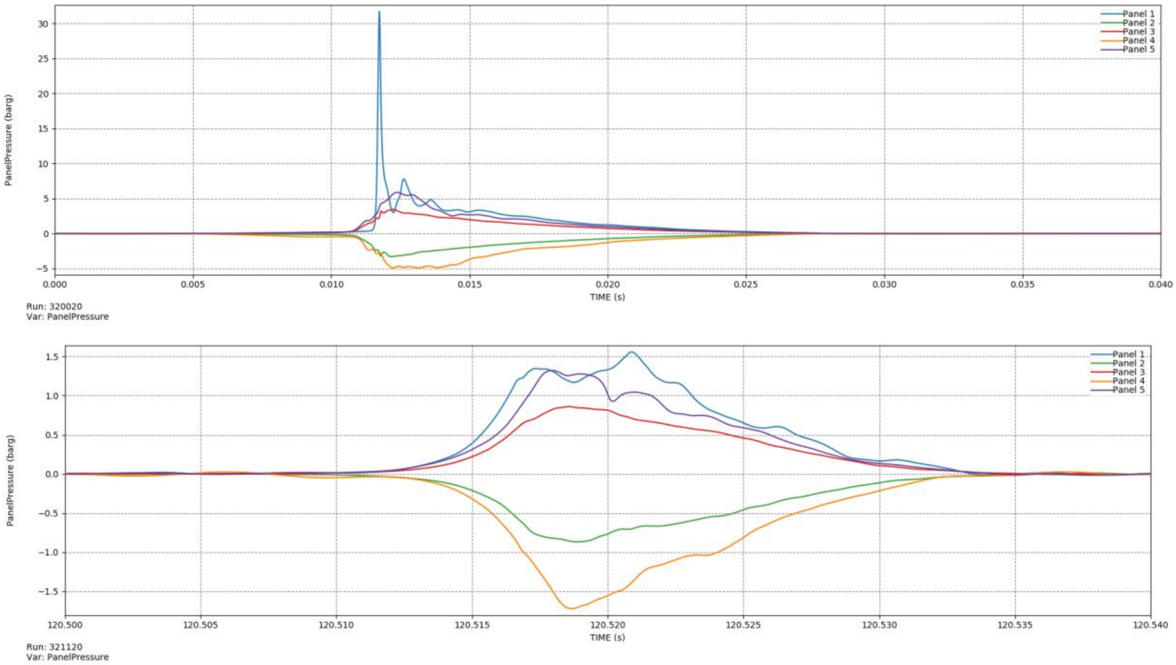

Figure 7-4: Curves showing maximum average pressure (barg) measured on the cabinet walls and ceiling throughout the simulation for stoichiometric cloud (top) and simulated cloud (bottom).

7.3 Leaks outdoors

For the outdoor leaks by the permanent storage tank, four explosion simulations have been run based on the steady-state cloud produced by the dispersion simulation for the large pipe leakage with weather condition 2F. This is the scenario producing the largest explosive hydrogen mass (based on the simulated cloud where the hydrogen concentration is above 8 vol%) and is thus considered to have the largest overpressure potential.

Among the four simulations (where the ignition point was the only varied parameter) relevant overpressures were obtained for only one, where the hydrogen concentration at the ignition point was close to stoichiometric. Maximum pressure levels logged throughout the simulation domain are shown in Figure 7-5. The plot indicates a maximum horizontal distance to 30 mbar of approx. 20 m, and no occurrence of pressures of 150 mbar or higher.

Regarding the large hose leakage, similar results are expected, as the estimated explosive mass is comparable, but somewhat smaller. For the remaining leak scenarios, FLACS is not expected to produce significant pressure levels.

