Project members: Albin Rosenqvist, Nellie Lexander & Alice Hansson
Supervisors: Björn Wickman, Department of Physics, Chalmers University of Technology
Marcus Runefors, Division of Fire Safety Engineering, Lund University

ASSESSMENT OF FUEL CELL SPECIFIC RISKS

TRA275 Fuel Cell Systems

Introduction

Hydrogen (H_2) is considered a promising energy carrier for a sustainable future and is today the major fuel used in fuel cells, but its use raises safety concerns. This poster presents an overview of historical incidents and risks associated with fuel cells and relevant fuels. Important safety aspects and preventive measures are highlighted to ensure high safety and efficient implementation of this technology.

Historical Incidents

Hydrogen incidents and accidents database is a database that is created to collect information based on previous incidents and accidents related to hydrogen. The information is based on 706 incidents occurring between 1937 – 2021. In the database examples are given based on different accidents but the accidents are not described in detail but instead for statistical use. Most incidents had multiple causes and many of the incidents were triggered by a combination of technical failure, design, material and human errors. [1]

Approximately two-thirds of the considered incidents occurred during normal operations while around one third took place outside normal operations during testing, maintenance and starting after maintenance. In one of the largest industrial hydrogen explosions reported, the combination of operational error, technical failures, and weakness in the design was the cause. The explosion caused by a series of events lead to a severe hazard with broken window glasses being found up to 700 m from the center of the explosion. [1]

Figure 1 shows the percentages of events that were caused by hydrogen systems or non-hydrogen systems and the different consequences that resulted from these events. The outer circle indicates that 75% of the events were caused by hydrogen systems and 25% by other systems. The inner circle shows that out of all the events, 48% involved explosions and 31% involved fire. The 15% of unignited releases were caused by a combination of reasons, such as small releases or prompt termination of unintended releases. The 6% of near misses indicate that early detection and prompt mitigation of potential releases can prevent events from escalating. [1]

