SAFE DESIGN FOR LARGE SCALE H2 PRODUCTION FACILITIES

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ABSTRACT

To contribute to a more diverse and efficient energy infrastructure, large quantities of hydrogen are requested for industries (e.g., mining, refining, fertilizers…). These applications need large scale facilities such as dozens of electrolyzer stacks from atmospheric pressure to 30 bar with a total capacity ranging from 100 up to 400 MW and associated hydrogen storage from a few to 50 tons.

Local use can be fed by electrolyzer in 20 feet container and stored in bundles with small volumes. Nevertheless, industrial applications can request much bigger capacity of production which are generally located in buildings. The different technologies available for the production of hydrogen at large scale are alkaline or PEM electrolyzer with for example 100 MW capacity in a building of 20000 m^3 and hydrogen stored in tube trailers or other fixed hydrogen storage solution with large volumes.

These applications led to the use of hydrogen inside large but confined spaces with the risk of fire and explosion in case of loss of containment followed by ignition. This can lead to severe consequences on asset, workers and public due to the large inventories of hydrogen handled.

This article aims to provide an overview of the strategy to safely design large scale hydrogen production facilities in buildings through benchmarks based on projects and literature reviews, best practices & standards, regulations. It is completed by a risk assessment taking into consideration hydrogen behavior and influence of different parameters in dispersion and explosion in large buildings.

This article provides recommendations for hydrogen project stakeholders to perform informed-based decisions for designing large scale production buildings. It includes safety measures as reducing hydrogen inventories inside building, allocating clearance around electrolyzer stacks, implementing early detection and isolation devices and building geometry to avoid hydrogen accumulation.

1.0 BACKGROUND / CONTEXT

The large deployment of hydrogen technologies for new applications such as heat, power, transport and other emerging industrial utilizations is essential to meet targets identified during COP21. In 2020 global electrolyzer capacity stood at 0.3 GW [1]. Electrolyzer manufacturing capacity has doubled since 2021, reaching nearly 8 GW per year; and the realisation of all the projects in the pipeline could lead to an installed electrolyzer capacity of 134-240 GW by 2030 [2]. For example, most announced projects range from 1 MW to 10 MW in size are close to industrial sites and ports [1]. Industries (e.g. mining, refining, fertilizers) need large quantities of hydrogen to contribute to a more diverse and efficient energy supply infrastructure. In order to supply industry, large scale hydrogen facilities such as dozens of electrolyzer stacks operating from atmospheric pressure to 30 bar with a total capacity ranging from 100 up to 400 MW and associated hydrogen storage from a few tons to 50 tons are required. Representative examples of large-scale projects where Engie is involved are given below:

- **Colombus** project in Benelux to produce 30 bar H2 (through 5MW alkaline electrolyzers) has a total electrical power of 100 MW based on renewable electricity. The hydrogen produced will be used to combine with CO_2 produced by lime to further generate e-methane.
- **Masshylia** is a collaborative 120 MW capacity project between Engie and Total Energies aiming to produce 50 tons per day of hydrogen to meet the needs of the biofuel production

process at Total Energies' La Mède biorefinery (France). Electricity will be generated by renewable sources, PPA and mixed national grid in order to supply pressurised alkaline electrolyzers.
- **H2SINES.RDAM** [3] is a collaborative 300 to 600 MW project between Engie, Shell, Vopak and Anthony Veder in order to produce up to 100 tons per day of hydrogen in the industrial zone of Sines port (Portugal). In order to transport large inventories of hydrogen, the gaseous hydrogen is to be liquefied before being shipped via liquid hydrogen carriers to the port of Rotterdam (Netherlands) for distribution and sale. Electricity will be generated through large wind and solar farms to supply electrolyzers.

In these projects, the area of the buildings hosting the electrolyzer stacks and associated equipment is between 3 000 and 6 000 m^2 while the total footprint of the facilities is between 15 000 and 40 000 m^2.

2.0 TYPICAL FACILITY CONFIGURATIONS

2.1 Different technologies involved

The configuration of hydrogen production facilities based on water electrolysis depend on different factors such as the end-use of the hydrogen, its location, environmental conditions and the technology selected for the electrolysis.

In alkaline electrolysis plants, the hydrogen produced at the stacks exits in a mixture with the electrolyte (lye), therefore it requires a separation and purification stage before being sent downstream for distribution, storage or consumption.

To respond to such needs, alkaline electrolysis plants include the following main process equipment [4]: electrolyzer stacks, hydrogen separators, oxygen separators, lye cooler and pumps, gas coolers and hydrogen purification module to eliminate humidity and oxygen. If compression is required for downstream consumers, then the facility will be provided with the required compression stages. Finally, the storage area allows to stock prior to distribution. Other equipment for the proper functioning of the facility include: transformers, rectifiers and utilities [5].

