STUBBERUD HYDROGEN REFUELING STATION FOR BUSES

Refueling Station for Hydrogen Buses – Concept Risk Analysis

Ruter AS

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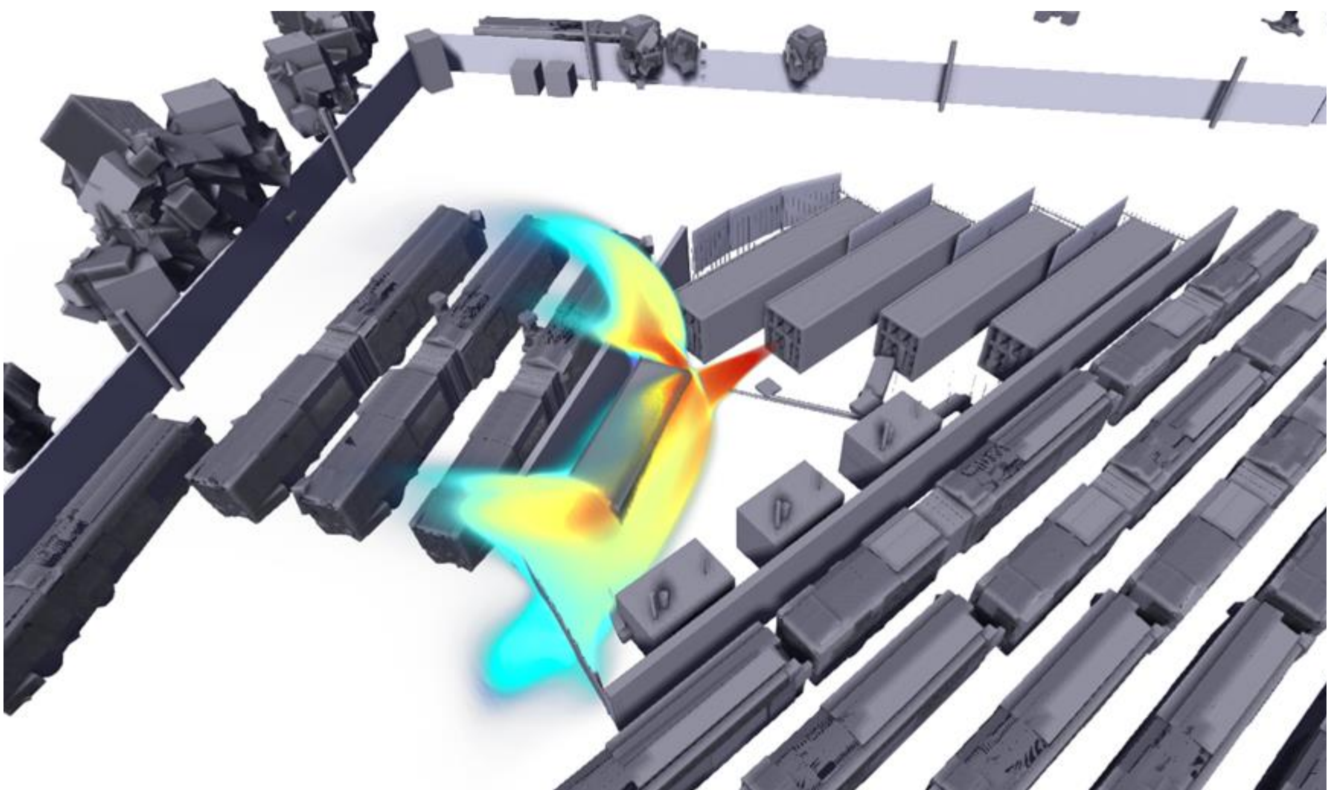

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Objective:

To assess 3rd party individual risk associated with the normal operation of the hydrogen refueling station at Stubberud. Perform detailed explosion risk analysis and incorporate CFD generated explosion results to established Safeti risk model to represent the effect of the blast wall and station design.

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1 EXECUTIVE SUMMARY

Ruters planed Hydrogen Refueling Station for buses is analyzed in the concept stage, where the size of the station is characterized by a use of 1.5-ton hydrogen per day. The present risk assessment includes a Quantitative Risk Analysis (QRA) including a detailed Explosion Risk Analysis (ERA) with use of Computational Fluid Dynamics (CFD) simulations.

The station equipment, arrangement and layout are first defined based on collaboration with Ruter and representative hydrogen refueling station providers in two HAZIDs. Since the station is in a concept stage, assumptions regarding layout and design are made with emphasis on using technology and practices that are common and possible to achieve with today's technology. Common safety system and settings are also applied as basis for the QRA.

The detailed ERA is performed using the CFD tool FLACS and the ERA tool Express. This includes 3D CFD modeling of the actual geometry of the station and the surroundings, ventilation, dispersion, and explosion simulations. Results from the consequence modeling are used to give input to the ERA model where the total explosion risk inside the hydrogen station is found in terms of pressure exceedance curves for the blastwall. Ignition probabilities and results from the CFD simulations are further applied in the QRA.

In the QRA, hazards and risks are identified, modelled, and assessed by Safeti v 8.23 modelling tool. The 3rd party individual risk is estimated in location specific individual risk contours (LSIRCs) and assessed against DSB risk acceptance criteria for 3rd party individual risk.

The QRA with SAFETI and the CFD analysis with Express is only performed for the basecase. A qualitative assessment is provided for three sensitivities

1.1 Main results

Main results from this analysis are pressure exceedance curves generated by the Explosion Risk Analysis, and location specific individual risk contours generated by the Quantitative Risk Analysis.

The risk is assessed to exceed the risk acceptance criteria of 1E-5 per year on the public road located on the north side of the bus depot when no blastwall is applied in that direction. The distance of this risk contour outside the bus depot fence is short, and it is assessed that measures can be implemented so that an acceptable risk level is obtained. Therefore, it can be concluded that it is possible to build a hydrogen station with the given capacities at the given location provided sufficient safety measures and safe designs are implemented.

The main risk drivers and effects that influences the risk are identified and could be used an as input for design improvement and optimization. The analysis indicates where designs can be improved, and safety measures can be added to reduce the risk to the acceptable level.

1.1.1 Explosion Risk Analysis

The ERA is quantifying the explosion risk inside the hydrogen wall and is used to set the design pressure level and point at risk drivers.

A design pressure load on the wall with return frequency of 1E-4 and 0.5E-4 per year is calculated to 0.3 and 1 barg, respectively. The pressure exceedance curve is relatively flat meaning that a small increase in the frequency can result in a large increase in pressure. The results, therefore, show that the risk is sensitive to the degradations of safety measures and uncertainties in assumptions and models. The duration of the pressure peak from hydrogen explosion is from 5 to 20 ms. and should be considered when setting design requirements to the blast walls, equipment and piping support.

The ignition probabilities are calculated in the ERA with a transient ignition probability model that is adjusted for hydrogen effects and used as input to the SAFETI model. The probability for delayed ignition is found to be up to 0.03 for the large and medium leaks with long duration. For small leaks and all leaks with short duration, the ignition probability is up to 0.003.

The CFD analyses that are used to develop the exceedance curves reveals physical effects that contributes to the explosion risk. These are summarized as follow (see also chapter 9.6.9):

- The ability to generate gas clouds inside congested regions causes the high explosion pressures to happen. Hydrogen gas are shown to go in the direction of the release jet before it eventually rises due to buoyancy. Especially, jets that are pointing downwards can generate large clouds.
- The layout of the congested regions where gas can be trapped is typical for hydrogen stations and is unfavorable since gas can be trapped inside partly open containers.
- The effect of the blastwall is good and gives up to 10 to 2 times reduction in the explosion pressure when moving from just outside the wall to a distance of 30 m from the wall.
- A station design that gives effective natural ventilation is assumed. Solid blastwalls are applied on two opposing sides, and partly open firewalls on the two other sides. This design gives natural air flow through the station with reduced stagnant zones and recirculating flow. If a station with less natural ventilation is selected, the risk level can increase.
- It is the long-lasting medium leaks (0.1 to 1 kg/s) from the tanks, or medium leaks when the detection and ESD system is failing that dominates the risk picture from the ERA. Tank scenarios cannot be mitigated by a good detection system and ESD failure scenarios are already assumed to have a good reliability (99% availability on demand). Hence, other measures also need to be in place to mitigate these scenarios.
- Leaks from anywhere in the piping system can develop critical clouds very quickly during a few seconds. This is due to the high speed-of-sound and low density for hydrogen that is also setting the speed of the gas from the high-pressure pipes. This can lead to critical explosions before the ESD shutdown is activated. This scenario is found to be dominating in the SAFETI model even when a fast detection and shutdown time is applied. This indicates that the fast and reliable system assumed is important to maintain, and if this is made worse, the explosion risk might increase.
- Location of the congested regions (tank containers) close to the blast wall causes explosion pressures on the wall to be so high. With other and improved layouts, the explosion safety can be improved.
- Hydrogens ability to generate DDT and detonations within short distances of gas clouds causes potential for extreme explosion pressures. The causes the flat exceedance curve and explosion risk that is sensitive to small changes in safety designs and safety systems.
- It is applied that no projectiles from the explosions can cause fatalities in the QRA. To obtain this, it is assumed that the walls and structures are built strong enough to withstanding the pressure loads that occurs so that no projectiles are made.

1.1.2 Quantitative Risk Analysis

The QRA identify and model hazards associated with normal operation of hydrogen refueling station and obtain individual risk for 3rd party located outside the hydrogen station and the bus depot fence.

For the base case, risk associated with leaks from the tanks/containers and hoses, with delayed ignited events, e.g. explosions, is found to be the main contributor to the 3rd party individual risk.

Since the main limitation related to the modelling of risk in Safeti is representation of the geometry of the facility's layout, including the blast wall, the detailed modelling of gas dispersion and explosion risk is performed by CFD.

The CFD results in form of pressure vs distance representing the effect of "No blast wall" and "Blast wall" are used to define the effect of the blastwall. The explosion parameters to represent the effect of the blast wall east and west of the facility are correspondingly modified in Safeti. Safeti modelling details are presented in Chapter 7, A-06/07.

Two sets of risk results with and without blast wall around the entire refueling station is presented in Section 10.1. Based on this, the risk reduction effect by installing a blastwall on all sides of the station is seen to reduce the size of the 1E-05 per year contour to an acceptable location without reaching outside the bus depot borders except for a small part on the green belt between the bus depot and the west neighbor "massehotel".

The Base Case results with the modeled blast wall only on the east and west side of the refueling station estimated 1E-05 average individual risk per year exposing the local road outside the fence on the north of the bus depot.

The high traffic E6 main road is not assessed to exceed the defined risk acceptance criteria and is outside 1E-06 individual risk contour. No accommodation or housing is assumed to be located around the future area of the station.

The IR contours of 1E-07 /average year do not expose areas with vulnerable targets (such as hospitals, kindergarten and schools, daycare centers).

The main contributors to the risk at the road north of the station for the Base Case are the following:

- Large leak from hose from swap container to the connection unit (A, B and C), contributing by 81% to the total risk at the specified location.
- Hose to the bus from 3 fast filling dispensers, contributing by 10% to the total risk at the specified location; and
- Swap containers A, B and C, contributing by 4% to the total risk at the specified location.

The same contributors are found for the west neighbor.

The large contribution from these segments is defined by relatively *high* release frequency compared to the other QRA scenarios, and extent of their consequences.

A qualitative assessment of the risk associated with the sensitivities is summarized below. The area occupied for the different cases is also assessed since this also have an impact on the extent of the risk contours, as well as the cost.

- Case 1, Basecase, with road containers and fast filling. Risk level is given by contour plots with and without the blastwall indicating that a blastwall towards north could make it acceptable.
- Case 2 with road containers and slow filling (slow filling is provided from 40 bus parking spaces to the east of the station). Contours towards north would be similar to case 1. Contours towards west would be reduced due to no fast filling dispensers. Contours towards east would be extended and is expected to cover just outside location of the slow filling buses. It is not expected that the slow filling slots to the south can cause unacceptable risk at the E6 highway to the south, provided noted measures are implemented. This case will require reduced total area since fast dispensers are not there.

- Case 3 with onsite production and fast filling. Contours in all directions would be similar to case 1 provided the area is extended. This case would require larger footprint area since more equipment is needed for production, compression, and permanent storage. If the area is made larger so that spacing between units on the station is maintained, it is not expected to increase the risk contours. This case would require a larger total area for the hydrogen station, hence occupying more of the bus parking spaces to the east of the station.
- Case 4 with onsite production and slow filling. Since the dispensers on the west side are not there, this area can be used for the extra equipment that is needed compared to case 1. With a blastwall to the west and north it is not expected to cause longer safety contours than case 1 to the north, and reduced safety distance to the west. To the east, the slow filling slots would cause risk contours to cover those, similarly to case 2.

Overall, risk levels for the four cases is assessed to be similar towards North and South provided the wall configurations are similar. There are some differences in the safety distances to the west and the east mainly due to the different dispenser solutions which are outside the blastwall. The cases also have different area needs, and case 2 and case 3 are expected to occupy the smallest and largest total area for the hydrogen station, respectively. Case 1 and case 4 would occupy similar areas.

General lack of recorded accidents associated with hydrogen refueling stations/operations creates uncertainty related to the failure frequencies associated with hydrogen equipment, as well as storage accidents and corresponding ignition frequency. Several adjustments to the failure frequency dataset related to HC accidents has been introduced to reflect on type of the material, type of installation and corresponding operations.

Detection times and corresponding detector coverage and reliability of the ESD system has a considerable impact on the risk results. It is seen that a large leak that is detected and isolated within 2 seconds can generate a critical cloud size resulting in a main contribution to the risk. Details on considered failure data and applied assumptions are documented in Section 7.

The modeling assumptions and settings are made to reflect the actual risk as realistic as possible with some assumptions on the conservative side and others that can be optimistically set. The overall results are assessed to be representative for the purpose of the analysis with the available models and information about the station.

1.2 Recommendations

Based on the results and findings from the assessments, the following recommendations can be given.

- Consider protecting north and perhaps west (for case 1 and 3) of the station by more blast walls. To the North there are no blastwall in the present model, and when the effects of a blastwall is included, the risk becomes acceptable. A blastwall to the north can in cases with road containers be located along the north fence since a heavy blastwall is not practical to install where the road containers are delivered. A separate blastwall on the border to west can also be considered due to the explosion risk caused by leaks in the dispenser hoses to the buses which is outside the modelled blastwall (in the fast filling cases).
- Results from the CFD simulations indicates that both the gas cloud buildup and explosion pressure can be greatly reduced by changing layout and design of the main elements in the station. Some of these measures can be achieved by current available equipment and systems, and others will require that equipment providers also develop their equipment further. Some ideas for improvement can be:
    - To avoid gas inside the tank containers, a gas tight plate can be installed in front of the container so that only the connection point to the tanks are outside this plate.

  - Tanks can be oriented vertically in the container with the connection point at the top and a gas tight plate just below the tank connection point to prevent gas building up inside the container. This solution would force gas from tank leaks higher up and greatly reduce the possibilities to build up gas along the ground and within the containers.
  - Improved locations of the high-risk leak areas such as the tank connection points so that gas from one container does not reach any of the other containers or congested regions. This can be achieved by using a larger distance between containers, staggering road containers or setting up protection walls between containers, etc.
  - Locating equipment and containers further away from blastwalls will reduce the pressure on the walls.
- In future designs of the hydrogen station, keep the partly open firewall configurations on two opposing sides of the station. This provides good wind draft through the area so that gas from smaller leaks are well diluted. If a more closed wall solution is made, it is expected that the risk will increase. The configuration with blastwalls on the other two sides provides also good protection in those directions. If further blastwalls are needed on the open sides, they can be located at a distance from the hydrogen equipment in the station so that both ventilation is maintained, and explosion pressures are protected against.
- Both firewalls and blastwalls need to be designed properly so that their functions are maintained during relevant accident scenarios. Several requirements should be provided for the structural integrity of these walls. These properties can be cost driving; therefore, they are indicated here. The following functions applies for the two different types of walls:
  - **Firewalls** need to stop high momentum jet fires, stop flying objects and projectiles from explosions in the station, withstand design explosion pressures and remind standing after an explosion so that it still can protect for jet fires, not cause flying objects from itself due to explosions, provide sufficient air flow through to maintain ventilation inside the station, the height need to be higher than all hydrogen equipment in the station and outside obstacles in the vicinity. The short duration of the hydrogen explosion and drag loads should be accounted for in the structural design of the walls and equipment (also valid for blastwall).
  - **Blastwalls** need to have most of the same properties as the firewall, in addition it needs to be fully solid and stop any explosion pressure wave up to a design pressure that is found from the ERA. This mean that the requirement to air flow through is not applicable for the blastwall. The height of the wall needs to be higher than all hydrogen equipment in the station, and it need to be 4 m high in order to obtain the effects that are found in the present CFD analysis.
- The ESD system is already assumed with a high reliability and with a fast detection time. It is therefore recommended to maintain or if possible, improve these settings when building the station.
- The risk and geometry models that are developed in this study can be used to quantify the effects of the proposed improvements in collaboration with Ruter and station providers. This way robust and safe refueling stations, that are also cost effective, can be achieved.
- It is recommended to perform dedicated QRAs of the refueling stations during the design phase with the actual design and safety systems that is applied at that stage. The present report can be used as an example for such analysis.

2 INTRODUCTION

2.1 Background

Ruter AS (Ruter) has requested DNV GL to perform a Quantitative Risk Analysis (QRA) including a CFD based Explosion Risk Analysis (ERA) for the planned hydrogen refueling station at Ruters bus depot at Stubberud, Oslo, Norway.

The QRA is performed during the conceptual stage of the hydrogen bus station development and will serve as a documentation of the safety requirements and barriers that are expected and recommended on the station when a bid is released.

The background for the analysis is a preliminary risk assessment performed in 2020 /10/ which found that the safety distances for the planned scaled-up hydrogen station would be longer than the available space at Stubberud when typical/standard safety barriers were employed. The present analysis is therefore performed so that a sufficient, improved level of safety barriers could be defined. One of the safety barriers that are implemented is the blastwall. Since DNV GLs standard tool for QRAs does not account for the effect of blastwalls, the analysis is performed with CFD tools and DNV GLs ERA tool EXPRESS. The CFD calculations are further employed to investigate ventilation, dispersion and explosion effects caused by layout and process. This gives an understanding of hydrogens behavior which is further used to suggest cost optimal solutions, at the same time as the safety level is made acceptable.

This QRA report provides DNV GL findings and conclusions.

2.2 Objective and scope

The overall objectives of the risk study are:

- To recommend design and safety barriers that are needed so that the scaled-up hydrogen refueling station can meet safety acceptance criteria.
- Find the dimensioning accidental explosion load on the blastwall, the firewall, and piping and equipment inside the refueling station. These loads are needed to prevent escalation of the scenarios, and to prevent projectiles from causing fatalities.
- To draw the 3rd party individual risk contours associated with the operation of the hydrogen refueling station at Stubberud after suggested safety barriers and systems are employed.
- To compare risk results with the DSB criteria and if needed, advise additional safety systems and barriers.
- Find risk drivers from the analyses and use those to suggest the most effective measures to reduce the risk.

2.3 Limitations of the scope

The QRA study is limited to the evaluation the location specific individual risk (LSIR) for 3rd party and explosion risk inside the station arising from the operations of the specific hydrogen refueling station at Stubberud.

The operation includes a hydrogen refueling station inside the bus depot with the capacity of 1.5 tons of compressed hydrogen per day. The total number of hydrogen buses is set to 40 articulated buses. The scope does not include the transport of hydrogen by road container to the filling station neither the swapping of the containers.

The following four cases are included in the QRA:

1. Base case: Delivery of hydrogen with swap containers, and 3 (three) fast filling dispensers.

2. Delivery of hydrogen with swap containers, and 40 (forty) slow filling spaces for overnight filling of the buses.
3. Production of hydrogen on site with electrolyzes, and 3 (three) fast filling dispensers.
4. Production of hydrogen on site with electrolyzes, and 40 (forty) slow filling spaces for overnight filling of the buses.

The explosion risk analysis with CFD and EXPRESS is only performed for the base case, case 1.

Occupational risk and hazards posed by other facilities around the area were not part of the scope of this analysis.

2.4 Abbreviations and acronyms

CFD	Computational Fluid Dynamics
ERA	Explosion Risk Analysis
ESD	Emergency Shut Down
HSE	Health, Safety and Executive
HC	Hydrocarbon
HCRD	Hydrocarbon Release Database
LSIR	Location Specific Individual Risk
OD	Outer Diameter
QRA	Quantitative risk analysis

3 APPROACH AND METHODOLOGY

3.1 Quantitative risk analysis

The risk analysis methodology adopted in this QRA is as presented in Figure 3.1.

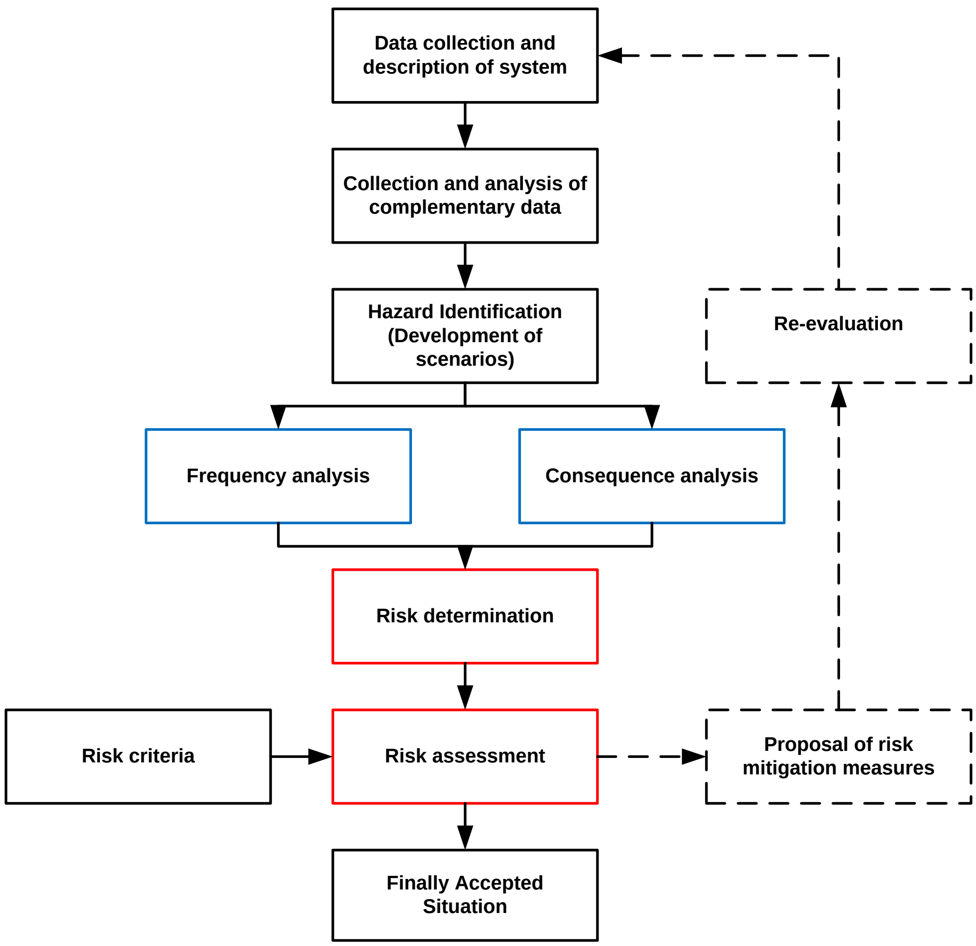


Figure 3.1: QRA Methodology

The assessment has been carried out following the ISO 31 000. The approach goes through 4 phases:

- Hazard identification,
- Frequency assessment,
- Consequences assessment, and
- Risk assessment and evaluation of mitigating measures.

3.2 Methodology for QRA with SAFETI

The consequence analysis as well as the risk assessment have been performed using DNV GL's commercial software Safeti version 8.23, which models the consequences from hazardous substance releases and their impact on people and/or structures according to predefined vulnerability rules.

The modelling has comprised the following steps:

- Modelling of defined QRA scenarios subjected to quantification, including:
  - Representative process conditions
  - Inventory mass
  - Release direction and height
  - Representative release location
  - Representative leak size
  - Integration of estimated leak frequency and ignition probability (by LEAK v3.3 and Express) per defined scenario
  - Modelling of obstructed regions and definition of representative explosion strength and blockage ratio
- Modelling of representative weather conditions and meteorological parameters
- Integration of refueling facility layouts/plots
- Modifying modelling parameters to represent hydrogen accidents, including:
  - Discharge parameters
  - Jet fire parameters
  - Explosion parameters
  - Outdoor vulnerability criteria

The applied modelling assumptions to represent hazardous events associated with hydrogen releases are documented in corresponding chapter 7.

For modelling of dispersion from hydrogen releases, Safeti was validated against carried out experiment showing consistently good results with default settings for dispersion modelling. It should be noted that final velocity for hydrogen releases was uncapped exceeding thus sonic velocity of about 1200 m/s. That was implemented to avoid indicated underestimate in jet fire results, that Safeti is believed to produce. Ongoing work with Safeti validation for horizontal jets indicates too small flames as lift-off distances becomes very large. To reflect it in the current QRA, the Chamberlain jet fire model was as well implemented to reduce expected un-conservatisms.

It is a well-known fact, that hydrogen is highly explosive. Explosive cloud formation, ignition and explosion is several orders of magnitude higher for hydrogen leaks than for methane. Hydrogen has 15-20 times lower ignition energy than methane. Thus, immediate ignition tends to be very high. The immediate ignition probability has thus been assumed based on insights from HyApproval and ref. /11/. The delayed ignition probabilities were provided by CFD.

Clouds tend to be buoyant so disperse vertically, meaning that delayed ignition may not rule out. To be able to represent the effect of delayed ignition in Safeti, including effect of detonation of the cloud, modelling of the delayed ignition outside the tool, in Express, was executed.

Unconfined/unobstructed explosions associated with hydrogen release, may still give significant overpressures. To represent it, the unconfined explosions with 100% explosion efficiency were modelled in Safeti.

Since the main limitation related to the modelling of risk in Safeti is representation of the geometry of the facility's layout, including the blast wall, the detailed modelling of explosion risk by CFD was performed. The overpressure exceedance curves produced by Express and pressure vs distance CFD results representing the effect of "No blast wall" and "Blast wall" were benchmarked against overpressure exceedance curves and overpressure contours produced by Safeti. The explosion parameters to represent the effect of the blast wall east and west of the facility were correspondingly modified to include the effect of the blast wall east and west of the installation. That mainly concerned adjusting the explosion strength represented by the ME curve and explosion efficiency for unobstructed explosions. Further details are documented in Assumptions A-06/07.

Two sets of risk results with and no blast wall included have been merged outside the Safeti environment by the contouring method. To reflect on the effect of the fire/blast wall, the hydrogen release direction was represented by the jet impinging the ground with reduced impinged velocity factor, and thus limiting cloud dispersion length and by the present fire/blast wall.

The jet direction in Safeti is always taken in downwind direction hence causing the shape of the jet moving around with the wind. That should be regarded as conservative approach since jet direction is not usually same as the wind direction, and jet will in this case be obstructed before it goes outside.

3.3 Methodology Explosion Risk Analysis with Express

The CFD and EXPRESS tools are regularly used to perform explosion risk analysis in industrial areas where explosive gases are present such as offshore gas processing plants. The modeling is here adopted for hydrogen by considering all effects and properties for hydrogen. The CFD models are validated for hydrogen by the code developers Gexcon.

The main steps in the explosion risk analysis are as follows:

- A realistic **geometry model** of the facility is constructed. The geometry model is imported into the CFD program FLACS, which is used for all CFD simulations.
- The **leak frequency** of the different isolatable segments is calculated as part of the QRA.
- A set of **ventilation simulations** are performed using FLACS, to calculate the natural ventilation rate through the different areas of the facility. Ventilation simulations are performed with eight different wind directions for a representative wind speed. The number of air changes per hour is calculated based on the volumetric air flow through each area. Gas dispersion leak scenarios are selected based on available gas inventory, realistic and representative leak positions in the different areas of interest. The selected scenarios are modelled in detail.
- The **gas dispersion scenarios** to be modelled are determined based on the layout of the facility as well as the inventory and leak frequency of the isolatable segments in the facility.
- **Gas dispersion simulations** are performed using FLACS. The simulations are used to establish relations between leak rates, leak directions, wind speed, wind direction and flammable cloud size for each representative scenario.

- **Curve fitting:** Mathematical relations between leak direction, wind direction, release rate, wind speed and the volume of the explosive cloud are fitted to the gas dispersion simulation results. A “Frozen cloud” approach is applied, where it is assumed that the volume of the cloud is related to the ratio between the volumetric flow of air and gas.
- **Explosion simulations** are performed in FLACS. The volume, location and ignition locations of the explosive clouds are determined from the dispersion simulations. The purpose of the simulations is to generate relations between cloud volume and the explosion load on walls and other equipment. Because the explosion loading is sensitive to location of the cloud and ignition point a large number of explosion simulations are performed.
- The **probabilistic explosion analysis** is performed using the DNV GL program Express. Express uses the dispersion and explosion relations and input form the risk analysis to calculate frequency versus overpressure exceedance curves.

4 RISK ACCEPTANCE CRITERIA

The DSB safety criteria [Ref. /5/ and /6/] are applied to assess whether or not the risk levels arising from the operation of the LNG terminal are acceptable, and whether or not any additional safeguards are required to reduce the risk levels to as low as reasonably practicable.

DSB's criteria are summarized in Table 4-1 and Figure 4.1.

Table 4-1 Summary of DSB risk tolerance criteria

Hazardous zones	Individual Risk up to	Description
Inner zone	1E-05 per year	This is basically the business's own area. In addition, for example, LNF area (Landbruks-, natur- og friluftsområder) can be included in the inner zone. Only short-term passage for third parties.
Middle zone	1E-06 per year	Public road, rail, dock and similar. Permanent industry and office can also be found here. In this zone, there should not be accommodation or housing. Scattered housing can be accepted in some cases.
Outer zone	1E-07 per year	Areas regulated for residential purposes and other uses of the general population can be included in the outer zone, including shops and smaller accommodations.
Outside Outer Zone	Not defined	Schools, kindergarten, nursing homes, hospitals and similar institutions, shopping centres, hotels or large public arenas must normally be placed outside the outer zone.

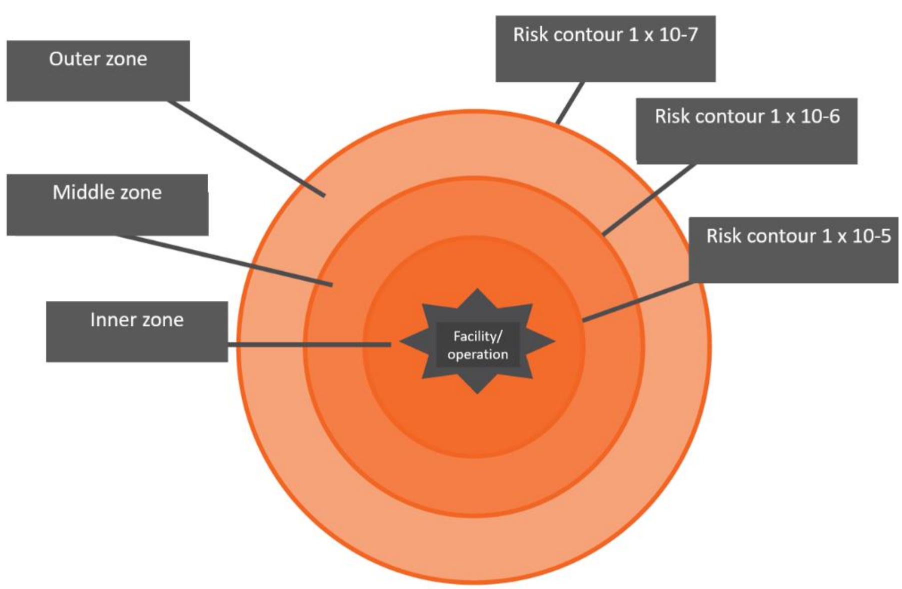


Figure 4.1 DSB criteria for hazardous zones.

5 HAZARD IDENTIFICATION AND STATION DESIGN

Two HAZID workshops were performed in the start of the project, one with Ruter, and one with possible providers of hydrogen stations. Additional meetings were also held with providers to define typical data. The purpose of these HAZIDs and meetings were to obtain safe and realistic station designs, to define equipment that would be installed, and to define typical safety systems that can be expected on a hydrogen refueling station. Available systems and equipment that could be installed today was used and it is not assumed that new types of equipment will be made available before the station is built.

5.1 HAZID with Ruter

In the first HAZID with Ruter, the location and operation of the HRS within the bus depot was established. DNV GL started with the coarse risk assessment that was performed earlier in 2020 /10/ where it was recommended to place the station in the northwest corner of the bus depot. To get a practical operation of the station, the location of hydrogen dispensers and swap tanks was suggested. After some iterations, it was found that an arrangement as given in Figure 5.1 would work.

The coarse risk assessment /10/ also indicated that the risk would increase due to the increased amount of hydrogen on the station compared to earlier assessed hydrogen stations, and a report to establish safety distances for DSB /11/. It was therefore suggested to include more safety barriers than normally applied. The main additional safety barrier added was the blast wall that was introduced on two of the sides of the station, Figure 5.1.

The following design principles were also used when setting up the layout of the station:

- Storage tanks and its connection points are located centrally in the station so that location of these critical leak points provide additional distance to the station limits.
- Two blastwalls on opposite sides, and open firewalls on the two other sides. This provides natural draft through the station without recirculation of air.
- No corners in the blastwalls so that no reflection pressures are obtained in the corners.
- Compressors are located towards the station limits since they have mainly short-lasting leaks.

5.2 HAZID with providers

During the HAZID and meetings with providers, typical safety systems and arrangements that can be expected was established. A HAZID log is provided in Appendix A where safety systems applied are listed. Possible additional safety systems are also noted.

The layouts of other hydrogen stations were also considered when developing the final station layout.

The station layout was further adjusted based on the HAZID with providers and got the final form as shown in Figure 5.1.

5.3 Summary from HAZIDs

The main hazards and associated safety measures are summarized below. It is essential that these safety measures are implemented to reach the safety level that is found from the QRA. When the final station is going to be built, a new QRA should be performed so that the actual data can be used.

The following measures and layout arrangement principles form the basis for the QRA and the ERA performed. The measures are sorted by consequence that is protected for.

- Unignited gas leak:

- Natural ventilation. Arrangement with possibility for wind flow through in one direction to minimize stagnant zones and recirculation where gas from smaller leaks can build up.
- ESD activated on gas detection
- ESD system with high reliability on all ESD equipment, and fast and reliable gas detection that lead to quick shutdown.

- Explosion from a gas leak with ignited cloud:
  - Blastwalls, safety gaps/separation distance between equipment units, Atex rating on all equipment within hydrogen station,
  - Firewall around station where it is not a blastwall. Both firewall and blastwall designed to withstand obtained explosion pressures to provide protection and to prevent projectiles from explosions. The latter is an important assumption in the QRA, that there are no fatalities caused by projectiles. This will provide certain requirements for the providers.
- Fire from an ignited gas leak:
  - Firewalls around station that can stop a jet
  - Protection between equipment units within the station. This is containerized storage systems where the container wall protects against jet fire from outside.
  - Flame detectors across the installation,
  - Pressure relief valves on tanks. In case of fire, to prevent pressure buildup in the tanks.

