HYDROGEN SAFETY STRATEGIES AND RISK MANAGEMENT IN EQUINOR

Samdal, U.N. [1], **Grainger, D.** [2], **Hamborg, E.S.**[3], **Nilsen, S.H.** [4], **Sommersel, O.K.**[5]
[1] **Equinor, PO Box 1004, 3905 Porsgrunn, Norway, usam@equinor.com**
[2] **Equinor, Forusbeen 50, 4035 Stavanger, Norway, davgr@equinor.com**
[3] **Equinor, PO Box 3, 1330 Fornebu (Oslo), Norway, espsh@equinor.com**
[4] **Equinor, PO Box 1004, 3905 Porsgrunn, Norway, sanil@equinor.com**
[5] **Equinor, PO Box 1004, 3905 Porsgrunn, Norway, olsom@equinor.com**

ABSTRACT

Equinor has, in recent years, focused on low carbon technologies in addition to conventional oil & gas technologies. Clear strategic directions have been set to demonstrate Equinor's commitment to long-term value creation that supports the Paris Agreement. This includes acceleration of decarbonization by establishing a well-functioning market for carbon capture, transport, and storage (CCS), as well as development of competitive hydrogen-based value chains and solutions. The specific properties of hydrogen must be taken into account in order to ensure safe design and operation of hydrogen systems, as these properties differ substantially from those of natural gas and other conventional oil & gas products. Development projects need to consider and mitigate the increased possibility of high explosion pressures or detonation if hydrogen releases accumulate in enclosed or congested areas. On the other hand, hydrogen's buoyant properties can be exploited by locating potential leak points in the open to avoid gas accumulation, thereby reducing the explosion risk. The purpose of this paper is to introduce Equinor's hydrogen-based value chain projects and present our approach to ensure safe and effective designs. Safety strategies constitute the basis for Equinor's safety and risk management. The safety strategies describe the connection between the hazards and risk profiles on one hand and the safety barrier elements and their needed performance on the other, as input to safe design. The safety strategies also form the basis for safe operation. Measures to control the risk through practical designs follow from these strategies.

1.0 INTRODUCTION

Energy is at the core of society and how we conduct our lives. The world needs affordable and reliable energy to support a growing population. At the same time, society needs to reduce greenhouse gas (GHG) emissions in order to manage the effects of climate change. Addressing this dual challenge requires governments, industries, and consumers to push for substantial and rapid changes to the global energy mix. A sustainable development path, consistent with a temperature increase well below the 2°C target, depends on new business models and technologies to change the way energy is produced, delivered, and consumed.

Equinor supports the goals of the Paris Agreement and believe it is a good business strategy to ensure competitiveness and drive change towards a low-carbon future, based on a strong commitment to value creation. Equinor is hence promoting hydrogen and carbon dioxide capture and storage (CCS) solutions as these technologies can remove carbon dioxide from high-carbon sectors that cannot be easily decarbonized, such as industrial processes, maritime transport, heating, and power generation.

In early 2021 Equinor updated its Climate Roadmap [1], announcing an ambition to become a net-zero energy company by 2050. The Climate Roadmap sets a path for future investments, projects, technology development and energy sector focus. Fig. 1 describes the core of the roadmap, where the ambitions represents three main directions: (1) growth and development of projects in renewables such as offshore wind, solar and others, where renewable-based hydrogen production can act as an energy carrier and part of a value chain solution; (2) energy and carbon efficient operations of offshore platforms and production plants; (3) acceleration of decarbonisation by establishing a well-functioning market for CCS, as well as development of competitive hydrogen value chains. For a safe and sustainable introduction of hydrogen technologies and value chains, sound risk management is a necessity, and the purpose of the current work is to present the risk management principles and safety strategies for hydrogen used in Equinor.