In PEM electrolysis plants, lye and its related ancillary equipment are not required since a solid electrolyte membrane is used, the purification unit is more compact compared to the alkaline electrolysis facilities due to the inherent higher purity of the produced hydrogen coming from the PEM stacks. Such differences along with a reduced gas compression need lead to more compact layouts compared to alkaline electrolysis facilities [6], [7].

Facilities based on the aforementioned technologies are currently more deployed than others [8] since they are more mature, therefore, the work presented here focuses on this type of facilities producing either hydrogen at atmospheric pressure or pressurised (at around 20-30 barg), pending on the selected electrolyzer supplier. This selection has therefore a non-negligible impact on the risk inherent to the production facility should a leak occur.

2.2 Hydrogen production facilities equipment and location

Safety-wise, hydrogen facilities shall be installed outdoor whenever possible since the low density of gaseous H2 rapidly drives it upwards, away from potential ignition sources from the facility and favouring dispersion with surrounding air at wind speeds that gradually increase as the altitude from ground level increases. However, and in order to maintain the integrity of the equipment, common practice is to consider a large enclosure to protect equipment from local environmental conditions.

Hydrogen production building

Electrolysis facilities are generally installed in building structures for protection against weather and environmental conditions. The free volume comprised between the walls and roof of large-scale electrolysis buildings is typically in the order of several thousand cubic meters and the space is generally ventilated at rates of 1 to 10 air changes per hour. Based on return of experience (lessons learned) from on-going large-scale projects where Engie is involved, it is seen that higher ventilation rates may be required particularly for relatively smaller building volumes and if there are temperature or imposed air velocity constraints in order to comply with heat balance control or to limit the generation of ATEX zones. When these constraints exist, dedicated studies (e.g. CFD ventilation studies) allow to optimize the specific number and location of the air inlets and outlets as well as the adequate ventilation flowrate for such particular configuration, which is specific to the studied facility.

The volume comprised in the interior of the building is an important parameter for establishing safety since in case of a hydrogen leak, the gas released will be dispersed in the available volume and mixed with the air, therefore, the size and concentration of the flammable cloud are dependent on it. Electrolyzer stacks are usually installed in the main open space of the building, meaning the length and width are in the order of magnitude of dozens of meters and the height between 5 and 15 meters with a sloped roof having a side or central apex. Sometimes other equipment such as compressors or purification units are installed in rooms or compartments inside the building. It shall be noted that this introduces confinement and limits the available air for hydrogen dispersion, which translates into dispersion and explosion behaviors that can be qualitatively different compared to large open spaces.

As a typical facility configuration for this work, it is considered that the electrolyzer stacks, separation and purification equipment are located inside the main open space of the building. Meanwhile, the storage is located outside as a good engineering practice.

Production building are usually designed as large open and well-ventilated building to favour heat dispersion (generated by warm lye) and dispersion of hydrogen in case of a leak. Electrical equipment (e.g. PCU, transformers) are segregated from hydrogen equipment by firewall to prevent risk of ignition and escalation. A minimum safety distance shall be respected between hydrogen separators and electrical part of stacks to prevent ignition. Sufficient distance shall be kept as well to facilitate handling/maintenance operations of main equipment in the building.

Separators and purification unit

Ideally, separators/hydrogen purification skids shall be implemented outdoor to prevent accumulation of hydrogen inside the enclosure.

Hydrogen compression and storage

Compressors, usually operating between 30 and 200 barg, shall be located outdoor (housed in a semi open shelter) as far as practicable considering they are more likely to generate leakages of hydrogen compared to other static equipment.

Hydrogen storage, through racks of tubes storing the compressed hydrogen at around 200 barg is usually placed outside given that the needs for weather protection are reduced, thermal balance control is not generally needed and potential leaks are diluted more rapidly compared to in-building leaks due to the wind effect on dilution and the lack of confinement that limits hydrogen accumulation and the extent of explosion consequences. Locating equipment outside is particularly important for the storage since the inventory of hydrogen that can be potentially released in case of leak is higher than the inventory in other equipment. This philosophy may be applied if technically feasible also to other equipment with relatively large inventory such as the separators.

2.3 Specificities of the production buildings

As opposed to hydrogen units inside relatively small containers/enclosures which are widely addressed by the literature, large-scale production facilities consider multiple possible configurations inside the enclosure housing the electrolyzer stacks, thus not extensively described. The equipment layout inside the large volume of such production building raises specific safe design considerations, such as:

- Escalation prevention (from hydrogen equipment to other equipment handling different fluids),
- Ignition source control,
- Ventilation type and performance.