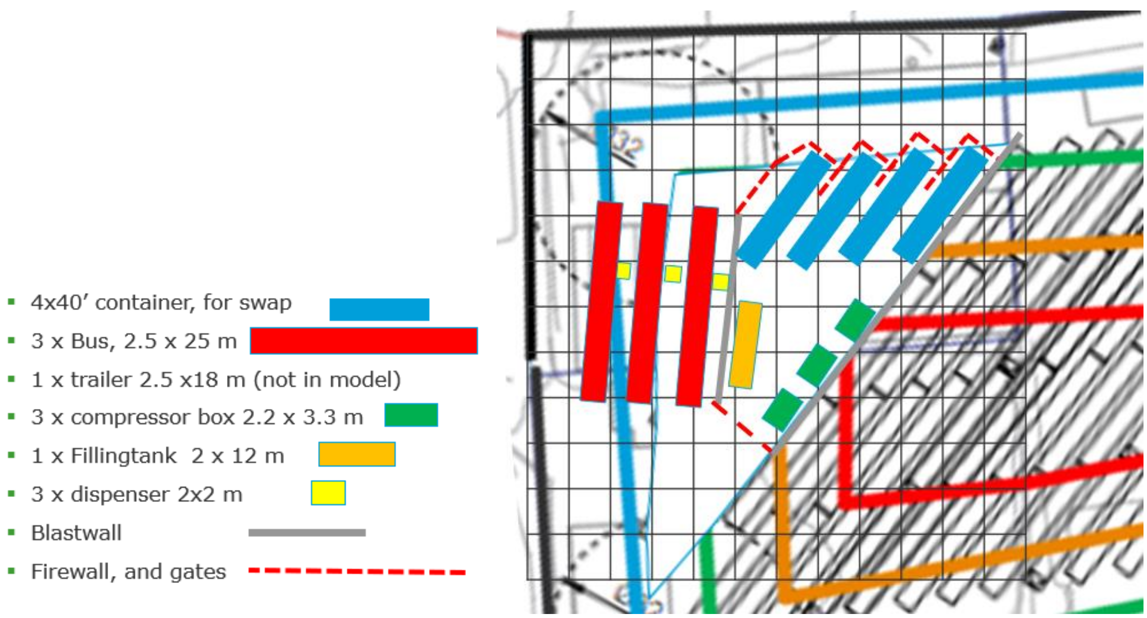


Figure 5.1 Final station layout based on the HAZIDs. The location is at the northwest corner of the bus depot. It was used as basis for the CFD simulations, and the SAFETI model. The dimensions of the main equipment and objects is also shown. A 5x5m grid is indicating the dimensions. The area occupied inside the blastwall and firewall where the hydrogen equipment is located is approximately 635 m2.

6 STUDY BASIS

6.1 Process description and study boundaries

Figure 6.1 shows the flow diagram of the hydrogen bus filling station at Stubberud. The hydrogen gas is delivered by trailers in the containers or produced on-site by electrolysis.

In case the H2 gas source is by H2-containers, the trailers arrive and leave a container at the filling station while switching with a SWAP container (empty). No lifting operations are considered. At the station, there are three hydrogen containing containers always pressurized. The containers are connected to the disposal unit by a hose and a connection unit (manifold).

For the case with onsite production of hydrogen gas by electrolysis, the process includes electrolysers connected to buffer tanks by fixed piping and then gas is routed further to the compression unit. The use of hoses is therefore not considered for this case.

At the disposal unit, for the case with use of SWAP containers, further referred as Case 1&2, the gas is fed to 2-stages compressors and stored in dedicated storage containers. From the storage units, the gas is sent to the dispensers to fill the Ruter bus fleet. For the case with onsite production of H2 gas, further referred as Case 3&4, a 3-stages compressor is accounted for to increase the pressure from 35 barg to 500barg.

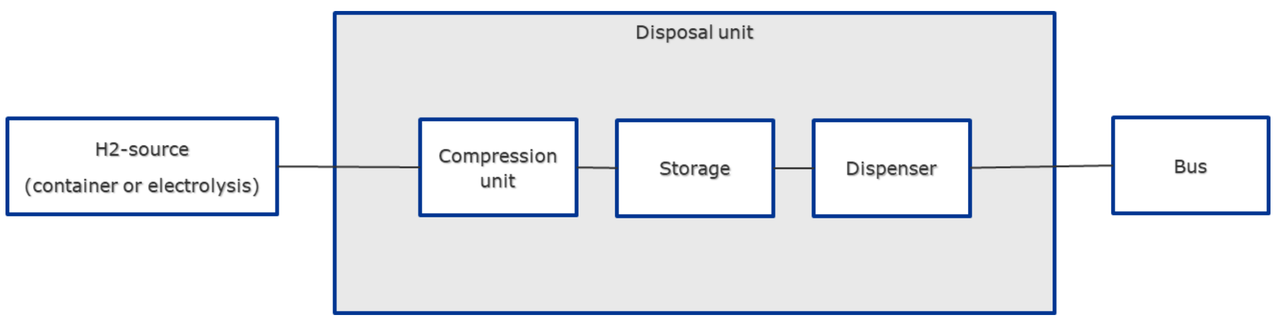


Figure 6.1 Flow diagram for the hydrogen filling station.

The current analysis is limited to the operations shown in Figure 6.1. It includes production (for the case with onsite electrolysis), storage, compression, and distribution of high-pressure hydrogen gas.

The risks associated with the following operations are not included in the risk analysis:

- Transportation to/from the facility and swapping of hydrogen containers;
- Battery fires on the buses;
- Occupational hazards;
- Dropped objects;
- Terrorism and sabotage.

6.1.1 H2 gas sources to the filling station

This analysis includes two different ways of providing hydrogen gas to the disposal unit and two different filling types.

Hydrogen gas can be fed to the disposal unit by:

- Use of H2-containers; or
- Produced on site using electrolysis.

6.1.2 H2 road-containers

When the H2 fueling station is fed by H2-containers, this analysis considers 3 containers and one SWAP container (empty). This study assumes:

- Three containers are fed to the H2 disposal unit in series, i.e. one by one. While one container is being fed to the disposal unit, the two others are being in standby condition and pressurized.

6.1.3 On-site electrolysis

The study considers the use of two containerized electrolysers, each with a daily production of 1000 kg of hydrogen gas. The electroliers are assumed to work in parallel and are connected to a buffer tank which feeds the compression unit.

The operating pressure of the electrolyser is 35 barg which is much lower compared to H2 road-containers operating at 350 barg.

6.2 Cases considered in the analysis

Two operational filling modes are included for the H2 filling station based on the type of filling. These are namely:

- Fast filling; and
- Slow filling.

The filling mode and gas source are considered in four cases, namely a base case and 3 sensitivity cases.

These are defined as follows:

- ***Road-Containers (Case 1 and 2)***

The base case refers to the use of H2-containers to feed the disposal unit.

Both fast filling and slow filling of the bus fleet is considered:

- **Case 1, <u>base case</u>: During fast filling,** a total of 40 buses during a day by three dispenser stations are loaded with hydrogen gas. The loading of each bus has a duration of 10 minutes. It is assumed one loading hose for each dispenser. It is considered a maximum of three buses loaded in parallel.
- **Case 2, During slow filling,** a total of 40 buses per day by 40 dispenser stations are loaded with hydrogen gas. The loading of each bus has a duration of 3 hours and it is performed during night. It is assumed one loading hose for each dispenser. The 40 buses are loaded in parallel.

- ***On-site production of H2 gas by electrolysis (case 3 and 4)***

The sensitivity case considers the on-site production of H2 gas using electrolysis process. For this case, both fast (case 3) and slow (case 4) filling cases are considered, as specified above.

Table 6-1 provides an overview of the cases considered in this analysis, classified for H2-source type and operational phase.

Table 6-1 Overview of cases considered in the analysis

Case Name	H2-source	Operational phase
Case 1 (Base case)	Road container	Fast filling
Case 2	Road container	Slow filling
Case 3	On-site electrolysis	Fast filling
Case 4	On-site electrolysis	Slow filling

6.3 Set up for H2 road-containers as gas source and fast/slow filling (Case 1 and 2)

6.3.1 ESD-segments

Based on the process description in Chapter 6.1 and the operational phases described in chapter 6.1.1, the ESD segments presented in Table 6-2 and Figure 6.2 are considered in the QRA study for the *base case*.

The segments are defined based on the following:

- **Segment S1, S2, S3, S4 – Container**

This study assumes 45 inches ISO Standard containers with 22 hydrogen cylinders (bottles) inside. The inventory of each container is established by reviewing typical values for these kind of containers from different providers. A total of three container is assumed in the study (A, B and C).

This study assumes that each container is split is 4 ESD-segments (S1, S2, S3 and S4) each with inventory of 250 kg.

For each container, a total piping length of 20 m with Outer Diameter (OD) of 1 inch is assumed. The length is assumed based on the dimensions of the container.

- **S5 – Hose to connection unit**

It is assumed that the hose from the container to the connection unit has a length of 3 m and an OD of 1 inch. The study considers the hose as *flexible.*

Table 6-2 SD Segments, inventory and process conditions adopted in the QRA analysis for Case 1

ID.	Segment Name	Inventory(kg)	Pressure(bar)	Temperature[1] (degC)	Phase
S1-S2-S3-S4	Container (4 parallel ESD segments per container)	250[2]	350	10	Gas
S5	Hose to connection unit	0.03	350	10	Gas
S6	Connection unit	0.01	350	10	Gas
S7	Compressor unit	0.50	350/500	10	Gas
S8-S9-S10	Storage	33	500	10	Gas
S11	Piping to dispenser and dispenser	0.30	500	10	Gas
S12	Hose to bus	0.05	500	10	Gas
S13	Bus	35	350	10	Gas

- **S6 – Connection unit**

The connection unit is considered as a manifold where the hose from the container is attached to. The inventory is set arbitrarily, and it is assumed to be isolatable from the rest of the disposal unit if needed.

- **S7 – Compressor unit**

The compression unit includes the piping from the connection unit to the 2-stages compressors and the piping to the storage tank. The length of these is assumed as 40 m and 10 m and the OD as 1 inch and 0.5 inch respectively. Piping is not buried.

- **S8, S9, S10 – Storage**

The storage area consists of 10 containers (A, B, C, D, E, F, G, H, I, L). These are assumed to be 20 inches ISO Standard containers with 9 hydrogen cylinders (bottles) inside. The total inventory of each container is assumed of 100 kg. Each container is split in 3 ESD-segments (S8, S9 and S10), each with inventory of approximately 33 kg.

For each container, a total piping length of 15 m with OD of 0.5 inch is assumed. The length is assumed based on the dimension of the container.

- **S11 – Piping to the dispenser and dispenser unit**

The piping to the dispenser is buried and has an assumed length and OD of 15 m and 1 inch respectively.

[1] The temperature assumed for the gas in the container and disposal unit is assumed as the average yearly ambient temperature for the area where the terminal is located (Oslo).

[2] Amount gas per ESD segment inside the container

- **S12 – Hose to bus**

The hose to the bus has a length assumed as 3 m. It is assumed to be *flexible.*

- **S13 – Bus**

The assumed storage capacity of each bus is 35 kg.

The following Table 6-3 shows the number of identical segments considered for the fast and slow filling of the bus fleet. Figure 6.2 Flow diagram and ESD-segments for the base case during fast filling. The flow diagram for the slow filling case is identical but for the number of buses and bus-filling hoses.

Table 6-3 Number of identical segments during fast and slow filling of the bus fleet

ID.	Segment Name	Number of identical segments during *fast filling* (Case 1)	Number of identical segments during *slow filling* (Case 2)
S1	ESD segment 1 in H2-Container A	3 (in H2-Container A, B and C)	3 (in H2-Container A, B and C)
S2	ESD segment 2 in H2-Container A	3 (in H2-Container A, B and C)	3 (in H2-Container A, B and C)
S3	ESD segment 3 in H2-Container A	3 (in H2-Container A, B and C)	3 (in H2-Container A, B and C)
S4	ESD segment 4 in H2-Container A	3 (in H2-Container A, B and C)	3 (in H2-Container A, B and C)
S5	Hose to connection unit	3	3
S6	Connection unit	3	3
S7	Compressor unit	1	1
S8	ESD segment 1 in Storage Container A	10 (in Storage Container A, B, C, D, E, F, G, H, I, L)	10 (in Storage Container A, B, C, D, E, F, G, H, I, L)
S9	ESD segment 2 in Storage Container A	10 (in Storage Container A, B, C, D, E, F, G, H, I, L)	10 (in Storage Container A, B, C, D, E, F, G, H, I, L)
S10	ESD segment 3 in Storage Container A	10 (in Storage Container A, B, C, D, E, F, G, H, I, L)	10 (in Storage Container A, B, C, D, E, F, G, H, I, L)
S11	Piping to dispenser and dispensers	1	1
S12	Hose to bus	3	40
S13	Bus	3	40

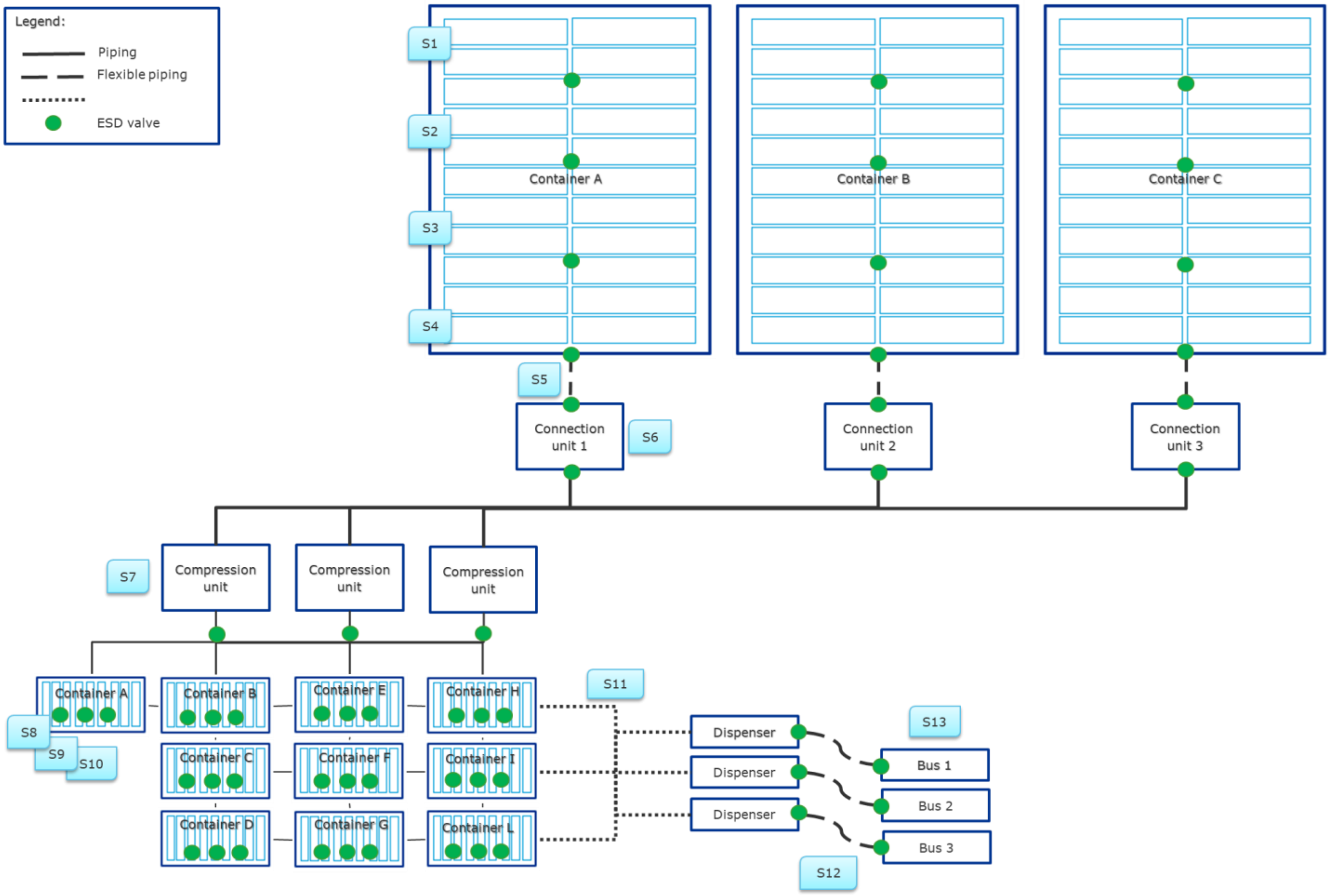


Figure 6.2 Flow diagram and ESD-segments for the base case during fast filling (Case 1).

6.3.2 Parts count

Table 6-4 presents the valves, flanges and other equipment modelled in each segment in the QRA study.

Table 6-4 Equipment in each ESD-segment

ID.	Segment Name	Equip.	Equip. type	No/	Size	P (bar)
S1-A[3]	Segment 1, Container A	EQ.1	Valve (act)	1	22	350
		EQ.2	Flange	2	22	350
		EQ.3	Small Bore Fitting	1	6	350
		EQ.4	Piping	15 m	22	350
		EQ.5	Bottles	5.5	N/A	350
S2-A[3]	Segment 2, Container A	EQ.1	Valve (act)	1	22	350
		EQ.2	Flange	2	22	350
		EQ.3	Small Bore Fitting	1	6	350
		EQ.4	Piping	15 m	22	350
		EQ.5	Bottles	5.5	N/A	350
S3-A[3]	Segment 3, Container A	EQ.1	Valve (act)	1	22	350
		EQ.2	Flange	2	22	350
		EQ.3	Small Bore Fitting	1	6	350
		EQ.4	Piping	15 m	22	350
		EQ.5	Bottles	5.5	N/A	350
S4-A[3]	Segment 4, Container A	EQ.1	Valve (act)	1	22	350
		EQ.2	Flange	2	22	350
		EQ.3	Small Bore Fitting	1	6	350
		EQ.4	Piping	15 m	22	350
		EQ.5	Bottles	5.5	N/A	350
S5-A	Hose to connection unit	EQ.1	Hose	3 m	22	350
S6-A	Connection unit	EQ.1	Valve (man)	6	22	350
		EQ.2	Flange	6	22	350
S7	Compressor unit	EQ.1	Filter	3	22	350
		EQ.2	Flange	9	22	350
		EQ.3	Valve (act)	3	6	350
		EQ.4	Valve (man)	3	22	350
		EQ.5	Piping	40 m	22	350

[3] This segment is identical for Container A, B and C at the H2-Container.

ID.	Segment Name	Equip.	Equip. type	No/	Size	P (bar)
		EQ.6	Compressor 1st stage	3	22	350
		EQ.7	Flange	12	22	350
		EQ.8	Heat exchanger	3	14	350
		EQ.9	Small bore fitting	6	6	350
		EQ.10	Compressor 2nd stage	3	12	500
		EQ.12	Flange	18	12	500
		EQ.13	Valve (act)	3	12	500
		EQ.14	Valve (man)	3	6	500
		EQ.15	Small bore fitting	6	6	500
		EQ.16	Flange	3	6	500
		EQ.17	Piping	10 m	12	500
S8-A[4]	Segment 1 in Storage Container A	EQ.1	Valve (act)	1	12	500
		EQ.2	Flange	2	12	500
		EQ.3	Small Bore Fitting	1	6	500
		EQ.4	Piping	5 m	12	500
		EQ.5	Bottles	3	N/A	500
S9-A[5]	Segment 2 in Storage Container A	EQ.1	Valve (act)	1	12	500
		EQ.2	Flange	2	12	500
		EQ.3	Small Bore Fitting	1	6	500
		EQ.4	Piping	5 m	12	500
		EQ.5	Bottles	3	N/A	500
S10-A[8]	Segment 3 in Storage Container A	EQ.1	Valve (act)	1	12	500
		EQ.2	Flange	2	12	500
		EQ.3	Small Bore Fitting	1	6	500
		EQ.4	Piping	5 m	12	500
		EQ.5	Bottles	3	N/A	500
S11	Piping to dispenser and dispenser	EQ.1	Filter	3	12	500
		EQ.2	Flange	10	12	500

[4] This segment is identical for the storage container A, B, C, D, E, F, G, H, I, and L.
[5] This segment is identical for the storage container A, B, C, D, E, F, G, H, I, and L.

ID.	Segment Name	Equip.	Equip. type	No/	Size	P (bar)
		EQ.3	Small bore fitting	2	6	500
		EQ.4	Valve (act)	2	12	500
		EQ.5	Valve (man)	2	12	500
		EQ.6	Piping (buried)	15 m	24	500
		EQ.7	Flange	8	24	500
		EQ.8	Valve (act)	1	24	500
		EQ.9	Valve (man)	3	24	500
		EQ.10	Small bore fitting	2	6	500
S12	Hose to bus	EQ.1	Hose	3 m	24	500
S13	Bus	EQ.1	Flange	6	24	350
		EQ.2	Small bore fitting	2	6	350
		EQ.3	Valve (act)	1	24	350
		EQ.4	Valve (man)	2	24	350
		EQ.5	Bottle	1	N/A	350

6.4 Set up for on-site H2 electrolysis as gas source and fast/slow filling (Case 3 and 4)

6.4.1 ESD-segments

Based on the process description in Chapter 6.1 and the operational phases described in chapter 6.1.1, the ESD segments presented in Table 6-5 are considered in the QRA study for the case with onsite production of hydrogen gas by electrolysis.

Table 6-5 SD Segments, inventory and process conditions adopted in the QRA analysis for Case 3, fast filling.

ID.	Segment Name	Inventory(kg)	Pressure(bar)	Temperature[6] (degC)	Phase
S1-S2	Electrolyser	50[7]	35	10	Gas
S3	Buffer tank to the compression unit	250	35	10	Gas
S4	Compressor unit	0.50	35/350/500	10	Gas
S5-S6-S7	Storage	33	500	10	Gas
S8	Piping to dispenser and dispenser	0.30	500	10	Gas
S9	Hose to bus	0.05	500	10	Gas
S10	Bus	35	350	10	Gas

The segments are defined based on the following:

- **Segment S1 and S2 – Electrolysers**

This study assumes two containerized electrolysers operating in parallel.

This study assumes that each Electrolyser represents one ESD-segment with an inventory of 50 kg.

- **S3 – Buffer tank to the connection unit**

The hydrogen gas produced by electrolysis is temporary stored in a buffer tank before feeding the compression unit. The buffer tank is assumed to be contained in a dedicated container and made up of cylindric bottles specific for the handling of H2. Piping is included in the segment.

- **S4 – Compressor unit**

The compression unit includes the piping from the connection unit to the 3-stages compressors and the piping to the storage tank. The length of these is assumed as 40 m and 10 m and the OD as 1 inch and 0.5 inch respectively. Piping is not buried.

- **S5, S6, S7 – Storage**

The storage area consists of 10 containers (A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q). These are assumed to be 20 foot ISO Standard containers with 9 hydrogen cylinders (bottles) inside. The total inventory of each container is assumed of 100 kg. Each container is split in 3 ESD-segments (S8, S9 and S10), each with inventory of approximately 33 kg.

[6] The temperature assumed for the gas in the container and disposal unit is assumed as the average yearly ambient temperature for the area where the terminal is located (Oslo).

[7] Amount gas per ESD segment inside the container

For each container, a total piping length of 15 m with OD of 0.5 inch is assumed. The length is assumed based on the dimension of the container.

These are the same of Case 1.

- **S8 – Piping to the dispenser and dispenser unit**

The piping to the dispenser is buried and has an assumed length and OD of 15 m and 1 inch respectively.

This is the same as per Case 1.

- **S9 – Hose to bus**

The hose to the bus has a length assumed as 3 m. It is assumed to be *flexible.*

This is the same as per Case 1.

- **S10 – Bus**

The assumed storage capacity of each bus is 35 kg.

This is the same as per Case 1.

The following Table 6-6 shows the number of identical segments considered for the fast and slow filling of the bus fleet. Figure 6.3 shows the flow diagram and ESD-segments for the onsite electrolysis case during fast filling (Case 3). The flow diagram for the slow filling case (Case 4) is identical except for the number of buses and bus-filling hoses.

Table 6-6 Number of identical segments during fast and slow filling of the bus fleet

ID.	Segment Name	Number of identical segments during *fast filling* (Case 1)	Number of identical segments during *slow filling* (Case 2)
S1	Electrolyser A	1	1
S2	Electrolyser B	1	1
S3	Buffer storage	1	1
S4	Compressor unit	1	1
S5	ESD segment 1 in Storage Container A	15 (in Storage Container A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q)	15 (in Storage Container A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q)
S6	ESD segment 2 in Storage Container A	15 (in Storage Container A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q)	15 (in Storage Container A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q)
S7	ESD segment 3 in Storage Container A	15 (in Storage Container A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q)	15 (in Storage Container A, B, C, D, E, F, G, H, I, L, M, N, O, P, Q)
S8	Piping to dispenser and dispensers	1	1
S9	Hose to bus	3	40
S10	Bus	3	40

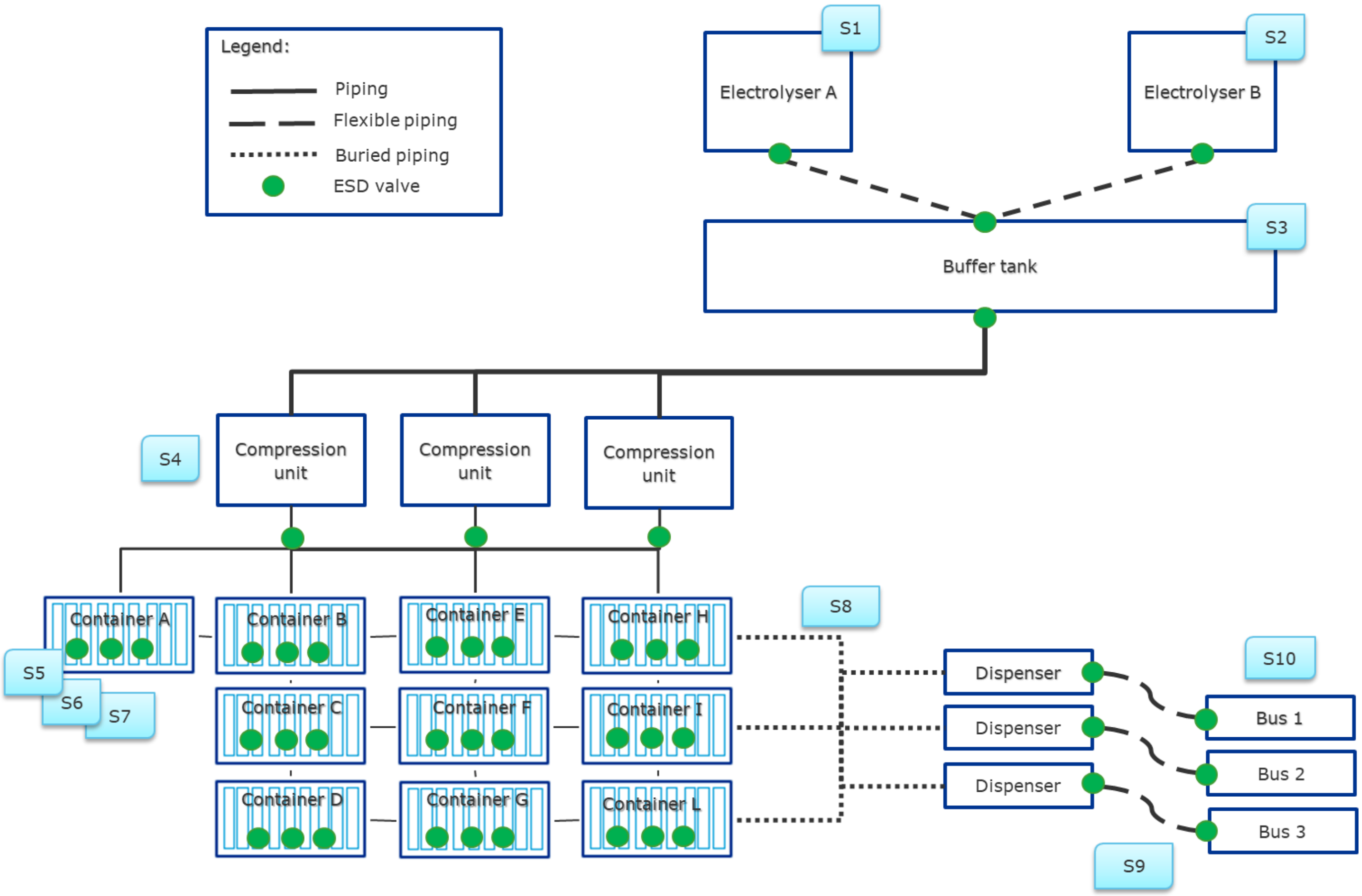


Figure 6.3 Flow diagram and ESD-segments for the onsite electrolysis during fast filling (Case 3). Case 4 is the same with 40 dispensers.

6.4.2 Parts count

Table 6-4 presents the valves, flanges and other equipment modelled in each segment in the QRA study.

Table 6-7 Equipment in each ESD-segment

ID.	Segment Name	Equip.	Equip. type	No/	Size	P (bar)
S1	Segment 1, Electrolyser A	EQ.1	Electrolyser	1	22	35
		EQ.2	Flange	2	22	35
		EQ.3	Small Bore Fitting	1	6	35
		EQ.4	Piping (buried)	15 m	22	35
S2	Segment 2, Electrolyser B	EQ.1	Electrolyser	1	22	35
		EQ.2	Flange	2	22	35
		EQ.3	Small Bore Fitting	1	6	35
		EQ.4	Piping (buried)	15 m	22	35
S3	Buffer tank	EQ.1	Valve (act)	1	22	35
		EQ.2	Flange	2	22	35
		EQ.3	Small Bore Fitting	1	6	35
		EQ.4	Piping	15 m	22	35
		EQ.5	Bottles	6	N/A	35
S4	Compressor unit	EQ.1	Filter	3	22	35
		EQ.2	Flange	9	22	35
		EQ.3	Valve (act)	3	6	35
		EQ.4	Valve (man)	3	22	35
		EQ.5	Piping	40 m	22	35
		EQ.6	Compressor 1st stage	3	22	100
		EQ.7	Flange	12	22	100
		EQ.8	Heat exchanger	3	14	100
		EQ.9	Small bore fitting	6	6	100
		EQ.10	Compressor 2nd stage	3	12	350
		EQ.7	Flange	12	22	350
		EQ.8	Heat exchanger	3	14	350
		EQ.9	Small bore fitting	6	6	350
		EQ.10	Compressor 3rd stage	3	12	500
		EQ.12	Flange	18	12	500
		EQ.13	Valve (act)	3	12	500
		EQ.14	Valve (man)	3	6	500
		EQ.15	Small bore fitting	6	6	500
		EQ.16	Flange	3	6	500
		EQ.17	Piping	10 m	12	500
		EQ.1	Valve (act)	1	12	500

ID.	Segment Name	Equip.	Equip. type	No/	Size	P (bar)
S5	Segment 1 in Storage Container A	EQ.2	Flange	2	12	500
		EQ.3	Small Bore Fitting	1	6	500
		EQ.4	Piping	5 m	12	500
		EQ.5	Bottles	3	N/A	500
S6	Segment 2 in Storage Container A	EQ.1	Valve (act)	1	12	500
		EQ.2	Flange	2	12	500
		EQ.3	Small Bore Fitting	1	6	500
		EQ.4	Piping	5 m	12	500
		EQ.5	Bottles	3	N/A	500
S7	Segment 3 in Storage Container A	EQ.1	Valve (act)	1	12	500
		EQ.2	Flange	2	12	500
		EQ.3	Small Bore Fitting	1	6	500
		EQ.4	Piping	5 m	12	500
		EQ.5	Bottles	3	N/A	500
S8	Piping to dispenser and dispenser	EQ.1	Filter	3	12	500
		EQ.2	Flange	10	12	500
		EQ.3	Small bore fitting	2	6	500
		EQ.4	Valve (act)	2	12	500
		EQ.5	Valve (man)	2	12	500
		EQ.6	Piping (buried)	15 m	24	500
		EQ.7	Flange	8	24	500
		EQ.8	Valve (act)	1	24	500
		EQ.9	Valve (man)	3	24	500
		EQ.10	Small bore fitting	2	6	500
S9	Hose to bus	EQ.1	Hose	3 m	24	500
S10	Bus	EQ.1	Flange	6	24	350
		EQ.2	Small bore fitting	2	6	350
		EQ.3	Valve (act)	1	24	350
		EQ.4	Valve (man)	2	24	350
		EQ.5	Bottle	1	N/A	350

6.5 Blast walls

The study for bas case assumes two blast walls at the Stubberud filling station, one on the West and one on the East sides as shown in Figure 6.4. It is assumed that all the equipment beside the buses and the hoses to the buses is located within the blast walls.

No blast protections on the North and South sides of the station are assumed, other than the perforated fire walls.

Both blastwalls and firewalls are assumed to protect against projectiles from inside the station and be strong enough to not cause any projectiles themselves.

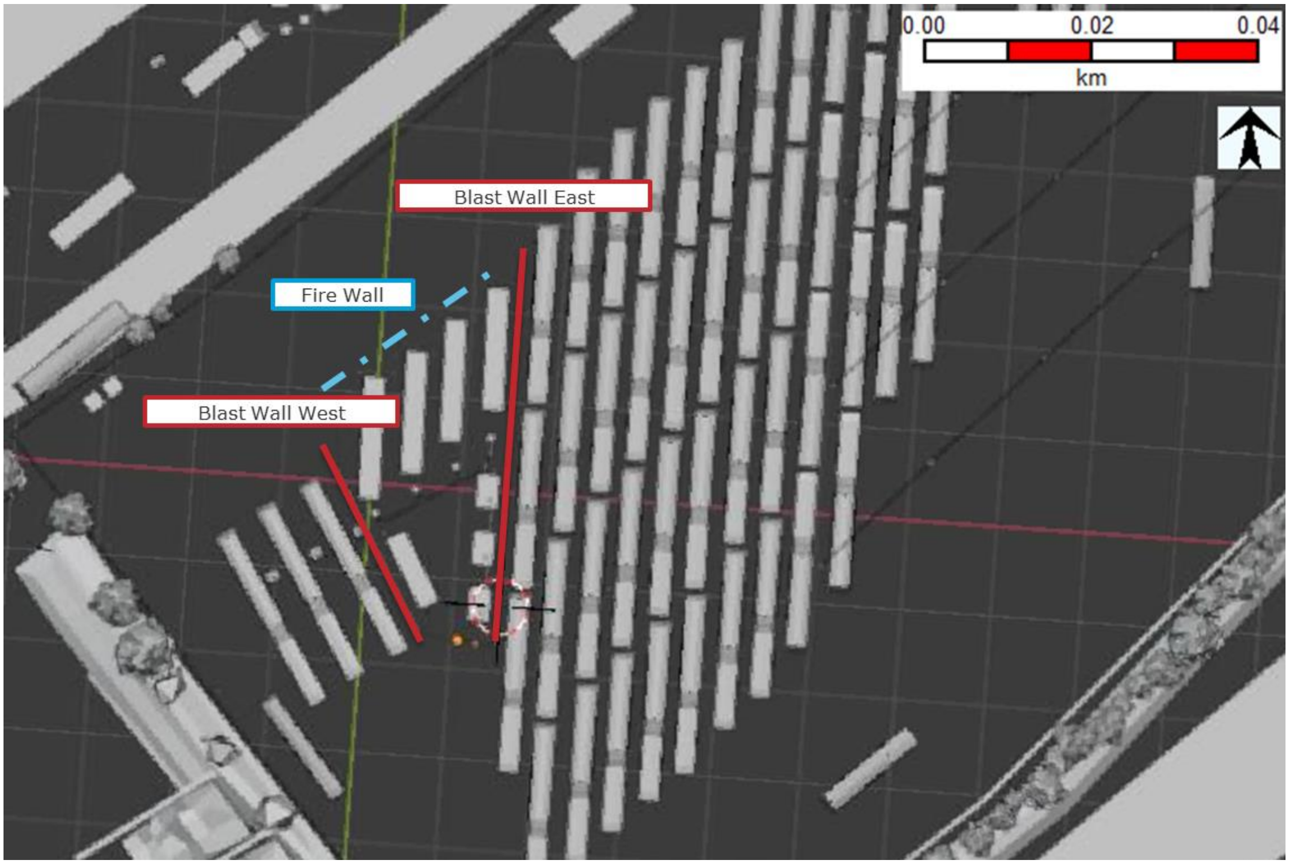


Figure 6.4 Blast walls at the filling station. It is also a short firewall to the south, see Figure 9.2.