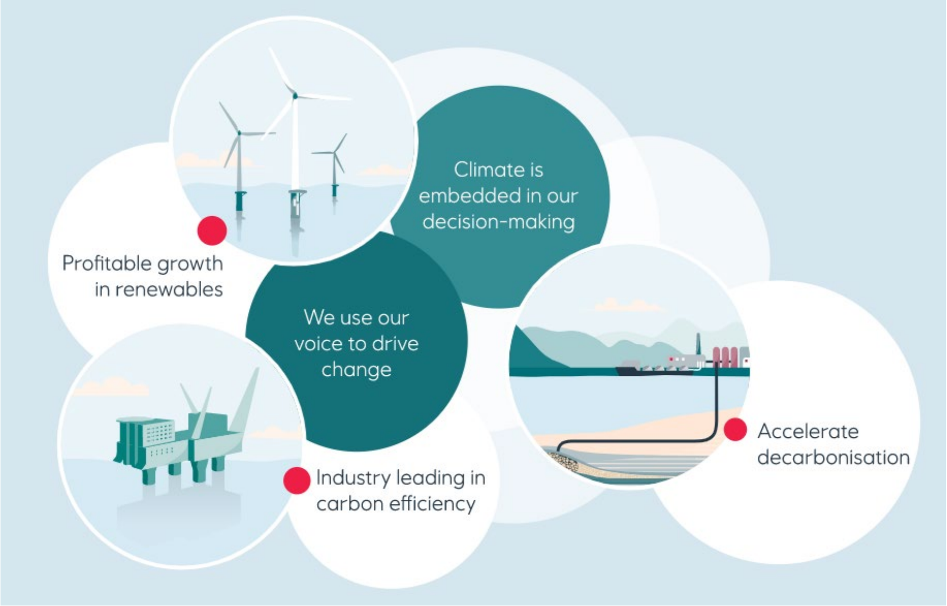


Figure 1. Equinor Climate Roadmap [1]

2.0 PROJECT DEVELOPMENT IN EQUINOR

Equinor has recently initiated the development of several hydrogen value chain projects. The background for these projects is described in the previous section. The current projects include hydrogen value chains based on both gas reformer-based ("blue hydrogen") and electrolyser-based ("green hydrogen") hydrogen production. A short description of these two types of hydrogen production is:

- **Reformer-based hydrogen production:** conventional technology for production of hydrogen at scale by catalytic conversion of natural gas (or other hydrocarbon-based feeds) and steam to hydrogen and carbon dioxide by addition of heat.
- **Electrolyser-based hydrogen production:** conventional technology for production of hydrogen at smaller scale by electrochemical conversion of water to hydrogen and oxygen (or the conversion of other aqueous systems to hydrogen and another gaseous products) by addition of direct current electric power.

Although both technologies are conventional and commercially available, they are both undergoing technology development with respect to increased efficiencies and construction costs.

A prerequisite for sustainable hydrogen production from reformer-based hydrogen production is the handling of produced carbon dioxide, i.e. CCS. Norway and Equinor have, along with partners, pioneered CCS technologies since the 1990s with demonstrated long-term operations at the Sleipner offshore facility and the onshore facilities at In Salah, Hammerfest and Mongstad, as described in detail elsewhere [2-4]. Since 2012, the Norwegian State, represented by its state enterprise Gassnova, has matured further CCS projects and applications in Norway, where the aim is to develop and construct CO_2 capture, transport and storage infrastructure [5]. The recent initiative of the Norwegian government has, along with the industrial partners Total, Shell and Equinor, been developed into the Longship CCS project. Investment funding has been secured from the Norwegian State and its partners [6-7].

Based on the aforementioned projects and also ongoing activities with electrolyser technologies, Equinor is well prepared for (co-)developing hydrogen value chain technologies and projects.

2.1 Current hydrogen projects in Equinor

Some of the current, early-phase hydrogen projects involving Equinor are [8]:

- **Zero Carbon Humber**: Blue hydrogen is planned to be produced at a new plant at Saltend in the UK in 2027. The hydrogen would be used by chemical industry and flexible power plants in the Humberside industrial cluster. Equinor is cooperating with Drax and National Grid Ventures on this project
- **H2Morrow steel:** A 2.7 GW blue hydrogen plant would be used to decarbonize German steel production, in partnership with ThyssenKrupp Steel Europe, in the second half of the 2020's
- **H2Magnum:** Equinor is working together with Vattenfall and Gasunie on a project to supply blue hydrogen to one of three 440 MW power plant trains at Magnum in the Netherlands, to produce flexible clean power
- **HyDEMO**: Equinor is evaluating a small-to-medium scale blue hydrogen plant on the west coast of Norway to serve onsite and maritime users, which would produce 60-130 MW of hydrogen [9]
- **NortH$_2$**: Equinor has joined the project which aims to produce green hydrogen from offshore wind off the north coast of the Netherlands. The project would produce 1 GW of hydrogen by 2027 and over 10 GW by 2040
- **LH$_2$ Maritime**: Equinor is a partner in a project led by BKK to produce green hydrogen at its Mongstad refinery, for use in maritime applications and other transport. Liquid hydrogen from the plant would also be distributed by hydrogen-fuelled ships along the west coast of Norway

3.0 SAFETY AND RISK MANAGEMENT

3.1 Understanding the risk

Managing risk is about understanding and controlling the hazards involved in the relevant activity. This includes having a perception about what can go wrong, what the causes can be and what the consequences may be. Uncertainty, or strength of knowledge, and how to deal with this is also a factor in risk management.