3.0 RISKS RELATED TO THESE FACILITIES

3.1 Return of experience

There are few lessons learned related to electrolyzers. Among the accidents that occurred on production facilities leading in most cases to a fire/explosion, it is worth distinguishing those due to an accidental release of hydrogen to the atmosphere in comparison with those resulting from an internal mixture of hydrogen with oxygen (e.g.: membrane cross-over) as consequences are different.

Accidents resulting from the internal mixture of hydrogen and oxygen

The Gangneug accident, detailed in HIAD report [9] is a representative example of what could go wrong if hydrogen mixes with oxygen in a closed service line.

According to HIAD [9] and due to the failure of an electrolyzer stack, an explosion of hydrogen storage tanks of a small fuel-cell power system in the eastern port city of Gangneung (South Korea) in 2019, occurred during a test operation at a venture complex. The three tanks of 40 m^3 capacity each were all destroyed in the explosion which sent debris scattered in an area well over 3 000 m^2. The preliminary investigation indicated that the hydrogen and buffer tanks exploded due to static spark in buffer tank while oxygen concentration exceeded 6%. The main causes of the accidents are:

- absence of oxygen removing component and oxygen detector in H2 produced,
- absence of static spark remover on hydrogen tanks,
- human error during operation by running water electrolysis system lower than the operation power level, which induced degradation of membrane and increased oxygen concentration (crossover).

A similar accident occurred in 1975, at the factory of Laporte Industries Limited [10] which resulted in extensive damage to an electrolyzer plant and the subsequent death due to injuries, of the plant operator.

The investigation indicated that flammable mixture of hydrogen and oxygen was formed following the physical breakdown of the internals of the cell blocks constituting the electrolyzer. A further examination of these showed that corrosion and erosion damage resulted in inter-connecting the hydrogen and oxygen ducts.

Again, the main lesson to be learned is that both hydrogen and oxygen quality should be monitored by intrinsically safe continuous analysers.

For Gangneug accident, the electrolyzer was outdoor, whereas it was within a single-storey building for the accident at Laporte Industries. Nevertheless, it highlights the inherent risk of explosion due to accidental mix of oxygen and hydrogen in separator of electrolyzer or by accumulation in the hydrogen storage downstream. This scenario is one of the worst scenarios specific to electrolyzer technology and can lead to severe consequences as the expected overpressure can reach a much higher level than the operating pressure. It also emphasised the requirement to implement in the design of such installations an early detection of an abnormal permeability of the electrolyzer membrane (e.g. higher oxygen content in the hydrogen stream, excessive intercellular differential pressure, higher temperature in the downstream purification unit) and ensuring the adequacy of these barriers through a proper risk assessment (e.g. HAZOP).

Accidents involving pressurised hydrogen leaks

In addition to the risk of accidental mix of oxygen and hydrogen, electrolysis which generally deal with technology at pressures higher than atmospheric (from 1 to 30 barg) can lead to hydrogen loss of containment in case of equipment failure and/or human error. Combustion properties of hydrogen such as laminar combustion velocity can lead to severe effects in case of loss of containment especially in confined space such as in buildings housing large scale electrolysis facilities.

The propagation of hydrogen in confined spaces in a leak scenario can be divided into ([11]):

- a release phase (in which the average hydrogen concentration in the space increases due to the leak and where its propagation is driven by the jet kinetic energy),
- a buoyant phase (in which hydrogen ascends due to its low density relative to air)
- a dispersion phase (in which the hydrogen disperses through diffusion),
- and an end phase (after the leak stops and the system evolves slowly to an equilibrium state).

Over time, the released hydrogen passes through a stratification phase at ceiling level which can last more or less time before diffusion becomes the predominant driving force and the system tends to a homogeneous distribution. This dynamic duration and the concentration gradient at the stratification layers, depend mainly on: the leak characteristics (pressure, orifice size, regime (turbulent, laminar) and duration), the confined space volume and the arrangement of obstacles. For large scale production buildings, stratification would generally occur to some extent in the first seconds and then ventilation would evacuate hydrogen and renovate the air before a homogenization through diffusion could occur.