7 MODEL SETTINGS AND ASSUMPTIONS ADOPTED IN THE QRA

In the following of the chapter, the relevant model settings and assumptions adopted for this QRA study are presented. These are summarized in Table 7-1. The assumptions are classified as *analytical*. Analytical assumptions are the basis of the analytical model developed in Safeti 8.23 for the hydrogen filling station. It should be noted that some of the assumptions are simplified because of the limitations of the software or to help with the modelling of complex scenarios.

Table 7-1 Overview of assumptions and settings used in the modeling.

No.	Description
A-01	Impact criteria adopted in the analysis for radiation and overpressure
A-02	Release size categories used in the QRA
A-03	Location of releases
A-04	Release direction
A-05	Performance requirements for the ESD system adopted in the QRA
A-06	Obstructed areas modelling
A-07	Unobstructed are explosions
A-08	Representative release height
A-09	Representative release direction
A-10	H2 bottles rupture

7.1 A-01 Radiation and overpressure vulnerability rules

The radiation and overpressure outdoor vulnerability in the current QRA is set using the *probit* model.

The probit equation for death due to heat radiation is expressed as:

$$Pr = A + B\ \ln\left(Q^N x\ t\right)$$

Where Pr is the probit value corresponding to the probability of death due to fire exposure, Q is the heat radiation (W/m2) and t is the exposure time (s). The parameters A, B and N set for the radiation probit equation are:

A	-36.38
B	2.56
N	1.3333

The probit equation is used to assess the outdoor vulnerability for fireball, jet-fire and pool-fire scenarios.

For flash fire scenarios, a fatality rate equal to 1 is assumed within the LFL concentration. The LFL fraction to finish is set as 100%.

For the modelling of the jet-fire cone, the Chamberlain model in Safeti is applied.

The probit equation for death due to overpressure effects is expressed as:

$$Pr = A + B \ln\ P^N$$

Where Pr is the *probit* value corresponding to the probability of death due to overpressure exposure and P is the peak overpressure (Pa). The parameters A, B and N set for the explosion probit equation are:

A	-16.7319
B	2.44
N	1

The impact criteria affect the risk results and the probability of fatalities due to fire and explosion events. Changed in the impact criteria might affect risk results of the QRA. The probit functions adopted for radiation and overpressure impact refer to DSB guideline ref. /5/ and /6/. It should be noted that based on this criterion, the analysis conservatively assumes infinite impulse duration resulting in a 50% fatality risk for a blast wave of 74 mbar. For the short durations of pressure waves from unconfined explosions, in particular hydrogen explosions, this criterion can be regarded as conservative.

7.2 A-02 Release sizes

The leak frequency associated with the H2 filling station are distributed per defined leak size category, as shown in Table 7-2. The hole size categories are proposed based on line/equipment size distribution considered for the concept.

Table 7-2 Leak size distribution per hole size

Size	Lower limit (mm)	Upper limit (mm)	Representative size (mm)
Small	1	3	2
Medium	3	10	5
Large	10	>>10	13 (*)

(*) for hose ruptures, the large size is considered as a full-bore rupture and the nominal diameter of the pipe is used as representative hole size.

It should be noted that catastrophic ruptures of storage tanks are represented by the Large release category with representative hole size of 13 mm. Consequences from sudden tank ruptures is this way assumed similar to consequences from a vapor cloud explosion from hydrogen. Since the frequency of this scenario is small, it is assessed that this assumption will not influence significantly on the risk results.

In the event of the tank overpressure, the pressure relief valve is assumed to be lifted and leading the gas to the vent thus limiting the frequency of tank rupture events.

7.3 A-03 Location of releases

The leak locations for the defined QRA scenarios at the filling station are represented by the green dots in Figure 7-1, Figure 7-2, Figure 7-3 and Figure 7-4.

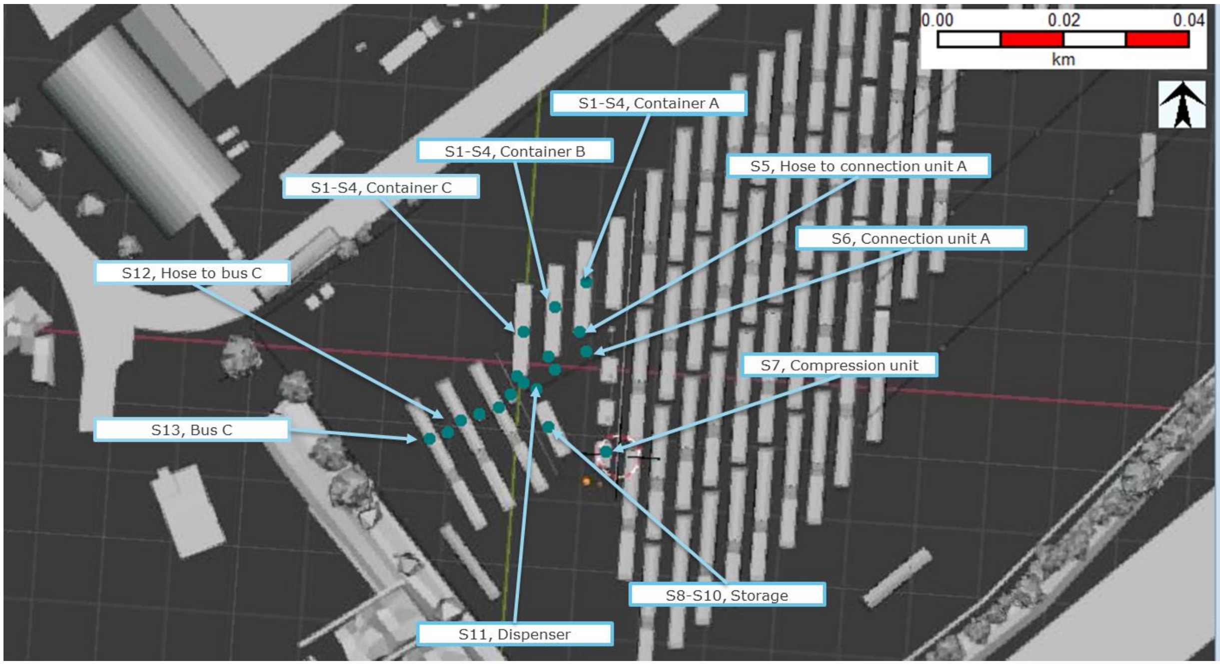


Figure 7.1 Location of releases for Case 1 (Base case: road containers and fast filling)

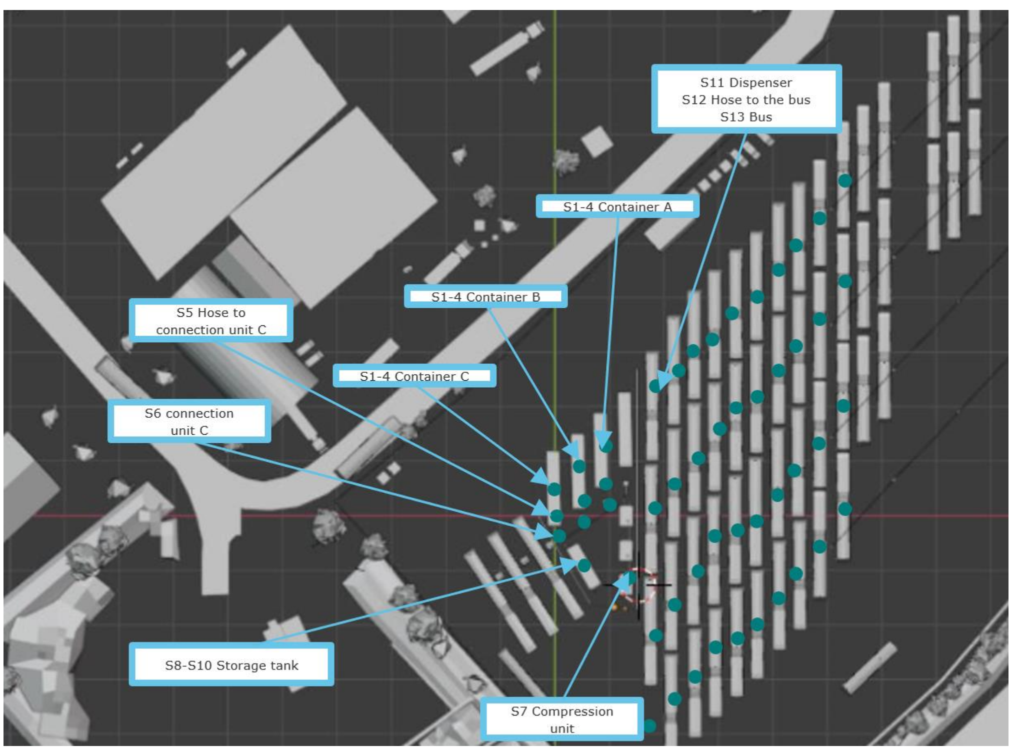


Figure 7.2 Location of releases for Case 2 (road containers and slow filling)

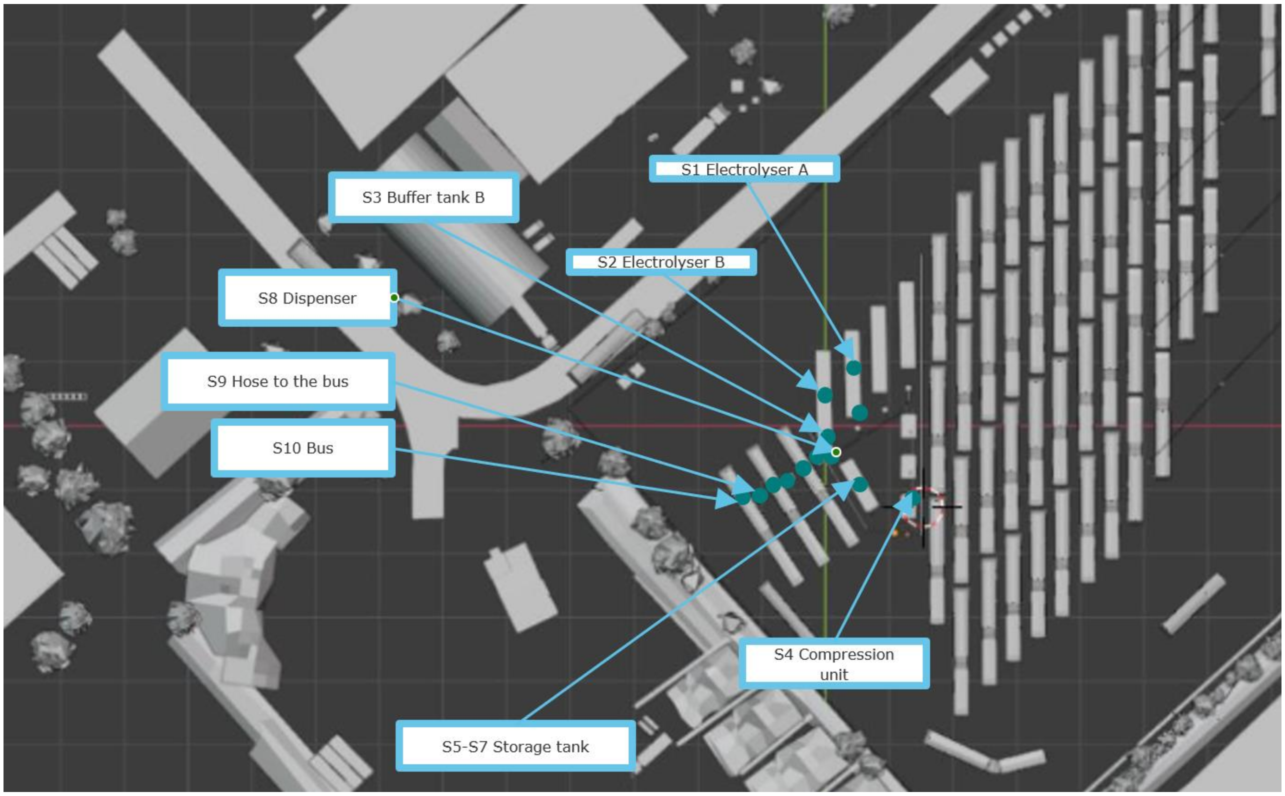


Figure 7.3 Location of releases for Case 3 (onsite electrolysis and fast filling)

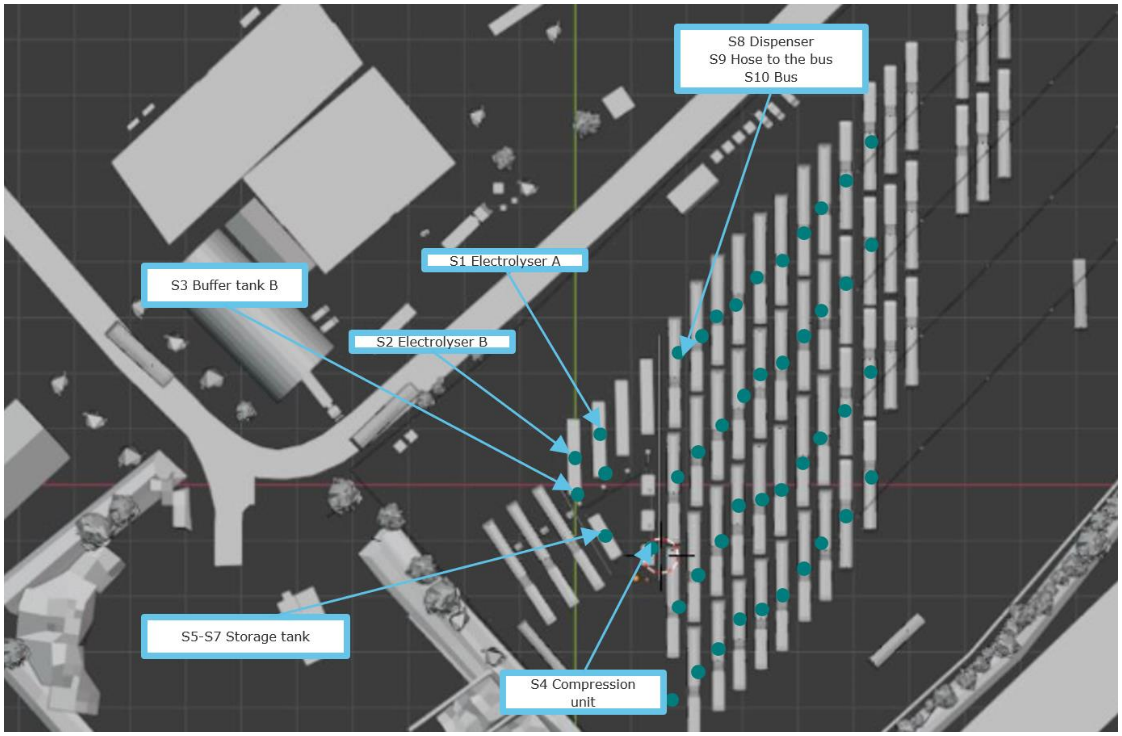


Figure 7.4 Location of releases for Case 4 (onsite electrolysis and slow filling)

The location of the leak point is an input used to calculate the risk levels during the different activities and the yearly risk for the local population. The effect of moving representative release location for the considered QRA scenarios is considered to have a limited impact on 3rd party individual risk as long as the location is within the fence of the considered layout.

7.4 A-04 Release direction

In the event of a leak, the release can be oriented in all directions. This QRA considers all the releases as angled from horizontal down towards the ground to reflect expected obstruction by other process equipment and/or blast/fire wall.

7.5 A-05 Performance requirements for the isolation system (ESD)

The time for isolation per leak size category applied in the QRA study are presented in Table 7-3.

Table 7-3 Isolation time per leak category

Release size	ESD time (s)
Small	30
Medium	10
Large	2

The PFD of the ESD system is assigned per leak size, as shown Table 7-4. For the compressor segment, it is assumed a PFD of 1% for *all* leak categories.

Table 7-4 PFD of the isolation system

Release size	PFD (%)
Small	10
Medium	10
Large	1

The assumed detection times affect the duration of the releases, and therefore inventory volume released and extent of consequences.

The assumed PFD defines failure frequency associated with isolation success/failure scenarios. It should be noted, that assumed PFD for small and medium releases greatly impacted by the size of release and thus failure of being detected when released to the atmosphere.

The PFD higher than 10% will result in higher frequency associated with isolation success scenarios, and higher risk results.

Probability of failure on demand (PFD) for safety systems. For small and medium leaks, the PFD of 10% is applied to cover the uncertainty related to the detection probability of tiny hydrogen releases. That has an impact of the outcome frequency related to the isolation success scenarios. The lower PFD, the higher the outcome frequency of the event.

7.6 A-06 Obstructed areas

Obstructed areas are inserted in the Safeti model to represent the congested volumes in the containers, around the buses, etc.

For calculating the vapor cloud explosion (VCE) overpressure, the TNO Multi-Energy method (MEM) is adopted in the study.

The MEM takes into account the total combustion energy of those parts of the cloud that are located in obstructed and/or partly confined areas (ref. /7/). An *obstructed area* is an area where obstacles are present in a configuration suited to accelerate a flame if the area is engulfed by a flammable gas mixture (ref. /7/).

The MEM is defined by two parameters:

- The blockage ratio; and
- The Multi-Energy curve number.

The *blockage ratio* is defined as the ratio of the volume of the obstructed area occupied by the obstacles and the total volume of the obstructed area itself. If this value exceeds 30%, the area is considered with high obstruction where the spacing between the obstacles is lower than 3 m.

The *Multi-Energy Curve* describes the initial strength of the blast. It is indicated by a number ranging from 1, for very low, up to 10, for detonative strength. The ME curves are shown in Figure 7.5.

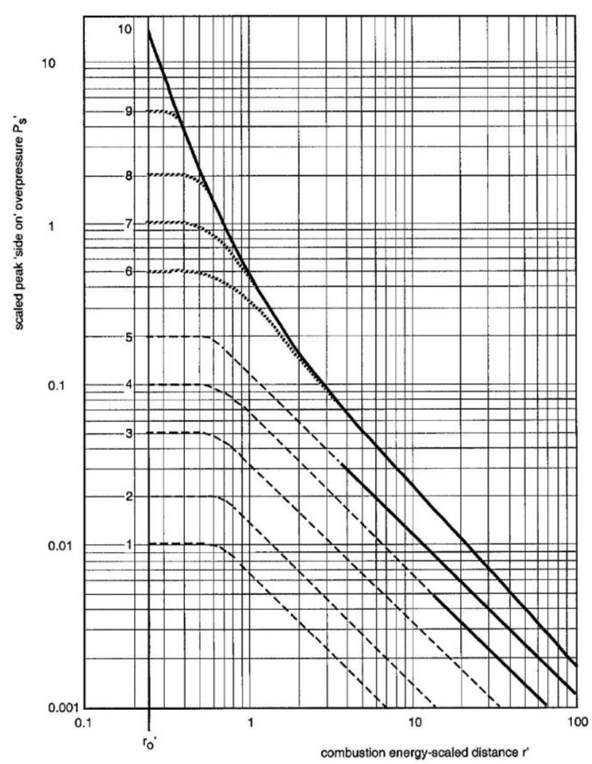


Figure 7.5 ME curves /2/.

In Safeti, a further parameter needs to be defined for the obstructed area, namely the *obstructed area height*, representing the top elevation of the obstructed region.

The obstructed areas considered for Case 1 (Base Case) are represented on the map in Figure 7.6. For the containers, the compressors and the buses the following MEM parameters have been considered:

Blockage ratio	50%
ME Curve	9 and 10

The ME curve 9 and 10 has been chosen for the current analysis to represent the high reactivity of hydrogen. In fact, the ignition and explosion potential of hydrogen clouds is several orders of magnitude higher than methane. Curve 9 is used inside the hydrogen area, and 10 by the dispensers. A comparison between the ME method and experiments is provided in a report for DSB indicating that curve 10 match best for hydrogen explosions /11/.

The height of the obstructed regions for containers and compressors is set as 3 m, while it is assumed as 3.5 m for the buses.

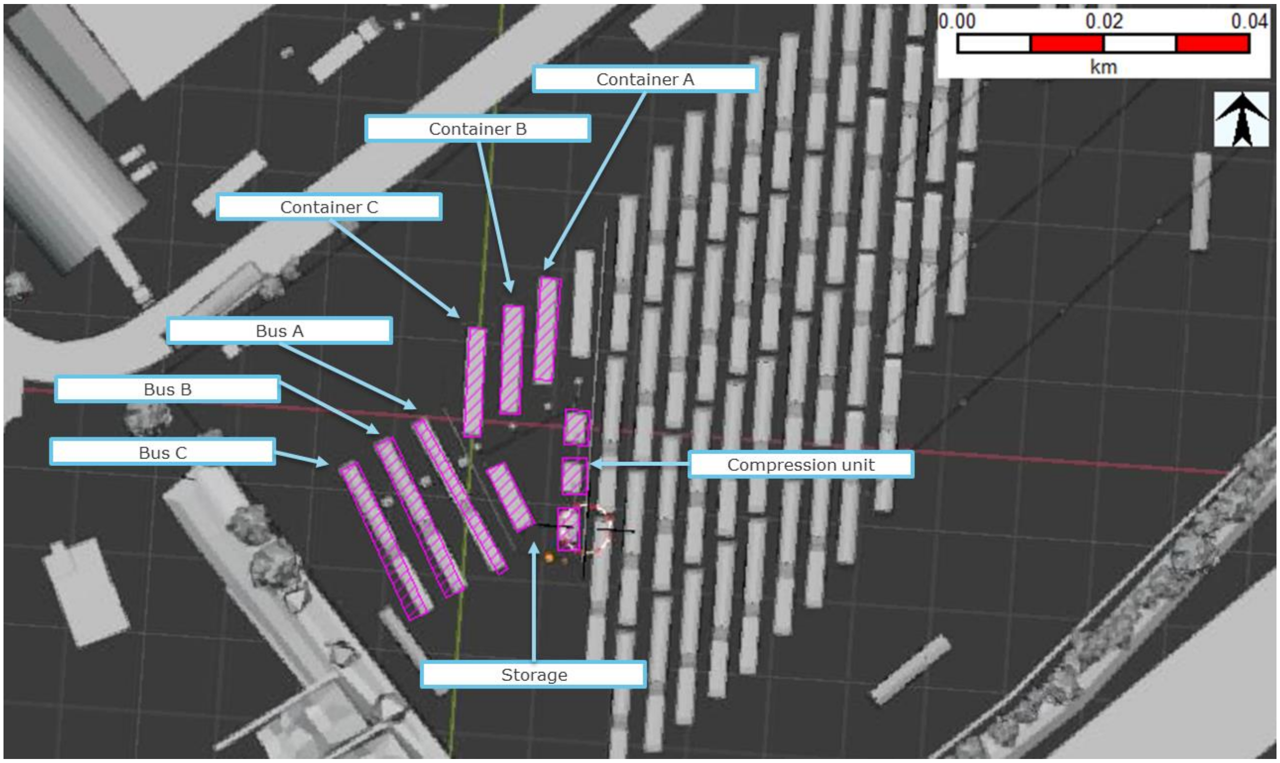


Figure 7.6 Obstructed areas for Case 1 (Base Case)

As described in chapter 6.5, 2 blast walls are planned at the Ruter filling station, one on the East and one on the West sides of the terminal. The buses are driving outside these blast walls. The North and South sides of the terminal are not protected by blast walls.

The SAFETI model has been ran with two different set-ups, using input from the CFD simulations. The risk results have been merged to obtain the final risk picture, as described in the following chapter 10.

To represent the effect of the blast wall on the west and east side of the terminal, the MEM parameters for the congested areas have been tuned. The representative curve number was selected following estimated overpressure reduction performed by CFD analysis.

The following values have been considered:

Blockage ratio	50%
ME Curve	4

It should be noted, that this set up has only been applied to systems located inside the fence. For example, dispensers and hoses to buses located outside the fence, were modelled with high explosion strength corresponding to ME curve of 9.

7.7 A-07 Unconfined explosions

Explosion happening in the obstructed area as defined as confined explosion. As opposite, explosions in the open field are called *unconfined explosions*. The unconfined explosions are represented by two parameters:

- Unconfined explosion strength; and
- Explosion efficiency.

The values adopted in the study are presented in Table 7-5 for the case with and without blast wall. The unobstructed area explosions parameters have been tuned in the model to align with CFD simulations.

Table 7-5 Unobstructed explosion parameters adopted in the model for the case with and without blast wall

Unobstructed explosion parameter	With blast wall	Without blast wall
Explosion strength	3.5	4
Efficiency	20%	100%

The unobstructed explosions are found to highly contribute to the explosion risk results, due to:

- Higher flammable mass available in unobstructed areas;
- High reactivity and ignition potential associated with hydrogen release.

7.8 A-08 Representative release height

The representative height for hydrogen releases of 1 m is modelled for all process systems comprising the facility.

7.9 A-09 Representative release direction

All releases at the hydrogen station are considered to be obstructed (either by other process systems, physical walls, or buses).

In addition, the releases occur inside the fence, will mainly be stopped by the wall from dispersing further outside the fence. For large releases part of the cloud will still be able to cross the wall, however due to the hydrogen's positive buoyancy it is not considered to touch the ground on other side of the wall.

Therefore, all events were modelled as down-impinging the ground with reduced impinged velocity factor and thus limiting dispersion length by the physical location of the fire/blast wall around the station.

7.10 A-10 Hydrogen bottles rupture

High-pressure cylinders can suddenly break and cause a powerful pressure wave, and subsequently the gas cloud can ignite resulting in a flash fire with potential explosion. Possible pressure waves from bottle fractures are not included in the risk analysis (ref. /11/). Bottles fractures are assumed to cause leaks that can develop in explosions and/or fires.

For the pressure wave, the design of a protective blast wall can be useful to limit the consequences.

It does not include the effect of projectiles or objects that come loose during an explosion or a bottle break that reaches the audience. Depending on the dimensioning and strength of a collision barrier, it can be assumed that a possible collision barrier will also prevent some projectiles from an explosion from reaching the third party.

7.11 A-11 Immediate ignition probability

The immediate ignition probability has been assumed based on insights from HyApproval and ref. /11/. The following immediate ignitions probabilities per release size in Table 7-6 have been used in the risk analysis.

Table 7-6 Immediate ignition probability per release size used in the QRA

Release category	Immediate ignition probability
Small	30%
Medium	30%
Large	40%

8 FREQUENCY AND CONSEQUENCE ANALYSIS

In the following of this section, the failure data used for the calculation of release frequencies for the Stubberud hydrogen filling station are presented. The assessed release frequencies, per ESD-segment and release size category (as defined in assumption A-02 in chapter 7), are summarized together with example consequence assessment with Safeti.

8.1 Leak frequency databases used in the analysis

In the following the database used for the calculation of release frequency adopted in the study are presented.

8.1.1 Hoses

The release frequency for the hydrogen transfer hoses is based on the Purple Book (ref. /2/). This is set as 4.4E-05 *per hour of transfer*. This is split between leak scenarios and hose rupture as 4.E-05 and 4.0E-06 per hour of transfer respectively.

A reduction factor of 50% is adopted to account of robust design and safety systems of hydrogen systems, as described in HYAPPROVAL (ref. /3/). The total failure frequency for hydrogen transfer hoses used in this QRA analysis is then 2.2E-05 per hour of transfer.

Table 8-1 Leak frequency per hour of filling for the hose /2/, /3/.

Release type	Leak frequency per hour of filling
Leak	2.0E-05
Hose rupture	2.0E-06

Failure frequency associated with hose leak/rupture scenarios. The HSE Purple book, /2/, loss of content (LOC) accidents related to road tankers, was used as a basis for leak frequency analysis conducted for hydrogen transfer hose. These frequencies may be regarded as conservative. These failure data set is considered to include failure mechanisms and causes do not fully comply with automated newbuilt hydrogen filling station. In comparison, HyRAM, /15/, hydrogen specific failure database demonstrates lower annual transfer frequencies. However, does not include failure data per filling operation with corresponding duration, enabling to reflect on specific number of fillings per type of operation (slow/fast filling). A reduction factor of 50% to HSE Purple book hose failure frequencies was adopted to account of robust design and safety systems of hydrogen operations, as described in HYAPPROVAL /3/.

8.1.1.1 S5 Hose to the connection unit (for case 1 and 2 only)

The approach described for the hydrogen transfer hose is adopted for the hose connecting the container to the connection unit to the disposal terminal (EQ.1 in segment S5) and for the dispenser hose filling the bus for hydrogen use (EQ.1 in segment S12).

*For **S5 – Hose to connection unit*** the following hours of filling per year are used in the QRA analysis:

Table 8-2 Annual number of filling hours through the hose to the connection unit (S5) for the base case (H2-containers).

Segment	Base case (H2-Container)
S5 – Hose to connection unit	2086 hours per year

For Case 1 the number of filling hours per year in Table 8-2 are based on the following assumptions:

Total number of buses filled per day	40
Kg of H2 per each bus	35 kg
Total demand of H2 per day for the bus fleet	1400 kg
Inventory of one container (S1, S2, S3, S4)	1000 kg

As described in the operational phases, each container is feeding the disposal unit in series. Given the daily consumption of H2 required to fuel the bus fleet, and given the inventory of each container, each hose is used for approximately 17 hours a day, every 2 days.

This results in:

Total filling time per year *per hose*	2086 hours per year

8.1.1.2 S12 Hose to the bus

For ***S12 – Hose to the bus*** the following hours of filling per year are used in the QRA analysis:

Table 8-3 Annual number of filling hours through the hose to the bus (S12) for the fast filling case and the slow filling case

Segment	Fast filling	Slow filling
S12 – Hose to the bus	811 hours per year	1095 hours per year

For the ***fast filling case,*** the number of hours per year in Table 8-3 are based on the following assumptions:

Total number of buses filled per day by the 3 dispensers	40
Filling type	Fast filling
Time for 1 filling	10 minutes
Total filling time per day (min)	400 min
Total filling time per day (hours)	6.7 hours

The total filling time per day is split among the three hoses for the fast filling case. The total filling time per day per hose is therefore calculated as:

Total filling time per day per hose	2.2 hours per day
Total filling time per year per hose	811.1 hours per year

For the ***slow filling case***, each of the 40 hoses fills 1 bus. The following is applied in the analysis:

Total number of buses filled per day by the 40 dispensers	40 (1 bus per dispenser)
Filling type	Slow filling
Time for 1 filling	3 hours

The total filling time per year per hose is calculated as:

Total filling time per year per hose	1095 hours per year

8.1.2 Cylinders (bottles)

For the hydrogen storage cylinders in the container (bottles, equipment no. A.4 segment A), the incident frequency is calculated based on the Purple Book (ref. /2/), as shown in Table 8-4.

Table 8-4 Small container incident frequency (ref. /2/)

Hole size range (mm)	**Nominal (mm)**	**Leak frequency small container**
1-3	2	4.40E-07
3-10	5	4.60E-07
	Catastrophic (full bore)	1.00E-07
Total		1.00E-06

8.1.3 Electrolyzers (for Case 3 and 4)

The release frequency for the electrolysers is retrieved from the EIHP2 project /13/ and shown in Table 8-5.

Table 8-5 Electrolyser release frequency /13/.

Hole size range (mm)	**Nominal (mm)**	**Leak frequency electrolyser**
0.1-5	2	4.00E-02
5-12	5	4.96E-02
> 12	13	9.17E-03
Total		9.88E-02

8.1.4 Other equipment

For other process equipment, the release frequency is calculated using the DNV GL internal software LEAK v3.3. This calculates the leak frequency based on data from the Health, Safety and Executive (HSE) Hydrocarbon Release Database (HCRD). The latest (2015) database is used in this study (ref. /1/).

LEAK is used to calculates the release frequency from valves, flanges, small bore fittings, filters, and compressors.

The frequencies are distributed per representative hole size as described in Assumption A-03.

8.1.5 Piping

The leak frequency for *process piping* in the HSE database is known to be very conservative for piping of small dimensions, and it is assessed that this type of process piping will not be representative for the small diameter piping on hydrogen plants. Therefore, instead of estimating piping length and calculate the leak frequencies for piping by use of HSE data in LEAK, the piping has been excluded from the calculation and a compensating factor of 10% has been applied to the total frequency estimate to account for the piping (ref. /3/).

8.2 Frequency assessment

8.2.1 Case 1 - Road container and fast filling - Base Case

In the following Table 8-6 and Figure 8.1, the overview of the release frequency per system at the H2 filling station for Case 1 are presented.

60% of the releases at the filling station are classified as *small,* while 30% and 10% as *medium* and *large* respectively.

The main contributors to the total release frequency for Case 1 are the hoses to the connection units (segment S5), which contributes by 50% to the total release frequency. They are followed by the hoses to the bus (S12), contributing for 16%, and the compression unit (S7, 15%).

The storage tank (S8-10) and the road-containers (S1-4) contribute for 4% and 2% respectively to the total release frequency at the filling station.

Table 8-6 Release frequency per leak category and system at the H2 filling station for Case 1

System	Total	Small	Medium	Large	%
S1-4 Containers A, B and C	5.7E-03	3.4E-03	1.8E-03	4.4E-04	**2**
S5 Hoses	1.9E-01	1.2E-01	5.8E-02	1.8E-02	**59**
S6 Connection units	6.8E-04	3.2E-04	1.8E-04	1.7E-04	**0.2**
S7 Compression units	4.9E-02	2.8E-02	1.3E-02	7.3E-03	**15**
S8-S10 Storage tank	1.4E-02	8.7E-03	4.6E-03	1.1E-03	**4**
S11 Piping to dispensers	6.7E-03	4.2E-03	1.8E-03	7.2E-04	**2**
S12 Hoses to buses	5.4E-02	3.2E-02	1.6E-02	4.9E-03	**16**
S13 Buses	2.1E-03	1.2E-03	7.1E-04	1.6E-04	**1**
Total station	**3.2E-01**	**2.0E-01**	**9.7E-02**	**3.2E-02**	**100**
%		**60**	**30**	**10**	

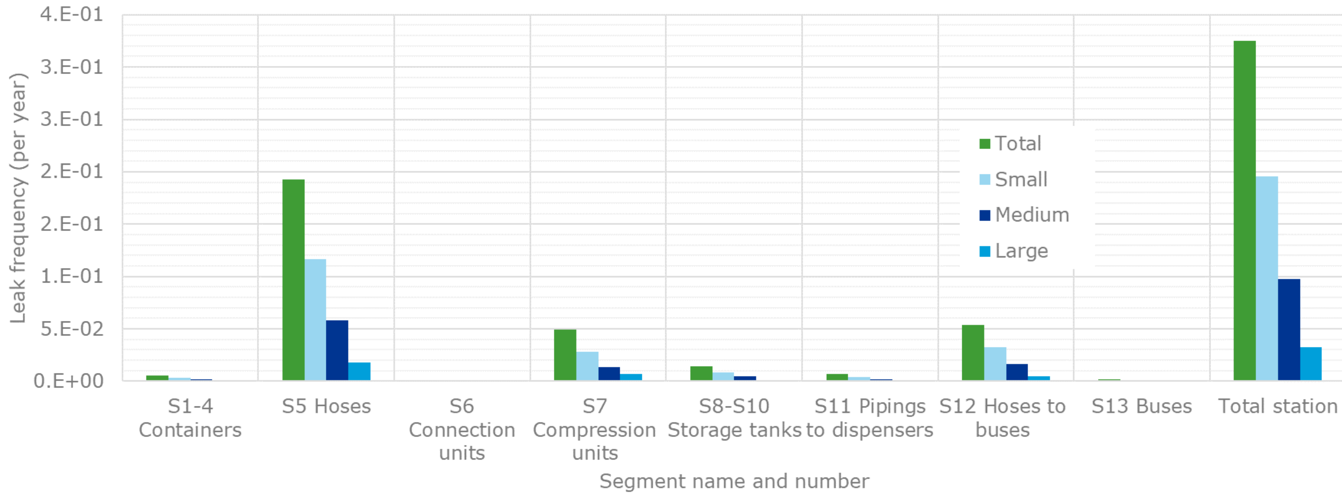


Figure 8.1 Leak frequency for the H2 filling station in Case 1 (base case).