Hydrogen has been used and handled in industry for many decades, and the strength of existing knowledge, at least regarding gaseous hydrogen, is high in the industries familiar with hydrogen. As a result of increased focus on a low-carbon society, utilisation of hydrogen as an energy carrier is also becoming more relevant for new types of industry. Hydrogen is introduced to new contexts and by users that have so far been unfamiliar with the properties and behaviour of hydrogen. Thus, transfer of experience and knowledge is vital.

Several of the potential new actors in low-carbon energy production, like Equinor, have a massive knowledge basis related to handling of other flammable gases, for example hydrocarbons, and therefore have a good understanding of safety barriers related to such gases. It is important to comprehend the differences between hazards introduced by hydrogen, compared to the gases the oil and gas industry are used to handle. The main differences are related to larger flammability range, lower ignition energy and higher laminar burning velocity. Table 1 shows the combustion parameters of hydrogen compared to other well-known fuels, ref. [10].

Hydrogen's properties mean that there is a high probability that a flammable gas cloud will ignite, and that if ignited in an obstructed or confined area, there is an increased possibility of deflagration-to-detonation-transition, causing very high explosion pressure loads. Appendix A provides a brief description of two accidents involving hydrogen, illustrating the hazards involved.

Other characteristics that need to be considered include the high gaseous buoyancy and diffusivity - meaning that if released in open air the gas will rise and dilute rapidly. In addition, the ability to cause embrittlement of certain common materials if certain conditions are present must be considered.

Table 1. Ignition and combustion properties for air mixtures at 25°C and 101,3 kPa for several common fuels (reproduced from [10])

Fuel	LFL[1] % vol. fraction	Stoich. mixture % vol. fraction	UFL[2] % vol. fraction	Minimum ignition energy mJ	Auto-ignition temperature K	Laminar burning velocity m/s
Hydrogen (H_2)	4	29.5	77	0.017	858	2.70
Methane (CH_4)	5.3	9.5	17.0	0.274	810	0.37
Propane (C_3H_8)	1.7	4.0	10.9	0.240	723	0.47
Gasoline (C_8H_{18})	1.0	1.9	6.0	0.240	488	0.30

When it comes to liquid hydrogen (LH2), the knowledge is somewhat weaker, or at least not as widespread. The boiling point of hydrogen is about 20 K at atmospheric pressure, a property which alone creates several challenges. Research is on-going on the behaviour and characteristics of liquid hydrogen, including required ignition energy at very low temperatures, ref. [11] and [12]. This paper will mainly focus on gaseous hydrogen but will also discuss some aspects of liquid hydrogen.

3.2 Safety strategies used in Equinor

In Equinor, all facilities shall establish an installation-specific safety strategy. The objective is to provide understanding of why a safety barrier (technical or operational) must be established, and which design solutions and performance requirements are needed in order to fulfil the barrier's intended function. The document provides a "bridge" between identified hazards and risks, on one side, and the need for and role of safety barriers in different areas of the facility, on the other. The description is based on relevant Equinor requirements and specifications for the safety barriers but further detailed, adjusted and made specific for the facility.

Fig. 2 shows how various conditions, documents and tools are related. Authority and company requirements form the framework conditions. Within these conditions, the risk picture, presenting the hazards, the risk contributions and the risk level, is the basis for establishing the safety strategy. Based on requirements and strategy, maintenance and inspection plans are specified. Verification activities are performed to prevent drifting into an unsafe state over time. Regular review is necessary.

For each safety barrier, its role / purpose and the specific design and performance requirements are described. For example, the role of gas detection can be described as: "The gas detection system shall continuously monitor for the presence of flammable or toxic gases, alert personnel and allow control actions to be initiated manually or automatically to minimise the probability of personnel exposure, explosion and fire". The description of the specific requirements would include type, location, and quantity (number or density) of detectors, voting principles and detection response (automatic and manual). References to further documentation must be included.

---

[1] LFL - Lower Flammability Level of fuel in air

[2] UFL - Upper Flammability Level of fuel in air

The safety strategy would normally include both technical and operational barrier elements. This paper will mainly focus on the technical elements.

Figure 2. Documents and tools for risk management

4.0 HYDROGEN SAFETY IN DESIGN

4.1 Hydrogen specific requirements to safety barriers

Main safety barriers to prevent, detect and control the fire and explosion risk connected to flammable gases are illustrated in the bow-tie diagram in Fig. 3. These barriers will also be applicable for hydrogen facilities. This chapter describes recommendations to be implemented in design based on the properties and the risk connected to hydrogen. These recommendations would be the basis for a facility specific safety strategy.

