QUANTITATIVE RISK ANALYSIS OF SCALED-UP HYDROGEN FACILITIES

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International Conference for Hydrogen Safety 2021, submission ID 27

ABSTRACT

Development of hydrogen facilities such as hydrogen refuelling stations (HRS) at scale is a fine balance between economy and safety, where an optimal solution would both prevent showstoppers due to cost of increased safety measures and prevent showstoppers due to hydrogen accidents. A detailed Quantitative Risk Analysis (QRA) methodology is presented where the aim is to establish the total risk of the facility and use it to find the right level of safety features such as blast walls and layout. With upscaled hydrogen facilities comes larger area footprints and more potential leak points. These effects will cause increased possible consequence in terms of vapour cloud explosions and increased leak frequencies. Both effects contributing negative to the total risk of the hydrogen facility. At the same time, as the number of such facilities is increasing rapidly, the frequency of incidents can also increase. A risk-based approach is employed where inherently safe solutions is investigated, and cost-efficient and acceptable solutions can be established. The present QRA uses well established tools such as SAFETI, FLACS and Express which are fitted for hydrogen risks. By using the established Explosion Risk Analysis tool Express, the explosion risk inside the station can be found. By using CFD tools actively one can point at physical risk drivers such as equipment layout that can minimize gas cloud build-up on the station. The explosion simulations are further used to find the effects of e.g. blast wall on the pressures affecting on people on the other side of the wall. This is used together with the results from the SAFETI analysis to develop risk contours around the facility. Current standardized safety distances are discussed by considering the effects of scaling and risk drivers on the safety distances. The methodology can be used to develop certain requirement for how hydrogen facilities should be built inherently safe and in cost-efficient ways.

1 INTRODUCTION

Risks from technical installations where large amounts of hazardous gases are present is today a broad topic and covered in many industries. Knowledge is traditionally advanced, though unfortunately, based on learnings from incidents, where the Seveso directive[1] is a relevant example that got its name from the Seveso disaster in 1976. Learnings from the Piper Alpha incident in the North Sea in 1988 [2], and the Buncefield incident in England in 2005 [3] has likewise led to major improvements in knowledge of incidents involving explosions. These incidents lead to large research and experimentation programs [3,4], which we today can benefit from through improved modelling tools, rules, and regulations. Explosion events are characterized by increasing pressure and severity when going from a fast combustion to deflagrations and detonations. When the speed of the combustion increases up to the speed of sound, it is called a deflagration to detonation transition (DDT), and when a detonation is reached, the flame travels faster than the speed of sound with an extreme pressure up to 10-20 barg. The hydrogen explosion that occurred in Sandvika, Norway, in May 2019 [5], which fortunately only lead to minor injuries, but a destroyed refueling station has also given some knowledge of how hydrogen incidents can evolve. The incident has also resulted in a slowdown of hydrogen station building in Norway. One reason for the slowdown is the potential of detonations from hydrogen incidents leading to extra cautious developments. In the present QRA approach, this uncertainty is accounted for by accepting a larger uncertainty at the high, unacceptable pressures. At lower pressures, the accuracy is higher, indicating that acceptable accuracy is employed where it is most needed. This is further discussed in Chapter 2.

Hydrogen is currently regarded the most mature energy carrier technology that can be employed at the scales needed to replace the fossil alternatives in the areas where electric cables and batteries cannot be used. Hydrogen has several drawbacks compared to fossil energy carriers of which one of them is the increased explosion risk. However, waiting for a better energy carrier would be gambling with the much larger climate risk. The world will need to achieve the same percentage of emissions reduction seen in 2020 (due to Covid19) every year through to 2050 to succeed in reaching the ambitions of the Paris Agreement [6]. Hydrogen is seen as the one accelerator that is mature enough to be employed at scales needed. An entire infrastructure for hydrogen needs to be built quickly, and this means both the scales of each installation will increase, and the number of installations will have to increase. It is evident that hydrogen technologies now need to be advanced in a much higher tempo than technologies are traditionally advanced. Tackling this challenge can be done if we employ modelling and experimentation in a much larger degree to understand the nature of incidents and risks, instead of doing improvements based mainly on learnings from incidents. By the current digital revolution, advanced Computational Fluid Dynamics (CFD) tools combined with advanced risk tools and detailed knowledge of the possible risk scenarios, a detailed risk based approach which is based on first principles and current databases with leak and ignition statistics can advance the hydrogen technology both to larger scales and to increased numbers.

The industry is following the standards for hydrogen refueling stations (e.g. ISO 19880-1) and this gives good general directions regarding safety measures and needs for the station. There is however a lack in the standards and literature which considers the overall layout and design that can be employed to make a station safer and potentially inherently safe, minimizing the number of major incidents by design. Standards does not address the issue of upscaling and does not mention any additional need for safety measure when the facilities are scaling up. Recent work with explosion risk analyses for a large number of hydrocarbon processing areas show indeed that the effect of scaling up the volume of a process area by a factor of two can result in increase of up to one order of magnitude in the probability of a fixed critical cloud volume [7]. The increased challenge with scaling up is the need for larger lot area and locations of hydrogen installations in crowded cities and closeness to public and vulnerable neighbors. Scaleup causes increased risk due to the main risk from hydrogen stations which is gas leaks with cloud build-up and explosion. The consequences from hydrogen explosions can increase exponentially when the size of the cloud is increased, and the size of the possible cloud is growing when the size of the station is growing. At some point hydrogen explosion can reach detonation, and at this stage, all combustible gas also outside congested areas results in a self-sustaining event that continues as long as there is flammable gas in the cloud. An increase in such events can result in a slowdown of the rollout of hydrogen. The need for re-considering the strategy for hydrogen safety on up scaled hydrogen facilities is therefore evident.

The present paper is therefore aimed at showing how upscaling of a hydrogen installation can increase the risk if the same design principles and safety measures are employed. The well-established risk-based approach is pointing at measures that can be employed to overcome the increase in the risk. The approach is also used in an example QRA of a scaled-up hydrogen re-fueling station for buses. By proactive use of the computer models, it is possible to advance hydrogen technology with a significantly reduced risk of major incidents, without need to wait for accidents to learn from.

Perspective from operator

Ruter AS is the administration company responsible for public transport services in larger Oslo County. They plan, commission and market public transport services. According to Oslo's and Ruter's ambition, all public transport services administrated by them shall have zero tailpipe emissions by 2028. Today, approximately 1200 buses are operated on transportation contracts for Ruter of which 156 are battery electric. From their previous experience of deploying fuel cell electric buses, with operation of five fuel cell buses since 2010, a major challenge in the planning and procurement phase has been creating a QRA for the hydrogen refueling infrastructure in line with Ruter's technology neutral procurement approach. The generalized design should accommodate for solutions that

minimize operational cost drivers such as area usage and worsened traffic flow in the bus depot. Thus, solutions that emphasize area-efficiency and efficient traffic flow in the bus depot are preferred.