8.2.2 Case 2 – Road container and slow filling

Case 2 includes the slow filling of 40 busses in parallel, each for a duration of 3 hours. That assumes increased number of dispensers from 3 in case 1 to 40 in case 2, in addition to number of hoses, i.e. from 3 to 40.

The “hose to the bus” segment (segment 12) is the second main contributor to the leak frequency at the HRS for the base case (case 1), which considers 3 buses loaded in parallel during fast filling. When increasing the number of buses loaded in parallel from 3 to 40 (as per Case 2), contribution of segments 11 (piping to dispenser), 12 (hoses to busses) and 13 (buses) to the total leak frequency will considerably be increased. Though, the major leak frequency impact due to the increase, will be observed outside the fence, i.e. related hoses and buses accidental releases. The leak frequency is spread over a large area where the 40 slow filling parking spaces are located, and the pipe to each bus has a smaller diameter also causing the frequency of large leaks to be reduced.

The database for hoses obtains a high contribution to the leak frequency based on observed leaks due to the manual connection point. The number of connections/disconnections of the hose is not reflected in the database; however, it is considered that the leak frequency for the slow filling will tend to reduce due to a single connection per day per hose. For comparison, the fast filling hoses will be used about 13 times per day per hose. The high leak frequency for hoses in the database is further expected to be on the conservative side for hydrogen hoses. This is also due to the tightness check that is normally performed before every filling starts to check if the connection is properly tightened.

Overall, the total leak frequency of the station will increase due to the higher number of buses connected at the same time to the HRS. Leak frequency for system inside the blast and fire wall are considered to remain the same.

8.2.3 Case 3 – On site production and fast filling

Case 3 includes the onsite production of H2 gas by electrolysis. This study assumes two electrolysers operating in parallel in producing the H2 gas feeding the HRS. The list of equipment considered for this case is shown in 6.4.

As presented in chapter 8.1, the total leak frequency for 1 electrolyser is estimated as 9.88E-02 /average year. Given that the study assumed 2 electrolysers on site, resulting in total release frequency of 1.98E-01 /average year.

The total leak frequency for the buffer storage tank between the electrolyser and the compression unit is calculated as 4.75E-04 /average year (i.e. identical to one ESD segment for the container in Case 1).

The electrolysers and the buffer storage tank, i.e S1-2 & S3 are replacing the segments S1 to S6 in the Case 1. The total release frequency for segments S1-6 in case 1 and segments S1-3 in case 3 are reported as follows:

Case 1(2)[8] **(Segments 1-3)**	**Case 3(4)**[9] **(Segments 1-6)**
1.96E-01 /average year	1.98E-01 /average year

For case 3 with onsite electrolysis, a higher number of compression stages is required compared to the base case 1 where SWAP tanks are used. The number of compression stages at the compression unit (segment 7) are therefore increased to 3. The frequency of the compressor unit for Case 3(4) compared to the Base Case 1 are summarized below.

Segment	**Case 1(2)**[10]	**Case 3(4)**[11]
7	4.9E-02 /average year	6.5E-02 /average year

The total release frequency for segment 7 in Case 3 is about 33% higher than in Case 1 for release scenarios located inside blast and fire wall.

No differences among the 2 cases are foreseen for the release frequency outside the HRS blast and fire wall.

8.2.4 Case 4 – On site production and slow filling

For Case 4, the conclusion described for Case 2 and 3 apply. The overall frequency inside and outside the fire and blast walls at the HRS will be increased due to the additional equipment related to the additional compressor stage, and increased number of dispensers, hoses and number of buses located outside blast and fire wall. This case is assessed with the highest release frequency among four (4) considered cases.

8.3 Consequence assessment

Quantitative consequence assessment with SAFETI is performed for Case 1. For the three sensitivity cases, only a qualitative assessment is performed.

8.3.1 Case 1 – Road container and fast filling - Base Case

In this chapter the consequence results for representative scenarios modelled by SAFETI are presented.

[8] Same frequency applies for Case 2
[9] Same frequency applies for Case 4
[10] Same frequency applies for Case 2
[11] Same frequency applies for Case 4

The rupture of the hoses from the containers to the connection unit at the disposal terminal and the hoses to buses are chosen are included in this Section.

These scenarios are estimated with the highest leak frequency contribution to the total leak frequency and risk results, presented in Section 8.2 and Chapter 10 correspondingly.

Figure 8.2 shows dispersion results and explosion consequence results for the max cloud footprint and worst overpressure radii from a large release from the hose.

The max cloud footprint represents the cloud width vs distance downwind from the release point. The max cloud footprint is presented as combination of cloud's "shape" and "effect zone". These are defined as follow:

- The *shape* represents the extension of the effect of the release scenario for one (arbitrary) wind direction;
- The *effect zone* represents the area where the release effects might have an impact depending on where the wind blows from. This release was modelled as angled from horizontal impinging on the ground, thus limiting the *initial* momentum of the release and its maximum dispersion distance from the release point. When releases gas hits the ground, that decreases its initial release velocity (momentum) and start spreading from around the area. In this way, the maximum dispersion distance at the ground from the release point was limited to represent the fire/blast wall on *all* the sides of the terminal.

It should be as well noted that consequence results are presented at weather conditions of 8D, which in contrast with 3F demonstrates worse consequences. The cloud is driven on longer distance downwind by the higher wind speed, and flammable concentration is preserved.

Figure 9-1 depicts the max cloud footprint. The effect zone of the cloud expands outside the assumed location of the fence. Even though the cloud has been modelled with reduced momentum, it detaches from release location (when all inventory is emptied and cloud is no longer fed by the release), it disperses beyond the fence. The flammable cloud in Safeti simulation does not "see" the obstacle in form of a wall. It is a well-known limitation of the software. Therefore, the presented dispersion results can be regarded as conservative since the gas, once released towards the ground, will eventually be blocked by the blast wall. Most of the flammable cloud volume is considered to stay inside the blast walls. The remaining volume, will go over the wall, rising due to its positive buoyancy. In the direction of the firewall, the clouds can reach outside the wall since it is partly open.

Figure 8.3 and Figure 8.4 presents the shape and effect zone for two different overpressure levels, specifically 0.03 bar and 0.074 bar for the case with and without the blast walls on the east and west side of the terminal. These overpressures are aligned with used *probit* values representing a probability of fatality of 1% and 50% correspondingly.

Figure 8.3 is considered representative for the east and west sides of the terminal, while Figure 8.4 for the north and south (since there are no blast walls on these two directions).

Figure 8.2 Max cloud footprint (shape and effect zone) for large releases from the hose to the connection unit A at a height of interest of 1 m. The concentration of interest is equal to LFL, at 8D wind conditions.

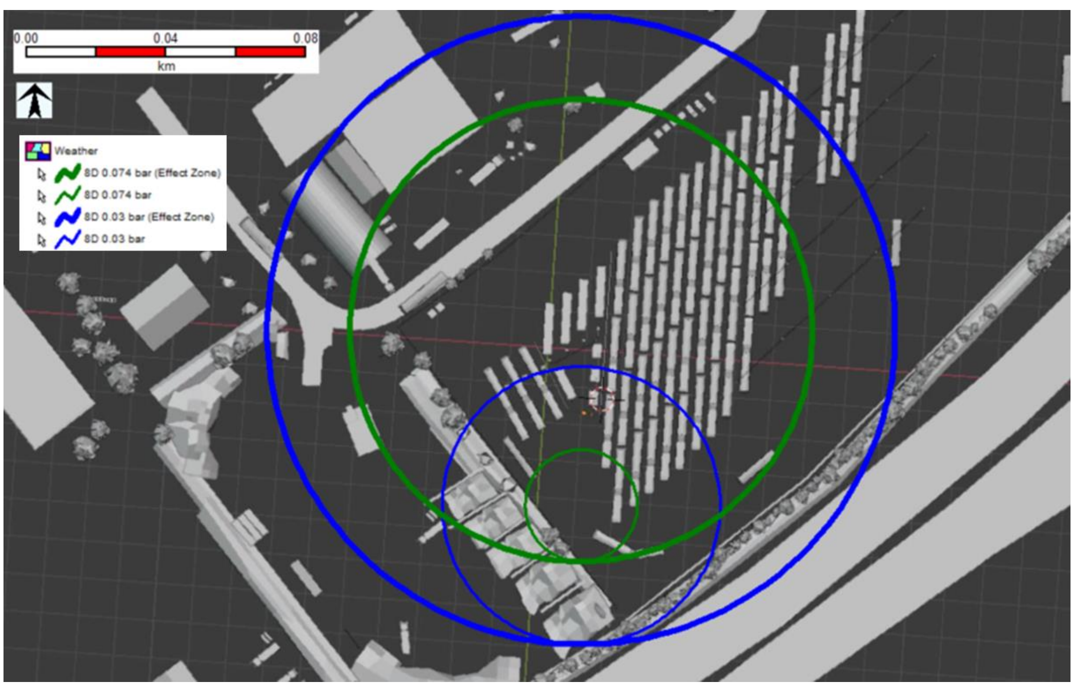


Figure 8.3 Worst case explosion radii (shape and effect zone) for large releases from the hose to the connection unit. The blue contour represents the shape and effect zone for an overpressure of 0.03 bar and the green one for 0.074 bar and the at wind condition of 8D. This figure refers to the case <u>with</u> the blast wall. This is representative for the east and west side of the terminal.

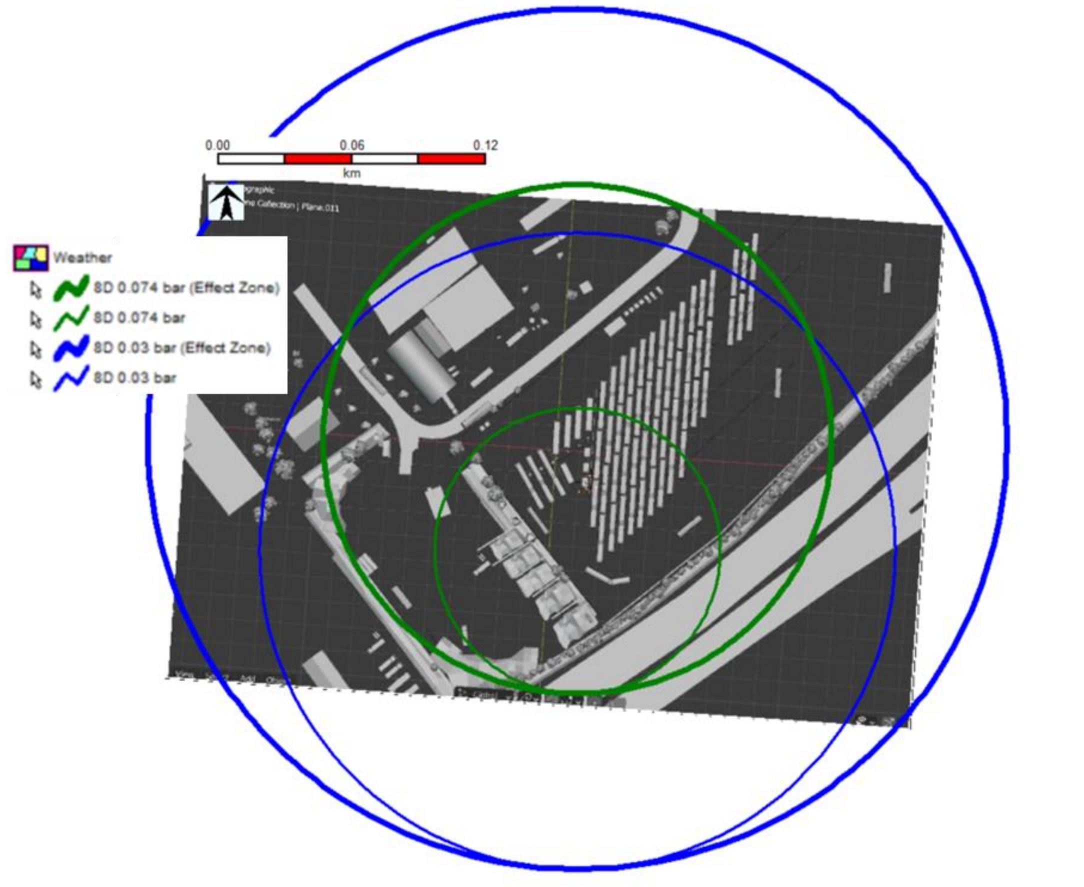


Figure 8.4 Worst case explosion radii (shape and effect zone) for large releases from the hose to the connection unit. The blue contour represents the shape and effect zone for an overpressure of 0.03 bar and the green one for 0.074 bar and the at wind condition of 8D. This figure refers to the case <u>without</u> the blast wall. This is representative for the north and south side of the terminal.

It should be noted that the dispersion and explosion results depicted below represents the max flammable cloud dimensions/worst overpressure radii for the worst wind conditions and entire duration of the release and are therefore not representative for the risk drivers. Figure 8.3 and Figure 8.4 are meant to illustrate the effect of different overpressure levels given different explosion set up representing scenarios with blast wall east/west of the station, and without blast wall north/south of the station.

8.3.2 Case 2 – Road container and slow filling

The consequence results assessed for Case 1 inside the firewalls are considered to remain representative due to the no change in inventory volume, and process conditions. Outside the firewall, the events will be moved to the east side where the 40 slow filling places are located. The events will have smaller leak rates due to the reduced pipe size to each bus. This will result in less flammable volume in case of accidental release and shorter dispersion distances.

It is assumed that a good and reliable ESD system with leak and gas detection is in place at each slow filling place. This system should detect a gas leak and stop it before it can generate a critical gas cloud. The consequences from a large leak that is not shut down by the ESD system can be critical if for example a bus is filled with hydrogen gas. Before this system is implemented it should therefore be demonstrated that a critically large leak is detected. Small leaks can be very difficult to detect in open air due to the good ventilation, and as long as they are small enough, it does not cause serious consequences. Small leaks can however develop to a larger leak; hence effort should be made to detect as small leaks as possible.

8.4 Case 3 – On site production and fast filling

The consequence results associated with the main contributor to the leak frequency, i.e. electrolysers, are considered to reduced compared to case 1 represented by the hoses to the connection unit. That is explained by significantly lower operating pressure, i.e. 35 barg vs 350 barg, effecting thus initial leak rate and momentum, resulting in less flammable mass released prior segment isolation. That is considered to impact size of the flammable cloud and potential exposure of the defined obstructed regions. The number of compressors and the permanent storage capacity is increased causing case 3 to increase the consequences and become similar to case 1. Overall, similar extent of consequences is considered.

8.5 Case 4 – On site production and slow filling

As for Case 3, similar consequences associated with the main contributor to the leak frequency, i.e. electrolysers and the increased compression capacity, located inside the fence is expected. Outside the fence, the consequence is as described in case 2.

9 EXPLOSION RISK ANALYSIS AND RESULTS

An explosion risk analysis is performed as a part of the QRA. The ERA uses leak frequency and definitions of the station layout, fluid and flow properties, safety systems and weather from the QRA. Results from the ERA in terms of delayed ignition probability is used as input to the QRA model. The ERA also has standalone results in terms of the pressure exceedance curve and detailed design specifications that are found from the CFD simulations.

The ERA uses detailed 3D models to calculate the ventilation conditions within the station, and consequences from gas dispersion and explosion simulations. These consequence results are used as input to the ERA model EXPRESS.

9.1 Site design concept

Figure 9.1 provides an overview of the area designated for bus parking, including the hydrogen refueling station located in the northwest part of the lot (marked in orange). The right side shows stipulated parking spots for buses and a close-up of the site allocated for hydrogen refueling. Allocated area equal 12 full-length parking spots.

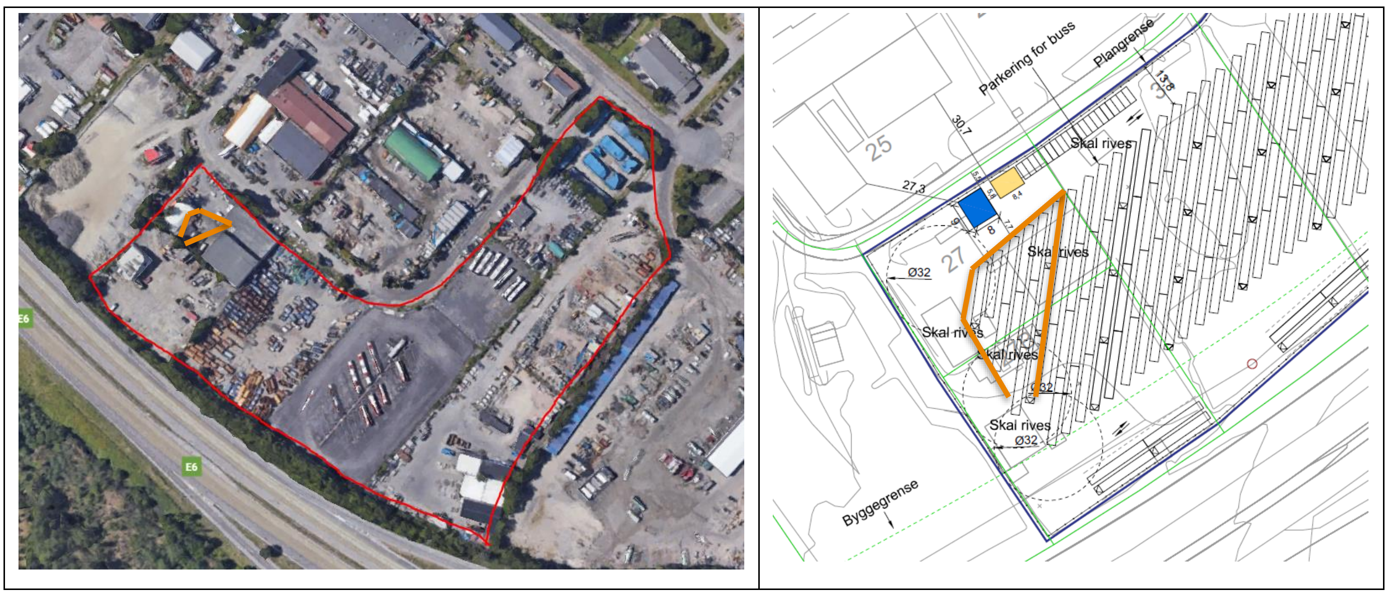


Figure 9.1 Aerial photography of the site planned for Ruter's bus parking facilities (marked in red). The hydrogen fueling station and process equipment are assumed to be situated inside the orange shape.

A preliminary concept for the design and equipment-layout of the station was developed during the HAZIDs to serve as a *base-case* geometry, see Chapter 5.

The technical/operational requirements include the following:

- Accessibility for on-truk delivery of four 45-foot containers with storage tanks. Under normal operations there are 3 full/active containers and one empty slot for swapping. In the model it is modelled with all four containers in place as it would be only during swapping.
- 3 compressor housings (provides redundancy that can operate in the event of malfunction)
- 3 easily accessible hydrogen dispensers for simultaneous filling (and redundancy in case of malfunction
- Buffer tank for compressed H2 (before connection to dispensers).

- Walls to protect from explosions and fires and prevent intrusion from unauthorized persons.

The suggested site layout is constrained by available area and the necessary equipment (listed above). Additionally, the following features and equipment are implemented in the geometry model for mitigation of safety risk:

- A main axis for natural ventilation is laid in a north-south direction. Ventilation is essential to prevent and mitigate the build-up of explosive clouds resulting from hydrogen leakage.
- Concrete walls (4 meter in height) on two sides to prevent gas spread, to reduce explosion pressure, and to stop jet fires and projectiles.
- Perforated fire walls (fire grid) with 1-meter openings at the ground on the remaining sides that provide natural ventilation. Such walls will also stop or slow down jet fires and projectiles, but do not provide the same protection against explosion pressure and allow gas clouds to spread by the wind.
- Piping inside the area is assumed to be above ground, while piping out to dispensers goes underground.

Adhering to the requirements listed above and evaluating compromises between practical feasibility and expected impact on safety risk, the design illustrated in Figure 9.2 was concluded to serve as the base case. The location of the various equipment, including tanks, compressors, dispensers, radiation grating, walls and piping are illustrated as an overlay over a photography of the (undeveloped) lot.

Tank delivery will take place through gates on the north side of the enclosed hydrogen equipment site, while refueling are performed on the west side. Three busses can refuel simultaneously without blocking the nominal clockwise driving direction through the bus depot. Concrete blast walls reduce explosion pressures toward the parking lot as well as dispensers and west neighbors. The container walls will prevent sideways directed jet fires from the end of the containers to hit the sides of the tanks.

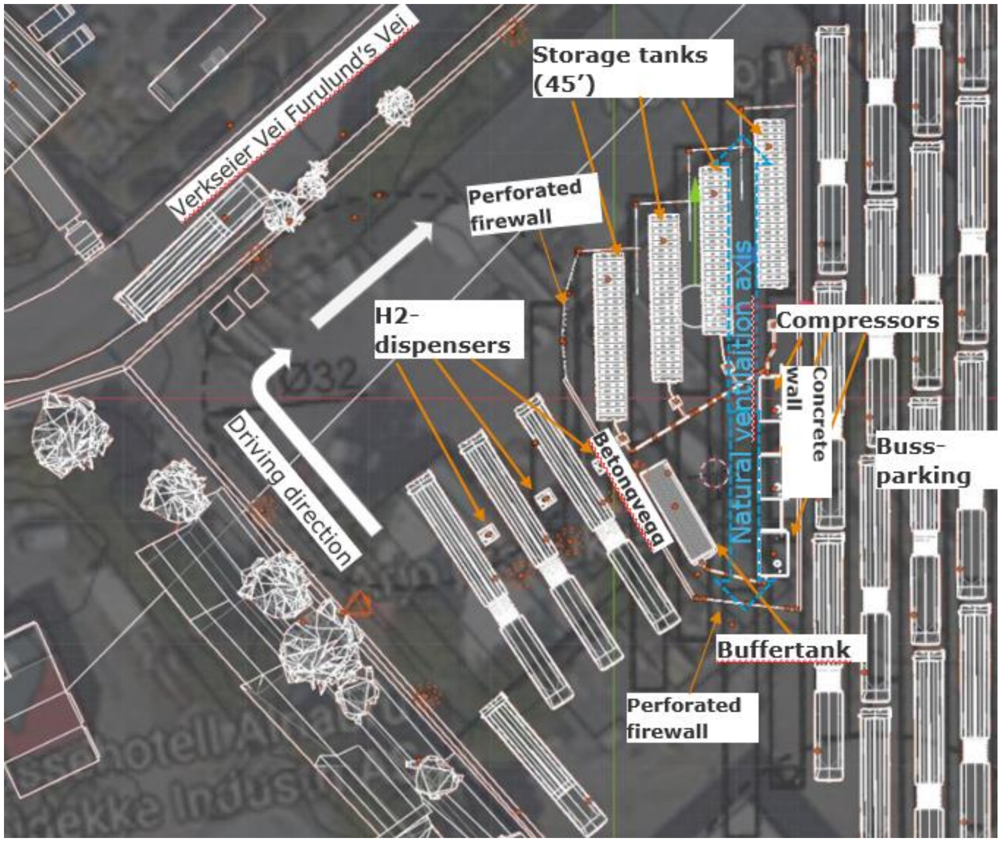


Figure 9.2 Wireframe representation of the base-case site layout as seen orthogonally from above.

9.2 Geometry model

In order to investigate the safety performance of the site design using detailed simulations of gas dispersion and explosions, a 3D model of the concept facility was constructed. Figure 9.3 and Figure 9.4 shows snapshots of the model placed over a 1-meter grid. The Y-axis (green line) was set to align with the east blast wall, which again is aligned with the angle of the bus parking lots. For simplicity of reference Y is referred to as site north, which is offset some degrees from true north.

Note that the geometric model not a technical drawing and will likely differ, perhaps significantly, from the final equipment. It is to be considered a high-level general visualization/illustration, but serve a valuable approximation of geometric extent, shape, and location to serve as a basis for simulations.

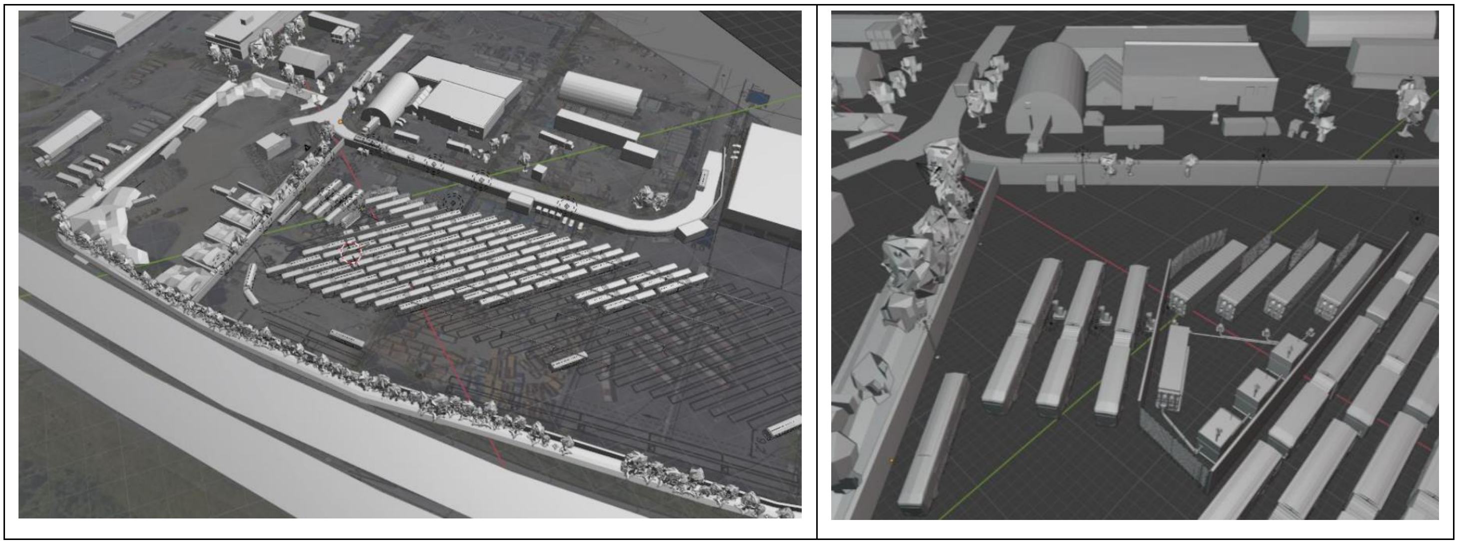


Figure 9.3 Overview screenshots of the 3D model projected onto aerial photography and 1-meter grid.

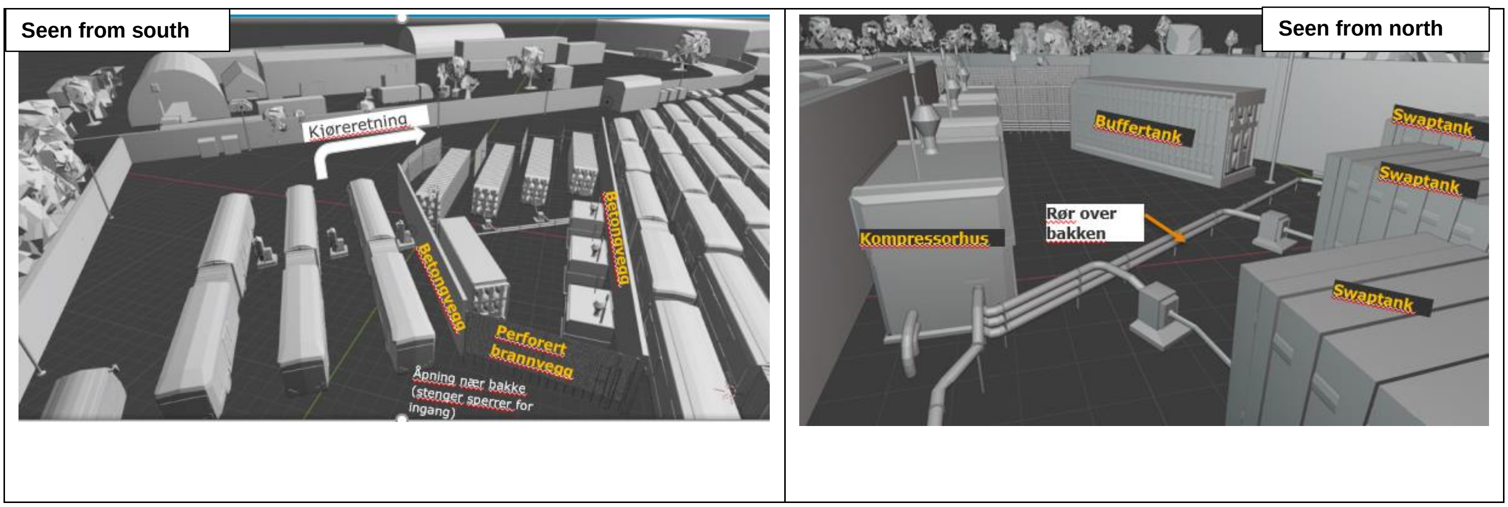


Figure 9.4 Close-up screenshots of the 3D model on a 1-meter grid, illustrating the placement of individual equipment.

DNV

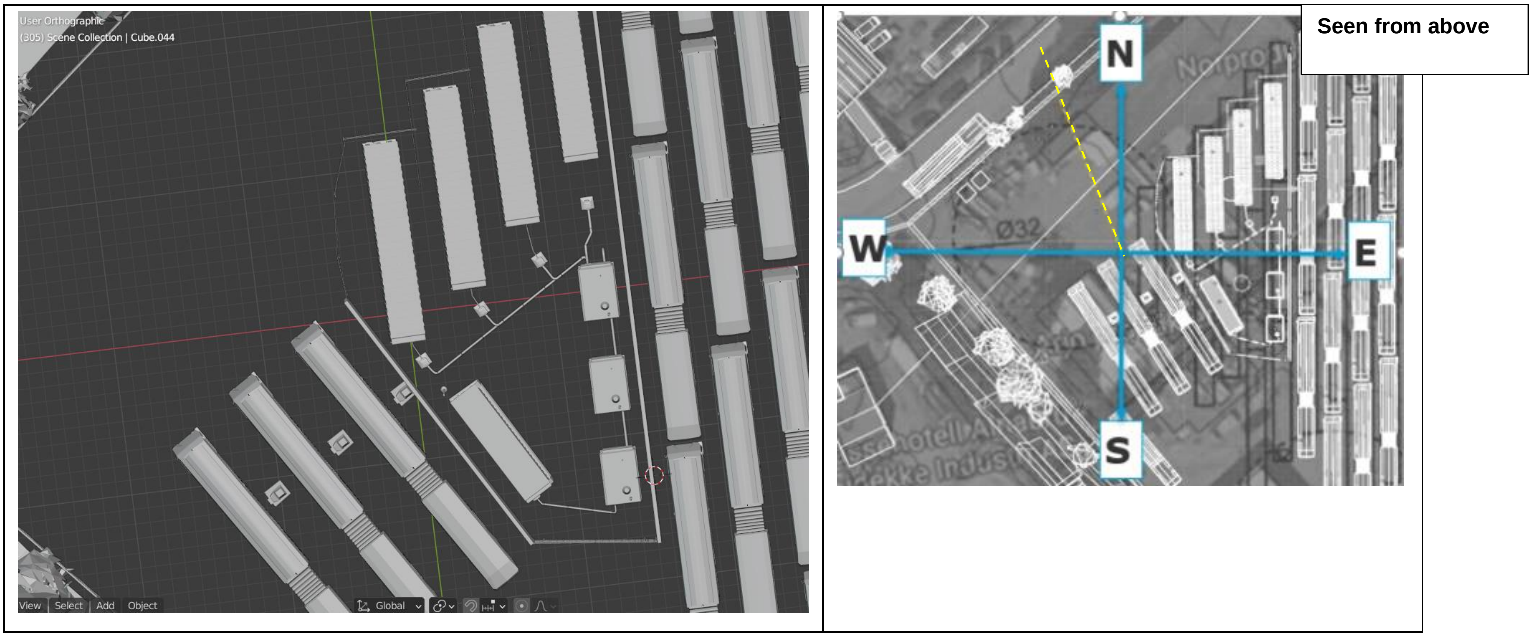


Figure 9.5 Model viewed orthogonally from above. The right image shows site directions compared to true north, represented by a yellow dashed line.

9.3 Airflow and ventilation analysis

In order to determine the ventilation level of the base-case hydrogen station, eight simulations featuring different wind directions were conducted. These purpose of these simulations, run without gas release, were to track the air flow through the site and to calculate the level of natural ventilation.

Figure 9.6 and Figure 9.7 depict velocity vectors of free flow cells, indicating how the air circulation behaves inside the vicinity. Comparing wind form northeast and northwest, it is evident that regions of turbulence, stagnation and re-circulation varies significantly depending on wind directions. For instance, in more confined areas between tanks and walls, opposite velocity patterns appear for the different wind directions. The swap tanks cause some stagnation zones immediate down-wind, but for the northeast case, effective channeling/air flow appears between the swap tanks.

In general, it appears airflow is reduced to half speed in approximately half of the enclosed area. The least effective natural ventilation comes from the southwesterly direction, where the concrete wall results in very low airflow within the station.

In contrast, wind from opposite direction, i.e., northeast, brings the most effective natural ventilation in most of the vicinity. An exception is the area between the compressors and the east blast wall, where stagnation occurs during northeasterly wind.

Table 9-1 provides an overview of the conducted ventilation simulations and the resulting ventilation, given in absolute rates (m^3/s) and relative rates (ACH).