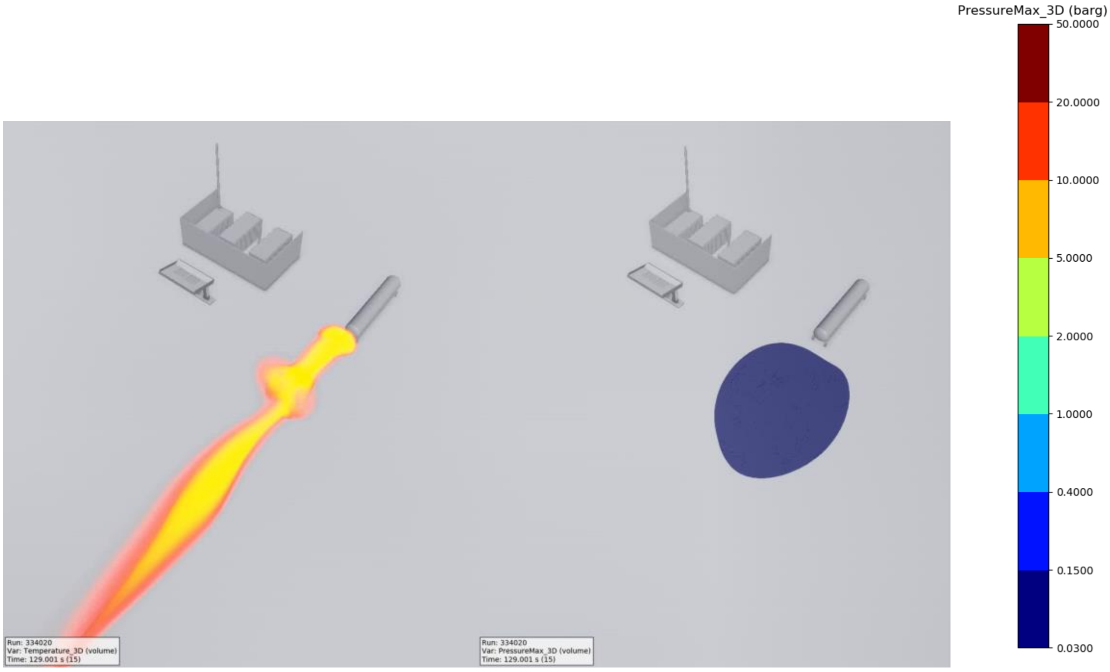

Figure 7-5: Visualized flame and maximum pressure (barg) levels above 30 mbarg for the large pipe leakage with weather condition 2F.

As discussed in Section 4.5.4, FLACS models only deflagration, and hydrogen is known to be prone to DDT. To assess potential hazardous distances from detonation, the Multi-Energy Method has been applied, based on the flammable mass of the simulated cloud where the hydrogen concentration is above 8 vol%.

The resulting maximum horizontal distances to relevant pressure levels are summarized in Table 7-1. The largest distances are obtained from the large pipe leakage, where a maximum distance to 30 mbar of 174 m has been obtained for both weather conditions.

Table 7-1: Potential hazardous distances with respect to overpressure from detonation for leaks by the permanent storage tank.

Scenario	Release rate (kg/s)	Weather conditions	Maximum horizontal distance (m)		
			30 mbar	150 mbar	400 mbar
Small leakage	0.0280	2F	NA	NA	NA
		5D	NA	NA	NA
Medium hose leakage	0.206	2F	66	26	19
		5D	66	27	20
Large hose leakage	1.29	2F	159	60	43
		5D	160	63	47
Large pipe leakage	1.57	2F	174	65	47
		5D	174	68	50
PRD release	1.11	2F	118	34	20
		5D	113	35	22

7.4 Leaks at MEGC parking

Also for the outdoor leaks at the MEGC parking, the steady-state clouds produced by the dispersion simulations have been used for explosion simulations. Maximum pressure levels logged throughout the simulation domain are shown in Figure 7-6 for the medium hose leakage (left) and the large hose leakage (right), both with weather condition 2F.

The plots indicate that, for the medium hose leakage, significant pressure levels are obtained only in the MEGC parking area. For the large hose leakage, the maximum horizontal distance to 30 mbarg is approx. 80 m. When igniting the steady-state cloud from the small leakage, no significant pressure levels have been obtained.

It should be noted that, as discussed in Section 4.5.4, simulating these scenarios is challenging due to the long and narrow flammable clouds. For the large hose leakage, resolving the flammable cloud with a sufficient number of grid cells, while ensuring that the computational domain is large enough to cover all relevant pressure levels, has not been feasible without stretching the grid outside the core domain (where combustion takes place). As a result, smearing of the far field pressure logged for this scenario cannot be ruled out.

