LESSONS LEARNED FROM LARGE SCALE HYDROGEN PRODUCTION PROJECT

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ABSTRACT

In August 2022 Shell started construction of Holland Hydrogen I (HH I), a 200 MW electrolyser plant in the port of Rotterdam's industrial zone on Maasvlakte II, in the Netherlands. HH I will produce up to 60,000 kg of renewable hydrogen per day. The development and demonstration of a safe layout and plant design had been challenging due to ambitious HH I project premises, many technical novelties, common uncertainties in hydrogen leak effect prediction, a lack of large-scale water electrolyzer operating history and limited standardization in this industry sector. This paper provides an industry perspective of the major challenges in commercial electrolyzer plant HSSE risk assessment and risk mitigation work processes required to develop and demonstrate a safe design and it describes lessons learned in this area during the HH I project. Furthermore, the paper lists major common gaps in relevant knowledge, engineering tools, standards and OEM deliverables that need closure to enable future commercial electrolyzer plant projects to develop an economically viable and plant design and layout more efficiently and cost-effectively.

1.0 INTRODUCTION

Holland Hydrogen I (HH I), will be Europe's largest renewable hydrogen plant once operational in 2025, reflecting Shell's commitment to become a net-zero emissions business by 2050. The HH I 200 MW electrolyser (equivalent to an installed hydrogen production capacity of 87 tons per day) will be constructed in the port of Rotterdam's industrial zone on Maasvlakte II in the Netherlands and will produce an average of up to 60 tons of renewable hydrogen per day. The renewable power for the electrolyser will come from the offshore wind farm Hollandse Kust (noord). The renewable hydrogen produced will supply the Shell Energy and Chemicals Park Rotterdam, by way of the HyTransPort pipeline1, where it will replace some of the grey hydrogen usage in the refinery. This will partially decarbonise the facility's production of energy products like petrol and diesel and jet fuel. As heavy-duty trucks are coming to market and refuelling networks grow, renewable hydrogen supply can also be directed toward mobility application to help in decarbonising commercial road transport.

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Figure 1. Artist impression of HH I plant

The development of the final HH I design was challenging since:

- The HH I project objectives demand a design featuring world leading sustainability credentials and aesthetics, hence to a certain extent requiring a departure from some of the design standards established and proven for Oil and Gas installations,
- the selected HH I plot is located at the coast, nearby public beaches and next to protected Natura 2000 sites [1], hence in a challenging and sensitive environment, resulting in more stringent and demanding environmental requirements, in particular with respect to waste treatment and noise emission,
- HH I was designed to meet all of Shell's safety requirements developed in many decades of oil/gas facility operation, many aspects of which are more stringent and demanding than permit requirements and current industrial standards,
- Current models applied for prediction of hydrogen leak effects, in particular for explosions, are complex and/or contain significant levels of uncertainty, which calls for either a conservative and typically less cost-effective design or for often high-effort fundamental studies and optimization addressing mentioned gaps
- Large-scale electrolyzer operating experience and dedicated industrial standards and regulations are scarce which adds to uncertainties and design risks,
- HH I will be the first of various projects deploying facilities in the port of Rotterdam's industrial zone and the HH I plant and plot design had to consider both, risk exposure from and towards future neighboring installations before details of the latter were known.

Above-mentioned boundary conditions posed significant challenges, particularly for the following design tasks:

- Selection of electrolyzer type and process parameters allowing for an economically viable plant design that will fit the available plot space and will feature separation distances and/or additional mitigation requirements, both of which typically increase with operating pressures.
- Design of compressor enclosures striking a proper balance between noise reduction, ventilation of accidental releases and potential for an explosion.

- Design of an electrolyzer building for weather protection / ambient temperature control, while meeting ATEX and fire and explosion safety requirements.

- Safe design of an architecturally aesthetic, multi-storey control room building featuring a visitor area.

- Safe siting of equipment, buildings and structures on the available plot to address risks to staff, to the public and to neighboring plots.

In the following chapter the above-mentioned challenges, associated HSSE risk assessment and mitigation approaches successfully applied during HH I design and respective lessons learned are discussed in more detail.

2.0 HH I DESIGN CHALLENGES

The following paragraphs are touching upon the major challenges of the HH I project in developing a viable design that would verifiably meet all external as well as the often more demanding internal safety requirements developed during many decades of oil/gas facility operation experience.