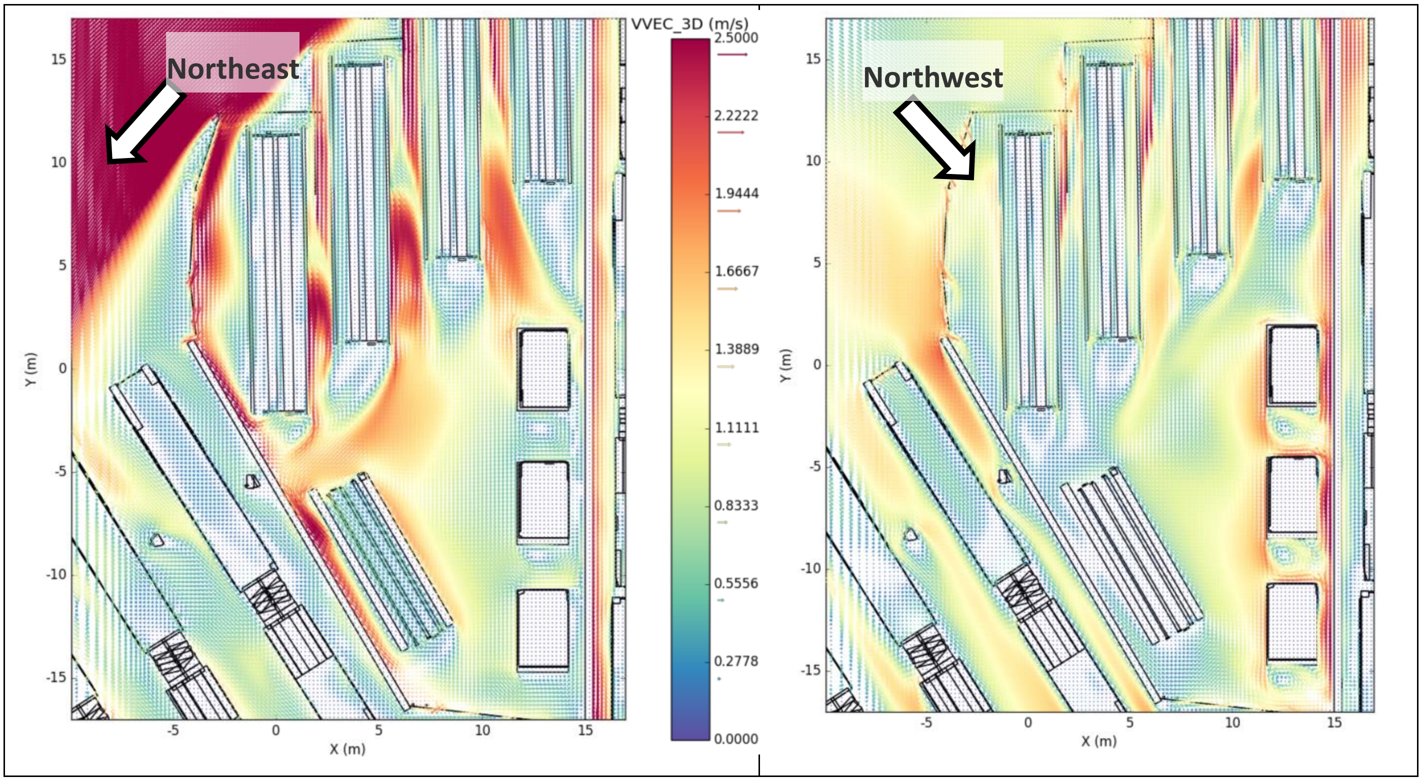


Figure 9.6 Wind velocity vectors illustrating air circulation patterns during wind from indicated directions.

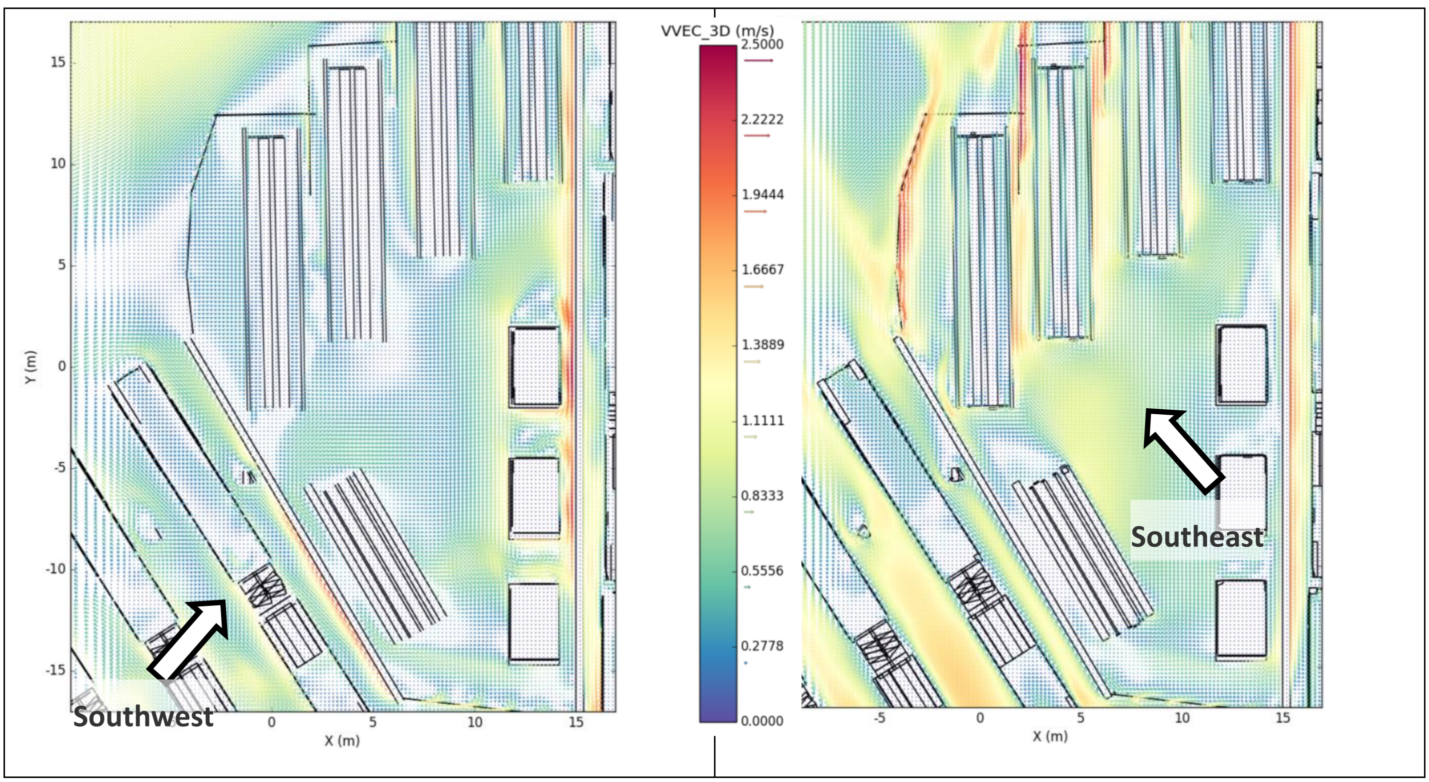
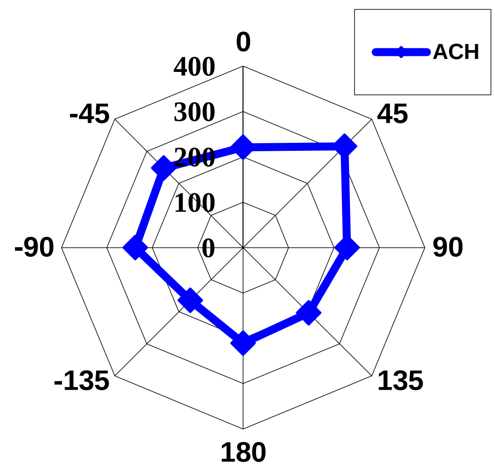


Figure 9.7 Wind velocity vectors illustrating air circulation patterns during 4 m/s wind from indicated directions

Table 9-1 Simulated cases and resulting ventilation rates. ACH refers to air changes per hour. Wind speed for all cases is 4 m/s.

Case Nr	Wind Dir	Site ref	ACH	Qa [m^3/s]
010101	0	N	221	332
010102	45	NE	315	473
010103	90	E	229	343
010104	135	SE	204	306
010105	180	S	211	316
010106	-135	SW	165	247
010107	-90	W	237	356
010108	-45	NW	247	371



9.4 Gas dispersion analysis

9.4.1 General

Following up the ventilation study described above, the next step was to investigate the potential for build-up for flammable hydrogen concentrations in the vicinity as result of a leak. Hydrogen is a highly volatile gas compared to hydrocarbons and other types of fuel, which quickly turns flammable when mixed with air.

Explosion pressures is strongly (exponentially) correlated with cloud sizes, which makes detailed gas dispersion simulations an important step in an explosion risk assessment. The methodology involves running a large number of simulations of different leak scenarios subjected to various wind conditions, transiently tracking gas concentrations and hence flammable clouds developing in the vicinity.

While it is unfeasible to simulate all possible/credible leaks, a simplification is employed by attributing the total expected frequency of leaks to a *representative leak-point*. The representative leak point is chosen as a credible (realistic) scenario. Different leak directions are also selected with some worst case and some realistic leak directions.

Figure 9.8 shows the location of the representative leak point, labelled L1, at the south end of swap container number two from west. Yellow arrows indicate leak directions considered in this report, which includes downward impinging, southward and eastward. The southward jet is considered especially critical as it will impinge onto the buffer tank and fill the void spaces within with gas. Downward jet will also cause a large cloud since it can spread more along the ground.

The hydrogen leak is driven by a back-pressure of 300 barg and is assumed to exit the rupture point at a velocity of approximately 650 m/s, equal to half the Mach-speed of hydrogen. Hole sizes range from 0.004 m^2 to 0.02 m^2, producing hydrogen jets with mass rates of 0.1 kg/s to 1 kg/s. These leak rates represent medium leak rates in the QRA.

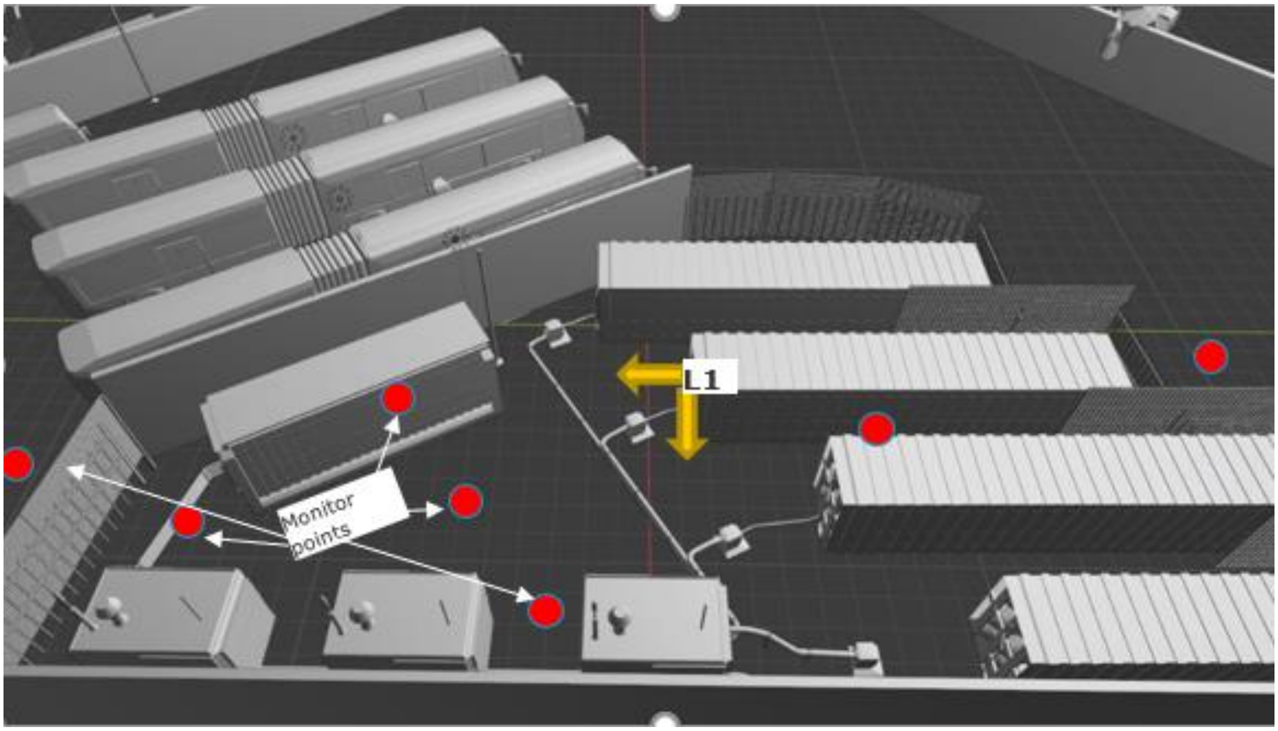


Figure 9.8 Representative leak point and placement of some of the virtual monitor points. Yellow arrow indicates simulated leak directions. The cloud volume is also monitored within the entire region to find it size.

9.4.2 Simulations

Simulations are conducted using the CFD software FLACS /4/. Simulations were run until *steady-state* on a high resolution grid of 4 million cells, with cell sizes as small as 0.06 m in the area of interest.

contains a complete list of the gas dispersion simulations conducted as part of this analysis. To enable direct assessment of the impact of individual parameters, groups of simulations (shaded grey) is run multiple times with only a single parameter change.

A volume of 5400 m3 is applied where the explosive gas cloud volumes Q9 are calculated from FLACS. This volume is 30, 45 and 4 m in the x, y and z directions, respectively.

Table 9-2 Table of simulated cases and main parameters. The resulting maximum cloud size with the equivalent stoichiometric cloud (Q9) is also listed.

Case number	Leak rate [kg/s]	Leak direction	Wind direction [deg]	Wind Speed [m/s]	Cloud size Q9 (m3)
203001	0.1	S	0	4.0	2
203002	0.2	S	0	4.0	4
203003	0.2	S	0	2.0	5
203004	0.5	S	0	3.0	37
203005	0.5	S	0	10.0	24
203006	1.0	S	0	3.0	65
203007	0.1	S	90	4.0	3
203008	0.2	S	90	4.0	6
203009	0.2	S	90	2.0	5
203010	0.5	S	90	3.0	41
203011	1.0	S	90	3.0	69
203012	0.1	Down	180	4.0	28
203013	0.2	Down	180	4.0	76
203014	0.2	Down	180	2.0	75
203015	0.5	Down	180	3.0	226
203016	1.0	Down	180	3.0	143
203017	0.1	Down	45	4.0	17
203018	0.2	Down	45	4.0	42
203019	0.2	Down	45	2.0	45
203020	0.5	Down	45	3.0	125
203021	1.0	Down	45	3.0	143
203022	0.1	Down	270	4.0	14
203023	0.2	Down	270	4.0	63
203024	0.2	Down	270	2.0	55
203025	0.5	Down	270	3.0	178
203026	1.0	Down	270	3.0	158
203027	0.1	Down	90	4.0	22
203028	0.2	Down	90	4.0	55
203029	0.2	Down	90	2.0	51
203030	0.5	Down	90	3.0	209
203031	1.0	Down	90	3.0	176
203032	0.1	S	180	4.0	3
203033	0.2	S	180	4.0	7
203034	0.2	S	180	2.0	5
203035	0.5	S	180	3.0	37
203036	0.5	S	180	10.0	0
203037	1.0	S	180	3.0	68
203038	0.1	S	270	4.0	4
203039	0.2	S	270	4.0	6
203040	0.2	S	270	2.0	5
203041	0.5	S	270	3.0	38
203042	1.0	S	270	3.0	72
203043	0.1	E	90	4.0	1
203044	0.2	E	90	4.0	5
203045	0.2	E	90	2.0	5
203046	0.5	E	90	3.0	39
203047	0.5	E	90	10.0	20
203048	1.0	E	90	3.0	110

9.4.3 Gas clouds at maximum cloud size

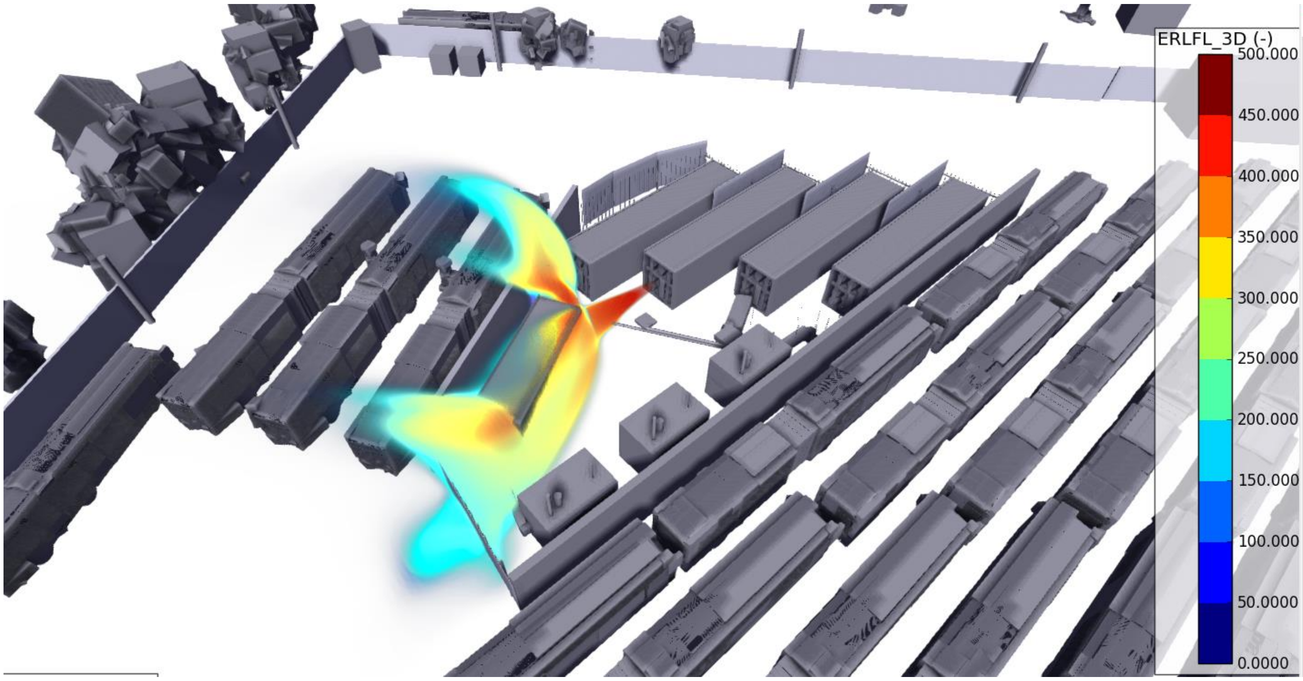


Figure 9.9 Leakrate 1 kg/s southward jet released from container #2, impinging on the buffer-tank. Colored regions indicate flammable gas mixtures.

Figure 9.9 shows a 3D volumetric rendering of a gas cloud at a time when the cloud is fully developed. Colors indicate regions of combustible mixtures (or denser). A high velocity 1 kg/s hydrogen jet is released southward from container #2 impinging on the buffer-tank, in which deflects the jet as demonstrated in the plot. Flammable concentrations pervade the entire west length of the site and roughly five meters beyond the radiation grating at the south side. Flammable clouds also ascend to well over the height of the wall (>5 m), but horizontally the clouds are mostly contained within the limits of the enclosed area.

Figure 9.10 shows concentration contours for the same scenario for four different leak sizes, i.e., (0.1, 0.2, 0.5 and 1 kg/s). Again, the color scale is defined so that all colors depict flammable concentrations, with dark blue representing the flower flammable limit. For the smallest release of 0.1 kg/s, combustible mixtures are limited to the void spaces inside the buffer-tank. At 0.5 kg/s, the space between the buffer-tank and the blast wall becomes flammable. For all leak sizes, the jet is mixed with sufficient oxygen to become flammable it impinges on the container wall.

Changing the leak direction to downward (impinging on the ground) results in a quite different gas cloud, as shown in Figure 9.11. Here, the entire area south of the swap containers, including spaces between compressors are subjected the flammable mixtures. It is also evident that void spaces inside the leaking swap container is becoming flammable regardless of wind directions.

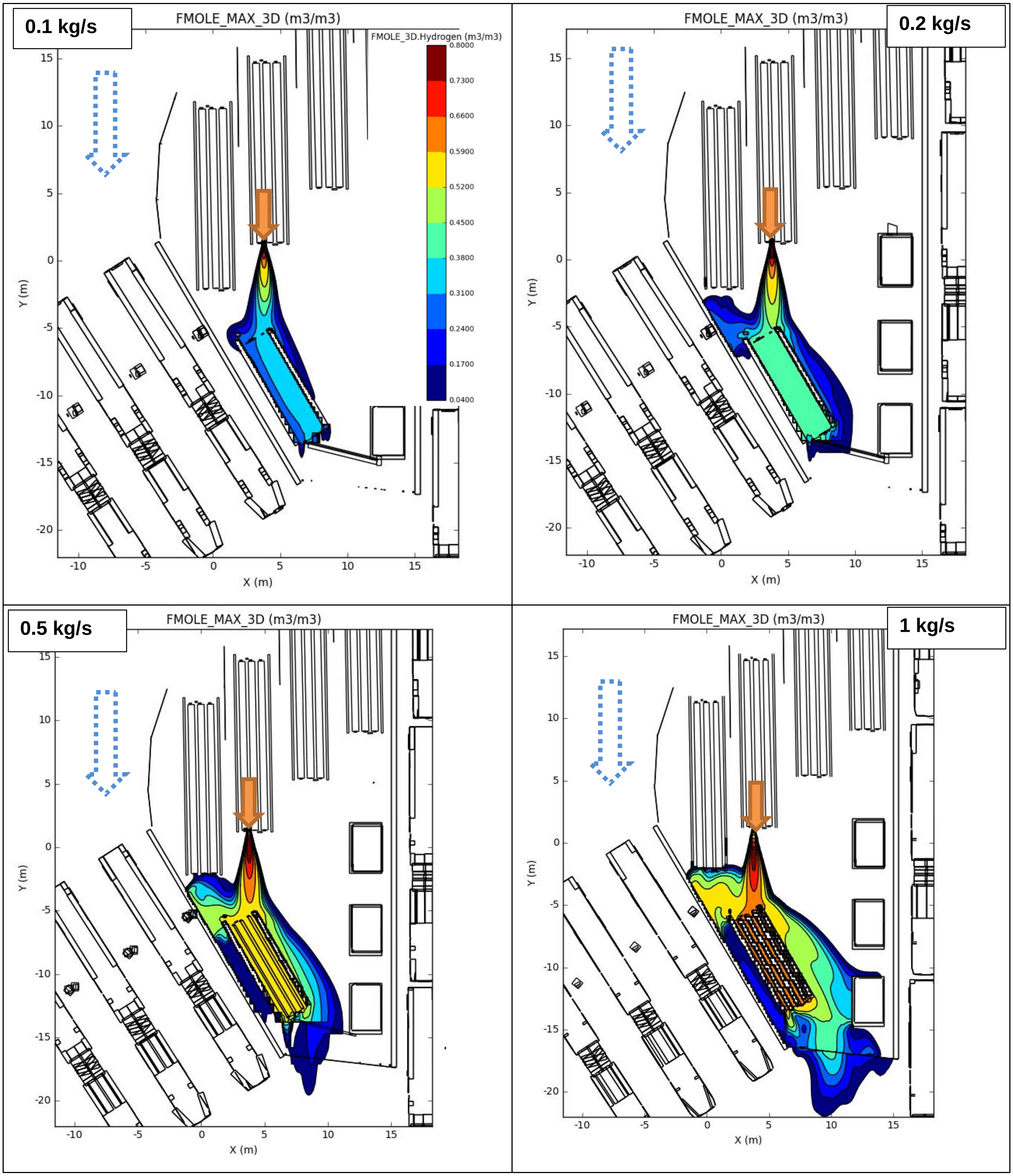


Figure 9.10 Contours of hydrogen concentration (at z=1.5 m) generated by a southward jet of indicated size, during northerly wind.

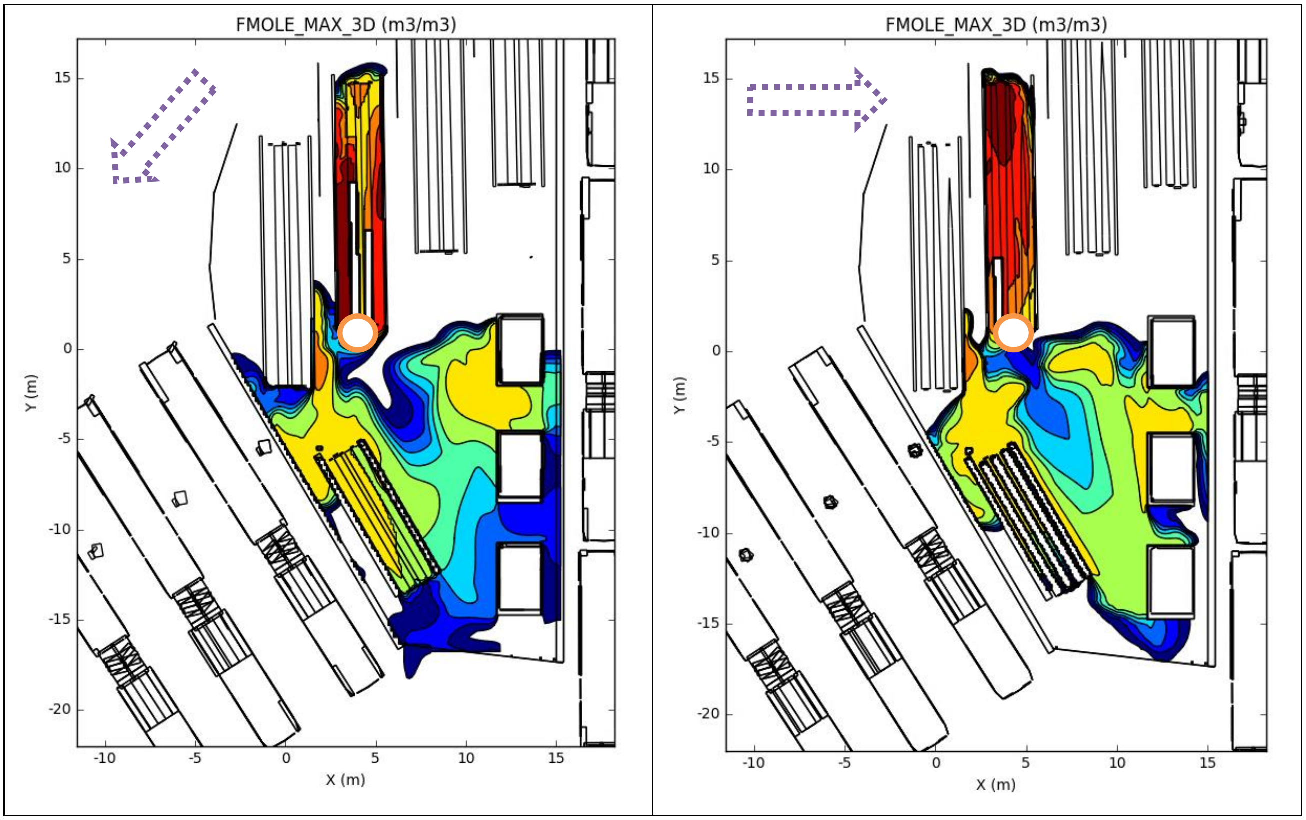


Figure 9.11 Contours of hydrogen concentration (at z=1.5 m) generated by a 1 kg/s downward impinging leak during 4 m/s wind from indicated directions.

9.4.4 Transient cloud development

The primary output of the dispersion simulations is the equivalent stoichiometric gas cloud, i.e., the hypothetical resulting volume when taking all of the heterogenic gas distribution in each of the cases above and distributing it evenly to a homogenic cloud at exactly stoichiometric concentration. The evolution of the size of the equivalent stoichiometric cloud are shown in Figure 9.12 and Figure 9.13.

For clarity and detail, small releases are plotted in Figure 9.12 while all larger releases are plotted in Figure 9.13. In general, the results indicate that 0.1, 0.2, 0.5 and 1 kg/s respectively result in cloud sizes in the approximate magnitude of 5-20, 20-50, 70-150 and 150-200 m^3. It should be noted that the cloud sizes are dictated as much by the leak direction as the leak rate; downward impinging leaks result in significantly larger clouds than free horizontal jets.

The build-up time varies significantly from case to case, where some cases reach full cloud size within 10 seconds while others take up to 90 seconds to reach final size.

The quick gas buildup is illustrated in Figure 9.14 where it is seen that the container sees gas inside across to the end already after 1 s, and after 2-3 s, a critical gas cloud is formed.

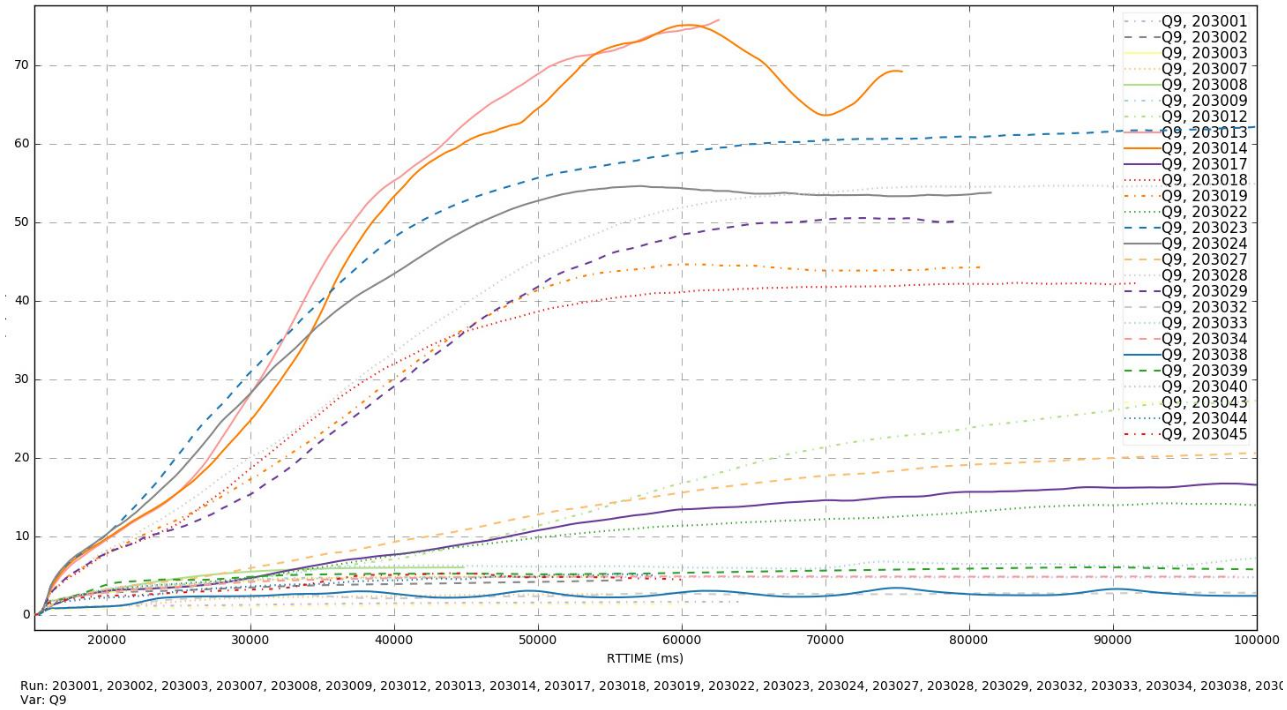


Figure 9.12 Could size (stoichiometric equivalent) versus time for small releases (<0.2 kg/s).

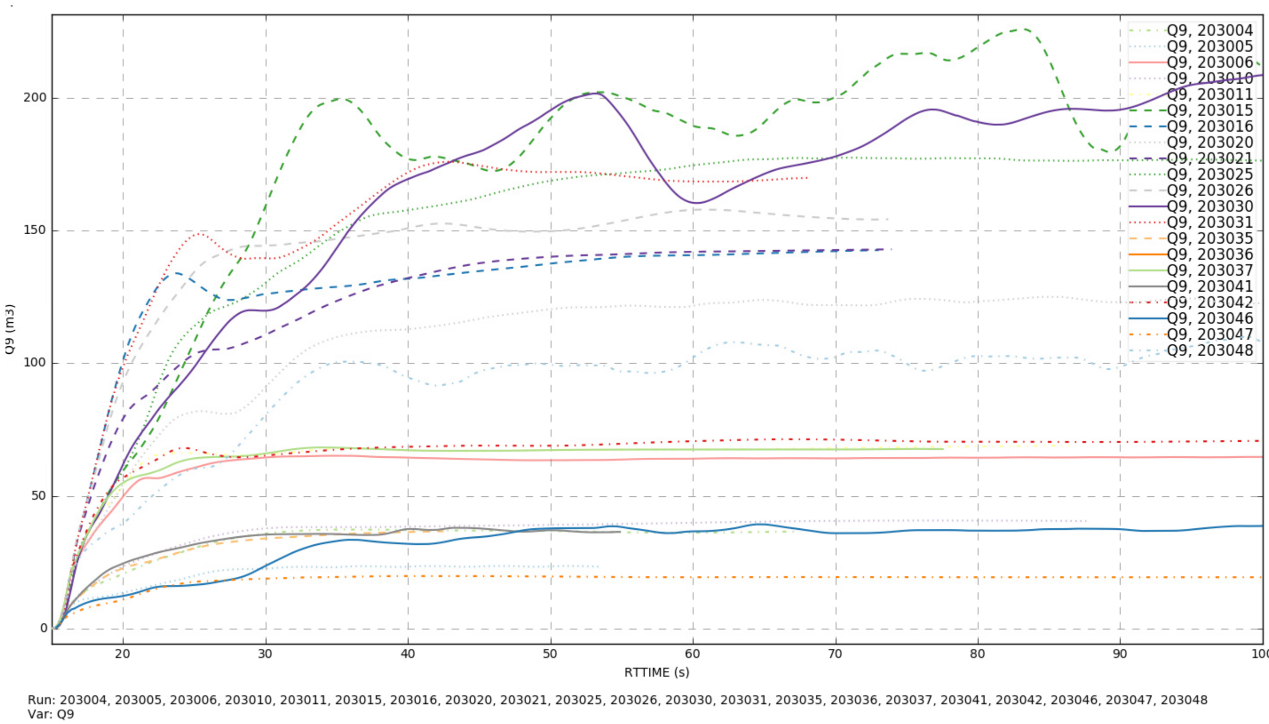


Figure 9.13 Could size (stoichiometric equivalent) development for large releases (>0.5 kg/s)

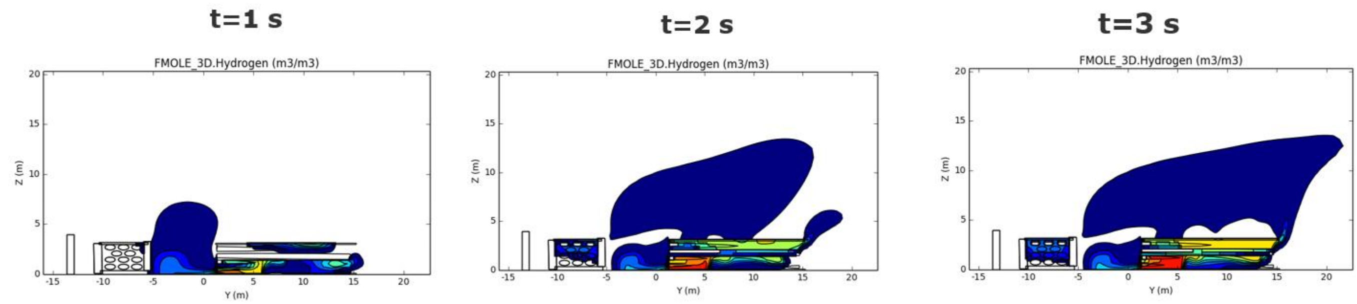


Figure 9.14 Transient gas cloud development for case 16. Same legend as in Figure 9.10.

9.4.5 Cloud length outside hydrogen station

Figure 9.15 and Figure 9.16 below show 3D plots of the stabilized development of the gas cloud for two cases. For both cases, the flammable gas cloud spread out over the inner area, with a distance of 20 m to 30 m from the blast wall or firewall. These cases are picked as the cases which spread the gas to the furthest distance away from the station in the wind direction. These cases can therefore be considered representative in terms of how far a flammable gas cloud could spread given the simulated conditions. The release rates used is up to 1 kg/s with a constant release rate in time. If leaks with larger release rates occur, they would reach further. Cases with larger initial release rates are often decaying due to reduction of pressure in the reservoir. Therefore, the possibility of a sustained leak with larger release rate is small.