Review on QRAs

Quantitative Risk Analysis (QRA) was initiated in 1975 by Rasmussen [18]. Rasmussen became known in safety engineering communities worldwide by applying the probabilistic approach to risk assessment to the nuclear industry for the first time [17]. In the early 1970s in the Netherlands, the QRA developed for nuclear safety, suddenly emerged and was proposed as the solution to guarantee safety from the frequent fires, explosions and other mishaps occurring in the process industry [17].

In the past 30 years, risk analysis techniques have strengthened process safety and showed their usefulness in supporting the process industry business by enabling risk management [19]. Nowadays, QRA plays a relevant role in the different aspects of chemical and process plants life cycle [19].

Extensive work is performed for development of risk analysis methods for hydrogen during the Hyapproval and Hysafe projects [10]. The use of CFD tools as part of ERAs for hydrocarbons is well established [23,24] from the oil&gas process industry, where it is common to use the explosion loads on a critical target such as a blastwall as a measure to quantify the risk and the load. The Safeti tool is also well established to calculate risk where the risk contours and safety distances are used as a measure for the risk, also for hydrogen stations [11,27]. Other methods are also being developed for hydrogen where CFD is used as input to the QRA [12]. By using a validated and well-established approach, it is possible to use the method actively for its intention to reduce the explosion risk and give decision support to hydrogen facility developers. The current ERA method is even used to develop standardized explosion loads for hydrocarbon processing platforms [7] involving investigating up to 100 different layouts. A recommended way to fast forward the development of hydrogen facilities can therefore be a similar approach to establish both inherently safe designs, and standardized explosion loads and safety distances for scaled up hydrogen facilities.

A generic QRA guideline is under development in [8] where also hydrogen is included. This should be followed in Norway to establish risk contours instead of using prescribed safety distances as is common in other countries. One of the goals with that the present work is to establish measures that can reduce the safety distances when scaling up, and eventually develop standardized stations and safety distances.

2 GENERAL RISK ASSESSMENT APPROACH

Quantitative Risk Analysis

The methodology for quantitative risk analysis (QRA) follow ISO 31 000 and included a HAZID, Frequency and consequence assessments, risk calculation and assessment against established Risk Acceptance Criteria (RAC). Risk drivers are assessed, and risk reducing measures can be proposed where it is seen to have the best effect as needed to reduce the risk to an acceptable level. The risk modelling and calculation is performed by SAFETI [9] and the consequence calculations and explosion risk analysis is performed using the CFD tool FLACS, and the explosion risk tool Express. The Hazard Identification (HAZID) comprise a comprehensive and systematic workshop review of potential hazards associated with operation of the hydrogen facility.

The frequency assessment is performed by counting all hydrogen equipment, including transfer appliances, storage, compression units, electrolyzers (if relevant), in addition to smaller equipment items such as filters, valves, connections, piping and instrumentation. For appliances including compressors, filters, valves, connections/joints and instruments, the release frequency is calculated based on data from HSEs large, high-quality collection of releases, HCRD database [13] by the software LEAK [14]. This database is intended to be applied to process equipment on the topsides of

offshore installations and on onshore facilities handling hydrocarbons but are not restricted to releases of hydrocarbons, IOGP [15].

The road tanker failure data defined by RVIM, Purple Book [16] is used as a basis for transfer leak frequency associated with a leak or rupture of loading/unloading hose. The frequency of catastrophic rupture of a loading hose (road tankers and tank wagons) is derived from the COVO study, [16]. In this, the frequency value for a lightly stressed hose is used. For derivation of failure frequencies associated with storage incidents of small packaging units – cylinders, the IOGP failure data for storage incident frequencies [17], is applied.

Consequence modelling and CFD-QRA integration

2D consequence modelling is performed with the PHAST models integrated in SAFETI [9]. For modelling of dispersion from hydrogen releases, SAFETI is validated against a few jet release experiments showing consistently good results with default settings for jet dispersion modelling. The model for passive gas dispersion for large releases lack validation.

Ongoing work with SAFETI validation for horizontal jets fires indicates too small flames as lift-off distances becomes very large. To reflect it in the current QRA, the Chamberlain jet fire model was implemented to reduce uncertainty.

A separate gas dispersion model is implemented in SAFETI where the gas from a leak can fill congested regions as defined in the area. With the leak directed down more gas will spread along the ground and enter into congested regions. The CFD tool was also used to model this effect indicating that large clouds can be generated in station area and get into congested regions. The SAFETI dispersion model is a 2D integral model which is linked to the ME explosion model [18]. Model settings are adjusted to hydrogens behavior so that a good match with the CFD tool is obtained. The transient consequences are calculated by the integrated PHAST consequence modelling package, for a full set of cases with all weather and safety system failure case, ignition probabilities and leak frequencies. The full event tree is then used to calculate the risks. The probability of fatalities caused by the different types of consequences in the area modeled is calculated via the probit function. This way the individual risk results is presented by location specific individual risk (LSIR) contours or iso-contours. It is assumed for individual risk that the population is outdoors and does not shelter or escape.

The well-known limitation of SAFETI package is that it does not consider actual layout or physical obstructions associated with the area considered. Software calculates downwind concentrations of a discharge in a free field and is not able to predict downwind concentrations for the case of a discharge impacting a wall or an obstacle located a few meters away. For representation of the geometry of the facility's layout, including blast and fire walls, the detailed modelling of explosion risk by FLACS was executed.

Further, 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 around the facility were correspondingly modified to include effect of the blast wall, derived by CFD. That mainly concerned adjusting the explosion definition parameters in SAFETI. For confined explosions the ME curve number was typically reduced by a factor of two. Other explosion parameters were also fitted to match the CFD results with and without the blast walls.

Explosion Risk Analysis with CFD

Central to the QRA is a CFD based Explosion Risk Analysis (ERA). This ERA contains two main parts: A CFD study focusing on the consequences under realistic conditions, which leads into a probabilistic consequence study. For the CFD study, the CFD tool FLACS is used, with the modelling adopted for hydrogen explosions. Validation of FLACS for hydrogen explosions show general good comparisons for standard cases [20] and larger variations for more complex cases [21]. For the

explosion risk analysis, the DNV tool Express is used [23,24] after adopting gas to hydrogen. This tool builds on first principles hence can consider realistic effects of hydrogen gas.