The hydrogen released in confined space can accumulate below ceilings and roofs till reaching a concentration higher than the LFL and could generate an explosion if an ignition source is present and damages due to the subsequent overpressures generated. In highly congested confined areas, deflagration to detonation transition phenomena could occur, which leads to even higher overpressures. Explosions and detonations should of course be avoided. For the case of 20 feet containers, the LFL can be reached very quickly but given hydrogen detection in place, the leak can be effectively detected and trigger the shutdown system prior an explosion. On the other hand, for the case of large production buildings, the space and configuration may not allow to detect in short time hydrogen leak and a flammable hydrogen cloud could be formed and ignite before leaked hydrogen is detected.

Besides overpressure consequences, which are the main concern in explosions and detonations, thermal consequences can be generated through other scenarios following a hydrogen leak in a production facility, such as:

- jet fire in case of immediate ignition of the flammable cloud with local effects - to be taken in consideration for escalation potential,
- flash fire in case of delayed ignition in conditions where the flame front cannot accelerate sufficiently to produce a hazardous pressure wave but thermal effects remain dangerous, for example, if the hydrogen cloud has a relatively low concentration and is not formed in a congested or confined space.

3.2 Asset vulnerability

Considering the above-described accidents, it is of critical importance to adequately protect the assets within these large-scale facilities, and particularly those:

- Where personnel presence is expected,
- Essential to allow a safe shutdown of the installation following an incident.

The identification of these assets is intimately linked to the environment of the facility and its end-use sector. Common examples are parking lots, control rooms (of concern particularly if the greenfield facility is integrated into a brownfield industrial site) which must, as far as practicable, be distant enough from the hydrogen production building or other equipment handling hydrogen at high pressure/with significant inventory. If this is not feasible, physical protections (fire/blast walls may be considered for escalation prevention purposes, as discussed in Section 5.4).

Hydrogen leaks inside production buildings might also jeopardize its structural elements (see Section 4), therefore the importance of segregating equipment according to their risk potential and to implement in the design adequate mitigating barriers.

Oxygen leaks inside production building could create an hyperoxia for the staff during the daily round or in case of maintenance operation in the building. Oxygen leaks are of limited importance if separators are located outdoor as a good dilution is expected around these equipments. Inside the production building, stacks contain a relatively small quantity of oxygen mixed with the lye. Therefore, a leak on the stack itself wouldn't be a big issue within this building. And it is not expected to get simultaneously hydrogen/oxygen leaks creating a flammable mixture. Furthermore and to early detect any potential oxygen leak inside the production buildings, good practice is to either implement a fixed oxygen gas detection system or to provide staff with portable detectors whenever entering such buildings. In any case, potential bigger O2 leaks would occur outdoor and at safe location.

4.0 CONSEQUENCES MODELLING

Due to the high reactivity of hydrogen upon ignition, leaks can cause serious injury or death and severe property damage, especially when the hydrogen is released in a confined/congested space.

4.1 Accidental phenomenology

The behavior of hydrogen dispersion depends on many factors such as: the discharge conditions (flow, pressure, location and direction), the geometry of the enclosure (size and shape, openings, presence of obstacles), and atmospheric conditions inside and outside the enclosure [11]. Mechanical or natural ventilation in enclosures or buildings also has a role in dispersion, which is especially relevant when the buoyancy-induced or jet-induced momentum have a lower contribution to the hydrogen propagation dynamic than the movement induced by the kinetic energy of air flows from ventilation, for example for small leaks that dilute below the flammable limit near the leak source (e.g. some leak sizes analyzed in ATEX studies). For relatively large leaks (e.g. on the order of magnitude of production rates), ventilation in the confined space will not be sufficient to avoid the generation of flammable regions during the leak phase, designing ventilation systems for such large release scenarios will rarely be feasible at an industrial scale and the explosion risk will still be present. Nevertheless, a good ventilation design is still necessary to be able to evacuate the flammable volume after the release phase has ended.

Ignition of hydrogen-air mixtures in confined spaces is frequently related to high risk due to: enhanced effect of confinement on hydrogen accumulation, flame acceleration, and pressure build-up [12].

A number of existing research studies describe the behavior of hydrogen accumulating in relatively small enclosed spaces (< 100 m^3) over long times (i.e. hundreds of seconds), little information however has been found on the behavior of dispersion and explosion in large buildings (> 10000 m^3) and especially on the early moments from a leak (first minute), when safety barriers and actions should be triggered to limit as much as possible the mass of hydrogen released and therefore to lower its consequences in case of explosion.

Releases inside small enclosed spaces such as small rooms, containers or equipment enclosures are outside of the scope of this document. Their explosion behavior can be significantly different, therefore conclusions from this document may significantly differ with such facilities.