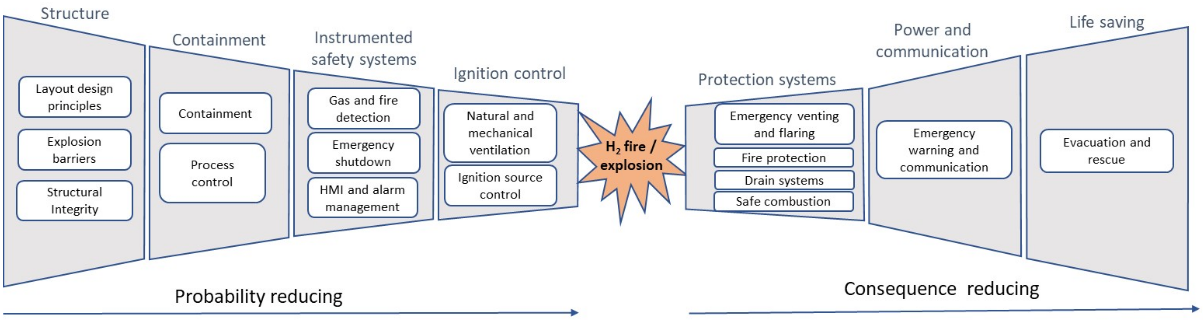


Figure 3. Bow-tie diagram summarising safety barriers in design for flammable gases.

Containment - Hydrogen storage might include very high pressure or cryogenic temperatures (for LH_2) which determine design specifications. Materials that are in contact with other materials must be compatible with each other, as well as with hydrogen. Material and equipment considerations for a hydrogen system may include choice of both metals and nonmetals (such as polymers and composites). The phenomena that influence material selection and system design are: temperature and pressure, hydrogen embrittlement, permeability, porosity and compatibility of dissimilar metals when used together. For metallic materials reference is made to the American Society of Mechanical Engineers (ASME) B31.12 standard [13]. For polymers reference is made to the DNV JIP proposal H_2 Composite Pipes [14].

Layout design principles - To exploit the diffusivity and buoyancy properties of hydrogen-containing / process equipment should be located in the open, as much as possible in *uncongested* areas, and at a high level. This will optimise the conditions for dilution and limit flammable gas cloud build-up, and it will also reduce the risk of strong explosions if ignition occurs. Pipelines should be located on the outside and upper part of buildings, structures and piperacks. Potential leak sources (filters, valves, flanges etc.) should be located in a common area and prevented from dispersing into congested areas. This is illustrated in Fig. 4, by an "open box" where hydrogen instrumentation and equipment could be located to avoid any leaks being directed toward the congested module. A leak will be forced upwards and into open air instead of flowing into the congested area.

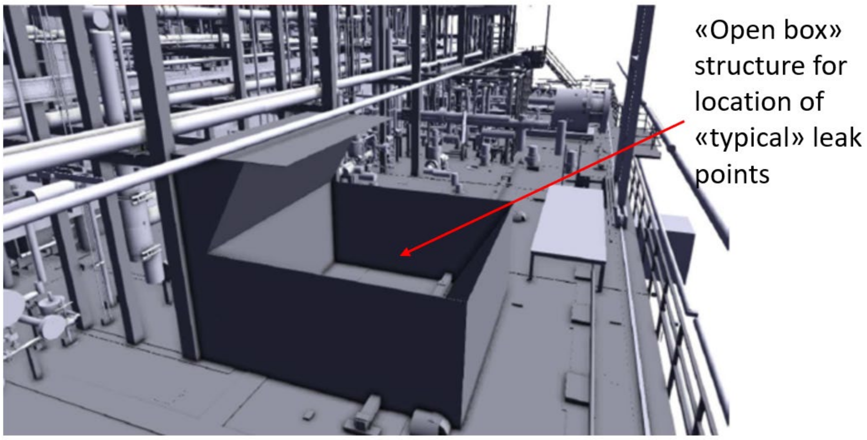


Figure 4. Illustration of "open box" structure. The left wall will prevent leaks from flowing into the congested process area to the left of the box and direct the leak upwards

If location of hydrogen pipes and equipment in enclosed and obstructed areas cannot be avoided, welded connections are recommended. An alternative option for piping is pipe-in-pipe solutions.

Natural and mechanical ventilation - Effective ventilation would dilute released hydrogen gas to non-flammable concentrations. Good natural ventilation will be achieved if the hydrogen containing/processing equipment is located in the open and as much as possible in *uncongested* areas, at a high elevation.

If enclosed areas cannot be avoided, mechanical ventilation might be used to dilute accidental releases. The properties of hydrogen should also be exploited for mechanical ventilation, with the air inlet at a low level in the room and the outlet at a high level. It must be ensured that the outlet leads to safe location and that the ventilation system is approved for the relevant hazardous area classification.

Since hydrogen mixes easily with air, and has a large flammability interval, it might be more challenging to achieve good enough ventilation compared to other gases. The effect of the ventilation should be validated, e.g. by gas dispersion calculations.