The general ERA approach includes first a CFD study with many ventilation-, dispersion- and explosion cases, and second a probabilistic Monte Carlo analysis where all transient scenarios are combined with probabilities for each event. Each main variable is assigned a probability distribution, and it is found that the distribution of e.g. cloud sizes and explosion pressure has a large impact on the results. These distributions are in the study found from the CFD simulations by running 50 or more CFD dispersion and explosion cases. It is then possible to generate not only the maximum pressures but also their distributions, giving a risk picture of both consequence and probability. The risk distributions are influenced by the wind, leak direction, geometry, blast walls, and equipment layout at the site.

The accuracy of the CFD explosion simulations is assessed to be acceptable for the present application also for hydrogen gas explosions. It is known that individual cases can show discrepancies from experiments when comparisons are made. However, models are made so that the results in average show a good fit for explosions up to DDT and for common cases. It is further known that the CFD models are calibrated against the experiments that are performed, and that when cases are moved too far from the validation cases, then larger uncertainties can be expected. Therefore, it is important to account for higher uncertainty when less validated effects are modelled. Such effects can be DDT, effects of release panels [21], or in general dynamic and geometry effects that are largely different from the experiments. There is therefore a need for experimental research to be able to better understand and model new situations at large scales.

In the present assessment several cases are simulated with different physical input parameters giving naturally varying results. This way the uncertainty due to possible variations in the input parameters is strongly reduced. Cases are also selected with a higher representation of cases with higher probability, and cases that has higher influence on the risk. Care is also taken when selecting the cases, and if it is found that a group of risk driving cases are not simulated in the first round of simulations, then this group is also simulated. With this approach it is argued that the risk results capture the main risk drivers in a robust way.

When explosions are reaching DDT and detonations, it is known that the CFD model is not able to capture the physics well, and that the accuracy therefore is reduced. Hence, for the extreme high explosions it is known that the results are uncertain. Therefore, the largest explosions are not simulated with many CFD cases. Instead they are modeled in the risk analysis with a typical high pressure, of the order 10 barg (in the example it goes from 3 bar and up, see Figure 7). When the risk analysis show that the frequency of these extreme high pressures is below an acceptable low value (e.g. less than 1.0E-6 per year) it is of less interest to know the exact value of the high pressure since it can create unacceptable damage regardless of if it is 5 or 10 barg in the local area. For the pressure at a distance from the station, the peak pressures are collapsing on a single curve in the multi-energy method when plotting the pressure as a function of the distance from the core explosion. This is indicating that the value of the core peak pressure is not influencing the distant pressure for strong explosions. It should be noted however that if a detonation is started within a congested region, it will also continue in a gas cloud which is flammable outside the congested region, and this effect is not captured well in the CFD models. Hence, the CFD models can underpredict the magnitude of the explosion also at a distance when detonations occur. To better understand this phenomenon with large hydrogen explosions, it is necessary to perform experiments. A cautious approach where onset of detonations is kept at a low acceptable frequency is recommended.

3 EXAMPLE QRA OF HYDROGEN REFUELING STATION

The example provided is a QRA of a scaled-up HRS for buses [22]. The station development is in the concept stage, and a part of the work, performed during the HAZID workshops, was also to establish the needed equipment units, placement of the units on the station, design of the station itself, and the

associated safety systems. The specifics of the station are given by a hydrogen delivery of 1.5 tons per day, and a bus depot lot with a limited area for the hydrogen station and given distances to the neighbors. The case considered is with compressed, 500 barg, hydrogen tanks delivered in road containers, redundant compressors and buffer tanks, and with three fast dispensers. The advantage of performing a QRA during the concept stage is that the arrangement of the station is not fixed. A layout can be suggested that fulfils the requirements of the operators, is cost effective and is designed to minimize gas build-up, explosions, and fire risk.

Hazard identification and station design

Hazard identification (HAZID) workshops with stakeholders including operators, equipment specialists, and HSE professionals were in the present example used to both identify hazards, design the station layout, and define the safety systems. This way an up-to-date station was designed using available technologies, commonly applied safety systems, and that would meet the capacity and operational requirements of the operator. Additional safety measures were also applied to account for the upscaled station compared to earlier built hydrogen stations.

The location and operation of the HRS within the bus depot was established considering distance to critical items such as neighboring highway and other neighbors, manned buildings, and the driving pattern on the bus depot. The HRS was placed in the northwest corner of the bus depot mainly because this would provide the longest distance to areas where people are located.

Earlier performed QRA work indicates that when an installation increases in size and complexity, the risk level will also increase and so will the safety distances [7]. A report for the Norwegian safety authorities (DSB) [27] with a HRS for cars indicates a typical safety distance of 65 m to 3rd party with industrial activity (not schools and kindergartens). The available distance at the bus depot was less, hence more safety barriers than normally applied should be applied. The main additional safety barrier added was the blast wall that was introduced on two of the sides of the station, Figure 1. The HAZID workshop was also used to work out a layout that would minimize cloud generation and improve ventilation.

Definition of the station, process, layout, and safety measures

The main design principles and safety measures that are assumed in the QRA are summarized here. It is hence essential that these principles and safety measures are implemented to reach the safety level that is found from the QRA.

Station air ventilation and explosion venting design should both provide one-way air ventilation to take away the gas, and it should vent out the combustion products efficiently in case of an explosion. To achieve this, two blastwalls on opposite sides, east and west, and semi open firewalls on the two other sides was applied, see Figure 1. This arrangement gives the possibility for natural wind flow through the station in the north-south direction to minimize stagnant zones and recirculation where gas from smaller leaks can build up. The ventilation direction is in this case also aligned with the most frequent wind direction in the area. No closed corners in the blastwalls so that no reflection pressures are obtained in the corners in case of an explosion. Blastwalls and firewalls around the station are designed to withstand the design explosion pressures so that projectiles are prevented. The wall strength can be a cost driver for the walls, therefore, one of the objectives of the ERA is to establish the needed design pressure. The height of the blastwall and firewall is set to 4 m so that it goes above the upper parts of the buses.

Layout principles inside station includes that storage containers and its connection points are located centrally so that location of these critical, long lasting leak points provide additional distance to the station limits. One container along the west blastwall is for the buffer tanks. Compressors are located towards the station limits (three containers along east wall) since they have mainly short-lasting leaks. Safety gaps/separation distance between blastwall and equipment units of 1 to 2 m or more is

generally applied to minimize gas cloud buildup from one unit to another. This is a critical distance for the safety and for the total area needed for the station. Equipment units are also aligned with the natural wind flow direction through the station, and no large pieces of equipment blocking this flow direction.