4.2 Consequence assessment

In addition to the hydrogen production equipment, high pressure storage generates a high risk of jet fire and explosion (confined or unconfined depending on its location) in case of a large leak; flash fire and asphyxiation risks are of course present but represent less devastating effects in comparison. At the moment, racks of bottles are the most mature solution for hydrogen storage. Firewalls are good means to mitigate potential thermal effects between them. However, it can generate a certain degree of confinement and consequently increase the severity of a potential explosion. CFD studies can help to define optimal arrangement and layout to prevent escalation effects between different racks and limit a potential severe explosion within storage area.

The safe design of facilities should be based on an analysis of the risk of the hazardous scenarios potentially occurring. The risk is a combination of severity (consequences) and likelihood (probability). Determination and evaluation of the risk allows stablishing adequate preventive and mitigating measures following a properly informed decision-making process.

In this section, a focus is made on the consequence assessment which allows to understand how severe and to what extent a scenario is dangerous in terms of harm to people or damage to equipment at a certain distance from the hazardous event location.

It shall be noted that catastrophic ruptures of storage tanks or large pipes represent one of the major hazards in a facility in terms of the extent of the consequences. These scenarios are commonly analyzed for acquisition of the maximum theoretical hazardous distances, usually required by local authorities for permitting. Nevertheless, good engineering practices (e.g. suitable material selection, pressure testing) should be the main strategies to reduce the likelihood of occurrence to a minimum, such that ALARP (As Low As Reasonably Practicable) level risk is achieved. Otherwise, the separation distances that would have to be established from the potential leak locations to people or equipment to prevent harm or domino effects (escalation) would be too large to implement in most cases.

The main hazardous scenarios in hydrogen production facilities involve either a hydrogen loss of containment from the process or the formation of a flammable mixture of hydrogen with oxygen inside the equipment which, in case of ignition and internal explosion, could cause a rapid pressure build-up inside the equipment likely to burst, further releasing a pressure wave that propagates to the environment potentially leading to damages to people or property. The above risk is by the relatively small quantity of oxygen handled, as well as by the limited personnel presence within the enclosure containing the electrolyzer stacks and the use of portable detection system.

The assessment of the consequences of such scenarios can be performed with models identified in scientific literature or dedicated software that integrate literature or in-house models. Whatever is the tool selected, it should be suitable to the phenomena occurring in the hazardous scenario.

The phenomena observed in loss of containment scenarios within large-scale production buildings include: fires (including fireballs and jet fires), confined explosions (by deflagration or detonation), vented deflagration (in open spaces, ventilation openings or relatively weak surfaces that open upon overpressure in building walls or roof) and asphyxiation [13]. In relatively small enclosures, pressure peaking phenomena can also be observed.

In the industry, the use of 2D and 3D validated consequence modelling software available in the market is common practice to evaluate the effects of such phenomena in industrial facilities given that experimental testing is commonly performed by the software developer to adjust and validate the integrated models, continuously improving the accuracy of results.

For 2D modelling, validated commercial software packages such as PHAST (Process Hazard Analysis Software Tool), by DNV based on the Unified Dispersion Model [14], or EFFECTS developed by GEXCON based on the Coloured Books (recognized reference for safety analysis in the industry) from the Dutch government, allow to perform calculations on jet dispersion and estimate its explosion consequences with correlations based the on multi-energy model [15]. However, these tools are limited in terms of indoor applications.

Gexcon FLACS CFD and DNV KFX (with EXSIM integration) are the main reference software packages for CFD dispersion and explosion analysis [16] at industrial level. Both have similar foundations (Reynolds-averaged Navier-Stokes (RANS) k-epsilon equations) and provide similar results [17]. Other CFD software exist such as FDS (based on Large-eddy simulation) as well as open source toolboxes such as OpenFOAM for which parameters selection and validation would be required.

Engie carried out in 2022 an internal study with FLACS CFD version 21.3 to perform a specific consequence analysis of dispersion and explosion of hydrogen releases inside a typical large-scale water electrolysis production facility operating at 30 barg. The inputs for this study are real projects data regarding building geometry, equipment size and layout, building ventilation rates, operating pressure and temperatures, H2 production rates and piping diameter. For confidentiality reasons the model information and results described here are limited, however, as for every large scale CFD analysis, the extrapolation of conclusions should be done with care and the intention is to provide hints for the orientation of specific studies. Note that this study was done for large scale electrolysis production facilities with electrolyzer stacks and separators installed indoor in the building in a single uncongested open space of a volume around 20000 m^3 with ventilation as described in previous sections and design based on good engineering practice such as sufficient equipment clearance to allow proper maintenance.