Recognised standards such as International Electrotechnical Commission (IEC) standard 60079-10 [15] open for introducing ventilation as a means for reducing the extent of, or need for, hazardous areas and thus explosion (Ex) proof equipment. However, this approach should be used with care for hydrogen.

Gas detection - Common technologies for flammable gas detection are infrared and catalytic detectors. Hydrogen does not absorb IR radiation; thus, IR gas detectors cannot be used. Catalytic detectors using palladium and/or platinum as catalyst can be used for hydrogen.

Acoustic detection, based on the measurement of ultrasound (typically 25 kHz+) generated by the leakage itself, can be also be used. A leak will produce noise within a frequency band of 80-100 kHz, which is normally different to the noise made by rotating and vibrating machinery, and other man-made noise sources. Acoustic detectors can detect a leak, but not indicate exactly *where* or *how large* the leak is. The detection reliability depends on the background noise.

Other means of detection are electrochemical, semi-conduction oxides, thermal conductivity, mass spectrometers and glow plugs (used to ignite flammable gas volumes which then can be detected by flame/heat detection instruments). Monitoring of process variables (pressure, temperature, flow, level) and process abnormalities can be utilised to indicate possible leaks.

In naturally ventilated areas hydrogen detectors should be located close to potential leak points (valves, flanges, process equipment, fuel dispenser), at locations where there is a natural flow path and where detection might indicate a hazard, like air intakes, ventilation outlets or vent stack outlets. For gaseous systems, location at a high elevation is important. For liquid hydrogen, being less buoyant, location of gas detection at low points is also relevant. In mechanically ventilated areas detector location should be based on the airflow to secure fast detection. Gas detection could also be implemented in pipe-in-pipe systems, at the upper end of the outer pipe where leaked gas would flow if open-ended.

Fire detection - The purpose of a fire detection system is to monitor for the presence of a fire, to alert people in the area and to initiate control actions. This will minimise the likelihood of fire escalation to other equipment and reduce the probability of people being exposed.

A pure hydrogen flame is almost invisible in daylight. The emissivity outside of the flame also decreases very quickly, so it may be difficult for people to know that they are approaching a flame before they are exposed to it.

There should be means for detection of fires in all areas where leaks, spills or accumulation of hydrogen may occur, where a fire might expose people or where it could lead to escalation, such as near hydrogen dispensers, close to storage vessels and main safety functions. Detectors should provide a rapid and reliable indication of the existence, location, and size of a hydrogen flame.

Thermal and optical sensors can be used to detect burning hydrogen. To cover a large area or volume, many thermal detectors are needed and should be located at or near the site of a potential fire. A hydrogen fire does not normally generate smoke, so smoke detectors are not effective.

More details about fire and gas detectors suitable for hydrogen can be found in [16], [17] and [18].

Fire and gas detection systems might have interfaces with the other safety systems and functions such as natural and mechanical ventilation, emergency shutdown (ESD), emergency depressurisation, flares or vents, active fire protection, layout and explosion barriers, emergency power and lighting, alarm and communications systems.

Emergency shutdown systems and "safe condition" – The purpose of the ESD system is to prevent escalation of abnormal conditions into a major accident and to limit the extent and duration of such events. ESD have interfaces to leak and fire detection, ignition source control, emergency depressurisation and flaring/venting systems and safety and automation systems. In addition, ESD initiation might activate (directly or indirectly) other safety systems and functions such as emergency ventilation, emergency power and lighting, alarm and communication system for use in emergency situations.

Emergency shutdown means that a technical system is set in a «safe condition» if a hazardous situation arises. Such situations are usually identified in design through a systematic identification of possible deviations (e.g. HAZOP analysis). Technical safety barriers are identified to set the system in a safe condition. This might involve closing of ESD valves to limit/stop the leak, safe venting, blowdown or flaring of contained gas to safe location. It might also activate emergency ventilation, deactivate ignition sources, start deluge or inert systems, etc.

Pressure relief systems, blowdown/flaring/venting – This requires that the gas can be released or burnt safely without causing additional risk to the surroundings. Flares normally include a pilot flame to ensure ignition. Backflow of air into a vent system must be avoided since ignition might lead to explosion in the vent line. This might be done by purging the vent line with a small flow of inert gas. Liquid storage must be equipped with boil-off valves and the outlet from such valves and other pressure relief systems must go to safe location. Liquid-hydrogen vent systems must not be exposed to water, including firewater, since there is a risk that these vent points are below the freezing temperature of water, leading to clogging of the vent system.