The main fire protection means are the blastwalls and the firewalls around the station which need to stop a hydrogen jet. Fire protection is also needed between equipment units within the station. Containerized storage systems are used where the container walls are assumed to give extra protects against jet fires from within the station. Gas and flame detectors across the installation so that leaks and fires are detected quickly (see assumptions below). Pressure relief valves on tanks, in case of fire this will prevent pressure buildup in the tanks and tank ruptures. Process equipment within hydrogen station is assumed with ATEX rating so that ignitions are minimized. The road trucks delivering hydrogen containers, and the buses are not assumed with ATEX rating.

Process safety systems were assumed with reliable and fast gas detection and shutdown system. For the medium and large leaks, it was assumed detection after 1 s and a total shutdown time of typically 3 s. The overall availability on demand of these systems was set to 99%. These assumptions can have a significant influence on the result, and if slower gas detectors are employed, it is recommended to account for it in the QRA.

Figure 1: Overview of the 3D geometry model with station layout. Left, entire model; right, fuel station with 3 dispensers with busses parked on left side, and hydrogen storage and processing area between the blastwalls on right side. Firewall to the south, and fire gates to the north where 4 road containers are delivered.

Leak frequencies

Leak frequency input used in QRAs comes normally from statistical data from historical incident databases. A challenge when performing risk analysis of hydrogen refueling stations and other hydrogen installations is the lack of historical incident data for such installations due to relatively new technology.

The HSE hydrocarbon release database [13] (HCRD) provides a large, high-quality collection of release experience. This database is intended to be applied to process equipment on the topsides of offshore installations and on onshore facilities handling hydrocarbons but are not restricted to releases of hydrocarbons. The HCRD was recently updated covering a period from October 1992 up to December 2015. Compared to previous version HCRD 2010 (1992 – 2006), the number of incidents recorded per year in the database has been steadily decreasing. Main uncertainty related to application of HCRD 2015 database to hydrogen leaks is mostly related to greater equipment size employed in

offshore industry (though frequencies for hole sizes in the range 2 mm – 10 mm are judged to be accurate within a factor of 2, higher or lower); lower operating pressures, certain differences in failure mechanisms, and absence of hydrogen specific equipment types associated with specialized connections, compressors in HCRD 2015.

In comparison, the leak frequency data provided by HyRAM tool [19], contains default values for the hydrogen gaseous leak frequencies from each type of component. These frequencies are assembled from generic data from offshore oil, process chemical, and nuclear power industries as well as hydrogen specific failure data. For the latter, the data quality (for example, exact pipe leakage sizes) and quantity is limited, mitigated somewhat by the employed Bayesian analysis. The Bayesian analysis is used to derive leak frequency distributions which is an advantage. However, where little or no data is available, the use of prior distributions is strongly subjective, the results of a Bayesian analysis are thus somewhat subjective [19].

The conducted comparison of Dutch Purple Book [16] and HCRD [13] vs HyRAM for equipment related to filters, cylinders, hose, and compressors indicated higher leak frequencies with HyRAM associated with compressors, whereas hose leaks were considerably lower. Leak frequency for filters and cylinders is found somewhat comparable. Thus, use of different databases may suggest different risk contributors associated with either leaks from compressors or hoses. To be consistent with earlier hydrogen QRA work, and since the HCRD database is the newest, the HCRD approach is applied in the present study. The differences in the frequency data are however not dramatic, hence it is assessed that the risk contours have a moderate uncertainty due to the variations in leak frequency.

Referring to IOGP Report, [15], the use of HCRD database for application to a specific plant conditions may be influenced by a number of physical characteristics and operating conditions, including but not limited to operating pressure, type of connections (welded), equipment age, material of construction, design code, safety management, etc. Higher operating pressure results in higher release rate. The use of DNV software LEAK to aggregate leak frequencies from the HCDR 2015 into release categories, based on the number of components, was performed as a part of QRA. It should be noted that software uses by default the properties of Methane when calculating the leak rate based on the hole size. Therefore, leak frequencies were generated based on hole-size approach followed by discharge/release rates simulation performed by DNV commercial software Safeti (using actual operating pressure and the properties of hydrogen).

Further research can be recommended to conclude on standard approach for frequency estimate for application to hydrogen leaks incidents to create consistency for future risk analysis.

Dispersion simulations with CFD

Explosion pressure is strongly correlated with gas cloud sizes. The methodology involves running around 50 transient dispersion simulations, subject to variations in wind speed and direction, leak rate and leak direction. This gives a statistical distribution of gas clouds that is used in the explosion risk analysis. The representative leak point is chosen as a credible (realistic) scenario. Different leak directions are selected with some worst-case and some realistic leak directions, and by varying the leak direction, the effect of different leak locations is also indirectly accounted for.

Simulations are run with a constant leak rate until steady state is reached. Then the leak is stopped, and simulations continues until the cloud vanishes. A high-resolution grid of 4 million cells, with cell sizes as small as 0.06 m is used in the area of interest.

Figure 2 shows two typical scenarios – a leak from a horizontal jet and a downwards-impinging jet. A jet pointed downwards gives far greater flammable gas volumes than horizontal jets, for similar leak rates. Build-up times varies significantly, with some cases reaching maximum and final cloud size within 10 seconds, while others take up to 90 seconds to reach final size. Figure 3, shows the transient development of the first three seconds of release, we see that the cloud build-up of flammable gas is extremely fast, and a large cloud size is observed after only a few seconds of release.

Even though hydrogen is a highly buoyant gas, the buoyancy effects are secondary to the momentum from the leak itself during the very beginning of the release. After some time, however, the buoyancy effects start to show. Figure 2 and Figure 3 and show the gas is highly concentrated along the ground, and only part of the cloud is lifted by buoyancy effects.