2.1 Selection of Electrolyzer Technology

The type of electrolyzer technology deployed in a large-scale hydrogen production plant has significant influence on the asset's risk profile. In view of the technological novelties Shell executed a thorough assessment and de-risking programme to support the electrolyzer technology selection for the HH I project. The main aspects addressed in this assessment were: low temperature alkaline electrolysis specific risks for pressurised as well as atmospheric electrolyser systems, deployment at very large scale of more than 100's MWAC and operation with some level of intermittency. This assessment covered 3 distinct technology classes: Filter-press stack design (Atmospheric pressure (<0.5 barg) versus pressurised (30 barg)) and cartridge cell design at atmospheric pressure (<0.5 barg). De-risking was only applied for the atmospheric pressure, cartridge type system that was eventually deployed in HH I. The assessment led to the following key requirements for the further development of HH I design:

1. Training & Competence Development Plans:
   Hazards of electrolysis processes are similar to traditional oil & gas plants in the processing of flammable fluids. But one of the key differences is the extent of electrical power present in the system, and the fact that this electrical power is closely integrated with the more typical process equipment such as pipes, pumps and vessels. Scenarios may exist where electrocution hazards are present from equipment or components that would not normally be considered as a risk in an O&G process.
2. Gas Analysis Requirements
   Due to the porosity of the separator in alkaline electrolyzer systems some level of gas mixing will always be expected, and any differential pressure across the membrane will accelerate this. Therefore pressurized electrolysis introduces greater acceleration resulting in more difficulty in the safeguarding required. The result is that two key requirements are identified; level (pressure) balancing to control the differential pressure across the membrane, and the analysis of the gas qualities to ensure that too much mixing of the gases does not occur.
3. Level Measurement Safeguarding
   Maintaining control on the pressure difference across the porous separator cells is critical to avoid the mixing of O_2 and H_2. The approach to this will vary depending on the pressure of the electrolyser and technology type. For atmospheric pressure electrolysers, the pressure, and pressure difference is low enough that it is unlikely that liquid can be pushed from one gas/liquid separator vessel to another via the balancing line (mixing of gas between the two gas/liquid separators). The possible pressure difference in the cells is also limited, reducing the crossover in the cells. In these systems, it is possible to implement passive control (such as with water seals), or to operate without a

balancing line (cartridge type) with pressure/level control. For pressurised systems, there will always be a balancing line to protect against pressure difference across the cell membranes and gas/liquid separator vessels. Practically this is implemented by level measurement, and control by valve operations on the gas outlet (pressure). Due to the high pressure, potential for differential pressures and the fact that even small differential pressures would result in large level imbalances; the level control for pressurised electrolysers requires high measurement accuracy and speed, with reliable safeguards.

4. Electrical Earth Fault Protection

   The electrical protection for electrolyser systems is highly vendor, and individual project specific (e.g., layout of equipment). It also represented new/ unfamiliar risks to the organisation, which had to be properly managed for HH I. For example, there is the potential for any part of the electrolyser module to be under voltage in the event of a fault, which is an electric shock hazard, and will require special attention by operators who may be used to typical oil and gas projects. The electrical design and protection should be investigated in the design phases of each project.

5. ALARP demonstration for H_2 Compression, Purification & Drying

   De-risking the compression and purification & drying of Hydrogen. Deployment of hydrogen purification & drying at the scale of HH I is a novelty for Shell. The compression of wet hydrogen from low pressure is also a new topic for Shell although hydrogen compression at this scale and greater is common within the confines of an O & G facility. In addition to the safety aspect, there is also investigation required for operability (dynamic and intermittent operation in order to follow the availability of power from offshore wind) and efficiency (appropriate design for the operating mode).

6. Demonstration of ATEX Compliance

   Compliance with the ATEX Directive [2,3] is a mandatory requirement, and is highly dependent on the final equipment design, layout, building design, ventilation system. As such compliance must be assessed and ensured in the detailed electrolyzer unit and building design. It is obvious that ensuring sufficient ventilation will become more challenging the higher the electrolyzer operating pressure and consequences resulting from a loss of containment incident would become more severe. For high pressure electrolyser systems local forced ventilation may be required as opposed to low pressure electrolyser systems where natural ventilation may be sufficient.

