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SAFE DESIGN FOR LARGE SCALE H2 PRODUCTION FACILITIES

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1 - Introduction / Goal

- **Goals** – To provide :
  - Overview strategy to safely design large scale H2 production facilities in buildings
  - Recommendations for H2 project stakeholders to perform informed-based decisions for design purposes – including specific safety measures

- **How ?**
  - Through benchmark (projects and literature reviews), best practices & standards coupled with risk assessment based on H2 behavior and influence of different parameters in dispersion / explosion of H2 in large buildings

2 - Background / Context

- Large deployment of H2 technologies for new applications (heat, power, transport) and other emerging industrial utilizations to meet targets identified during COP21

- Expected installed electrolyzer capacity of 134-240 GW by 2030

- Various on-going projects close to industrial sites and ports – supply industries who need large quantities of H2 (mining, refining, fertilizers) to contribute to an efficient energy supply infrastructure

- Requirement of production facilities with dozens of electrolyzer stacks (atm-30 bar) with total capacity of 100-400 MW and associated H2 storage (few to 50 tons)

3 - Typical configurations – H2 large scale units

- **Alkaline vs PEM technology**

➢ Alkaline electrolysis plants include : electrolyzer stacks, H2 separators, O2 separators, lye cooler and pumps, gas coolers and hydrogen purification module (+ compression & storage if required by downstream consumers).

➢ In PEM electrolysis plants : lye and related ancillary equipment are not required (use of a solid electrolyte membrane), purification unit is more compact → optimized layouts compared to alkaline electrolysis facilities

➢ Focus on alkaline technology as currently more deployed than PEM

3 - Typical configurations – H2 large scale units (cont.)

- Safety-wise, H2 facilities to be installed **outdoor** (dispersed H2 driven upwards, away from potential ignition sources). However, equipment integrity shall be preserved (protection against environmental conditions) → use of **large enclosure** for housing electrolyzer stacks

- **<u>Production building features</u> :**
  - ➢ Large open space – free volume comprised between the walls and roof typically in the order of 3000-6000 m^3
  - ➢ Ventilated at rates of 1 to 10 ACH
  - ➢ May contain ancillary equipment → introduces confinement and limits the available air for H2 dispersion – Configuration considered forward : main open space of the building is housing the electrolyzer stacks, separation and purification equipment (compression and storage located outside).

4 - Risks involved

- H2 equipment located inside production building raises specific safe design considerations :
  - ➢ Escalation prevention,
  - ➢ Ignition source control,
  - ➢ Ventilation type and performance.

- Accidents observed led in most cases to a fire/explosion either from accidental (direct) release of H2 to the atmosphere or following internal mixture of H2 with O2 (membrane cross-over)

➢ Internal mixture of H2 with O2 : Gangneung (South Korea) accident in 2019. Failure of an electrolyzer stack, leading to the explosion of H2 buffer tank of a small fuel-cell power system. Investigation indicated that the tank exploded due to static spark while O2 concentration exceeded 6%.

Sources : 강원테크노파크 GANGWON TECHNOPARK; CENTER FOR Hydrogen SAFETY

4 - Risks involved (cont.)

- Gangneung accident highlights inherent risk of explosion due to accidental mix of O_2 and H_2 in separator or by accumulation in the H_2 buffer tank downstream. This scenario is one of the worst scenarios specific to electrolyzer technology (severe expected overpressure reaching a much higher level than the operating pressure) → requirement to implement in the design an early detection of an abnormal permeability of the electrolyzer membrane and to ensure adequacy of this barrier through a proper risk assessment

- <u>Accidental release of H_2 to atmosphere</u> : due to equipment failure and/or human error. Severe effects can be expected, particularly in confined space such as in buildings housing large scale electrolysis facilities given the properties of H_2 such as laminar combustion velocity → **focus of this article**

4 - Risks involved (cont.)

- **Overpressures consequences** : H2 released in confined space can accumulate below ceilings and roofs till reaching a concentration higher than LFL and could generate an explosion (if an ignition source is present)

- Specificity of large production buildings : space and configuration may not allow to detect in short time H2 leak → flammable cloud could form and ignite before leaked H2 is detected

- **Thermal consequences** can be generated in addition to overpressure effects :
  - jet fire (immediate ignition of the flammable cloud) with local effects – to be taken into consideration for escalation potential,
  - flash fire (delayed ignition in conditions where the flame front cannot accelerate sufficiently) producing thermal effects

5 - Consequence modelling (phenomenology)

- Accident phenomenology
  - Behavior of H_2 dispersion depends on many factors (discharge conditions, geometry of the enclosure, atmospheric conditions inside / outside)
  - Little information available on the behavior of dispersion / explosion in large buildings, especially on the early moments from a leak

- Consequence assessment
  - **Objective** : Understand how severe and to what extent a scenario is dangerous in terms of impact to people / asset at a certain distance from the hazardous event location
  - **How** : Internal Engie study in 2022 using FLACS (v 21.3) for specific consequence analysis of dispersion and explosion of H_2 releases inside a typical large scale water electrolysis production facility (30 barg)

5 - Consequence modelling (assumptions / dispersion results)

- **Study framework** : electrolyzer stacks / separators installed indoor in a single uncongested open space of around 20000 m^3 with ventilation
- **Assumptions** :
  - maximum duration of the leaks = 60 s
  - full bore rupture leaks from 6.2, 12.5 and 25 mm diameter piping
  - steady-state flowrates
  - building built under sound engineering practices
  - uncontrolled accumulation of H2 in the building over long times not likely for relatively small leaks (6.2 mm)

- Dispersion analysis – identification of key parameters influencing the reactivity of gaseous H2 flammable clouds released in the building :
  - **piping pressure / diameter, leak location & duration, presence of large obstacles** in the environment of the release (firewalls and the direction of release)
  - **ventilation flowrate, ceiling shape, building height or separation between electrolyzer stacks** found to have less influence

5 - Consequence modelling (dispersion results cont.)