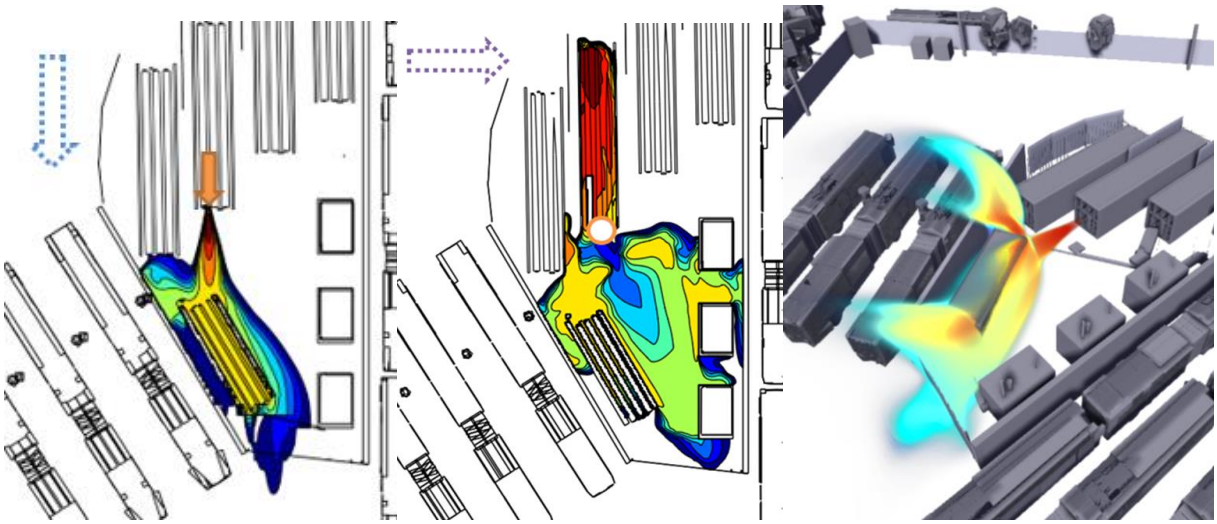

Figure 2: Typical gas cloud formations, from a horizontal release (left), downward impinging leak (middle), 3D rendering of horizontal release (right); coloured regions indicate regions with flammable gas concentrations (or higher).

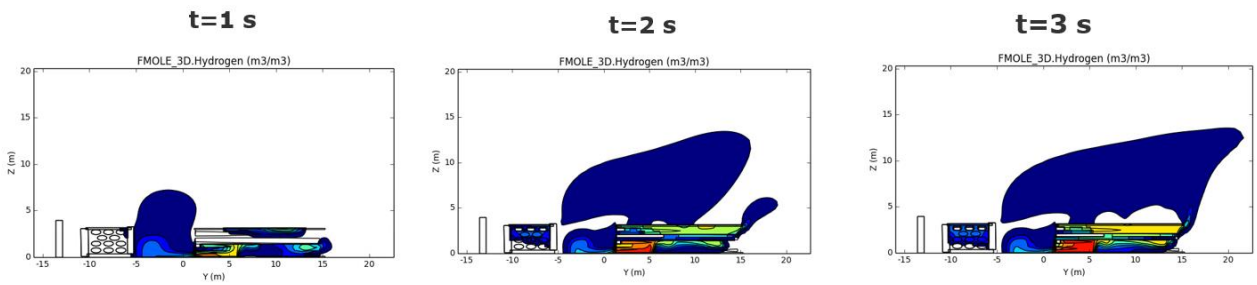

Figure 3: Initial development of flammable cloud. 1 kg/s release, 3 m/s wind from south.

Explosion simulations with CFD

Results for gas cloud location and volumes from the dispersion simulations gives input to the explosion simulations. 72 explosion simulations are performed in FLACS, with stochiometric cloud sizes ranging from approx. 10 m^3 to 160 m^3. Cloud locations were selected at representative places around the station area based on the dispersion results. Ignitions were then specified at the centre and corners of the cloud. Figure 4 shows the maximum recorded overpressure from a typical 60 m^3 explosion with a central ignition. The facility contains some quite confined areas, which leads to a high increase in pressure in these areas, particularly inside the containers themselves, between the containers and, in the areas near the blast walls. The right side of the figure shows the maximum recorded pressure as a function of distance, for areas shaded by, and not shaded by, the blast walls. The locations of the blast walls are approx. 10 m from the centre, indicating a sudden drop in the pressure in the dashed curve. The drop in the pressure at 18 m in the full curve is due to the modelled extent of the gas cloud, on average. The figure shows rapid decline in pressure directly outside the blast wall, and the pressures are consistently lower in areas shielded by the blast wall, even at significant distances – there is a factor of two reduction in pressure at 50-meter distance.

Figure 5 shows the effect of the blast wall. The figure shows an aggregated plot of the maximum recorded overpressure over all simulations, with cuts in the *xz*-plane and *yz*-plane. In the *xz*-plane cut goes through both the western and eastern blast wall, and the effect of the blast wall is clearly seen, with significantly lower pressures directly outside the blast wall –more than a factor of 10 reduction in pressure. There is some pressure overflow over the blast walls, and the effect of the blast wall is weaker further away from the wall. In the *yz*-plane there are no such blast walls (only a small, perforated firewall) and the pressure drop is more gradual.

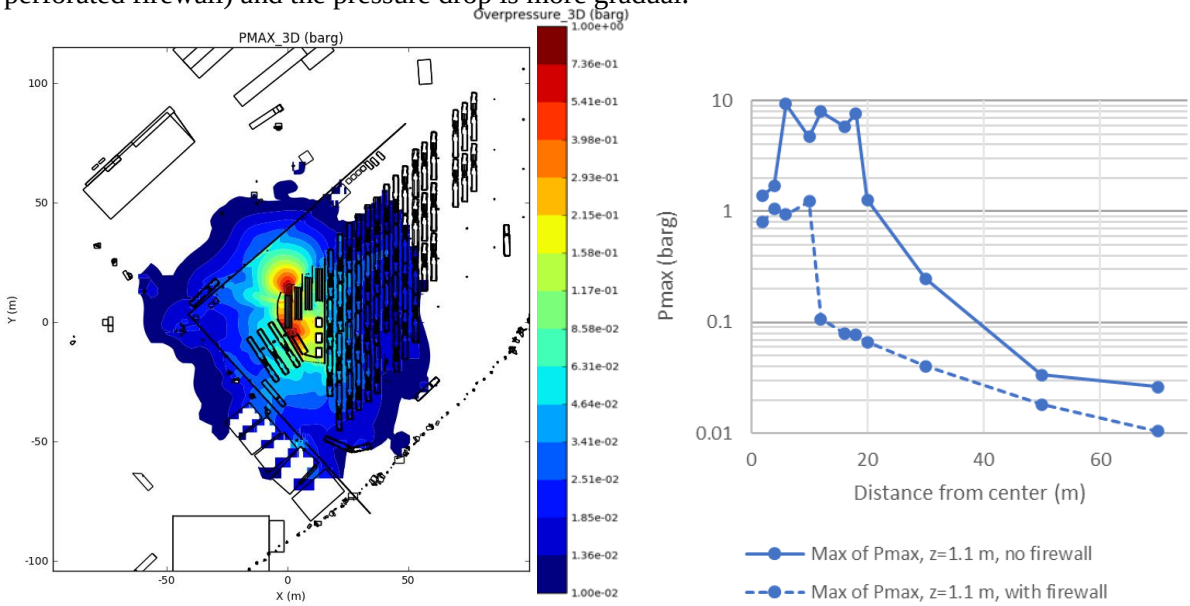

Figure 4: Maximum pressure from an explosion of a 60 m^3 stochiometric gas cloud, cut plane at *z*=1.1 m (left); and maximum explosion pressures as a function of distance from center considering only the highest explosion cases (right).