2.2 Safe siting

Experience in the process industry shows that large leaks are rare but do happen, despite learning from previous incidents and continuous improvement, safeguarding against process deviations, proper design, material selection, maintenance and inspection, operator training and compliance with internal and external safety standards. Despite a low likelihood of a leak occurring the corresponding leak consequences (injury / fatality, asset damage) may be severe enough to push the risk to a level that society, the local authorities or the operating company are not willing to tolerate. Such residual risks can principally be reduced by providing sufficient separation distance between the leak source and any vulnerable objects that require protection against the potential, hazardous leak effects, in case of hydrogen leaks typically a fire or overpressure from an explosion. While the chance of undesired leak consequences impacting the vulnerable object decreases with increasing separation distance, the overall plant footprint and cost increase. So, an optimised plant design and layout will ensure that the risk won't exceed levels specified in any internal and external standards but beyond this seek a balance between additional cost spent and the level of risk reduction achieve by this additional investment. Accurate prediction of required separation is a prerequisite for a safe design without excessive conservatism that might make any venture economically unviable. In comparison to conventional process plants the prediction of required separation distances turned out to be significantly more challenging for a commercial electrolyzer plant such as HH I due to:

- Limited company and industry experience: Look-up tables of distance to be applied do not exist unlike many options available within the O &G industry

- Uncertainty in the leak size probability distribution: Electolyzer-specific design features, e.g. plastic hoses for electrolyte supply/removal from cells, hydrogen properties and containment failure modes are not yet reflected in the empiric models [4] typically used for QRA to assess risk at the fence line or occupied buildings.

- Uncertainties in prediction of hydrogen explosion characteristics and resulting overpressures: Hydrogen features a very high flame velocity and a significantly higher propensity of deflagration to detonation transition. While it is well understood that detonation will result in significantly higher overpressures as compared to deflagration the predictability of the regime is still rather poor [5,6].

- Congestion and confinement in the relevant vicinity of a leak generally increase the probability of ignition and explosion and the resulting explosion overpressure levels in the congested / confined area and hence required separation distances. At the same time more advanced and time-consuming model work is required to predict the gas cloud and explosion overpressure contours for these circumstances as compared to uncongested/unconfined situations where rather simple engineering tools often suffice. Minimum congestion and confinement are preferred from a process safety point of view but often conflict with other project or technical requirements like minimizing plant footprint, climate control or noise reduction.

- Layout optimization aims at incorporating a large range of often conflicting requirements on safe siting and logistics while minimizing plant footprint. It is a rather complex and in practice typically iterative process that involves changing relative location and orientation of plant elements and subsequent re-evaluation of the new layout. Such changes may create new risks, e. g. if a leak source has been moved away from the property boundaries but close towards an occupied building on site and/or it may change the congestion in the relevant leak vicinity so that consequences of a leak must be reassessed for the new layout. This often requires additional risk or effect calculations for this leak scenario.

The above-mentioned layout development task was particularly challenging in combination with the ambitious HH I project premises described in previous paragraph and the novelty of incorporated technology. HH I had to deviate from some of the common design features proven in decades of oil and gas plant operating experience and invested in significant subject matter expert efforts for developing and demonstrating a safe layout and design, in particular:

- The HH I control room featuring a visitor viewing area and is mostly build from wood and glass as opposed the standard design from reinforced concrete and required thorough explosion risk assessment and dedicated evaluation of the building's structural integrity against credible blast loads at the building's location.

- An oval wall designed to protect the complex against the local heavy winds and sand drift without adversely creating confinement, reduced ventilation flow across the site or increased escalation in the unlikely event of an explosion on site. This required additional ventilation modeling similar to an offshore risk assessment, design changes to the oval wall (strength and permeability) to prevent potential injuries or even fatalities on and offsite.

- The HH I hydrogen compressors a well as the electrolyzer trains had to be installed in a confined area, which significantly influences dispersion of any hydrogen leak, potential leak consequences and the building strength required to achieve a safe layout, see the following paragraph for further details.

2.3 Confined Equipment Areas

Based on experience with gaseous hazards in the oil and gas industry Shell's major design philosophy is to generally ensure installation of all equipment in hazardous gas service in an unconfined and well-ventilated area. This is also the basis for the leak dispersion and effect models incorporated in our standard engineering tools, e.g. FRED (Gexcon) [7], typically applied for development and demonstration of a safe layout. For certain parts of the HH I we had to depart from this philosophy and standard work, in particular:

- Efforts required for achieving the noise exposure limits stipulated for the Maasvlakte II industrial zone and hence location of HH I were substantial. In fact, it required installing walls to sufficiently absorb the noise emitted by the hydrogen compressors. These walls however did increase the confinement around the compressors and adversely affected ventilation and explosion overpressures potentially created in case of hydrogen leakages in the compressor area. This area has the highest operating pressures and inventory of hydrogen in the plant therefore higher risk than low pressure systems. Dispersion and explosion calculations for this geometry where complex and time-consuming requiring non-standard model work, verification and significant subject matter expert support for assurance of the quality of the calculations. Results of these calculations where only available at a point of time where the plot layout had been rather advanced already, unfortunately the outcome indicated that the early project stage layout philosophy would not be feasible and had to be fully reworked. With the available plot space and footprint and separation distances of other pieces of equipment the only feasible option was designing an 80 cm thick steel-reinforced concrete wall that would also be able to absorb explosion pressures of any of the credible leak scenarios.