Open drain systems - The intention of this system in general is to prevent further hazardous spreading of the spill, and to lead spilled flammable liquid to safe disposal, but it must be ensured that the spill does not lead to an additional hazard. This could for example be prolonged duration of a flammable gas cloud in congested and confined areas, or risk of a fire exposing storage vessels or other equipment containing hazardous chemicals. This is highly relevant for liquid hydrogen since a liquid leak might cause a significantly heavier gas cloud than gaseous leaks. According to the National Fire Protection Association (NFPA) standard 2 [19] "diking shall not be used to contain a liquid hydrogen spill". This also means that liquid H_2 containers cannot be located in diked areas with other hazardous materials.

Ignition source control - The minimum ignition energy is significantly lower for hydrogen compared to other fuels, meaning ignition might occur without any clear ignition source. Pressurized hydrogen can, if released under certain conditions, self-ignite due to shock effects [20].

Based on the minimum ignition energy, electrical and mechanical equipment in hazardous areas must be approved for gas group IIC. Additional requirements are necessary to reduce the ignition probability. These are 1) proper grounding and bonding of metallic equipment, 2) avoid materials that might cause static electricity, 3) use of anti-static materials on floors and walls, antistatic window glass, 4) avoid open fire, hot work such as welding, air intakes of combustion engines or other combustion processes, presence of cell phones and smoking 5) use antistatic clothing and shoes, conductive footwear 6) spark-proof tools. The IEC 60079 series [21] provides comprehensive information on ignition mitigation. NFPA 2 [19] provides design and operational requirements related to ignition source control and avoidance of ignition sources specific for hydrogen.

Since accidental leaks might be significantly larger than the scenarios used to determine hazardous areas/ex-zones, the additional measures as listed above, should be used also outside the actual hazardous areas.

Passive and active fire protection - The role of passive fire protection (PFP) is to ensure that relevant structures, piping and equipment components have adequate fire resistance, whereas the main purpose of the active fire protection is to provide quick and reliable means for firefighting in addition to cooling of equipment and structures.

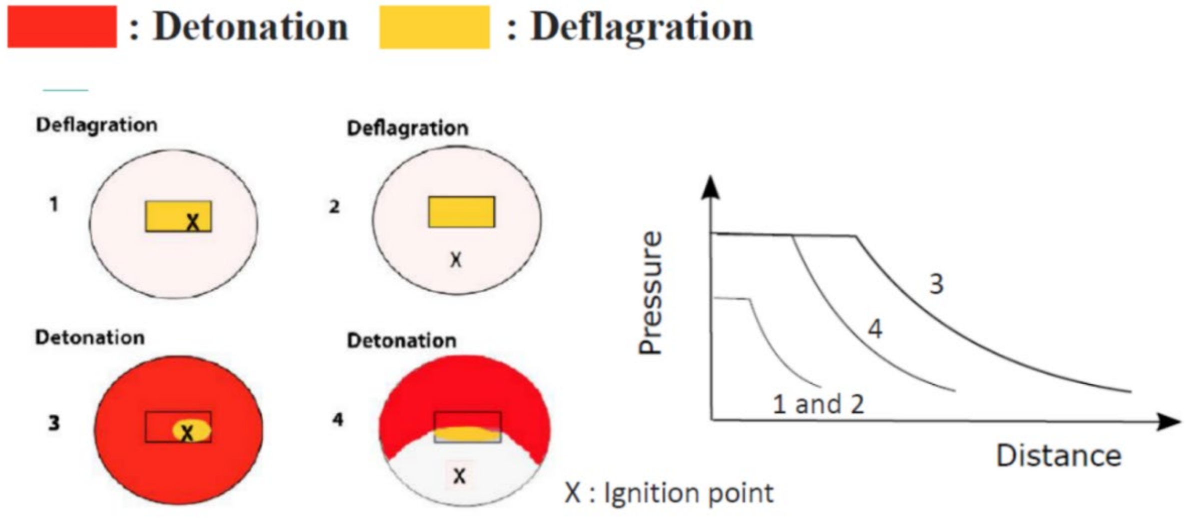
The best way of handling a hydrogen fire is to let it burn under control until the hydrogen flow can be stopped, unless it exposes equipment that could rupture. Extinguishing the fire may create a larger hazard due to an increased potential for an explosion if gas from a release subsequently re-ignites. This applies especially in congested areas and where hydrogen can accumulate in case of a leak.

Water deluge activated by gas or fire detection systems, can be effective at reducing worst-case explosion pressures for natural gas. However, the performance of water deluge will depend on parameters like scale, confinement, congestion and how water is applied [22], and the performance is not fully understood for hydrogen. Recognized international standards for general design of deluge or water spray systems are NFPA 13 [23] and NFPA 15 [24]. However, this is an area where more research is needed.