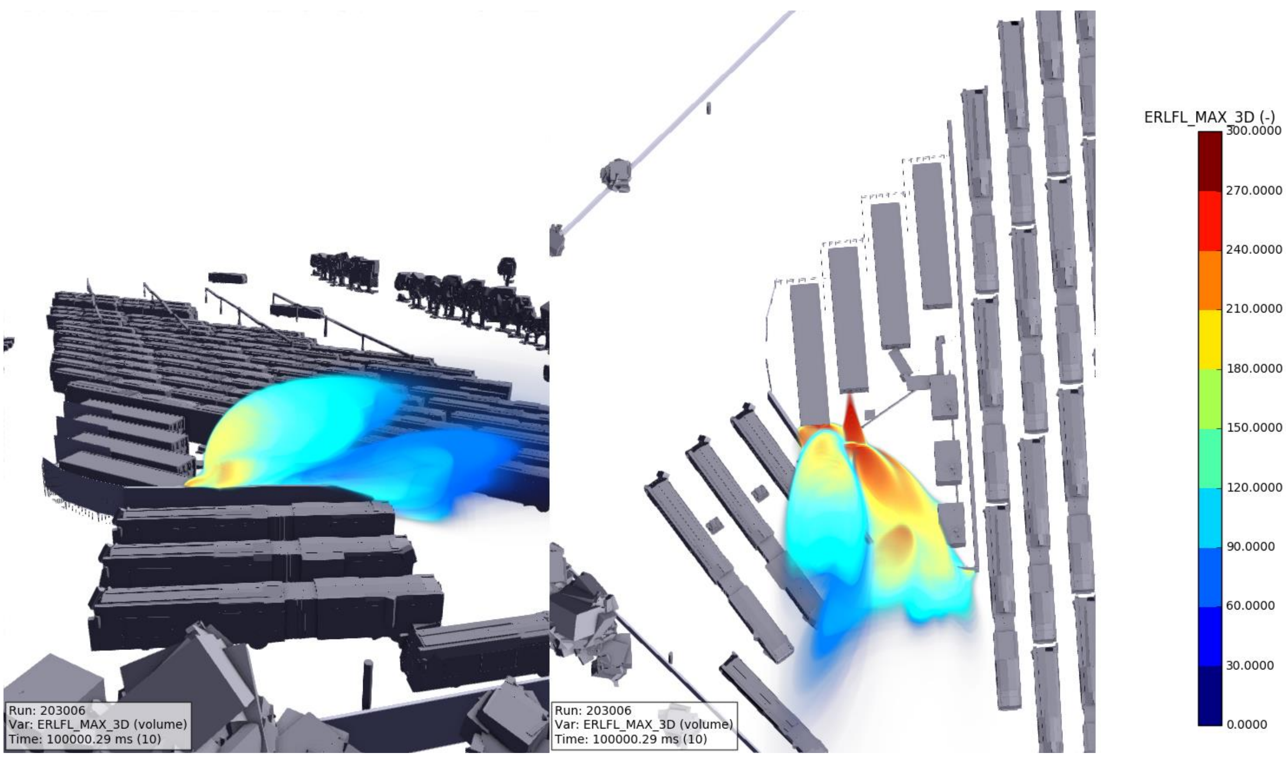


Figure 9.15 Stationary gas cloud for case 06. Left, seen from west; right, from above. Leak towards south, 1 kg/s; and wind from north, 3 m/s. Light blue colours and above indicate the flammable region.

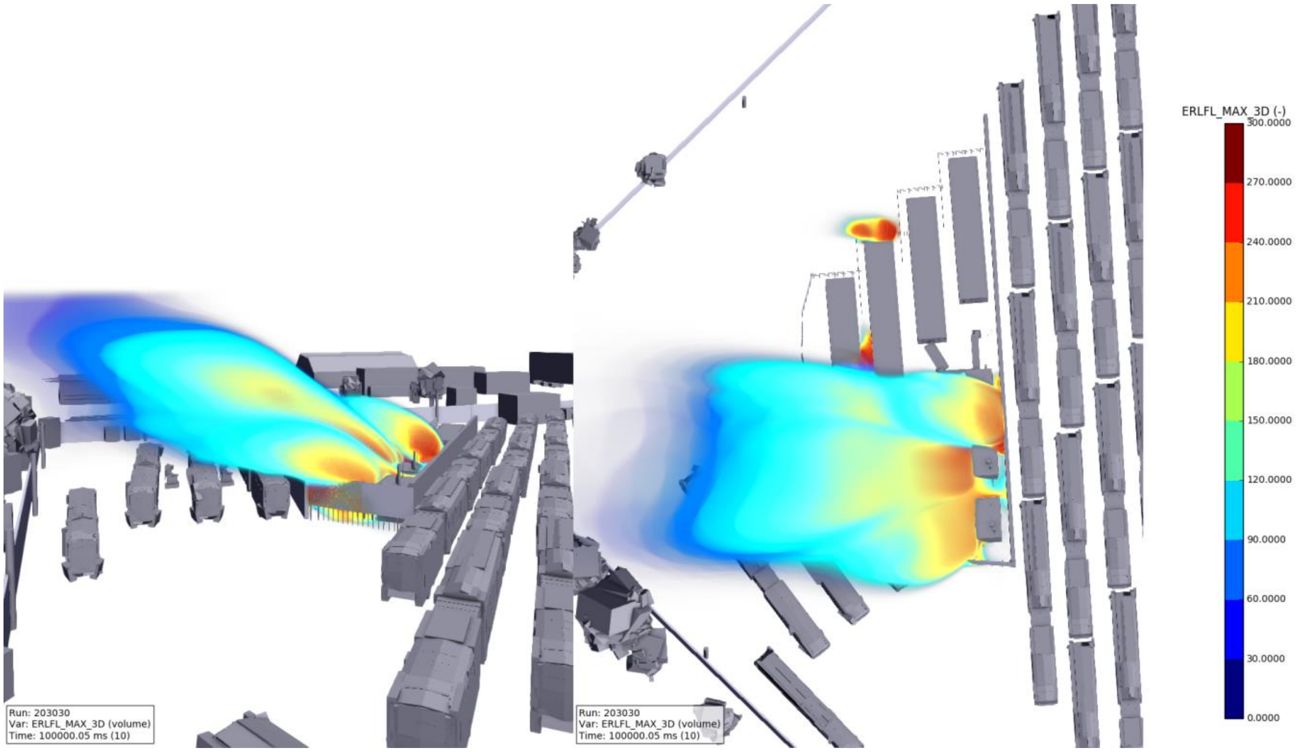


Figure 9.16 Stationary cloud development for case 30. Left, seen from south; right, from above. Leak down, 0.5 kg/s; and wind from east, 3 m/s. Light blue colours and above indicate the flammable region.

9.5 Explosion analysis

9.5.1 General

Based on the dispersion simulations, a range of stoichiometric gas clouds are generated and ignited. The simulations are performed with FLACS. For each leak location (scenario), a set of Q9 cloud sizes is defined based on the dispersion results. Cuboid shaped clouds are then placed in the geometry. The location and sized of the cuboid shapes is based on the dispersion results, best practices, and local geometric considerations. All the cuboids have a rectangular footprint with an aspect ratio of two, with a height equal to the shortest side of the rectangular footprint. The gas clouds locations and sizes are generated at random by a program which require input on minimum and maximum gas cloud volumes, and “bounding box” coordinates reflecting the geometrical domain in which the clouds are to be positioned. After generating the gas clouds, they are visualized and inspected manually, and non-physical gas clouds are removed or manually adjusted to fit the project-specific requirements.

Each cloud is ignited in three separate locations to capture the effect of various ignition locations on the final explosive overpressure on structure and equipment. The three ignition locations are two edge ignitions that allow the flame to travel lengthwise through the cloud, and a central ignition. A principle drawing of Q9 cloud orientation with one ignition position is provided in Figure 9.17.

The pressure and produced by each explosion on various targets are measured with pressure panels and monitor points. Pressure loads on the blast walls have been the main objectives for this project, while pressure within and on the containers have also been investigated. The data is then used to establish relations between overpressure and cloud volume for different cloud locations. This relationship is called the explosion response surface. These explosion response surfaces are used in Express to calculate exceedance curves for selected, critical loads such as panel pressure on the process deck and firewall. These load targets can cause escalations to safety critical elements or to other main areas.

From experience, it is known that maximum explosive pressure tends to grow exponentially for small cloud volumes, and then linearly for large cloud volumes. The overpressure transitions from exponential to linear growth as the cloud grows too large for the module and all the flammable gas to effectively contribute to the total turbulence generation as the cloud burns towards the target. The growth rates for both the linear and the exponential parts of the response surface are strongly dependent on the geometry of the relevant module. The transition point between linear and exponential growth rate also depends strongly on the geometry.

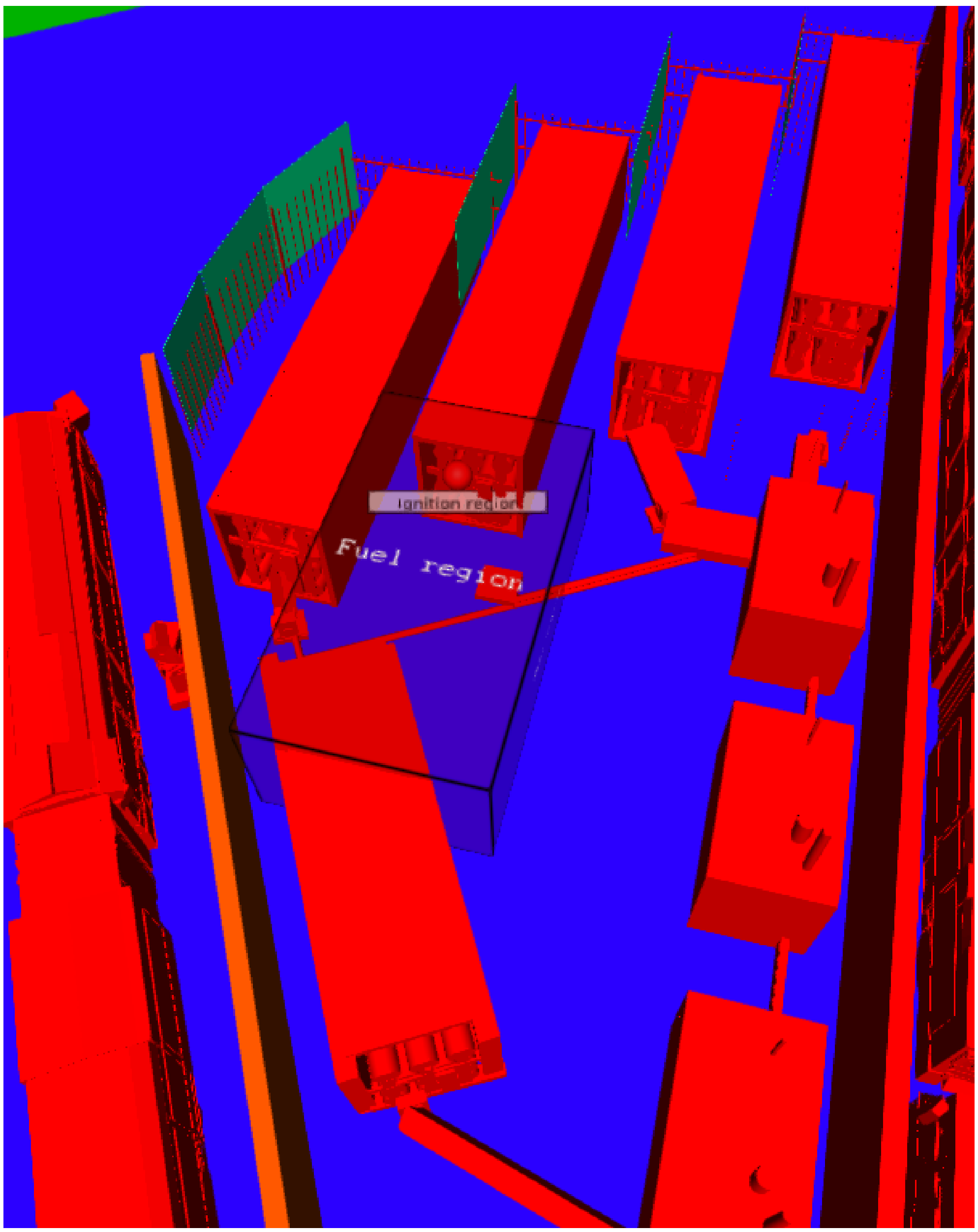


Figure 9.17 Example of hydrogen gas cloud to be ignited. In this case, a stochiometric gas cloud of approximately 150 cubic meter is ignited near storage container B

9.5.2 Simulations

9.5.2.1 Overview of explosion simulation cases

A total of 72 explosion simulations were performed: 24 gas clouds, with three ignition locations each. Figure 9.18 show the projected location of the gas clouds, along with the ignition points. The gas clouds also vary in vertical position and size. A histogram of the simulated gas cloud volumes can be seen in Figure 9.19.

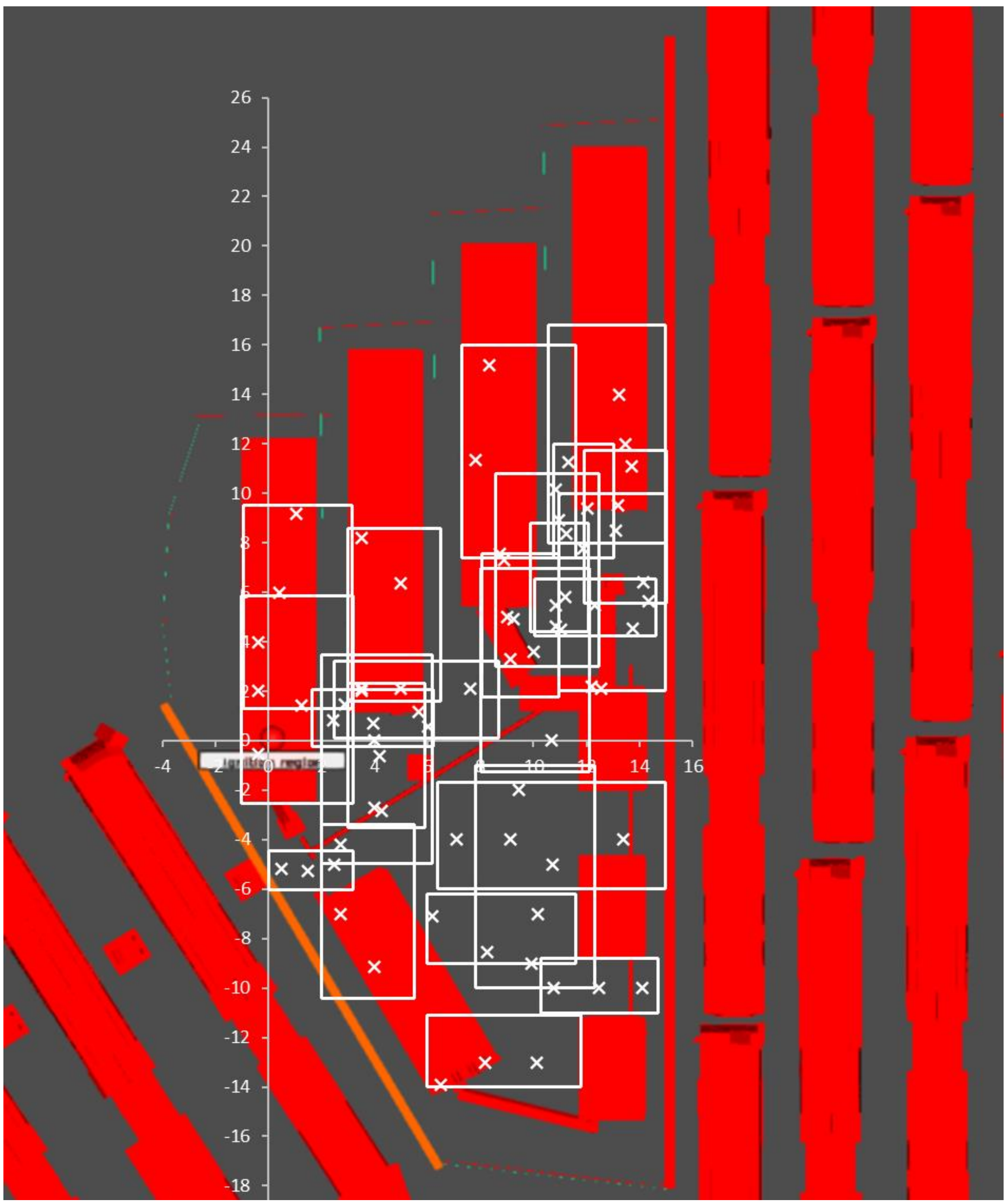


Figure 9.18 Location of explosion gas clouds and ignition points, projected top view

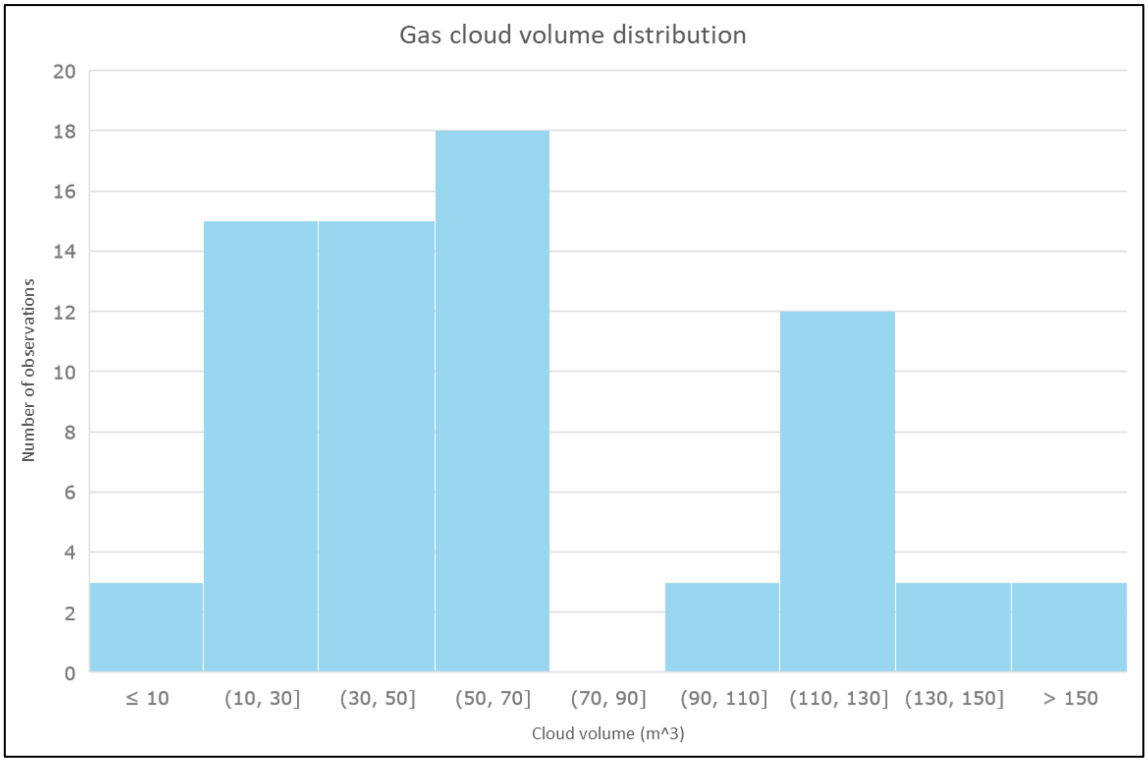


Figure 9.19 Histogram of ignited gas cloud volumes used in the explosion simulations

9.5.2.2 Simulation results

Figure 9.20 shows the maximum recorded overpressure from an explosion case projected onto the surrounding geometry. The explosions are from a typical 60 m^3 stochiometric gas cloud partly located inside one storage container, with the ignition point being inside the container. The contours are cut at z=3.1 meters, to show the pressure within the container. The figure shows very high pressures within the container itself, as well as the direct surroundings. The effect of the blast wall is clearly seen, with pressures of more than 1 barg directly on the inside of the wall, while the pressure drops to about 0.1 barg directly outside of the blast wall. A similar effect is seen on the east blast wall. The overpressure contours of 0.01 barg reaches about 70 meters from the explosion location.

Figure 9.21 shows the maximum recorded overpressure through all simulations at two heights, z=1.1 meters and z=3.5 meters. The figure shows the same effects as Figure 9.20 – the higher overpressures are largely contained within the central area, and there is a significant effect from both the west and east blast walls. The effect is very prominent at z=1.1 m, while somewhat less prominent at higher locations and further out from the central area. Figure 9.22 and Figure 9.23 also show the maximum recorded pressure over all simulations, but through planes at constant *x* and *y*. In the central area, high pressures are seen up to 10 meters. The effect of the blast wall is clearly seen, especially when comparing the two different cut planes in Figure 9.22. The upper subfigure, at x=0.0 m crosses through the west blast wall, while the lower subfigure, at x=9.0 m, crosses through the perforated fence, and there is no clear “breaking” of the overpressure contours.

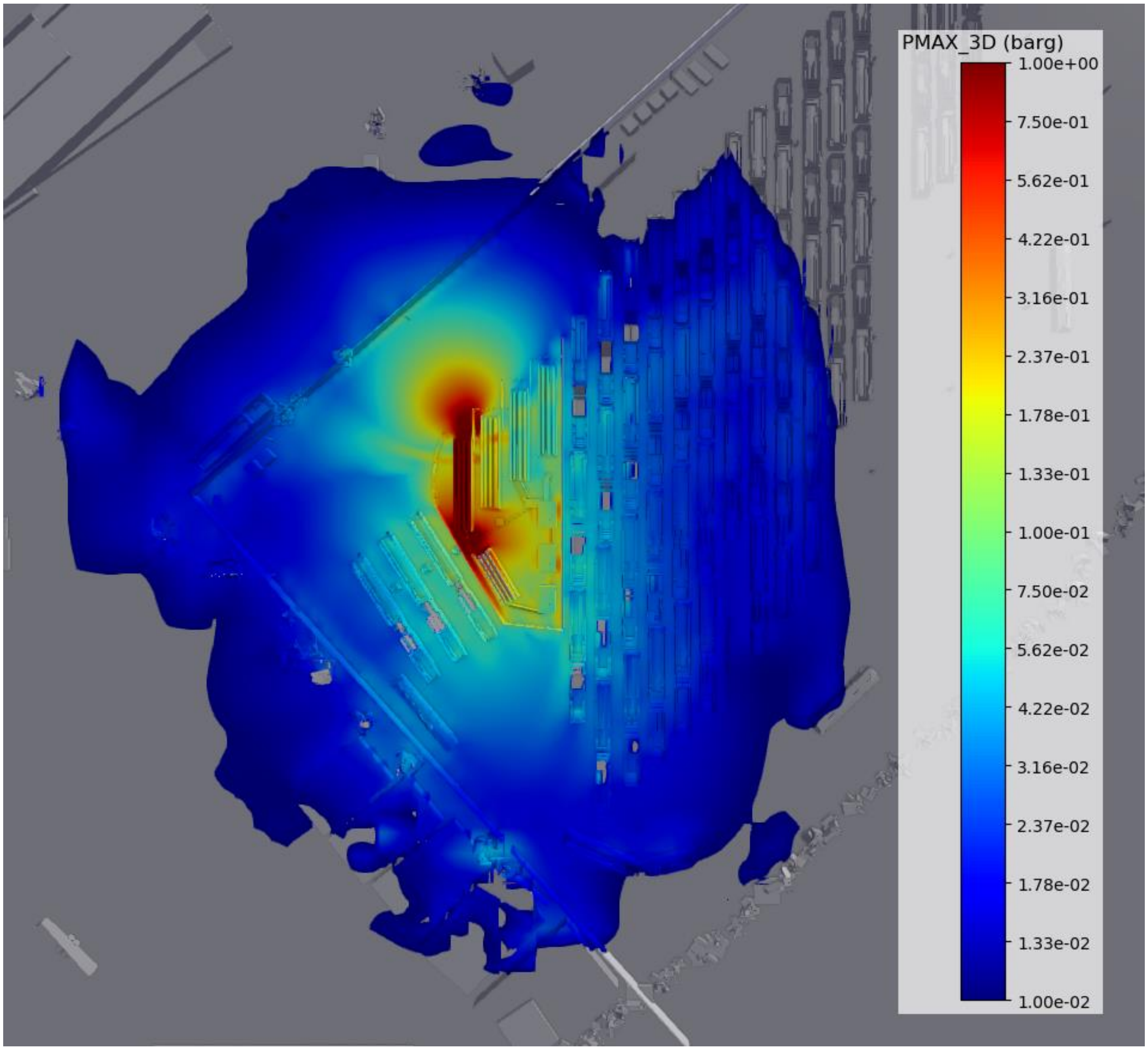


Figure 9.20 Maximum pressure from an explosion of a 60 m^3 stochiometric gas cloud, projected onto surrounding geometry. Note the logarithmic color scale. Cut plane at z=3.1 m. Dark red areas indicate maximum pressure above 1.0 barg.

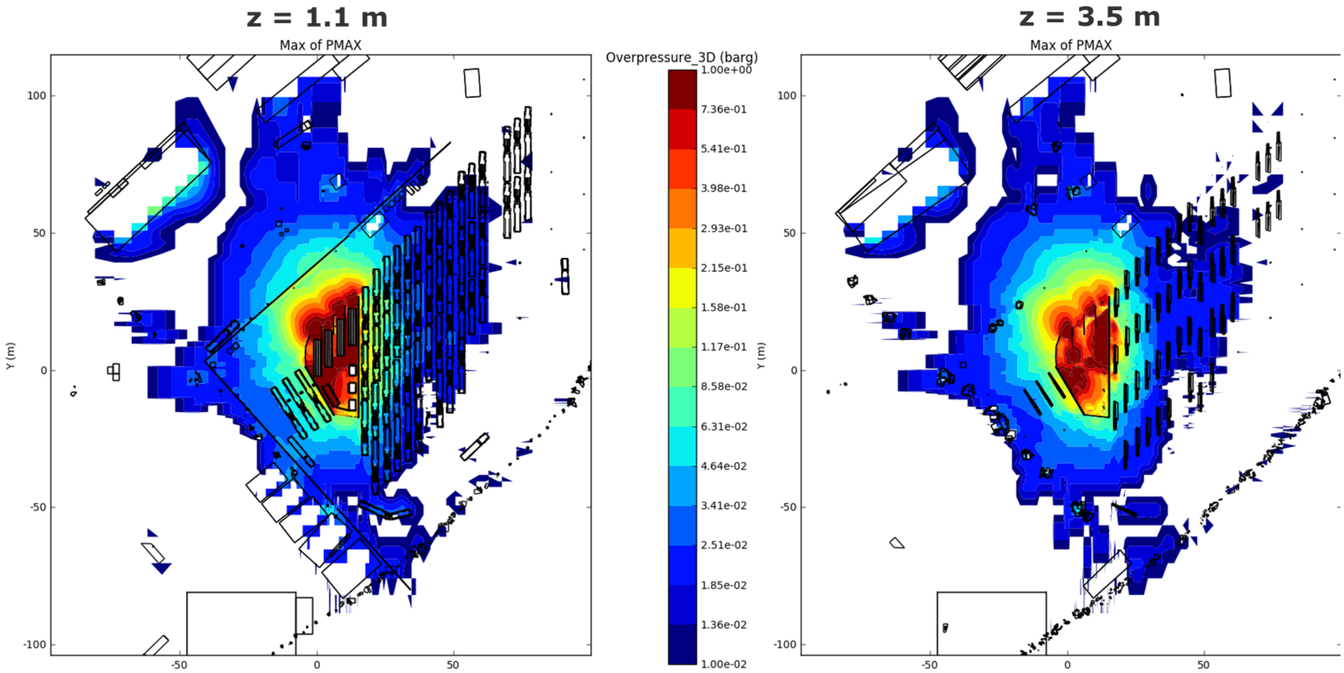


Figure 9.21 Maximum recorded overpressure recorded in all explosion simulations, at constant z-values

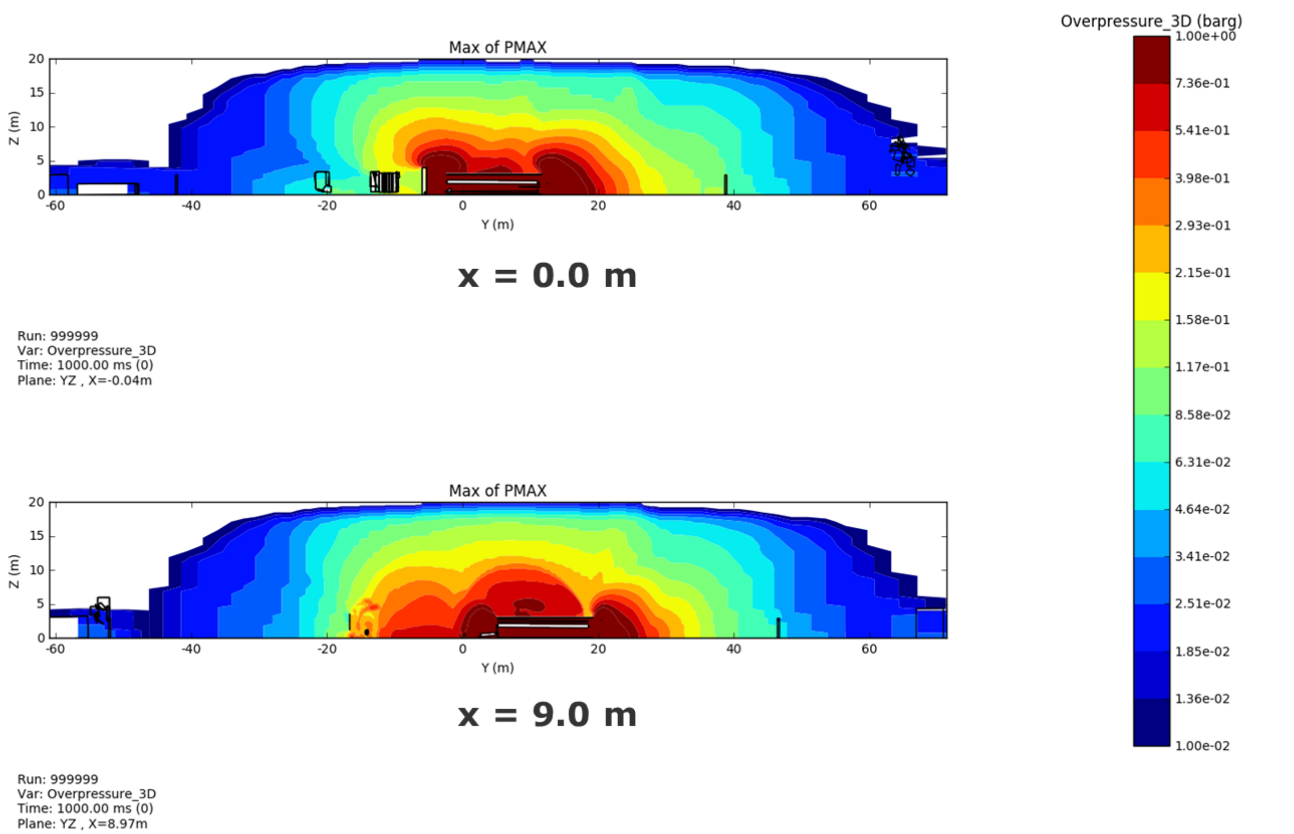


Figure 9.22 Maximum recorded overpressure in all explosion simulations, at constant x-values; no blastwalls.

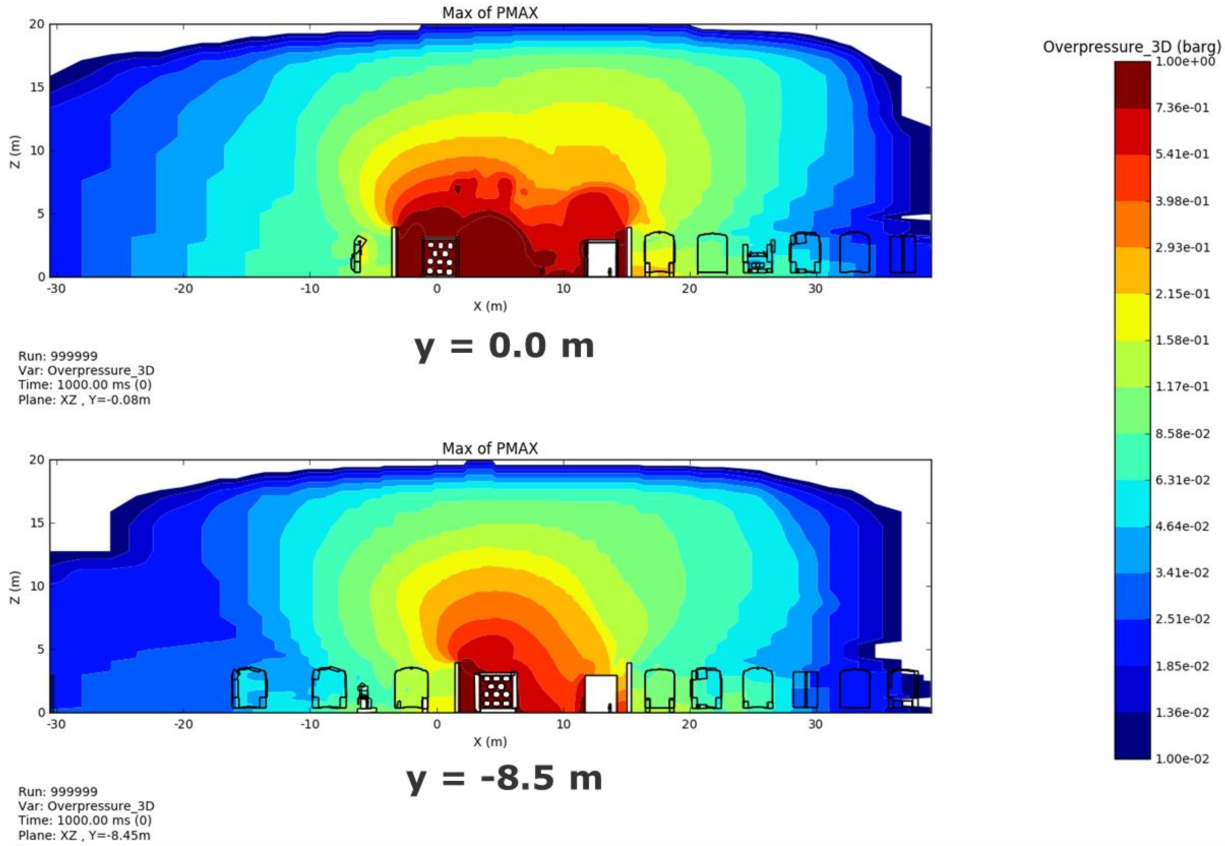


Figure 9.23 Maximum recorded overpressure in all explosion simulations, at constant y-values with blastwalls

While the maximum aggregated figures give a good overview of what larger gas cloud explosions or explosions of some size within the containers would look like, it is also useful to look at the average explosion overpressure contours. Figure 9.24 shows the average overpressure over all explosion simulations. Evidently, the overpressure contours are lower and smaller than the maximum values in Figure 9.21, with smaller gas clouds and explosions happening more “in the open” now being factored in. Note that this is just a simple average, e.g. not weighted in terms of probability. Still, higher pressures are clearly seen in the central area, near the storage container openings and the blast walls, showing good effect of the blast walls, while there still is some pressure overflow over and around the blast walls.

A key focus has been to estimate the pressure loads on the blast walls. This has been important in order to provide input to EXPRESS analysis, and to give an indication to the necessary structural integrity of the walls. Figure 9.25 shows the maximum overpressure per simulation on the two blast walls. For smaller and more medium-sized clouds (less than 80 cubic meters), the pressure grows exponentially with cloud size. Apart from one simulation, the highest pressures were seen in the left blast wall. This is due to its diagonal orientation relative to the storage containers where explosions can be “channeled” towards the wall, creating very high pressures. Also, clear is the large spread in recorded overpressure showing how sensitive the explosions are to geometric variations. Most simulations give maximum pressures between 0.01 barg and 0.5 barg, while only as small number of simulations give pressures higher than 0.5 barg.