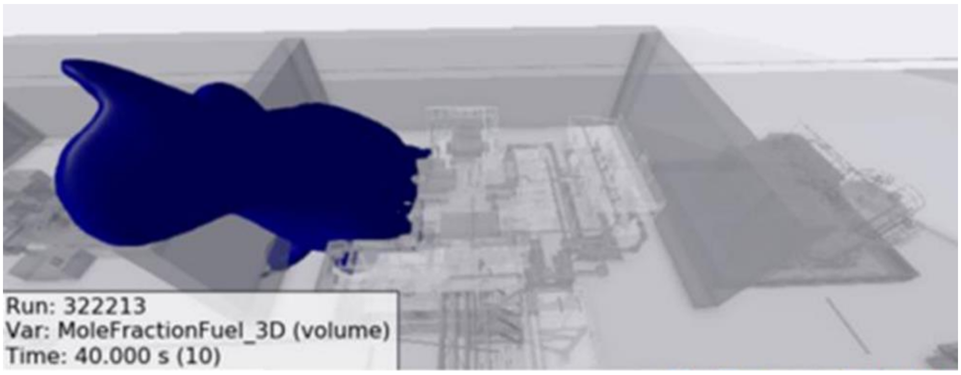

Figure 2. Example of leak dispersion calculations for HH I hydrogen compressor

- The electrolyzer technology selected for HH I requires installation in a building and indoor temperature control to allow operation at sub-zero ambient temperatures. The building was not part of the electrolyzer OEM scope. Consequentially, the HH I project had to fully develop a suitable building design including heating, natural ventilation system and gas & fire detection system from scratch. The constraints on the design were to demonstrate ATEX compliance and provide a tolerable and ALARP level of explosion and fire safety. This involved building a detailed 3D model of the site to study the wind flow across the site as well as through the building. Once inside the building the model was adjusted to reflect the particular electrolyzer geometry and temperature profiles to predict natural convection patterns and the thermal effects of the electrolyser equipment. Using this model it was demonstrated that ATEX requirements could be met although not all equipment could be provided to meet area classification zoning requirements. The internal building model was also used with to optimize the ventilation design as well as the gas detector mapping.External wind flow modelling was used to optimize the compressor wall height (while also considering the change in overpressures and noise levels) and location of the air cooler which needed to be moved to the opposite side of the site.

2.4 Assessment and Mitigation of Operational Risks

Shell's risk management process complies with the international industry standards for risk assessment and mitigation such as IEC 61882 [8] for execution of Hazard and Operability (HAZOP) studies and IEC 61511 [9] for determining safety integrity levels required for mitigating operational risks to ALARP level. IEC 61511 standard leaves room for selecting from a range of risk assessment methodologies and methods of ascertaining specific risk data, e. g. initiating event frequencies, Mean Time Between Failure (MTBF) of barriers, ignition and explosion probabilities, etc. Shell has been testing and upgrading its risk management process and underlying risk data and is incorporating findings from incidents, internal and external research and development work over decades.

Experience from engagements with OEM in the hydrogen businesss, in particular start-ups offering novel technologies, shows that they may apply above-mentioned industry standards but incorporate questionable risk data and arrive at significantly different, often lower safeguarding integrity than the Shell method. Unfortunately, the differences in methodology and underlying risk data are often too large to allow any quantitative comparison and a final evaluation / validation of respective method and its result. In view of the comparatively low maturity of these technologies and low level of global standardization and the uncertainties on the residual risk Shell decided that we wouldn't be able to judge HSSE risks and tolerability of the design on basis of compliance with the few existing industry standards alone nor on basis of existing OEM HAZOP reports. Instead, it was decided to execute a full HAZOP and LOPA assessment with participation of the OEM on Shell terms and to upgrade safeguarding where required and to ensure that quality, contents and format match the Shell's requirements for ALARP demonstration, maintenance, operation and assurance. Associated efforts for HAZOP execution and closure of identified gaps were substantial, absorbed a significant share of the project's engineering capacity and delayed the project progress. During the first HAZOP still a few design issues and interface inconsistencies between electrolyzer scope and balance of plant were identified that required design changes and another risk review. In fact, the changes compared to the previously assessed design were that plenty that it was decided to fully review the previous HAZOP in order to ensure that all relevant scenarios for the changed design are identified and properly addressed.