Explosion barriers and design to avoid detonations – The risk of explosions is, also for hydrogen, mainly connected to enclosed or densely obstructed areas. The large flammability interval, effective mixing with air, low ignition energy, high burning velocity and small detonation cell size (i.e. high reactivity) increase the risk of strong explosions or even deflagration to detonation transition (DDT). The risk of high explosion pressures in enclosed areas is higher for hydrogen than for most other flammable gases. To reduce this risk the following safety barriers must be considered: 1) Limited number of leaks points inside the enclosure, 2) restricted inflow of hydrogen (i.e. limit the maximum leak rate) 3) high ventilation rate, 4) ESD and relief of gas inventory to safe location in case of confirmed gas detection, 5) explosion relief panels that pop out to safe location at low pressure, 6) designing the enclosure to withstand explosion.

For gaseous hydrogen, the risk of a detonation propagating in an unconfined gas cloud is less relevant since hydrogen gas clouds in open and unconfined areas will be limited in size due to the buoyancy and diffusion properties. There might, however, be a higher risk for detonations in unconfined areas for LH_2 systems. Fig.5 illustrates how a detonation can be initiated for flammable gases. This mechanism was studied by Oran et al [25]. The circle represents a flammable gas cloud and the rectangle an enclosed/obstructed area. The cross illustrates the ignition point, the yellow area a cloud that deflagrates and the red area is the cloud that detonates. Illustration nr 3 represents the worst-case situation: Ignition and DDT might start in an enclosed area, caused by a strong ignition source and/or a high degree of obstruction/congestion increasing the turbulence in the combustion. The detonation can then propagate to the whole flammable volume, causing very high pressures and at longer distances.

For accidental releases of LH_2, the very low temperature and tendency to form a heavier gas cloud at ground level with prolonged duration can cause significant flammable gas clouds in open areas. A DDT might then be initiated in an obstructed or enclosed area and propagate into flammable gas remaining in the open area. This mechanism needs to be considered in design, by avoiding strong ignition sources and obstructed areas and ensuring good natural ventilation.



E.S. Oran, G. Chamberlain and A. Pekalski/Progress in Energy and Combustion Science 77 (2020) 100804

Figure 5. Illustration of the risk of detonation and dependence on ignition point [25]

5.0 CONCLUSIONS

Equinor has recently initiated the development of several hydrogen value chain projects. These are based on hydrogen production from either electrolysis or reforming of natural gas or other hydrocarbon-based feeds, with CCS. For a safe and sustainable implementation of hydrogen value chains, safety strategies and risk management are a necessity. Equinor's system for establishing safety strategies has been presented in this article, illustrating how safety barriers are designed based on the risk picture. Safety barriers in design, adapted to the properties and risk characteristics of hydrogen, have been described.

6.0 REFERENCES

1. Equinor's Climate Roadmap, https://www.equinor.com/en/how-and-why/climate.html, 2020.
2. Eiken O, Ringrose PS, Hermanrud C, Nazarian B, Torp TA, Høier L. Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit. Energy Procedia 2011; 4:5541-5548
3. Ringrose PS. The CCS hub in Norway: some insights from 22 years of saline aquifer storage. Energy Procedia 2018; 146:166-172
4. Technology Centre Mongstad, www.tcmda.com, 2020
5. Mulighetsområdet for realisering av fullskala CO_2-håndtering i Norge. NC00-2012-RE-00034; 2012 (Translation: The opportunity area for realization of full-scale CO_2 handling in Norway; in Norwegian only)
6. Northern Lights – A European CO2 transport and storage network, https://northernlightsccs.com/en, 2020
7. Longship – Project by the Norwegian government for full-scale CCS that comprises of capture, transport and storage of CO_2, https://langskip.regjeringen.no/longship/article, 2020
8. Equinor website on hydrogen; https://www.equinor.com/en/what-we-do/hydrogen.html, 2021
9. Hamborg, E.S., Gulbrandsen, T.H., Steeneveldt, S, Svenes, S, Berggren, H, Kvarsvik, S and Pettersen, J. Norwegian hydrogen value chain demonstration based on decarbonized natural gas. 15th International conference on greenhouse gas control technologies, 2021
10. ISO/TR 15916: Basic considerations for the safety of hydrogen systems. Second edition, 2015-12-15.
11. PRESLHY, Pre-normative Research for Safe Use of Liquid Hydrogen, Research and Innovation Action Supported by the FCH JU - Grant Agreement No 779613, www.preslhy.eu, 2021
12. SH2IFT project, Safe Hydrogen Fuel Handling and Use for Efficient Implementation, www.sintef.no/projectweb/sh2ift/, 2021
13. ASME B31.12 Hydrogen piping and pipelines
14. DNV Joint Industry Project proposal for H_2 Composite pipes, 2021
15. IEC 60079-10-1:2020 "Explosive Atmospheres. Part 10-1: Classification of areas. Explosive gas atmospheres
16. Bain, A., Barclay, J.A., Bose, T.B., Edeskuty, F.J., Fairlie, M.J., Hansel, J.G., Hay, D.R. and Swain, M.R., Sourcebook for hydrogen applications, Hydrogen Research Institute and National Renewable Energy Laboratory, 1998
17. Buttner, W.J., Post, M.B., Burgess, R., Rivkin, C., 2011, An overview of hydrogen safety sensors and requirements, International Journal of Hydrogen Energy, 36(3), pp. 2462–2470. doi: 10.1016/j.ijhydene.2010.04.176
18. H2tools website: https://h2tools.org/bestpractices/leak-and-flame-detection, 2021
19. NFPA 2 Hydrogen Technologies Code, 2020 Edition
20. Astbury, G.R., and Hawksworth, S.J., Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms, International Journal of Hydrogen Energy, Volume 32, Issue 13, 2007, pp 2178-2185, https://doi.org/10.1016/j.ijhydene.2007.04.005