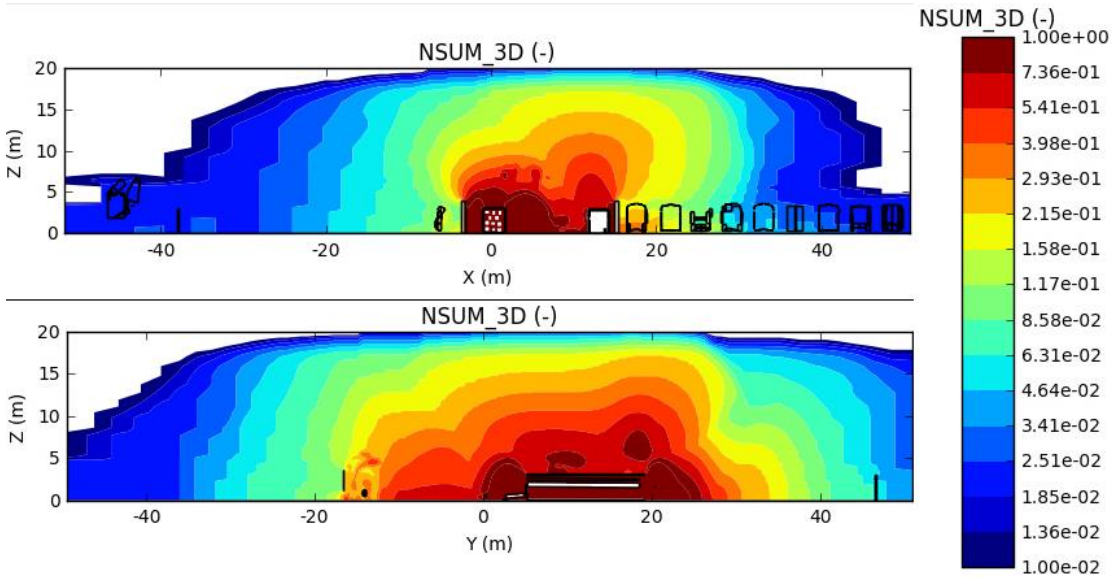

Figure 5: Effect of blast wall – cut plane through blast wall in *xz*-plane (top) and without wall in *yz*-plane (bottom). Values show the average of all max pressure values from all cases in barg.

Explosion Risk Analysis

In the explosion risk analysis, all possible scenarios are modelled with a transient model from leak to explosion using model equation from physical relations and fitted response surfaces. Each main

variable has a probability distribution which is found from the CFD simulations or known distributions (e.g. wind rose). It is hence necessary to run many CFD simulations which is used to develop distributions. The cloud volumes from the simulations (Figure 6, left) are used to develop the response surface for cloud sizes. An example of the response surfaces is shown in Figure 6, right, indicating how the leak rate and wind speed influences 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 increases, then the cloud size is reduced since the gas clouds becomes rich and not so flammable. The distribution of cloud sizes is important for the explosion risk. 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 naturally not generate the same large cloud sizes. It is hence only 1/6th of the leak cases that causes the largest clouds. The leak location is also influencing the cloud size, and this is selected to be a representative location where leak frequency is high. Ignition time is also a variable with a probability distribution, and it get the highest probability at an early stage since it can be ignited by possible continuous ignition sources or effects.

Simulations show where risk contributing clouds are formed and can be used directly to suggest improvements. In this case since gas can go into the storage containers, the explosion risk is high. With an arrangement where gas cannot enter skids and containers, the explosion risk would likely drop significantly. Another risk driver is the fact that leaks are possible from lower elevations. If the valves and piping from tanks are located above the containers it would reduce the cloud buildup along the ground. By running a large enough number of realistic CFD simulations, their results can be used to quantify distributions, and this is a main contributor to the final explosion risk result.

Equations and parameters that describes the volume of gas that can ignite are used to calculate the ignition and explosion probability in Express [23,24]. The transient gas cloud model is used together with the transient ignition probability model [25] which is also recommended for hydrogen risk analyses[10]. The volume of the flammable cloud is found to be in average 16 times larger than the equivalent stoichiometric cloud. Note that for natural gas, this increase is only 3 times. This difference is due to the wide flammability range for hydrogen, and it causes the ignition probability to increase significantly for hydrogen. The increased ignition density due to hydrogens lower ignition energy is quantified according to [27]. Here, the ignition density is increased from natural gas density with a factor from 2 to 5 times for different ignition sources depending on the strength of the ignition source. For other sources such as static electricity, ignition density is increased 5 times because static electricity has a low ignition energy which would result in more ignitions with hydrogen. Due to the large differences in gas and ignition properties compared to other gases, it is recommended to use an approach which accounts for these differences. Tabulated generic ignition probabilities should be used with care, especially for cases with long lasting or poorly ventilated areas.

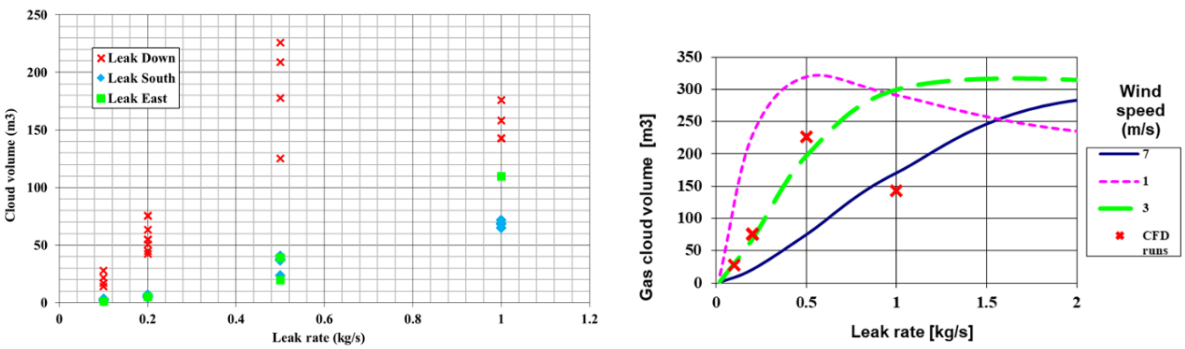

Figure 6 Left, cloud volume (Q9) as a function of leak rate for all CFD dispersion cases. Right, example of Cloud volume (Q9) as a function of leak rate for tree wind speeds as modelled with the Express response surface for leak directing down and wind from south. Comparison with relevant CFD cases.