It shall be noted that the maximum duration of the leaks analyzed in Engie internal study was 1 minute and the leaks studied were full bore rupture leaks from 6.2, 12.5 and 25 mm pipes (¼, ½ and 1 inch) considering steady-state flowrates. These assumptions were made on the basis that the buildings are built under sound engineering practices (e.g. proper building ventilation, gas detection at ceiling level) and uncontrolled accumulation of H2 in the building over long times is not likely for relatively small leaks (e.g. 6.2 mm). For larger leaks, significantly hazardous consequences are already expected (confirmed later through the simulation results) within 1 minute duration. Therefore, larger simulation times are of less interest, since safety barriers were proposed to prevent such catastrophic scenarios.

4.3 Dispersion analysis

In preliminary design development phase, it is recommended to evaluate, with simplified tools (2D dispersion tools) the dispersion plume of hydrogen in the production building and estimate the risk of an explosion in case of ignition. It allows to define the credible potential event in the building without being too conservative. In later development phases, it is advised, if risk is deemed critical by the preliminary approach, to perform a CFD study to estimate better the risk of an explosion in the building.

Engie internal study was carried out in FLACS to understand the particularities of H2 dispersion behavior of representative leaks in a typical large-scale production building configuration for the definition of suitable and technically reasonable safety barriers. The results highlighted that the main key parameters influencing the reactivity of gaseous hydrogen flammable clouds released in the building are : the piping pressure and diameter (directly correlating with the leak flowrate), the leak location relative to the building, its duration, the presence of large obstacles in the environment of the release such as firewalls and the direction of release; for the latter, despite being difficult to modify or control in practice, sensitivities are important to identify worse case scenarios. Other parameters such as ventilation flowrate, ceiling shape, building height or separation between electrolyzer stacks were observed to have less influence in the reactivity of the hazardous flammable volume.

Further results from this internal study suggest that leaks of 12.5 mm or less from piping or equipment installed near ground level such as separators produce flammable clouds whose reactivity in the proximity of the leak (in the jet and the nearby if obstacles have diverted a part of the jet) is significantly higher than at ceiling level; in fact ignition sources located in the close environment of the leak may be able to produce an explosion while ignition sources at ceiling level would rarely cause explosions for such leak sizes. Meanwhile, leaks of 25 mm produce flammable clouds whose reactivity at ceiling level is sufficient to produce an explosion. As noted hereinabove, conclusions are based on releases on the order of one minute, such time is not sufficient for a ceiling layer to grow downwards or increase sufficiently its average concentration in the representative facility cases studied (i.e. large scale production buildings on the order of 100 MW with average ceiling heights greater than 7 m).

It is important to note that leaks located close to building walls resulted in more reactive flammable clouds than those leaks at the centre of the building. Similarly, simulation results of configurations with firewalls also increased the reactivity of the flammable cloud locally (Q9 increased up to 60% compared to no firewalls configuration), but they successfully limited the spread of the cloud horizontally. Therefore, installation of firewalls while they reduce jet fire or flash fire risk, help directing faster the hydrogen to the ceiling, at the same time they increase the cloud reactivity locally and thus explosion potential consequences. Specific analysis to each facility are consequently recommended for firewall installation.

4.4 Explosion assessment

With standard arrangement (i.e. including separators inside the production building), consequence modelling of a worst-case explosion inside the building shows that overpressure around the building gives significant effects up to several hundreds of meters. Indeed, a large leak is considered able to fill the whole building with hydrogen. However, if separators are located outdoor, the remaining equipment located indoor mainly contain lye (in case of alkaline technology) and therefore cannot release a large quantity of hydrogen in case of leak. In this suggested configuration, worst case explosion within the building can therefore be dismissed.

Engie CFD internal study in FLACS, which was performed considering a standard arrangement to evaluate consequences inside the building, allowed to understand the particularities of H2 explosion behavior of representative leaks in a typical large scale production building configuration for the definition of suitable and technically reasonable safety barriers. The results determined that the main key parameters influencing the overpressure consequences from the deflagration of the released cloud are: the piping pressure and diameter (directly correlating with the leak flowrate), the leak location relative to the building, the duration of the leak and the direction of release, which as stated in Section 4.3 above is studied to identify the worst case scenarios. Other parameters such as ignition time, ventilation, ceiling shape, building height, length or height, or separation between electrolyzer stacks were observed to have less influence in the overpressure consequences in the building walls and ceiling or nearby stacks. Explosions were simulated using the real gas cloud calculated in dispersion simulation.