21. IEC 60079 Series Explosive Atmosphere Standards, 2021
22. Gexcon website: https://www.gexcon.com/us/products-services/Explosion-and-Mitigation/35/en, 2021
23. NFPA 13 Standard, Installation of Sprinkler Systems, 2019 Edition
24. NFPA 15 Standard, Standard for Water Spray Fixed Systems for Fire Protection, 2017 Edition
25. Oran, E.S., Chamberlain, G., Pekalski, A., Mechanisms and occurrence of detonations in vapor cloud explosions, Prog. Energy Combust. Sci., 77, 2020, p. 100804, 10.1016/J.PECS.2019.100804
26. Bjerketvedt, D. and Mjaavatten, A.: A hydrogen–air explosion in a process plant: a case history. 1st International Conference on Hydrogen Safety, Pisa, Italy, 8-10 September 2005
27. Bjerketvedt, D. and Mjaavatten, A., Accident report N1 6.7.85, Norsk Hydro Research Centre, Doc.nr. 86B.BM7 (report, Norwegian), 1986
28. Pande, J.O and Tonheim, J: Explosion of Hydrogen in a Pipeline for CO2. Process safety progress, Vol.20 (1), p.37-39, 2001

APPENDIX A: TWO HYDROGEN ACCIDENT CASE STUDIES

Explosion in ammonia plant, 1985

This hydrogen accident has been published in [26], and illustrates the forces if a hydrogen gas cloud, even when containing a limited amount of hydrogen, ignites in a confined area.

In the summer of 1985, a severe hydrogen-air explosion occurred in an ammonia plant in Norway. The accident resulted in two fatalities and the destruction of the building where the explosion took place, see Fig. A1.

Figure A1. Damage caused by the explosion (accident investigation [27], Photo: A. Kjellevold)

The event started when a gasket located inside of a large factory building was blown out, first causing a leak of water, but after about three minutes hydrogen reached the leak point and started to form a flammable gas cloud inside the building. The discharge of gas lasted some 20 to 30 seconds before the explosion occurred. The total mass of the hydrogen discharge was estimated at 10 to 20 kg hydrogen. The main explosion was very violent, and it is likely that the gas cloud detonated. The ignition source was almost certainly a hot bearing. Investigations concluded that 3.5 to 7 kg of hydrogen combusted violently in the explosion. The damage indicates that explosion pressures inside the building must have reached at least 10 bars. Windows were broken up to 700 m from the centre of the explosion.

Concrete blocks weighing 1.2 metric tons were thrown up to 16 meters. The roof of the building was lifted by an estimated 1.5 meters before resettling [27].

Explosion of hydrogen-air mixture in a pipeline, 1997

Information on this explosion has not been extensively published. However, the potential of the accident was significant, and the learnings are important. The description below is based on ref. [28].

In 1997 the transfer pipe for CO_2-gas from an ammonia plant in Norway exploded. There were no injuries, but 850 meters of the 1000 m long line were destroyed, and a large number of glass windows were broken. The pipeline was temporarily out of service. The investigation team concluded that the trip system had been disabled prior to the explosion, hydrogen enriched gas had entered the pipeline, the nitrogen purge had not been effective, air had leaked into the line and formed an explosive mixture, and the mixture had ignited. The investigation team concluded that the damaged line must have been filled with a mixture containing more than 10-15% air and 40% hydrogen. About 10 kg hydrogen was involved. A computer simulation indicated that the combustion front had quickly accelerated and propagated through the line within a couple of seconds, causing it to rupture (estimated pressure of 10-15 bars) at intervals of 10-20 m. Four of the ruptures are shown in Fig. A2.

Figure A2. Flame acceleration in a hydrogen-air explosion inside a pipeline resulted in several ruptures [28]