The transient development of the gas cloud is also found from the simulations and this is used to model the cloud growth in Express. The initial cloud growth rate is important for the explosion risk since it can form a critical cloud before the leak is stopped. The initial growth rate is also larger for hydrogen compared to natural gas.

The explosion pressures on blast wall panels is used as representative in the Express simulations. These pressures are plotted in Figure 7 together with the response surface that is used. The pressure increases rapidly with the cloud volume already at 40-50 m^3. 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 7. 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, see Figure 4, left side. 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.

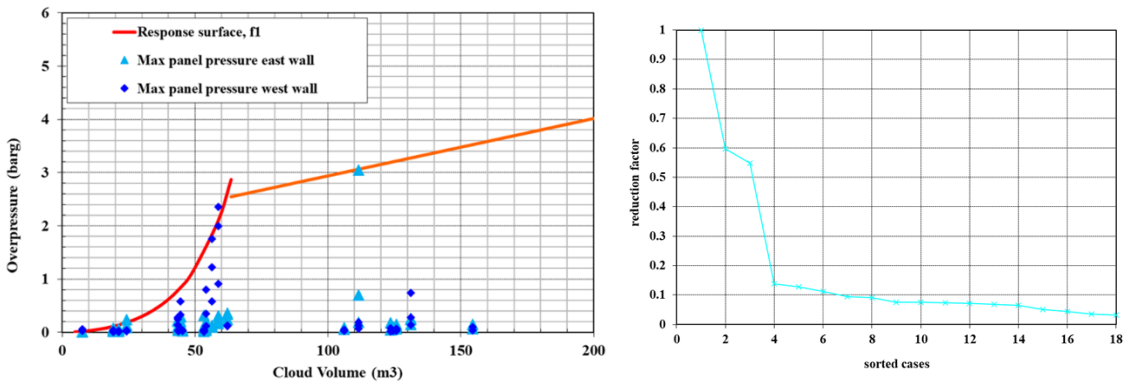

Figure 7 Left, explosion pressures on the blastwall panels as a function of the Q9 cloud volume, all cases. Maximum pressure from each case is plotted. Right, reduction factor based on 18 of the explosion simulations with cloud sizes of 40 to 60 m^3.

Main results ERA and QRA

The pressure exceedance curves giving the accumulated frequency as a function of the pressure on the blast wall is the main result from the ERA, see Figure 8. The total (black) 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 at least 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 8, right. It can further be recommended to perform a structure response analysis for the blastwalls and firewalls, piping and containers, etc. so that it does not cause any escalation of the event and does not create projectiles that can harm people. The ignition probabilities are calculated in the ERA and used in the SAFETI model. The probability for delayed ignition is found to be up to 0.03 for the large and medium leaks with long durations. For small leaks and all leaks with short duration, the ignition probability is up to 0.003.

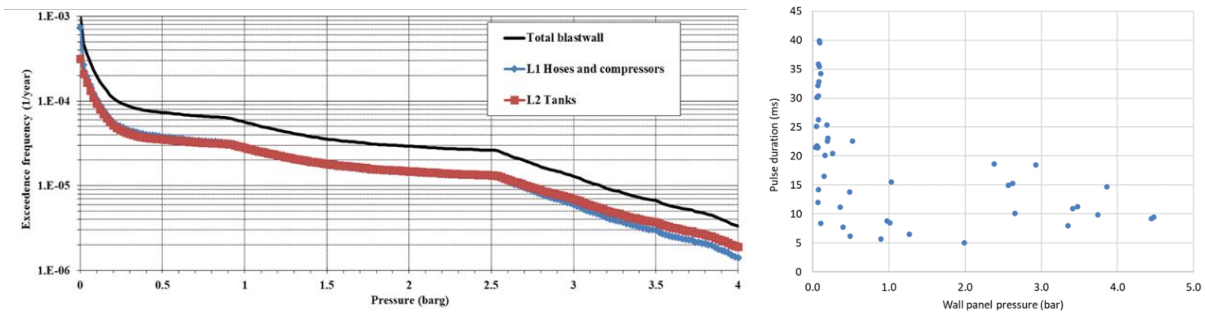

Figure 8 Left, pressure exceedance curve for the blastwall. Contributions from L1 and L2 are almost the same. Right, pressure pulse duration as a function of the blastwall pressure.

The main results from the SAFETI QRA is the risk contours shown in Figure 9. It is seen that the accept frequency lower than 1E-05 per year on the neighboring road to the North is only obtained when a blast wall is applied. The effect of the blast wall is only applied for scenarios that occurs inside the hydrogen station, therefore the dispensers causes the risk contours towards west to be almost the same for the two solutions in Figure 9.

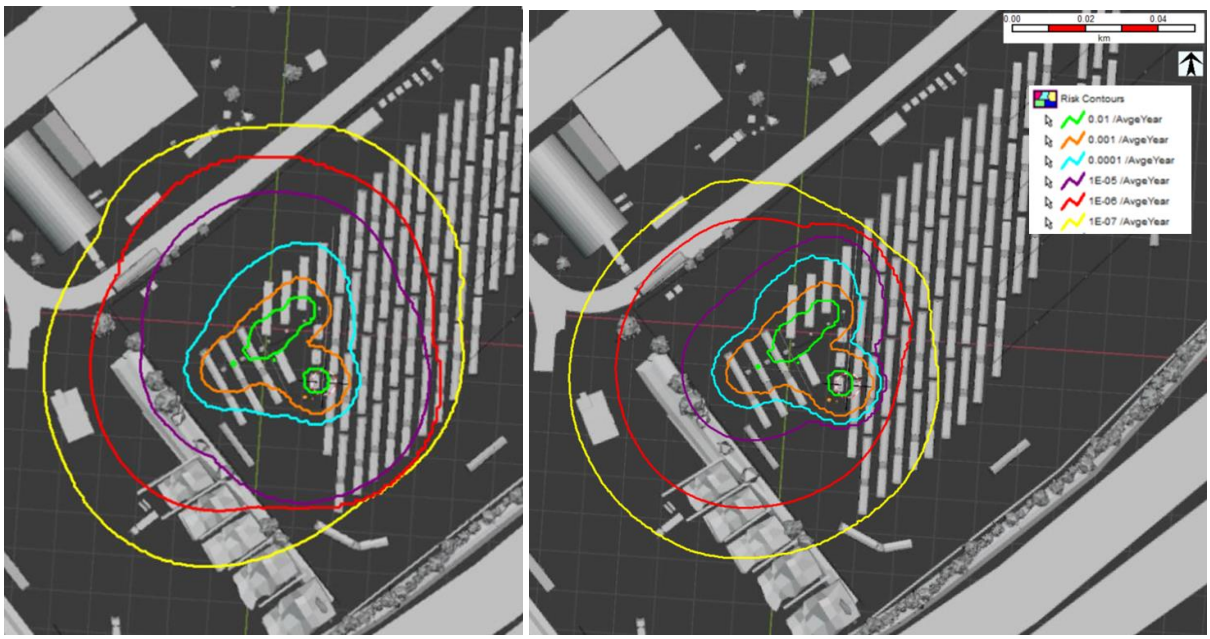

Figure 9 Individual risk contours from SAFETI results without blast walls (left) and with blast walls all around the hydrogen station (right).