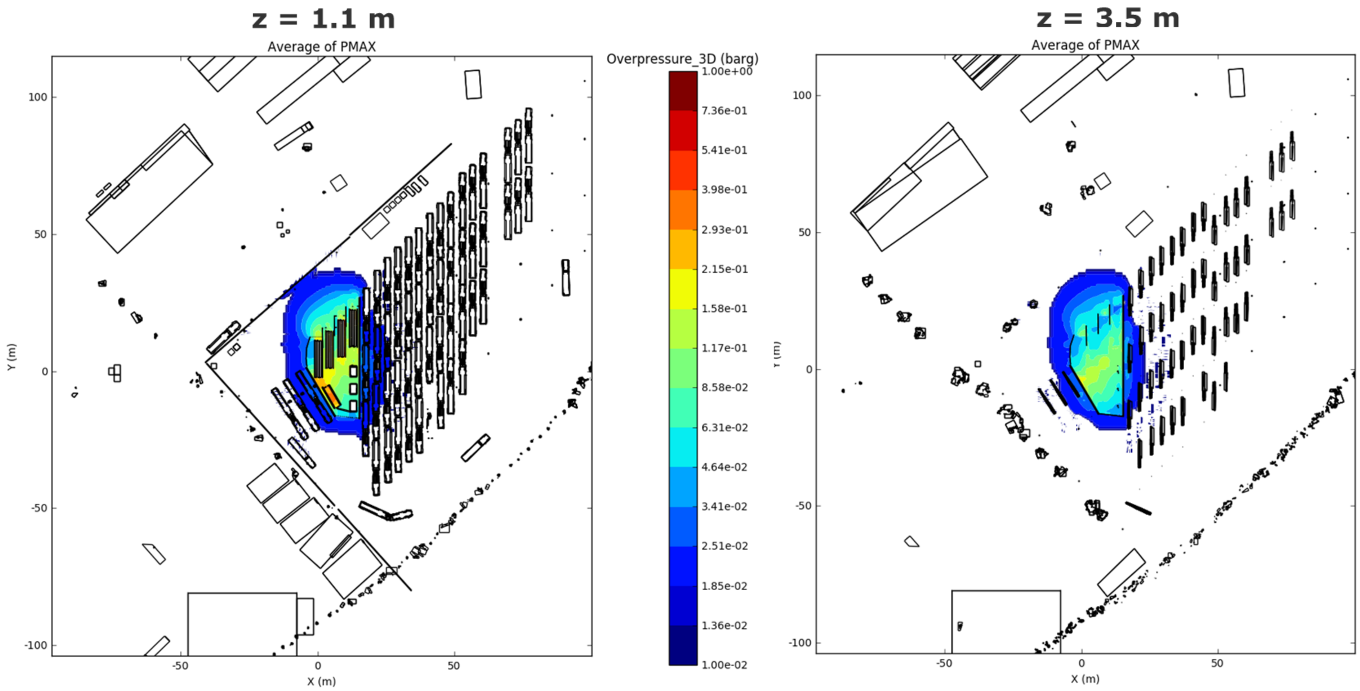


Figure 9.24 Average recorded overpressure recorded in all explosion simulations, at constant z-values

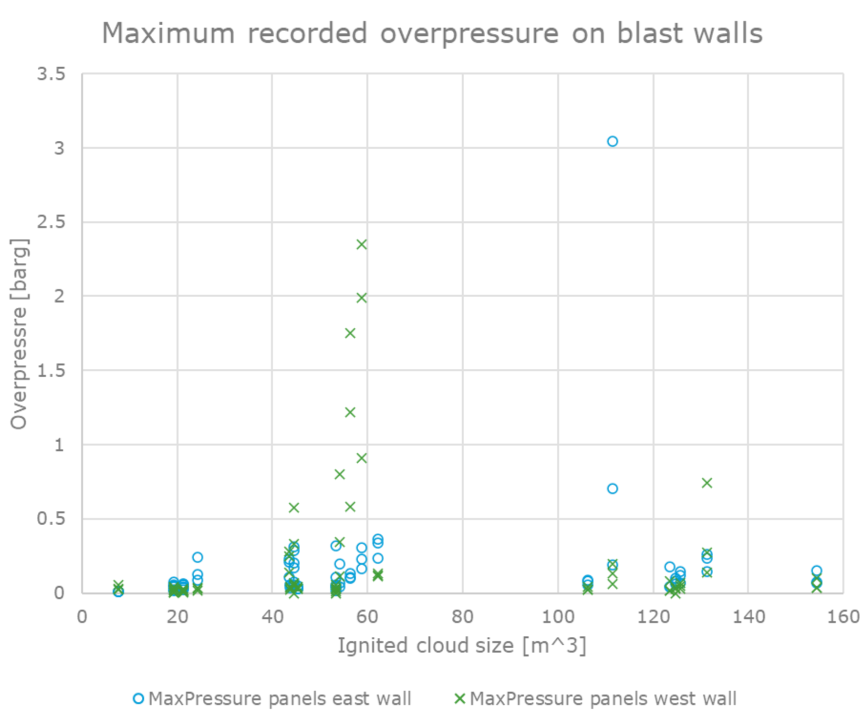


Figure 9.25 Maximum overpressure on the blast walls, per simulation

Another focus has been to estimate the far-field explosion pressures, to give an indication of the risk picture on neighboring locations. To measure the far-field pressure due to the explosions, a number of monitor points were places along eight “spokes” originating from the approximate center of the explosion area. Measured at 2 m, 4 m, 6 m, 10 m, 12 m, 16 m, 18 m, 20 m, 30 m, 50 m and 70 m from the center, at two elevations (1.1 m and 4.0 m) maximum recorded pressure was logged for each simulation. Figure 9.26 shows the location of the monitor points used to measure the far-field explosion pressures.

These results were aggregated to global maximum values and global averages for each elevation, per the eight directions. This is shown in Figure 9.27 and Figure 9.28, respectively.

The pressure reducing effect of the blast wall is clearly seen in Figure 9.29 where the averaged lines away from center with and without a blast walls are compared. A reduction effect from 10 to 2 times is seen when moving from just outside the blast wall to about 30-40 m from the center.

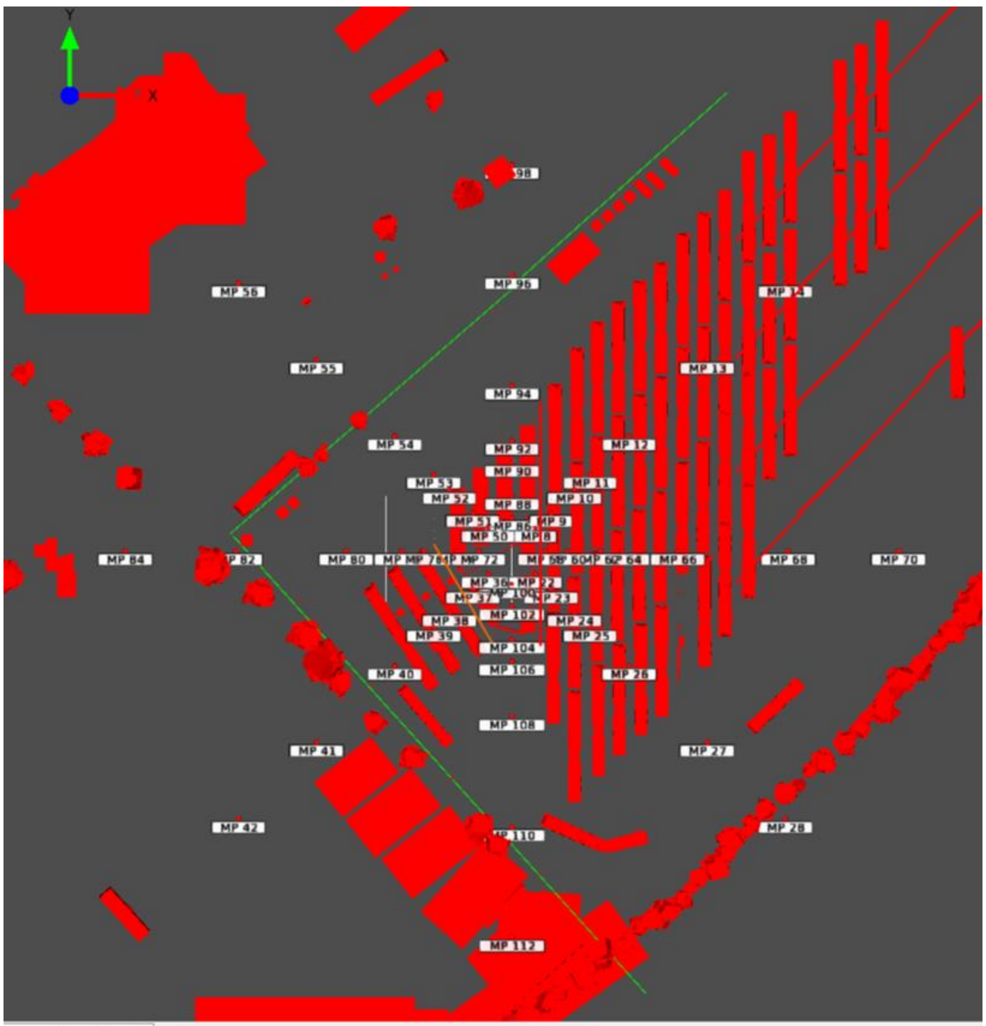


Figure 9.26 Monitor points used to measure far-field explosion pressures.

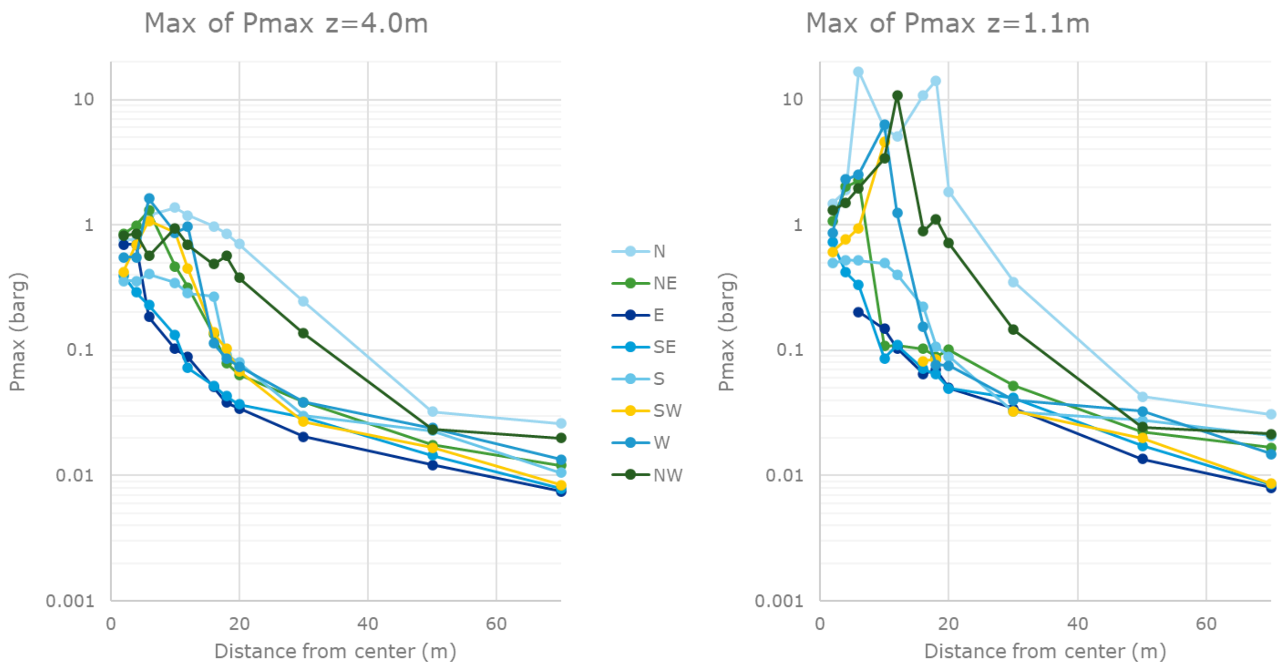


Figure 9.27 Maximum over all simulations of maximum recorded pressure by direction and distance from center. The directions are defined by the 8 "spokes" shown in the figure above where N is up on the figure.

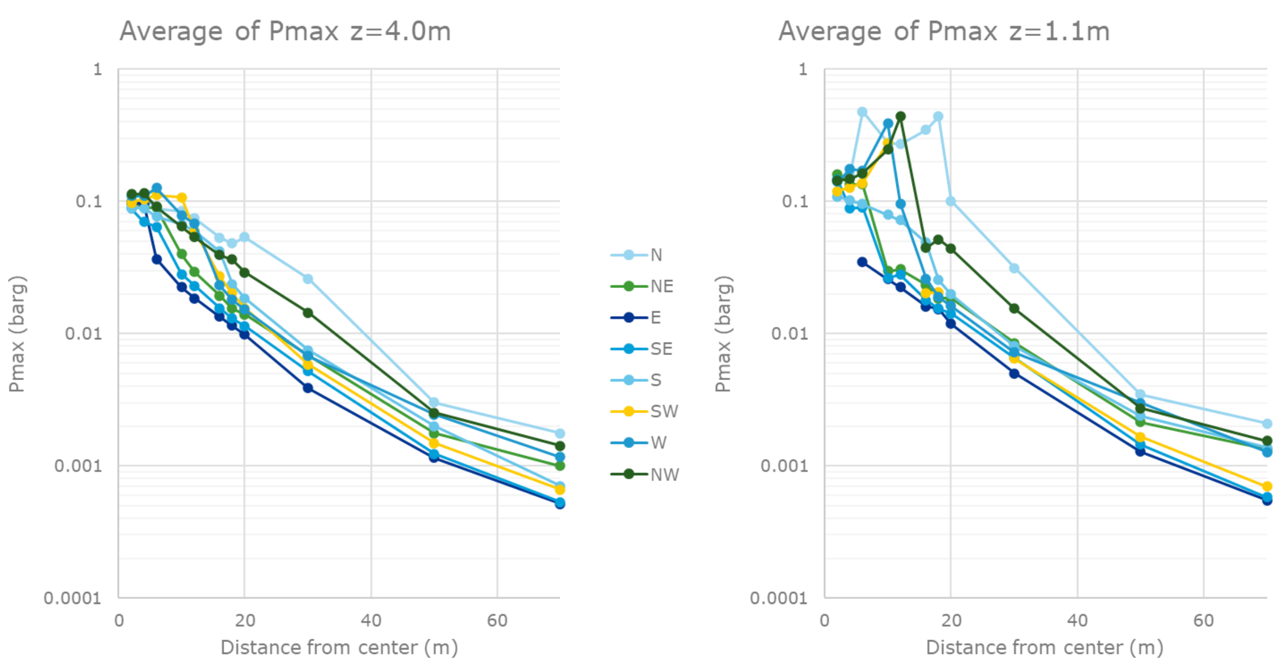


Figure 9.28 Average over all simulations of maximum recorded pressure by direction and distance from center.

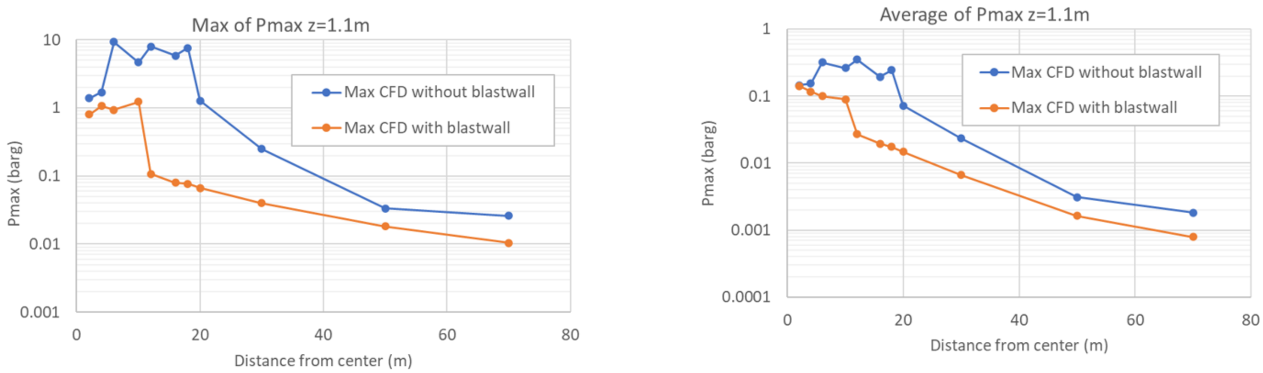


Figure 9.29 Max explosion pressures as a function of distance from center considering only the highest explosion cases (left) and an average over all explosion cases (right). In each figure is compared all results in the directions where there is a blast wall with all results where here are no blast walls. The location of the blast wall at 10 m from the center indicating a sudden drop in the pressure in the orange curve. The drop in the pressure at 18 m in the blue curve is due to the modelled extent of the gas cloud, on average.

9.6 Probabilistic analysis with EXPRESS

In the probabilistic explosion analysis, all the scenarios are modelled from leak to explosion using model equation from physical relations and fitted equations that are fitted to the CFD results (response surfaces). Illustrative examples of these models are here shown together with the input used in the Express model.

9.6.1 Initial QRA

An Initial QRA (IQRA) is performed to select representative leak cases to be used in Express. The segment inventory and the leak frequency for all segments is shown in Figure 9.30, and this figure is used to select representative cases. The 3 cases with inventory above 30 kg are grouped into representative leak case L2. These are the tanks and the buses. The reminding 5 cases are grouped into leak case L1. These have small inventories less than 0.7 kg and are dominated by the hoses and compressors. The total frequency is this way represented by two scenarios. Note that it is conservatively applied that bus and dispenser scenarios are lumped into the same two scenarios. This is only done in the EXPRESS model. For the SAFETI model all 8 types of scenarios are included.

The resulting inventory and leak frequencies used in EXPRESS are given in Table 9-3.

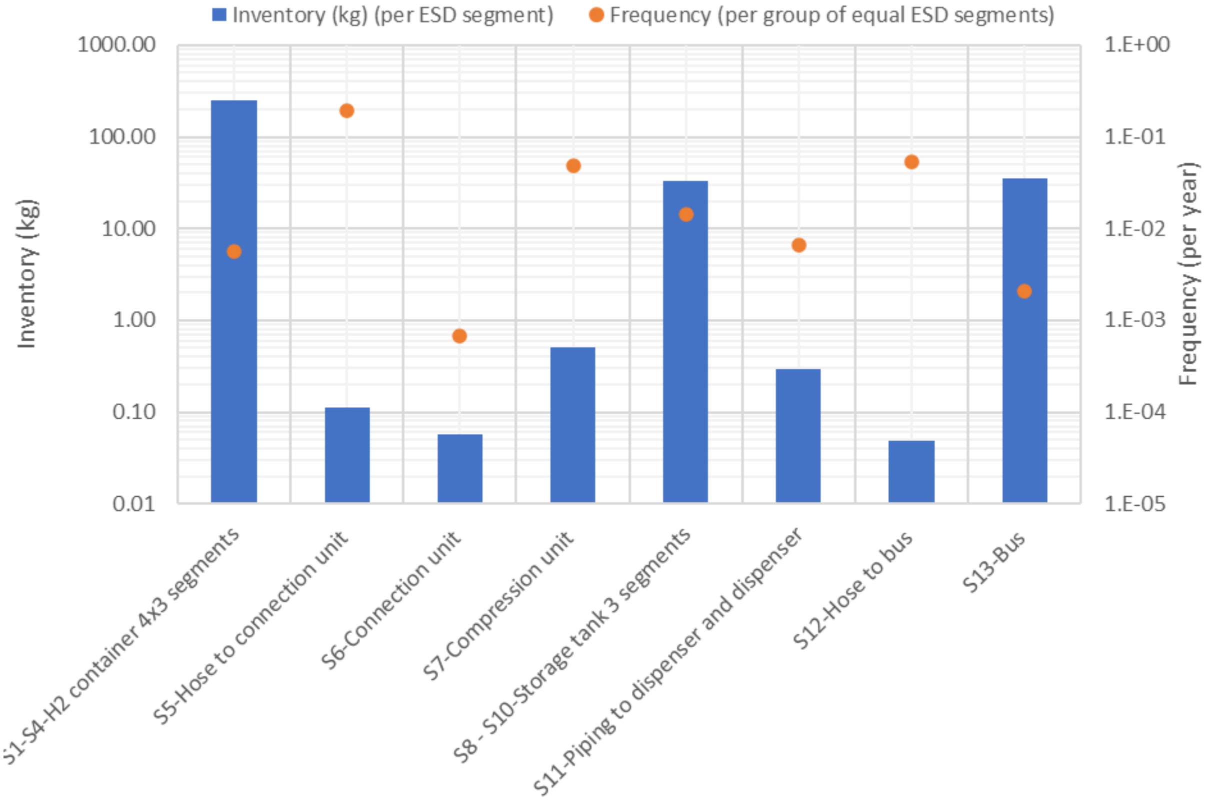


Figure 9.30 Inventory (left axis) and leak frequency for the QRA cases. The total leak frequency is the sum of small, medium and large for each segment or group of segments. The inventory is the amount of H2 that can leak from one segment.

Table 9-3 Inventory and leak frequencies used in Express for the two representative segments, L1 and L2.

Representative segment name	Inventory (kg H2 gas)	ESD volume (m3)	Total (per year)	Small	Medium	Large
L1 leak hoses and containers	0.11	0.02	3.03E-01	1.82E-01	9.01E-02	3.06E-02
L2 leak storage tank (s)	33	8	2.21E-02	1.33E-02	7.18E-03	1.67E-03
Total			0.3248	1.95E-01	9.72E-02	3.22E-02

9.6.2 Leak rates used in EXPRESS

The 3 leak rate categories used in SAFETI is split into 3 leak rates each in EXPRESS as shown in Table 9-4. The probability distribution within each category is obtained from typical distributions used in the leak frequency model /1/. Note that the leak rates used in EXPRESS are fixed and the same for both cases L1 and L2. In SAFETI, a fixed hole size is used. The pipe pressures are similar for the different cases; therefore, it is justified to use a constant initial leak rate for the two EXPRESS cases.

Table 9-4 Leak rates and probabilities assigned to the cases in Express.

Size category	Hole size SAFETI (mm)	Typical rate QRA (kg/s)*	Rate and probability used in Express			
Small	2	0.05	Rate (kg/s)	0.02	0.05	0.1
			Probability	0.66	0.19	0.15
Medium	5	0.5	Rate (kg/s)	0.2	0.5	1
			Probability	0.31	0.56	0.13
Large (full bore)	13	5	Rate (kg/s)	2	4	10
			Probability	0.31	0.56	0.13

* dependent on pipe pressure.

9.6.3 Release profiles

The following is applied when calculating the release profiles in Express, see Figure 9.31. Textbook flow equations for compressible flows with constant real gas properties is used to calculate the leak profiles with the LeakPro program.

- Inventory, 33 kg (L2 case); 0.11 kg (L1 case).
- Segment pressure, 350 barg
- Reservoir temperature, 10C
- Time to close ESD valves, 1s
- Blowdown is not included
- Probability of failure for the ESD: small, 0.1; medium, 0.01; large, 0.01

Constant real gas properties are used for hydrogen during the release with compressibility, $Z = 1.15$, and $Cp/Cv = 1.4$. This gives a speed of sound in the release of 1336 m/s, and a release temperature of 34 degrees Celsius.

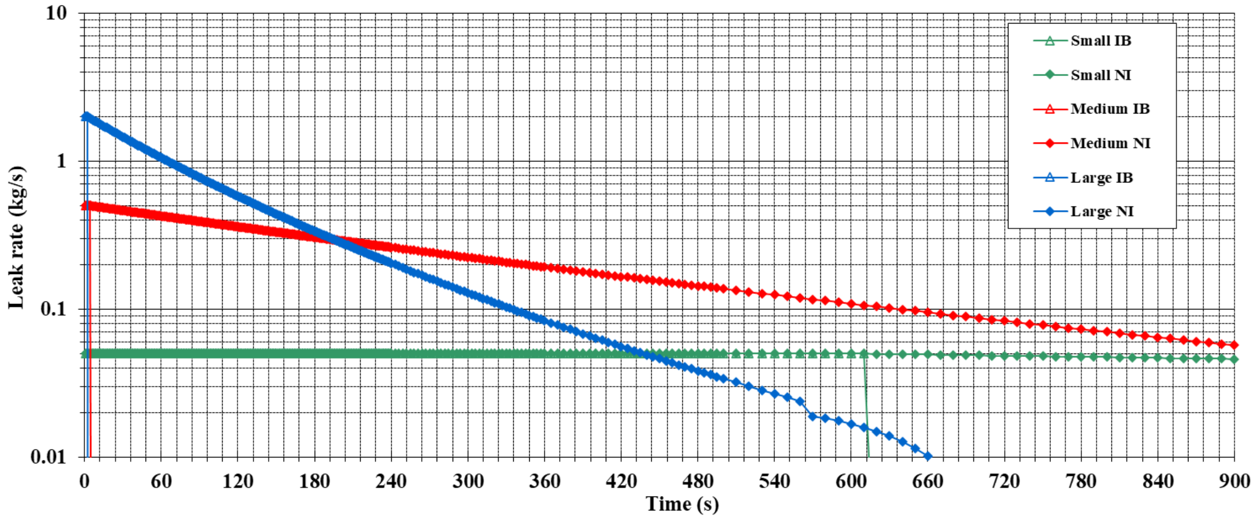


Figure 9.31 Typical release rates for small, medium and large is here shown with initial leak rates 0.05, 0.5 and 2 kg/s, respectively. The IB and NI means with Isolation and no isolation, respectively. The long-lasting NI cases are also representing leak from a 350 barg segment with 33 kg hydrogen. The short IB segments have a duration of 1 to 3 seconds until the ESD valves are closed. After the ESD valves are closed, the learate drops to zero almost immediately due to the small segment inventory of 0.11 kg.

9.6.4 Wind rose and ventilation

The wind rose from Alna station is used, see Figure 9.32. This wind rose is similar to other wind roses in Oslo characterized with preference for winds from NE and SW.

The ventilation simulations show increased relative wind inside the fence for wind from NE, see Figure 9.33. This is due to the large gates towards NE where air is coming through. There are openings in the fence in the SW direction, however, this is a shorter opening which does not show an increased wind speed inside the fence.

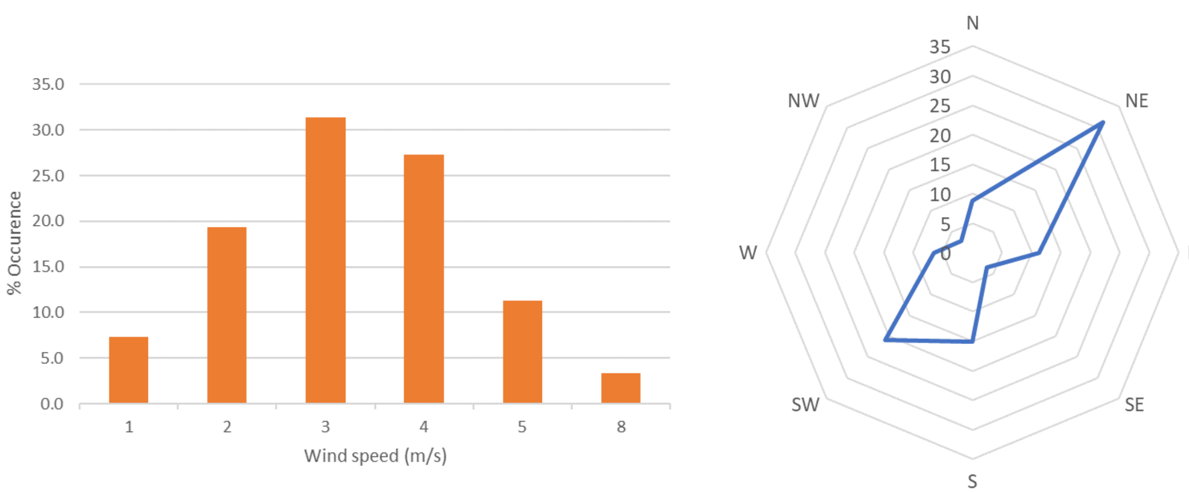


Figure 9.32 Wind speed (left) and direction distributions applied in Express.From the Norwegian Meteorological Institute, station Alna, Oslo, 2007 to 2015.

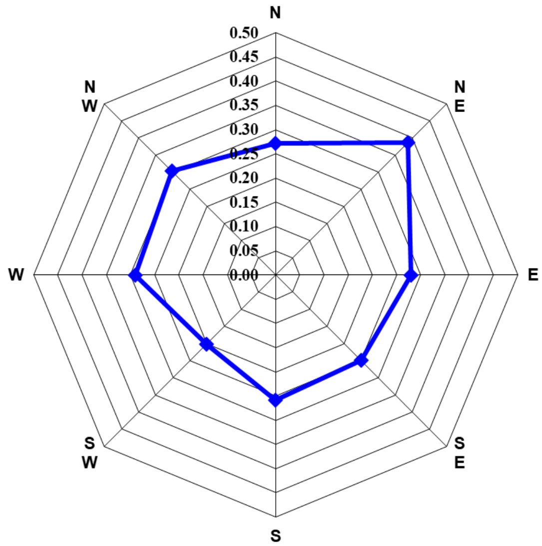


Figure 9.33 Relative wind speed inside the hydrogen area for the 8 wind directions simulated. The number is the fraction of the reference wind at 10 m height that is obtained inside the fences.

9.6.5 Dispersion

The cloud volumes from the simulations (Figure 9.34) are used to develop fitted curves (response surfaces) that are used in EXPRESS. An example of the response surfaces is shown in Figure 9.35 indicating that the wind speed has an effect on the cloud size. The cloud size is typically reaching a maximum value at a medium to large leak rate (above 0.5 kg/s). When the maximum cloud size is reached, and the leak rate is increases, then the cloud size is reduced since the gas clouds becomes rich and not so flammable.

An important factor for the explosion risk analysis is the distribution of cloud sizes for each leak rate. It is only a few unfortunate cases that leads to the largest clouds. In this case it is leak direction down that creates the largest clouds. The horizontal leaks do not generate the same large cloud sizes. It is hence only 1/6th of the leak cases that causes the largest clouds. The cloud sizes is this way distributed with 1/6th for each leak direction. Also, the leak location will cause different cloud locations and sizes. In the CFD simulations, a leak location is selected that are at the end of the container where there are several valves and hose connections. The leak location is this way selected to be a representative location, and not a worst case.

Two parameters that describes the volume of gas that can ignite are used to calculate the ignition probability, Q7 and FLAM. These are plotted on Figure 9.36 indicating that a much larger volume than Q9 is used to calculate the ignition probability. This difference is due to the wide flammability range for hydrogen, and it causes the ignition probability to increase significantly. In average, based on the simulations, the parameters used in EXPRESS are Q7/Q9 = 10, and FLAM/Q9 = 16.

The transient development of the gas cloud is also found from the simulations (see Figure 9.12 and Figure 9.13) and this is used to model the cloud growth in EXPRESS. It is the initial cloud growth that is important for the explosion risk.

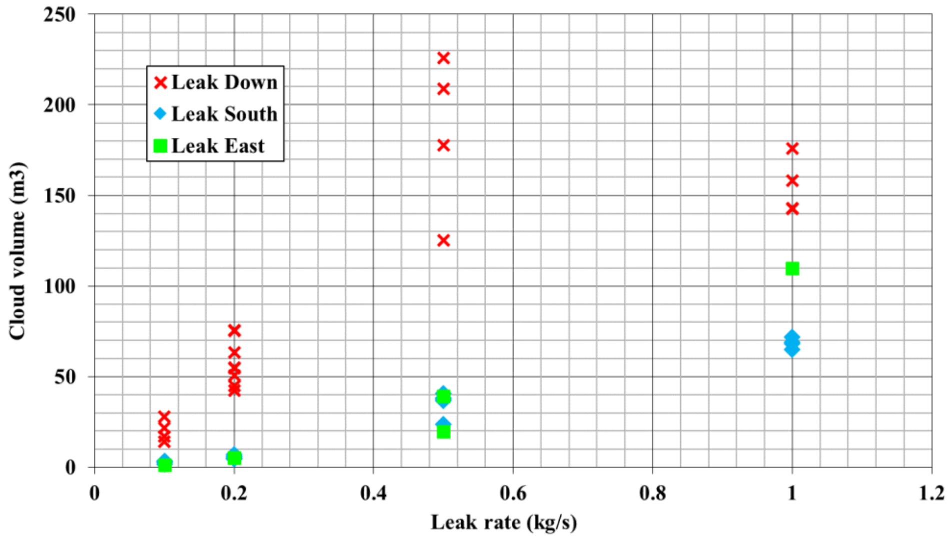


Figure 9.34 Cloud volume (Q9) as a function of leak rate for all CFD dispersion cases. It is a variation in wind speed within the leak directions South and down.

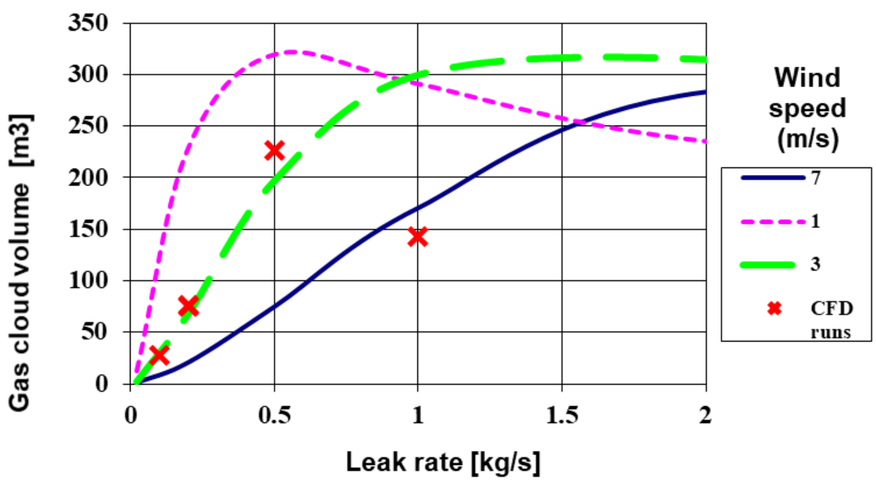


Figure 9.35 Example of Cloud volume (Q9) as a function of leak rate for tree wind speeds as modelled with the Express response surface for leak directing down and wind from south. Comparison with CFD cases for this wind direction and leak direction.

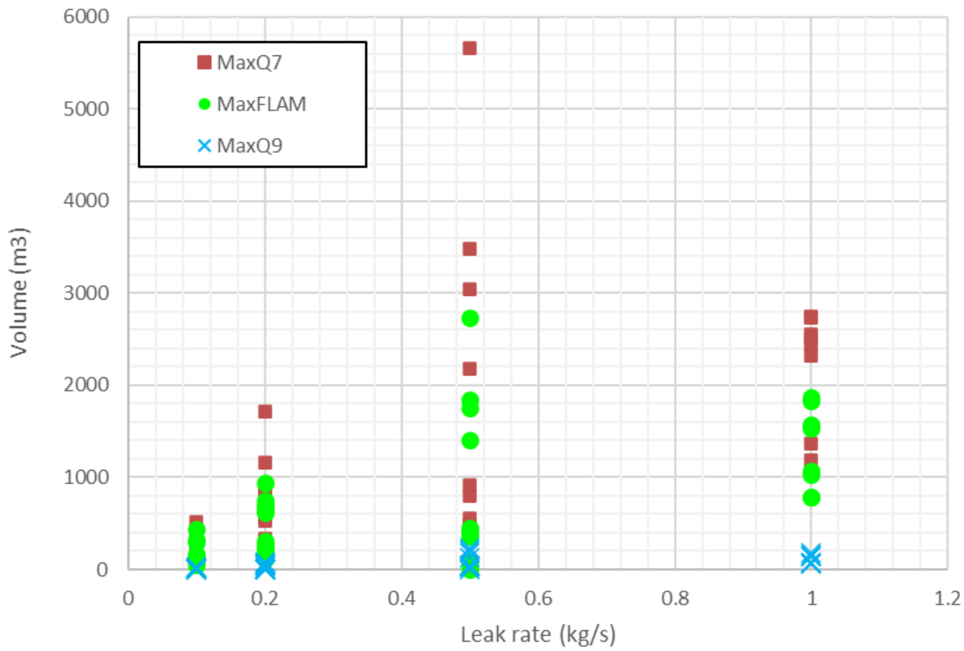


Figure 9.36 Cloud sizes as a function of leak rate for all CFD cases. Q7 is the volume that is exposed to flammable gas during the scenario, FLAM is the volume between LEL and UEL, and Q9 is the equivalent stoichiometric cloud size.