- Leaks of **12.5 mm** or less from piping / equipment near ground level produce flammable clouds whose reactivity in the proximity of the leak is significantly higher than at ceiling level
- Leaks of **25 mm** generate flammable clouds whose reactivity at ceiling level is sufficient to produce an explosion
- Leaks **located close to building walls** resulte in more reactive flammable clouds (compared to leaks at the centre of the building)
- Configurations **with firewalls** also increase the reactivity of the flammable cloud locally (by 60%) while successfully limiting the spread of the cloud horizontally. Installation of firewalls [to reduce jet fire risk] help directing faster the H2 to the ceiling, but at the same time increases the cloud reactivity locally → **need of a specific analysis at design stage**

5 - Consequence modelling (explosion results)

- Key parameters influencing the overpressure consequences :
  - **piping pressure / diameter, leak location, duration / direction of release** (to identify the worst-case scenarios)
  - other parameters : **ignition time, ventilation, ceiling shape, building height, length or height, or separation between electrolyzer stacks** observed to have less influence on overpressures on building walls and ceiling or nearby stacks

- Leaks of **12.5 mm** or less present maximum overpressure levels equivalent to those experienced outdoor in unconfined spaces. However, for leaks of **25 mm** inside the building, maximum overpressure levels are much greater than those experienced outdoor in unconfined spaces.

- Escalation (overpressures higher than 300 mbar) is likely for leaks of **25 mm** but unlikely for lower leak diameters

6 - Strategies for safe design

Based on key parameters observed :

- Piping pressure / diameter **–** Higher pressures and diameters lead to worse consequences :
  - In design, these can be reduced by **installing high pressure equipment outdoor and by reducing piping diameters of the main headers** (installation of multiple headers of smaller diameter)
  - During the operating life of the facility, particular attention to be drawn to the **inspection and maintenance program for large diameter pipes**

- Leak location relative to the building **– Locate piping and equipment as far as possible from the building walls** to significantly reduce the maximum overpressure levels

6 - Strategies for safe design (cont.)

- Confinement – Presence of large obstacles like firewalls around the leak increasing confinement and significantly impacting the shape of the flammable cloud, **conduct dedicated risk assessment**. Congestion also have a very significant impact ; however its effect being highly dependent on the specific design, this was less relevant in the configurations studied compared to other parameters.

- Duration of the leak – Longer release durations imply generally larger flammable mass and thus greater hazardous potential. **Reduce static inventories, subdivide piping network and make provision for automatic detection and fast responding isolation shut-off systems** to limit the released inventory, the maximum overpressures as well as the probability of ignition (shorter duration of flammable cloud).

- Direction of release – **Recommend to perform sensitivities to account for the worst-case scenarios** rather than to produce design recommendations given uncertainty on the orientation of a leak (downwards releases resulted in worse consequences for equipment at ground level, this may be different for leak sources near the ceiling)

6 - Complementary (safe design) principles

- Safe layout
  - **Outdoor location of H2 equipment to be preferred** to avoid accumulation of H2 and build-up of ATEX areas
  - **Use of fire walls** (separate electrical and H2 equipment **to be considered in the risk evaluation.** 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.
- Ignition sources control / prevention
  - In buildings containing equipment handling H2, **ventilation to be carefully designed** to mitigate any hazardous area around equipment, particularly for relatively small buildings
- Safety barriers
  - **Adequate material selection** (stainless steel preferred)
  - Consider **PSV for H2 pressurized equipment**. However, safety issues on the stack itself may arise in case of PSV opening and pressure release which can further create an unbalance between O2/H2 separators.
  - Implement **specific F&G technology** (e.g. ultrasonic). **Position gas detectors just above the potential leak points / at the ventilation outlet**.

7 - Conclusions

- Production of H2 at large-scale **more and more developed**

- **REX** highlights that main accidents involving fires/explosions are either due to an accidental release of H2 or result from an internal mixture of H2 with O2. In either situation, consideration of additional prevention barriers in the design is key. Safety-wise, **H2 facilities (high pressure equipment) shall be installed outdoor** whenever possible to favor dispersion in case of H2 leak.

- To **evaluate consequences of a H2 loss of containment inside the enclosure**, CFD modelling is a useful alternative for capturing behaviors of dispersion and confined explosions. A recent internal Engie study identified parameters having a high influence on overpressure levels : piping pressure and diameter, direction of release, leak location, and duration of the leak.

7 - Conclusions (cont.)

- **Main recommendations** for the design of H2 large scale production facilities are :
  - ➢ locate piping and equipment as far as possible from the building walls
  - ➢ limit congestion and confinement
  - ➢ build enclosure geometry to avoid H2 accumulation
  - ➢ reduce H2 inventories inside building
  - ➢ reduce piping diameters of the main headers (by installing multiple headers), implement early and 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, designing the ventilation system to mitigate any hazardous area around equipment and implement safety barriers (F&G detection, PSV, venting systems) according to risk assessment carried-out engie.com