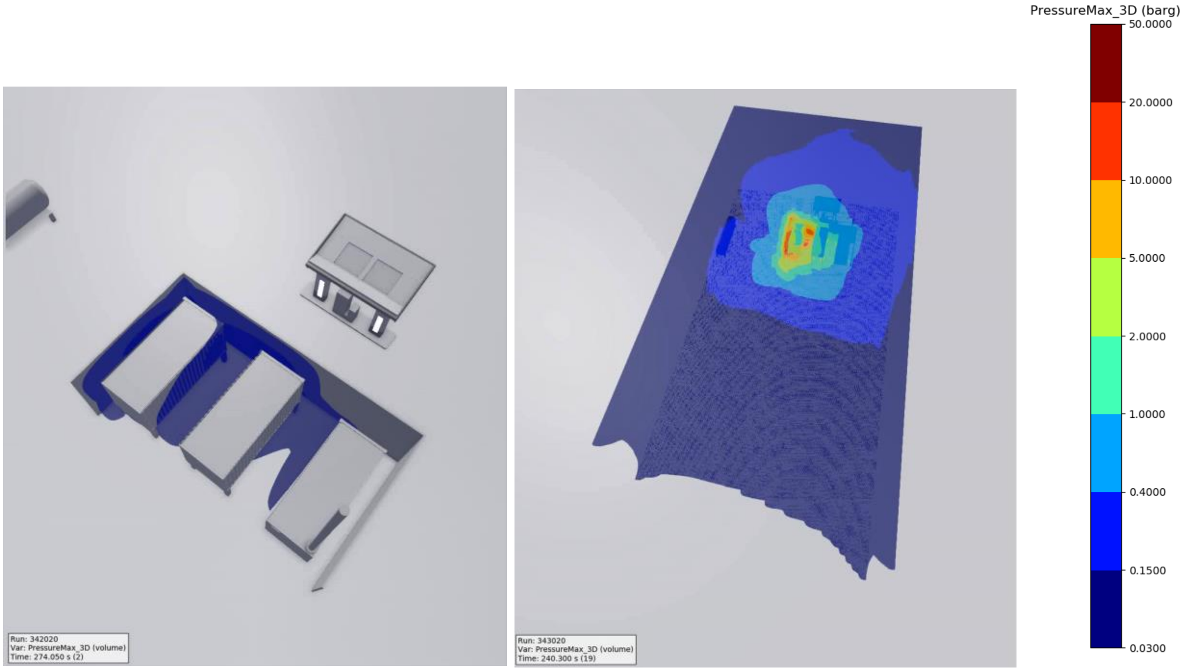

Figure 7-6: ***Maximum pressure (barg) levels above 30 mbarg for the medium hose leakage (left) and for the large hose leakage (right), both with weather condition 2F.***

Also for these scenarios, potential hazardous distances from detonation have been assessed using the Multi-Energy Method, based on the flammable mass of the simulated cloud where the hydrogen concentration is above 8 vol%. The resulting maximum horizontal distances to relevant pressure levels are summarized in Table 7-2. The largest distances are obtained for the large hose leakage with weather condition 5D, where a maximum distance to 30 mbar of 166 m has been obtained.

Table 7-2: ***Potential hazardous distances with respect to overpressure from detonation for leaks at the MEGC parking.***

Scenario	**Release rate (kg/s)**	**Weather conditions**	**Maximum horizontal distance (m)**		
			30 mbar	**150 mbar**	**400 mbar**
Small leakage	0.0148	2F	NA	NA	NA
		5D	NA	NA	NA
Medium hose leakage	0.150	2F	78	24	16
		5D	80	24	15
Large hose leakage	0.95	2F	150	45	28
		5D	166	48	29

8 Conclusions and recommendations

Hydrogen dispersion, fire, and explosion simulations have been performed for potential hydrogen release scenarios related to a generic vehicle fueling station. The objective of the work has been to analyze and visualize the potential consequences, and to estimate hazardous distances with respect to:

- Flammable gas at concentrations down to 50 % LFL
- Heat radiation at levels down to 4 kW/m^2
- Overpressure levels down to 30 mbar

8.1 Dispersion simulations

For the dispersion simulations of leakages inside the compressor container, the maximum horizontal distance to 50 % LFL is 81 m (large leakage, normal ventilation, weather conditions 2F).