It was concluded also that, full bore rupture leaks of diameters of 12.5 mm or less undergoing an explosion in an open uncongested space of a large-scale building present maximum overpressure levels that are equivalent to those experienced outdoor in unconfined spaces. Note this statement is not applicable for very congested confined areas of the building (e.g. equipment with an enclosure, very congested packaged equipment, technical rooms), which could drastically change the conclusions of the study especially if the release environment can induce detonation phenomena. Meanwhile, for full bore rupture leaks of diameters of 25 mm inside the building, maximum overpressure levels are much greater than those experienced outdoor in unconfined spaces.

Escalation due to overpressures higher than 300 mbar (domino effect threshold considered here) impacting adjacent equipment or damaging the building structure is likely for leaks of 25 mm and unlikely for 12.5 mm or less, if typical maintenance separation distances between equipment are applied.

The effect of a light roof (or explosion relief venting panels) in mitigating overpressure consequences was also evaluated, using both standard and very light construction materials. The results concluded that even with very light materials no significant mitigation is observed in the environment close to the leak (i.e. maximum overpressures remain essentially unchanged) but that there is a generalized reduction on overpressures in the whole building as distance from the leak increases. It is important to note that these conclusions are based only on the leaks simulated which were located on equipment installed at ground level, not on pipe racks on the ceiling, for that case the mitigation effect is expected to be greater.

4.5 Engie internal CFD study conclusions

The main conclusions from Engie study regarding the key parameters in explosion consequence assessment and related possible design strategies for safe design of large-scale production buildings are:

- Piping pressure and diameter (directly correlating with the leak flowrate). In general, higher pressures and diameters lead to worse consequences. In design, these can be reduced for example by installing high pressure equipment outdoor and by reducing piping diameters of the main headers, which could be done by installing multiple headers of smaller diameter instead of a single large diameter header. During the operating life of the facility, particular attention can be drawn to the large diameter pipes during inspection and maintenance to prevent major accidental releases.
- Leak location relative to the building. In design, locating piping and equipment as far from the building walls as possible can significantly reduce the maximum overpressure levels as well as the potential damage inferred.
- Confinement. The presence of large obstacles like firewalls around the leak increase confinement and significantly impact the shape of the flammable cloud. In design, it is recommended that the location, dimensions and materials are selected taking into account the results of specific consequence assessment. Congestion (i.e. concentration of distributed obstacles in a certain volume) is another parameter known to have a very significant impact depending on the configuration, however its effect is highly dependent on the specific design and was less relevant in the configurations studied compared to other parameters.
- Duration of the leak. Longer release durations imply generally larger flammable mass and therefore a greater hazardous potential. In design, the reduction of static inventories, the subdivision of the piping network to split the production system into independent production units and the provision of automatic detection and fast responding isolation shut-off systems contribute to limiting the released inventory, the maximum overpressures as well as the probability of ignition (shorter duration of flammable cloud).
- Direction of release. Sensitivities on this parameter are recommended to account for the worst-case scenarios rather than to produce design recommendations given that there is uncertainty on the orientation a leak may have. Downwards releases resulted in worse consequences for equipment at ground level, but this may be different for leak sources near the ceiling.

5.0 SAFE DESIGN PRINCIPLES / RECOMMENDATIONS

A set of considerations and recommendations for a safe design of such large-scale production facilities are summarized hereafter.

5.1 Regulations / Standards / Good practices

At the time being, few hydrogen facilities are in operation and therefore the feedback from such facilities is very limited. That is why the regulation related to hydrogen is still missing in most countries. Few standards exist for hydrogen facilities (e.g. NFPA 2) but these are not necessarily relevant for large hydrogen production facilities or for indoor ones. Good engineering practices can be retrieved from the O&G industry to develop projects safely. Specific methodologies of risk analysis can be worked out for hydrogen projects. However, approach has to be customized to take into account the particularity of hydrogen properties and hydrogen handling equipment.

5.2 Safe layout

Layout of equipment is a key principle of inherent safety. Location of hydrogen or electrical equipment has to be validated carefully throughout a safety approach. Escalation effects and risk of ignition should be taken into accounted for. Credible scenarios of Loss Of Containment (LOC) have to be calculated and relevant thresholds (e.g. dominos effects, LFL) have to be used to ensure a safe layout is considered.

Outdoor location of hydrogen equipment should be preferred to avoid accumulation of hydrogen and build-up of ATEX areas. Electrolyzers have to be located indoor for operational issues. The use of fire walls to segregate the electrical equipment from the one handling hydrogen shall be considered in the evaluation of the risk. Indoor, fire walls can also be used to prevent escalation between the separators and purification unit taking into consideration however the resulting increase in confinement. In the other side, other hydrogen equipment (separators, purification, compressors, storage) should be located outdoor to prevent the risk of accumulation of hydrogen. Outdoor separators should be located in a non-congested area to limit the severity of a potential explosion.