4 CONCLUSIONS AND RECOMMENDATIONS

It is demonstrated how a detailed QRA approach that is well established for natural gas can be used for a hydrogen facility. The method can be used actively to select safer designs and necessary safety measures. The method is recommended used to guide the development of scaled up hydrogen facilities so that the adverse scaling effect of hydrogen explosions is captured with state-of-art modeling tools. Results from the QRA performed show risk drivers and uses them to give specific recommendations. The approach is based on first principles and can therefore be applied in hydrogen developments where new risk elements such as new technologies and larger scales are introduced. Since hydrogen

can result in major incidents, with subsequent setback of the rate of implementation, the present approach provides an assurance which has a cost that is negligible compared to alternative cost of major accidents. Many countries have already established “standardized” safety distances from some given hydrogen applications, while other countries rely on tailored risk assessments to be performed for new hydrogen stations. It should be the interest of both regulatory authorities and station operators to apply a cautious risk based approach when stations are scaled and the present tailored CFD based QRA approach represents a state-of-the art approach which can give an overall faster implementation of hydrogen at scale.

To maintain acceptable fire safety, fireproof walls around the facility that can also stop a direct jet or flash fire from the hydrogen equipment should be employed. That leaves the explosion risk to become dominating; hence a dedicated Explosion Risk Analysis is performed as a part of the QRA. The ERA is quantifying the explosion risk inside the hydrogen facility and is used to set the design pressure level and point at risk drivers. A design pressure load on the blast wall with return frequency 0.5E-4 per year is found to be 1 barg. 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 barriers, and uncertainties in assumptions and models. The CFD analyses that are used to develop the pressure exceedance curves reveals physical effects that contributes to the explosion risk. These effects can be addressed when reducing the explosion risk further. I.e. 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. A design which minimizes the probability of leaks filling gas into congested areas and for downward directed jets should therefore be sought after. The layout and equipment in typical hydrogen stations does have several congested regions where gas can get trapped and cause explosions. Typically, partly open tank storage containers, and narrow gaps between walls and equipment causes high explosion risks. Layout which prevents gas in such areas should be sought after.

The effect of a blast wall is found to be good and gives up to 10 to 2 times reduction in the explosion pressure when moving from just outside the wall to 30 m from the wall. Installation of a blast wall at least in the direction towards critical areas and close neighbors can therefore be recommended. At the same time, a station design that maintain air flow through the station in a defined direction should be applied. This can be achieved by solid blast walls on two opposing sides and more open firewalls on the two other sides.

It is the long-lasting leaks with leak rates above 0.1 kg/s that dominates the risk. These risk driving leaks are found to be from the tank system upstream the first ESDV, or from any leaks downstream the first ESDV when the ESD system fails, even when detection and shutdown time is set optimistically to 2 seconds, and the probability of failure on demand for the ESD system is assumed to be 0.01. Hence, additional measures such as blast walls and layout design also need to be in place to mitigate these scenarios for the station investigated.

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 of hydrogen that is also setting the speed of the cloud dispersion 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.

Although the CFD models cannot model detonations directly, it should be noted that hydrogens ability to cause DDT and detonations within short distances of gas clouds causes potential for extreme explosion pressures. Since detonations are not captured in the CFD model, a high unacceptable pressure is applied for cases where conditions for detonations are met. This causes the flat exceedance curve and explosion risk that is sensitive to small changes in layout designs and safety systems. It is

further applied that no projectiles from the explosions can cause fatalities in the QRA. To obtain this, it is assumed that the blast walls, firewalls, and structures are built strong enough to withstanding the pressure and drag loads that occurs so that no projectiles are made. Experiments with full scale hydrogen drag loads and detonations, and effects of blast walls should be undertaken to be able to increase knowledge of such scenarios and validate and update CFD models.

The present upscaled hydrogen facility is investigated with a detailed QRA showing safety risk contours at approximately 35 m from the center of the station to the 1E-05 per year contour when no blast wall is employed. This distance is shorter than earlier QRAs performed for smaller stations [27]. The reasons for the shorter distance in the present QRA can partly be explained by using a newer version of the leak frequency database with lower leak frequencies, and using a detailed CFD model for gas dispersion, ignition probability and explosion loads. Assumptions regarding safety systems and station design are also affecting the results. Therefore, a fair comparison with other hydrogen facilities cannot be made. A trend is seen in risk analyses of hydrocarbon process areas where the increased volume and capacity of the area causes the explosion risk also to increase when everything else is kept constant [7]. The same is expected for hydrogen facilities indicating the importance of assessing the risk when larger hydrogen facilities are being planned and available areas are limited.

It is assessed that increasing the number of hydrogen facilities introduces certain constraints due to the lack of experience with its operation and understanding of underlying risks. Potential operator error (if installation is manned), or maintenance and inspection latent fails may potentially contribute to failure propagation resulting in hydrogen leak. To be able to establish a quantitative basis, a Human Reliability Analysis (HRA) can alternatively be carried out for a specific installation to identify critical tasks and corresponding human error probability. Based on the insights from this analysis, a comprehensive safety management set of procedures may be established for hydrogen facilities. This QRA, considers unmanned operations. Potential maintenance errors and influence of those on the generic leak frequencies have not been specifically addressed. For simplicity, it was considered that established safety management procedures comply with oil&gas industry safety management practices.

Uncertainties can be found within the three main categories: consequences, frequencies, and assumptions regarding the process and safety system. The uncertainty in consequence models can be important for new or extreme situations that are not well captured by the models such as DDT. Uncertainty in frequencies can have a direct impact on the exceedance curves and the risk contours. And changes in the system parameters and assumptions can in some instances have a large impact on the risk results. Being aware of these uncertainties, one can employ validity ranges and safety margins for the uncertainties in consequence and frequency before more experiments and frequency data are available. The method is also well suited to compare different design parameters and safety systems and use results actively for decision support to arrive at solutions where the safety level is acceptable together with cost effective solutions.

5 ACKNOWLEDGEMENTS

The opinions expressed in this paper are those of the authors and should not be constructed to represent the views of DNV.

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