9.6.6 Explosion

The explosion pressures on the blast wall panels is used as representative in the EXPRESS simulations. These pressures are plotted in Figure 9.36 together with the response surface that is used. The pressure increases rapidly with the cloud size already at 40-50 m3 cloud volumes.

The distribution of explosion pressures for each cloud volume is also represented in the EXPRESS model. This distribution has the majority of the cases at pressures below 1 barg. A pressure reduction factor is used to represent the distribution of explosion pressures. The factor has a distribution from 1 to 0.05 as shown in Figure 9.38.

It is only the poorly located clouds that generates high pressures on the blastwall. For example, the case with explosion inside the container closest to the west wall where the pressure wave hits directly onto the wall (Insert figure). These high pressures can hence be further reduced by locating the containers further away from the walls. If this is done, it would directly influence on the explosion risk results.

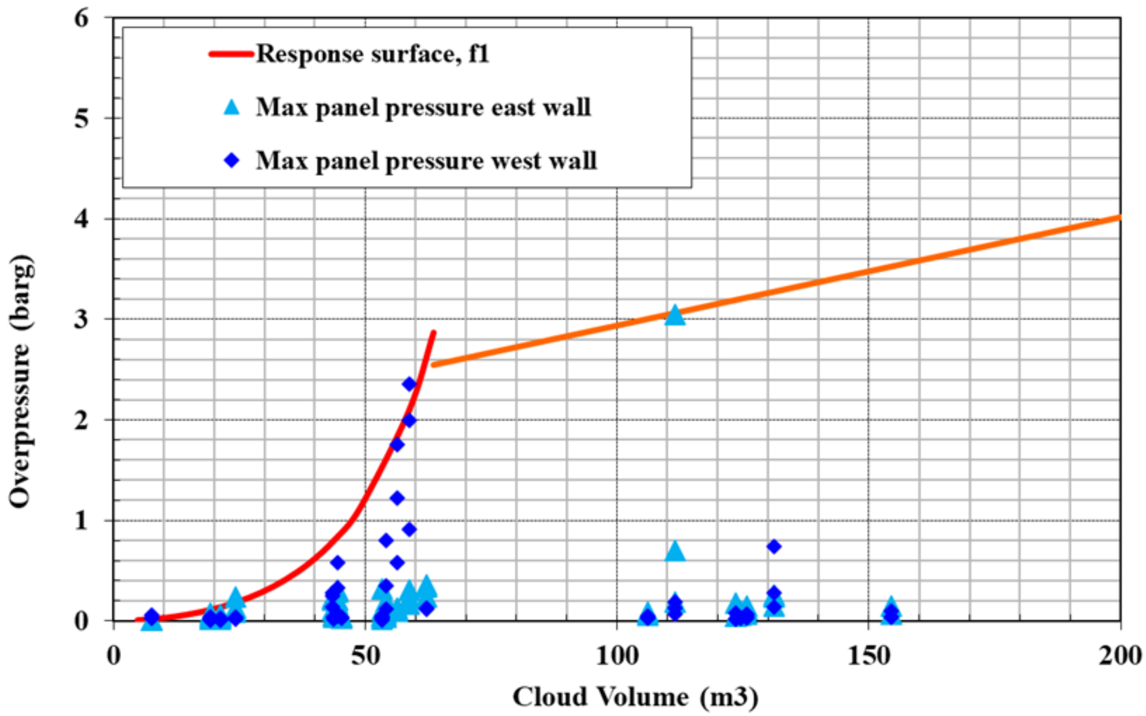


Figure 9.37 Explosion pressures on the blastwall panels as a function of the Q9 cloud volume. Maximum pressure from each case is plotted.

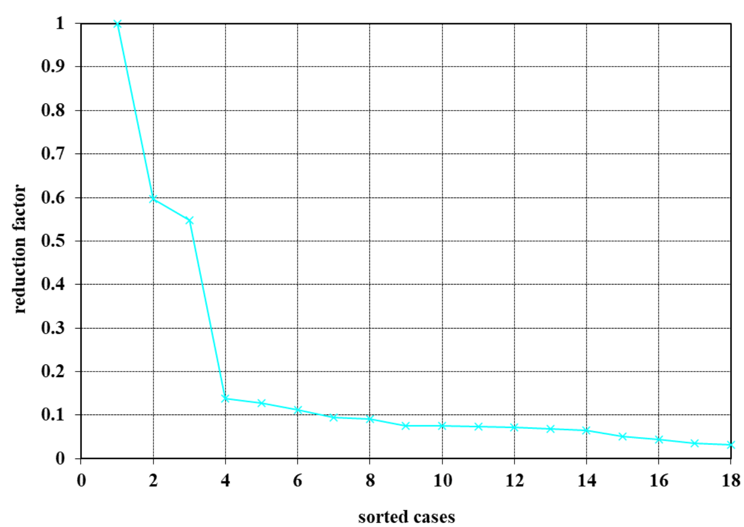


Figure 9.38 Reduction factor based on 18 of the explosion simulations with cloud sizes of 40 to 60 m3.

9.6.7 Ignition modeling and ignition sources

Explosions occur due to delayed ignition, and therefore only the delayed ignition probability is used when calculating the explosion risk. The immediate ignition happens in the same instant as the leak starts and will result in a fire only. The delayed ignition is modeled separately for internal and external ignitions. The internal ignition is happening inside the hydrogen station, and the external ignition happens outside.

9.6.7.1 Internal delayed ignition

Ignition modeling in EXPRESS uses the transient TDIIM model which was first developed in the JIP ignition project /8/, and further modified for hydrogen in the Hysafe project /9/. In the model is defined all possible ignition sources and associated ignition densities for hydrogen are given in Table 9-5. The ignition densities are multiplied with the area or the number of items to give the ignition probability given gas. All ignition sources inside the hydrogen walls are applied to be EX rated with these given intensities. The delivery truck is not assumed to be EX rated and is therefore given an increase factor 7.5 up compared to pump densities. The increase factors for hydrogen are also given in Table 9-5 indicating the increased ignition potential due to the low ignition energy needed to ignite hydrogen.

Table 9-5 Ignition sources applied in the station and ignition densities used for hydrogen. An increase factor is applied based on /9/**.**

Ignition source	Number of sources	Continous gas intensity	Discrete gas intensity	Units	Increase factor used from methane to Hydrogen
Hot_Work	10			hours/year	
Electrical_equipment	1	5.20E-06	5.40E-08	/m²(/s)	2
Delivery truck	1	7.20E-04	1.58E-06	/item(/s)	7.5
Compressor	3	3.45E-03	7.65E-06	/item(/s)	1.5
Other	1	6.50E-06	8.50E-08	/m²(/s)	5
Personnel	1	9.00E-06	1.20E-07	/m²(/s)	3
OtherEq	1	5.20E-06	4.20E-09	/m²(/s)	2

9.6.7.2 External delayed ignition

The probability of external ignition outside the hydrogen station is here estimated. The calculations are based on assumptions that only passing buses and delivery trucks when outside the fence are contributing to external ignition probability.

It is assumed that the parked buses to the east, and the buses at the dispensers to the west are lower than the blastwalls, and that gas is not reaching over the wall and down to them.

Note that if electrical installations for battery charging, etc. is installed next to the hydrogen station, then they can contribute to external ignition and this way increase the explosion risk. The present results are therefore dependent on no ignition sources above the height of the blastwall in reasonable distance from the blastwall. The distance where higher equipment can be accepted can be set to 20 to 30 m from the blastwall without considering detailed simulations. This distance is the maximum distance to flammable clouds found from the CFD simulations, see chapter 9.4.5. The electrical powerline that goes along the south border of the lot is too far away from the station to be reached by a hydrogen cloud.

It is applied that unignited jet leaks larger than 0.5 kg/s can reach outside the station through the partly open fire walls and gates to the north and south. This can only happen in the combination of jet towards north, and wind from south directions, or jet towards south and wind from northerly directions. For the other directions, the cloud will rise due to buoyancy, or be stopped by the solid blastwall.

At the same time as gas reach outside, it needs to coincide with a bus passing, or a delivery truck arriving or leaving. The probability of bus or truck outside is therefore multiplied with the probability of gas outside. The total external ignition probability is found to be 0.0073 from buses, and 0.0026 from trucks, and together the external ignition probability is therefore 0.0073 + 0.0026 = 0.0099.

9.6.8 Results from EXPRESS

Results from EXPESS are reported as the delayed ignition probability and the pressure exceedance curves together with an overview of risk drivers.

The delayed ignition probabilities are used as input to the SAFETI model. The cloud sizes and explosion pressures obtained from CFD and used in EXPRESS are further compared with their equivalents in Safeti. This comparison indicates that the model results are comparable for the situation without blastwall. The CFD results with the blastwall present are further used to adjust Safeti models so that the protective effect of the blastwall can be accounted for in Safeti.

9.6.8.1 Delayed ignition probability

The delayed ignition probabilities are calculated in EXPRESS and shown in Table 9-6. It is only the IB case when isolation is working that are shown. For the NI cases when isolation is not working, both L1 and L2 gets the same ignition probability, and this is the same as the L2 IB case in the table due to the long-lasting leaks.

The medium and large L2 cases also get an addition due to external ignition. The external ignition is not calculated in EXPRESS and is therefore added to the EXPRESS results.

The ignition probabilities presented here are used in the SAFETI model.

Table 9-6 Delayed ignition probabilities for IB cases when isolation is working. The L2 medium and large gets an addition from the external ignition; internal ignition + external ignition = total delayed ignition probability. For the other cases, the external ignition probability is zero.

Leak case	Small	Medium	Large
L1, Hoses and compressors	0.0011	0.0017	0.0025
L2, Tanks	0.003	0.020 + 0.01 = 0.030	0.023 + 0.01 = 0.032

9.6.8.2 Pressure exceedance curves and loads on the wall

The pressure exceedance curves show the accumulated frequency as a function of the pressure on the blastwall. The total curve can be used to select the design pressure on the wall. A typical acceptance frequency used in the offshore industry is 1.0E-04 per year. If this is used, the design pressure is 0.3 barg. Since the curve is relatively flat after 0.5 barg, it is advised to use a lower acceptance frequency. A design pressure of 1 barg can be recommended to give a more robust design. This corresponds to an acceptance frequency of 0.5E-04 per year.

Hydrogen explosions have a short pressure pulse duration, and a duration between 5 and 20 ms can be used for pressures between 0.5 and 3 barg, see Figure 9.40.

It can further be recommended to perform a structure response analysis for the blastwall and piping, containers, and equipment so that it does not cause any escalation of the event, and not creates projectiles that can harm people.

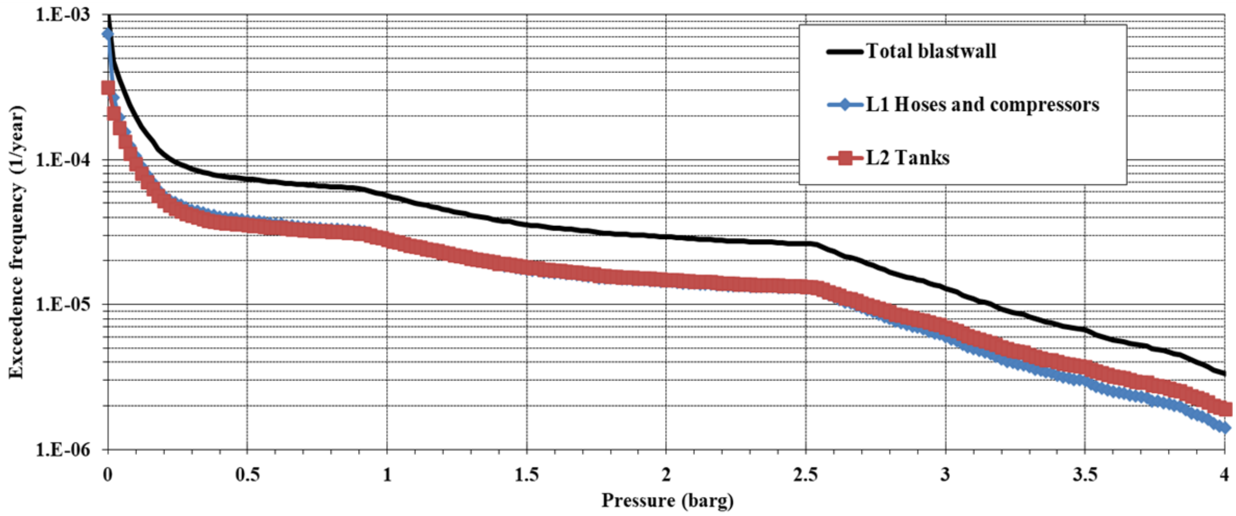


Figure 9.39 Pressure exceedance curve for the blastwall. Contributions from L1 and L2 are almost the same.

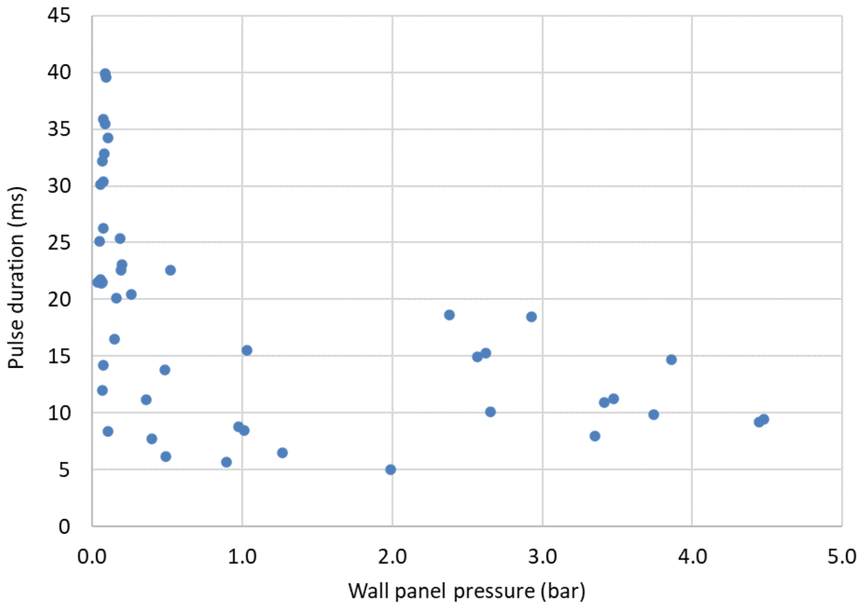


Figure 9.40 Pressure pulse duration as a function of the wall pressure.

9.6.9 Layout and barriers influence on risk based on CFD results

The results are dependent on the process system, safety barriers and designs of the hydrogen station that is applied in the present analysis. An assessment of the driving, most contributing events and safety systems is therefore provided. This is further used to give recommendations that can maintain and reduce the risk.

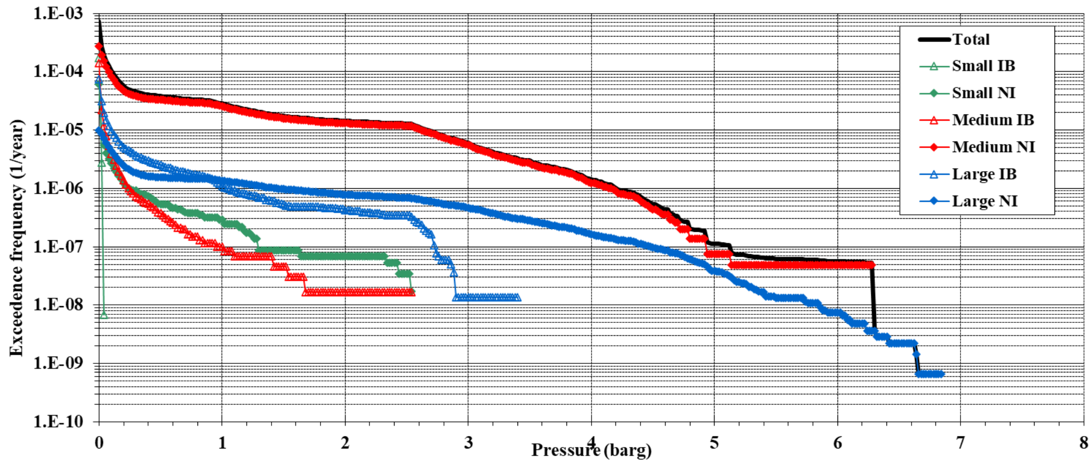
The most contributing events for the explosion loads inside the station are the medium leaks for both L1 and L2, see Figure 9.41. It is further the events where isolation is not working for L1 leaks (Medium NI). This is leaks from hoses and compressors which has a small segment inventory, but when the ESD is not working, it will result in a long-lasting leak. It is therefore important to maintain a good reliability on the ESD system (including gas detection and valve closure systems). The L2 leaks from the tanks has the largest contribution from cases when the ESD is working (Medium IB). These long-lasting leaks can generate large clouds and even with a lower leak frequency, they contribute to the explosion risk.

The fact that gas can accumulate inside containers or other confined and congested areas is a main risk driver. The configuration of possible leak locations close to congested areas causes this.

The speed of gas cloud buildup is another risk driver. A critical cloud size can be generated during a few seconds after the leak starts. In this time, the detection and shutdown has often not had time to react.

For the blast wall, it is the explosions that happens close to the wall that causes the highest pressures on the walls. The leaks that happens further away from the walls does not cause the high pressures on the wall.

Another risk driver with hydrogen is the possibility for extremely high pressures caused by DDT and possibly detonations. This is a low frequency and high consequence event. This causes the exceedance curves to be relatively flat with a large increase in the explosion loads due to a small reduction in frequency. The frequency can get a small reduction if some of the safety barriers experiences degradation.



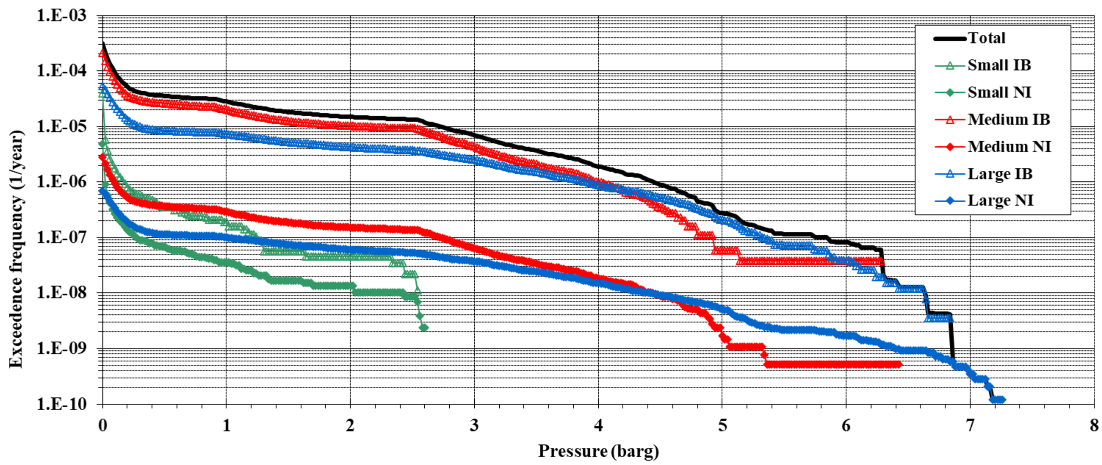


Figure 9.41 Pressure exceedance plots for L1, hoses and compressors (above); and L2, tank leaks. IB means Isolation works, and NI means No Isolation. The twp total curves in the above plots are added in Figure 9.39 to give the overall exceedance curve.

10 QRA RISK RESULTS

The risk results for the different cases are here presented as average Individual Risk (IR) per year contours.

The risk results are presented to a height of interest of 1.1 m above the ground which is considered representative for the analysis to reflect the positive buoyancy of the hydrogen gas cloud.

A detailed QRA is performed for the base case where the IR contours is found with and without a blastwall. A qualitative assessment is then performed for the three sensitivities where the risk is compared with basecase.

10.1 Case 1 - Road container and fast filling - Base case

Figure 10.1 and Figure 10.2 show the IR contours for the case without and with blast walls, respectively. In the Safeti model with the blastwall, it is applied that the blastwall is going around all sides of the station. Therefore, the effect of a blastwall in Figure 10.2 is seen also on the North and the South side. In the actual model of the station it is no blastwall but only a partly open firewall towards North and South. The contours for the actual model would therefore be a combination of the two figures, where the contours in a sector towards North and South without a blastwall is following Figure 10.1, and the contours in sectors towards East and West is following Figure 10.2.

The effect of the blastwall can be seen on the east and west side of the station with a reduced size of the 1E-05 /average year individual risk contour and with some reduction effect for 1E-06 and 1E-07 /average year risk contours.

As mentioned elsewhere in the report, the systems located outside the fence, i.e. dispenses and hoses to buses, were modelled with the explosion parameter set representing “No wall” case. Thus, significant reduction in 1E-06 and 1E-07 risk is not observed towards the west side in Figure 10.2.

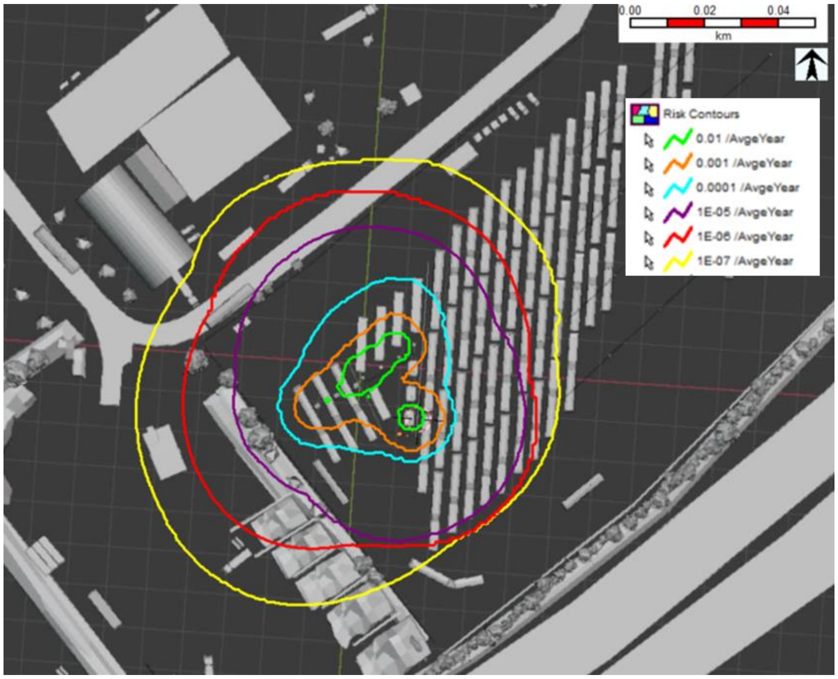


Figure 10.1 IR contours (/average year) for Case 1 (Base Case) <u>without</u> blast walls. These contours are representative for the north and south sides of the terminal since there are no blast walls assumed in those directions.

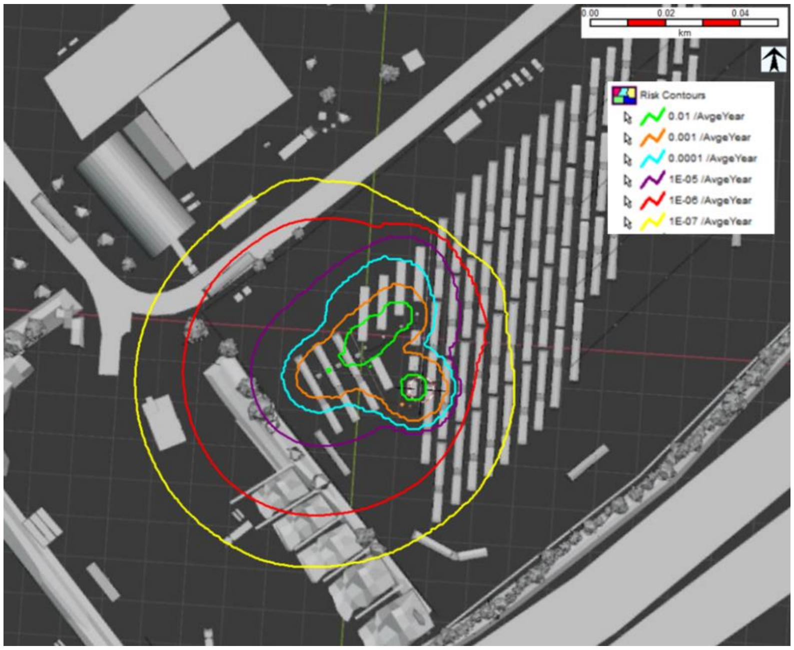


Figure 10.2 IR contours (/average year) for Case 1 (Base Case) <u>with</u> blast walls on all sides of the hydrogen station except where the dispensers are. These contours are representative for these east and west sides of the terminal since blast walls are assumed here.

The risk for the actual station is assessed against DSB criteria as follows:

- 1E-05 /average year IR contours covers part of a public road north of the station (see Figure 10.1) used by the personnel of neighboring facilities and by public. Since this risk level includes an area outside the property of Ruter, the risk is assessed as not acceptable according to DSB criteria.
- 1E-05 /average year IR contours cover assumed permanent industry/“massehotel” west of the station (see Figure 10.2), exceeds the risk acceptance criteria and therefore found as not acceptable.
- 1E-06 /average year IR contours do not cover permanent housing or residential areas and therefore it is assessed as acceptable in compliance with DSB risk criteria.
- 1E-07 /average year IR contours do not cover any vulnerable target, such as schools, kindergarten, daycare centers or hospitals and therefore is assessed as acceptable in compliance with DSB risk criteria.

The road north from the terminal is included in 1E-05 /average year risk level. Table 10-1 summarizes the main contributors to the risk at the local road (north of the filling station). These contributors are presented for the case with no wall.

The hoses to the connection units (ID 1 and 2) are contributing for a total of 83.8% to the total risk at the road north of the terminal. The high contribution from these two segments is due to their high release frequency and associated consequences, as described in chapters 8 and 9**Error! Reference source not found.**. Within 2 seconds of the full-bore release, about 13 kg of hydrogen is released. When this is mixed with air it creates a sufficient volume to generate critical explosions.

Table 10-1 Main contributors to the risk level at the local road north from the filling station for the base case

ID	Event	Size	ESD	Phase	% risk	Total risk
1	Hose to connection unit A, B and C	Large	Yes	Gas	75.9	5.54E-06
2	Hose to connection unit A, B and C	Medium	Yes	Gas	7.9	5.76E-07
3	Hose to bus 1, 2 and 3	Large	Yes	Gas	7.5	5.47E-07
4	Container A, B and C	Large	Yes	Gas	6.1	4.41E-07

Fire effects are blocked/stopped by the firewall and thus have limited/no impact on 3rd party individual risk. The main contributing outcome is explosion.

10.2 Case 2 – Road container and slow filling

Larger number of leak locations outside the fence associated with hoses to buses combined with reduced number of connection times for each dispenser, in addition to reduced consequences due to smaller pipe sizes to each bus, and distribution of scenarios over a larger area are considered to generate similar risk contours size as for around the fast filling dispensers in case 1.

It should be noted that possible events from the slow filling connections apply for night-time (i.e. when the slow filling takes place). Then less traffic density is expected related to both local road and high-way (E6), and less people present outside. It is not expected that the 1E-05 per year contour will reach to the E6 highway due to the distance and the protecting noise ridge between the bus depot and the E6 high-way. It should be noted that this conclusion is based on a qualitative evaluation and a quantification is required to confirm it.

This assessment is relying on good gas and leak detection and reliable automatic shutdown system on each slow filling dispenser and bus, as well as a protecting wall or ridge between the bus slow filling places and the E6 high-way to shield from explosion waves, projectiles and jet fires from possible events.

The area needed for the filling station inside the blastwall/firewall is reduced since the 3 fast filling dispensers are taken out. This means that the filling station can be moved more towards west making more room for bus parking spots on the east side of the filling station.

10.3 Case 3 - On site production and fast filling

As presented in chapter 8.2.3, the total leak frequency is slightly higher in Case 3 compared to Case 1.

The expected consequences from releases from the electrolysers, i.e. main contributor to the leak frequency in Case 3, are defined by system's operating pressure and representative hole sizes. The electrolysers run on significantly lower operating pressure, i.e. 35 barg vs 350 barg for Case 1. Therefore, reduction in associated consequences is expected.

The combination of slightly increased leak frequency and reduced consequences for main contributor in Case 3 are considered to give similar risk contours as for Case 1. This qualitative evaluation is consistent with another quantitative QRA which is conducted for both onsite production and road tankers. Comparison of safety distances for these two cases show similar contours and parts of the contours have a 5 m shorter distance for the onsite production. Thus, the conclusions drawn for Case 1, may conservatively remain applicable also for case 3.

For case 3 with electroyzers and permanent storage, it is not necessary with gates towards north, and it will be possible to extend the blastwall across on the north side. Some openings should still be provided with e.g. overlapping blastwalls so that air ventilation is maintained.

The onsite production case 3 needs a larger footprint area than in case 1 and this is assumed when assessing the risk above. The distance between storage and compression units is assumed to be similar to case 1, and with more total footprint of the units, it will lead to a larger total area of the station inside the firewalls. When the fast filling dispensers are located on the west side, this will require more area to the east to be used by the filling station in this case.

Note that if the onsite production should have the same area inside the firewalls as in case 1, then the congestion and distance between the units will be reduced which could result in an increased safety distance.

10.4 Case 4 - On site production and slow filling

For case 4, the qualitative evaluation conducted for case 2 for slow filling, and case 3 for onsite production apply.

The risk contours to the west with a blastwall are not considered to reach the neighbor to the west (Massehotell). This is also valid when the area inside the station is extended towards the west to occupy the fast filling spots. The blastwall is effectful and it is seen that the distance to the 1E-05 contour is approximately 10 m.

Risk contours to the North will be as in Figure 10.2 with a blastwall in place to the North, similar to Case 3 where the blastwall can be built along the North side of the filling station.

Outside the firewall/blastwall, the risk contours will be shifted to the east side covering the slow filling parking slots, like case 2.

It should be noted that this conclusion is based on qualitative evaluation and quantification is required to confirm it.

Inside the firewall/blastwall, the risk is considered similar to the road container as long as a larger area is applied. On this case, the fast filling dispensers are assumed to be eliminated, hence the filling station area within the blast/fire walls can be extended to the west. The total area of the filling station inside the blast/fire wall is therefore not expected to be larger than in case 1.

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APPENDIX A
HAZID log

ID	HAZID node location and event	HAZARD (what incident could happen)	CAUSE (Threats) (that may trigger the incident)	Possible CONSEQUENCE	Safety design and Controls/Barriers implemented	Risk Level	A: Proposed Actions/improvements C: Comments
#1.0	H2 leak in storage area delivered gas						
#1.1	Normal operation layout 1	Max hydrogen leakage, long duration	Material degradation, vibrations, hot/cold dilatation/variation, fittings getting loose over time	Unignited gas leak in the container	Natural ventilation, ESD, daily and weekly maintenance/leak test		C: The concern is on loose fittings more than on FB ruptures. The philosophy for desing is to avoid releases (rather than mitigating measures after the release) --> leak before rupture
#1.2				Explosion	Explosion walls, safety gaps and physical separation distances (At least: *1 m* around any fitting (this is ATEX distance, **not** safety distance); segregation wall/containers around tanks and equipment to avoid jetfire domino in between the storage, ventilation (natural), design (pressure safety valves at the tanks), reduce ignitions (operational barrier), tank design to prevent a leak to develop explosion. Gas detectors, process valves and shut down valves. No automatic blowdown of tanks.		A: deluge on gas detection; C: flow restriction valves at connections to reduce release rates Restriction valves would impact the performane dramatically. Normaly not used. The shut down valves are implemented as close as possible to the storage tank. C: small releases are detected in long time, if at all. The philosophy is that NV will spread the leak and it will not pose an hazards. They are experimenting acoustic detectors also for small leaks. A: increase the *separation distance* between the equipment to 2 m; A: change the layout to one with a better ventilation

ID	HAZID node location and event	HAZARD (what incident could happen)	CAUSE (Threats) (that may trigger the incident)	Possible CONSEQUENCE	Safety design and Controls/Barriers implemented	Risk Level	A: Proposed Actions/improvements C: Comments
#1.3				Fire	Protection walls/containers, flame detectors across the installation, storage volume sectionalization, ESD activated on gas detection, pressure relief valve on the trailer, manual blowdown (no flare tower, but vent), fire protection between the valve compartment and the body of the container to avoid fire exposure of the container, fire department to discuss on deluge philosophy, No flanges connections (as cannot deal with pressures) but specific fittings which would not leak if exposed to fire		C: typical ground storage 200 kg (smaller than container, which is up to 1/1.3 tonns = 45/50 000 L). Max 5000 L (this is not a standard that has to be like this); C: some time they have deluge, some time the fire brigade comes with their own equipment
#1.4				Unignited gas leak outside the container entering confined/congested areas (containers)			
#1.5	Normal opetation	Overpressure blast	Explosion	Debris of projectiles	Weekly maintenance to inspect loos fits - everything that is in place should be inspected and make sure pieces do not fly away, firewalls should be designed to avoid projectiles/flying objects		
#2.0	H2 leak in filling tanks						

ID	HAZID node location and event	HAZARD (what incident could happen)	CAUSE (Threats) (that may trigger the incident)	Possible CONSEQUENCE	Safety design and Controls/Barriers implemented	Risk Level	A: Proposed Actions/improvements C: Comments
#2.1	Normal operation	Max hydrogen leakage, long duration	Material degradation, vibrations, hot/cold dilatation/variation, fittings getting loose over time	Unignited gas leak	Gas detection, PRVs (designed for the fire scenario), manual blowdown system (not operated from remote), volume segregation, fatigue failure prevention: monitoring of no of cycles (when they get to 70% of tank life expectancy the operator gets an alarm)		C: similar to storage tank area, similar container. Big difference: steel tanks (trailer is composite); C: 200 kg typical volume for storage sectionalization
				Explosion	See #1.2.		
				Fire	See #1.3.		
#3.0	H2 leak in compressors						
#3.1	Normal operation	Max hydrogen leakage, long duration	Material failure, dropped object, chock, etc.	Unignited gas leak	The compressor receiving the hydrogen is placed in a compartment that is closed, monitored and actively ventilated		
#4.0	H2 leak in dispenser area						
#4.1	Filling operations	H2 leakage	Manual operations, vibrations, hot/cold dilatation/variation, fittings getting loose over time	Unignited gas leak	Gas detection at the filling station (tower), gas detection on the bus, ESV shutting down the filling in case of leak, pressure drop will stop fueling, check valve on the bus only not ESV (if the check valve at the bus is leaking the bus will come to the filling station empty and the filling will not start as it needs to check a back pressure to start it, the check valve is the only barrier at the bus station, it acts as master valve)		

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