5.3 Ignition sources control / prevention

General recommendations – coming from industrial facilities in operation – have to be implemented on hydrogen facilities. These are design recommendations (e.g. earthing of equipment, safety distances to electrical equipment, ATEX design, lightning protection) and operational recommendations (hot point, no smoking). In buildings containing hydrogen equipment, ventilation has to be carefully designed to mitigate any hazardous area around equipment particularly for relatively small buildings; specific studies allow to determine the location and flowrate of air inlets and outlets, noting that the position of such ventilation openings relative to the others and relatively to the facility geometry have a significant impact on the stability of the air flow pattern around equipment, which is important for the control of ATEX areas and heat balance.

5.4 Inherent process design

Sizing of hydrogen equipment/piping should be optimized to withstand a potential high pressure in case of process drift. Buildings with hydrogen equipment inside should be designed for jet fire/blast to protect from escalation effects behind walls, according to the sensitivity of the environment of these buildings.

Venting systems should prevent internal explosion and be designed to release hydrogen to safe location.

5.5 Prevention safety barriers

Prevention safeguards should be preferred and implemented to avoid LOC (e.g. adequate material selection, safety instrumented functions).

The first prevention barrier to consider is an adequate material selection which shall be suitable for the characteristics of the hydrogen stream (composition, pressure, temperature). Carbon steel is to be avoided due to the risk of embrittlement, stainless steels (e.g. 316L) are much more adequate.

Furthermore, and given the particularly small size of the hydrogen molecule, the number of flanges/instrument connections on the hydrogen service lines shall be limited to the strict minimum.

Pressure safety valves are considered for hydrogen pressurized equipment. However, and for specific designs of separators, there can be safety issues on the stack itself in case of PSV opening and pressure release which can further create an unbalance between O_2/H_2 separators and the formation of a flammable mixture. Specific solutions have to be designed and implemented on a case-by-case basis.

5.6 Mitigation safety barriers

Fire and gas (F&G) detection & protection strategy should be implemented in case of failure of preventive measures. F&G detectors should be specific to hydrogen (e.g. ultrasonic). Gas detectors shall be positioned just above the potential leaks points as well as at the ventilation outlets. Strategy to intervene on hydrogen leak (e.g. cool down of equipment with water) should be relevant and adequate to the hazardous scenarios identified.

6.0 CONCLUSIONS

Production of hydrogen at large-scale in configurations such as 100 MW capacity installed in a building of 20000 m^3 and outdoor hydrogen storage areas with large inventory is more and more common and developed to respond to the increasing hydrogen demand.

The return of experience on such production facilities, although being still limited, highlights that main accidents that led to a fire/explosion are either due to an accidental release of hydrogen to the atmosphere or resulting from an internal mixture of hydrogen with oxygen (membrane cross-over) with different consequences. In either situation, the consideration of additional prevention barriers in the design is key to avoid such dramatic events.

Safety-wise, hydrogen facilities shall be installed outdoor whenever possible to favour dispersion in case of hydrogen leak and further reduce the risk of fire and/or explosion. However, and in order to maintain the integrity of the equipment, common practice is to consider a large enclosure where equipment sensitive to the local environmental conditions are gathered.

The phenomena observed in loss of containment scenarios in large scale production buildings include: fires, confined explosions, vented deflagration (in open spaces, ventilation openings or relatively weak surfaces that open upon overpressure in building walls or roof) and asphyxiation. To evaluate the consequences of confined explosion, 2D modelling tools are usually considered in the early development stages of the facility but are recognised to have limitations in terms of indoor applications because they do not take in consideration the obstacles and the ventilation for example.

Thus, CFD modelling can be a useful alternative for capturing behaviors of dispersion and confined explosions of indoor large-scale hydrogen production facilities. An Engie internal CFD study on dispersion and explosion in a large production building showed that the following parameters have a high influence on overpressure consequences: piping pressure and diameter, direction of release, leak location relative to the building, and duration of the leak.

The main recommendations of the study for the design of hydrogen large-scale production facilities are: locate piping and equipment as far from the building walls as possible; limit congestion and confinement; install high pressure equipment outdoor; reduce piping diameters of the main headers (by installing multiple headers), implement automatic detection and fast responding isolation shut-off systems to limit the released inventory.

Other safe design principles can be recommended according to standards and best practices such as : adequate material selection, reduced number of flanges/instrument connections, to locate hydrogen equipment outdoor whenever possible, design the ventilation system to mitigate any hazardous area around equipment and last but not least implement safety barriers (F&G detection, PSV, venting systems) according to risk assessment carried-out.

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