Furthermore, it became apparent that the lack of operating experience and history of novel technology features can make it very challenging to validate HAZOP / LOPA assumptions with respect to initiating event frequencies, credibility of certain leak consequences, barrier effectiveness and barrier reliability, for example:

- Initiating event frequencies for internal failure of electrolyzer separators leading to a significant H_2/O_2 crossover
- Ignition probabilities for internal O_2/H_2 mixtures
- Consequences of an internal explosion in a single cell after failure of a membrane (injuries / fatality in case of presence of an operator?)
- Rupture frequency of non-metal hose connections applied in the electrolyzer electrolyte circuit
- Validity of barriers suggested for certain scenarios (can there be successful detection of deviations and is the trip activated fast enough to prevent the final consequence?). In particular further development of safeguards for single and/or multi cell membrane failure and for gas detection would help reducing uncertainty, conservatism and eventually cost significantly
- Probability of ignition and explosion for hydrogen leaks in confined areas e.g. the compressor area, which has significant impact on the safeguarding integrity level required for achieving tolerable risk for leak scenarios (e.g. overpressure) in the compressor section.

3.0 CONCLUSIONS

The design of the first large-scale water electrolyzer plant included many novelties and additional challenges as compared to our experience with more conventional gas processing plant projects. Lessons learned during this exercise should enable a more straightforward and time-efficient design process and an even more economic design of further upcoming electrolyzer plants. Major lessons learned in the HSSE space are listed below:

- The selection of a suitable plot requires an initial idea of a feasible layout and estimate of the corresponding plant footprint, which is to a large extent determined by safe siting requirements, i. e. separation distances between plant elements and separation distances towards the property boundary required from an HSSE perspective. An over-ambitiously small plot space will likely result in large efforts in layout optimization and underlying leak effect simulation calculations and might eventually require significant additional CAPEX for mitigation efforts (e.g. installation of explosion-proof walls to reduce required separation distance(s)) to at least achieve all obligatory HSSE requirements. So, consider starting off with a larger, less ambitious footprint to prevent later cost escalation and project delays.

- Advanced leak effect calculations will be required to demonstrate safe siting on the final layout, since required separation distances do not only depend on the equipment / piping leak scenarios but the spatial distribution, relative position and orientation of these elements on the plot. These calculations are complex, time-consuming and require subject matter expert support. They are therefore less suitable for evaluation of the many design iterations typically seen during the design process. In particular for the initial layout a generic guidance on recommended minimum, equipment specific separation distances (to be reviewed in final detailed calculations) will be more helpful in steering involved disciplines towards a feasible layout, reduce the overall modelling effort and number of iterations required to arrive at the final design. Shell has established a matrix for generic separation distances for the Oil & Gas processing plants and is working on an update to also include electrolyzer plants and hydrogen specific aspects.

- Electrolyzer OEM might be able to help accelerating deployment of further global electrolyzer capacity by reducing design uncertainty of future projects and operating companies, in particular by:

  - Developing and proving stand-alone electrolyzer modules including the building design, HVAC system, gas detection, standardized safeguarding and guidance for safe siting and plant integration so that modules can be easily combined to a system of targeted production capacity. This would hopefully relieve projects from the necessity to develop dedicated designs for each electrolyzer plant.

  - Driving global standards for electrolyzer design features (material, safeguarding, ventilation, etc.)

  - Confirm failure scenarios, failure frequencies, worst case consequences, safeguard validity and performance requirements for respective scenarios. In particular for credible failure scenarios of cell membranes, and the realistic severity of consequence coupled with availability of effective safeguards.

- Methods for predicting hydrogen leak effects (in particular explosions) in confined/congested situations and resulting consequences are complex, require significant subject matter involvement for quality assurance and contain significant levels of uncertainty. At the same time leak size / frequency distributions commonly applied for leak risk calculations in the oil & gas and chemical industry are not entirely valid for hydrogen service and electrolyzer design features. Further advances in explosion research and modelling and predictability of leak size /

frequency distributions will help reducing uncertainty and hence reducing conservatism and project CAPEX required to ensure a safe design.

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