The dispersion simulations of leakages inside the container and dispenser cabinet all show that the enclosures fill up with flammable concentrations relatively fast. Ventilation has limited effect on the flammable cloud extension, since the volumetric release rate of hydrogen is large compared to the volumetric air rate provided by the ventilation. Active ignition sources inside such enclosures should therefore be avoided, i.e. by use of ATEX approved equipment.

For the outdoor leakages by the permanent storage tank, the maximum horizontal distance to 50 % LFL is 146 m (large pipe leakage, weather conditions 5D). Overall, weather conditions 5D tend to give slightly larger maximum distances to flammable concentrations.

For the leakages at the MEGC parking, the maximum horizontal distance to 50 % LFL is 81 m (large leakage, normal ventilation, weather conditions 2F). The results indicate that spreading of flammable gas along the ground towards the dispenser could be further limited by extending the side walls surrounding the MEGC parking.

8.2 Fire simulations

For the fire simulations inside the container, the maximum horizontal distance to a radiation level of 4 kW/m^2 is 33 m (large leakage, normal ventilation, weather conditions 2F). For the small leakage, the combustion mainly takes place inside the container. For the medium and large leakages, the fire inside is to a larger extent ventilation controlled, and combustion occurs primarily outside the container.

For the outdoor fires, the maximum distance to 4 kW/m^2 is 37 m (large pipe leakage, weather conditions 5D). Overall larger hazardous distances are seen for weather condition 5D than for 2F.

For the fires at the MEGC parking, the maximum distance to 4 kW/m^2 is 26 m (large hose leakage, weather conditions 5D). The results demonstrate that the walls have a preventive effect against fire loads exposing the surrounding area. Relevant fire loads on the ground outside the parking area are seen only for the large hose leakage.

8.3 Explosion simulations

For both the compressor container and the dispenser cabinet, two explosion simulations have been run: one with a stoichiometric cloud filling the entire enclosure, and one with a conservatively chosen simulated cloud. For the compressor container, both simulations show maximum average pressures on the ceiling of approx. 7 barg. For the dispenser cabinet, the maximum average pressure seen on the walls/ceiling is approx. 32 barg for the stoichiometric cloud, which suggests that detonation is likely for such a scenario. For the simulated cloud, the maximum average pressure acting on the ceiling is approx. 1.7 barg.

Notably, the walls/ceilings are modelled as perfectly stiff, and no pressure relief is provided except from the ventilation inlets/outlets. This is conservative when only considering the overpressure obtained inside the container/cabinet. The effect from pressure relief panels and/or walls/ceilings yielding at certain pressure levels may be evaluated by running dedicated FLACS simulations. This approach also allows for evaluating the consequences outside the enclosures, e.g. due to a pressure wave escaping through a yielding wall.

For the releases by the permanent storage tank, FLACS simulations indicate significant pressures only for the large leakages, with maximum pressure below 150 mbarg. Since hydrogen is prone to DDT, potential hazardous distances from detonation have been assessed using the Multi-Energy Method. These calculations suggest a maximum distance to 30 mbarg of 174 m (large pipe leakage).

For the medium hose leakage at the MEGC parking, a FLACS simulation has been run indicating relevant pressure levels only within the parking area. For the large hose leakage, a FLACS simulation has been run showing a maximum distance to 30 mbarg of approx. 80 m. However, due to stretching of the grid outside the core domain, smearing of far field pressure cannot be ruled out. Calculations for assessing potential hazardous distances from detonation indicates a maximum distance to 30 mbar of 166 m (large hose leakage, weather condition 5D).

9 Bibliography

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Appendix A

A presentation containing more detailed simulation results has been provided as Appendix A to this report: *Gexcon-22-101542-R1-rev01-AppA*.