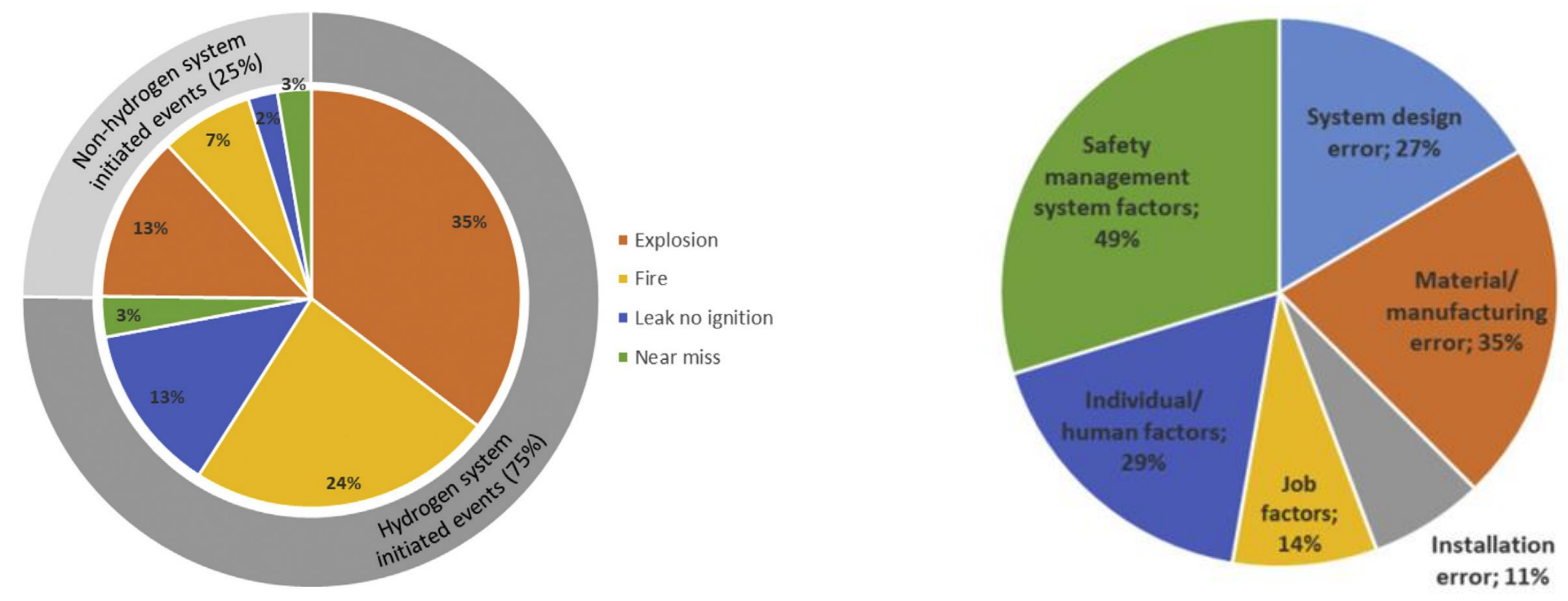

Figure 1. Illustration of what kind of accidents that have occurred and the reason why the accidents did occur [1].

The reasons why accidents did occur can be seen in the diagram to the right in *Figure 1* and examples to each category can be seen below.

- System design error – e.g. components or system not compatible with hydrogen
- Material/manufacturing error – e.g. usage of the correct component but wrong material or manufacturing errors
- Installation error – e.g. wrongly installed temperature pressure relief device or lack of maintenance
- Job factors – e.g. poorly maintained equipment, design fault or high workload
- Individual/human factor – e.g. lack of competence or human factors during operation
- Safety management system factors – e.g. poor planning, stress, lack of safety instructions or poor management [1]

Fuel Cell Specific Risk And How To Mitigate Them

General Risks

The most frequent event, according to several studies, is internal combustion within the fuel cell. Commonly a fuel leakage due to mechanical stress, corrosion or fueling error, or an rupture due to overheating or overpressure. The risk is significantly higher during refueling and fuel handling of methanol and H_2. These sources of errors are often related to design issues and not detected through inspections, or lack of maintenance. Awareness of weak points in the system must be taken into account when designing and selecting materials, for example weldings, connections and gauge glass. [2]

Corrosion of alloy components is a recurring issue, especially in high temperature fuel cells (e.g. SOFC, MCFC operating above 600°C). A conclusion is that stainless steel (SS316L) is the best available alloy solution, though in the long term there is still high degradation of these components. Better alloy compositions are required to prevent this. [3]

A simple safety comparison between different fuel cell technologies implies that DMFC and LT-PEMFC were the safest technologies, while AFC, HT-PEMFC and PAFC scored lowest on the safety criterion. The operating temperature affected these results due to increased risk of fire from fuel leakage in combination with hot surfaces, or due to increased component wear and damage because of the high surface temperatures. [4]

A study from 2018 made a risk assessment of accidents in the energy sector, based on European data from the Energy-related Severe Accident Database (ENSAD), and includes the whole energy chain for each fuel, for example accidents related to production, transportation and usage. Regarding H_2, only incidents equivalent to heat and electricity generation have been included since risks were calculated in relation to produced energy. Most hydrogen accidents occur during transportation and was caused by human errors and lack of maintenance. Comparing the fuel cell types PEM, AFC, PAFC, and MCFC, the first two seem to be safer according to the study. The risk of serious fuel cell related accidents, for various fuels, seems to be generally lower than fossil fuel technologies (in EU20). Although, fuel cells and H_2 generally have higher fatality rates higher than most renewable technologies besides CHP biogas. Fuel cells and H_2 seem to entail less risk of high consequence accidents compared to fossil fuels. However, it is important to emphasis that this is a difficult comparison because the consumption and usage of these fuels and technologies differ significantly. It is also important to mention that different fuel cell technologies run on different fuels. For CHP fuel cell types, natural gas is the most used fuel together with LPG and biogas. In addition, a decrease of H_2 related accidents can be seen after 2004 (in relation to H_2 production), thanks to developed regulations and safety infrastructure. *Figure 2* shows the maximum consequences and fatalaties between electricity generation technologies and fuel cell types. [5]

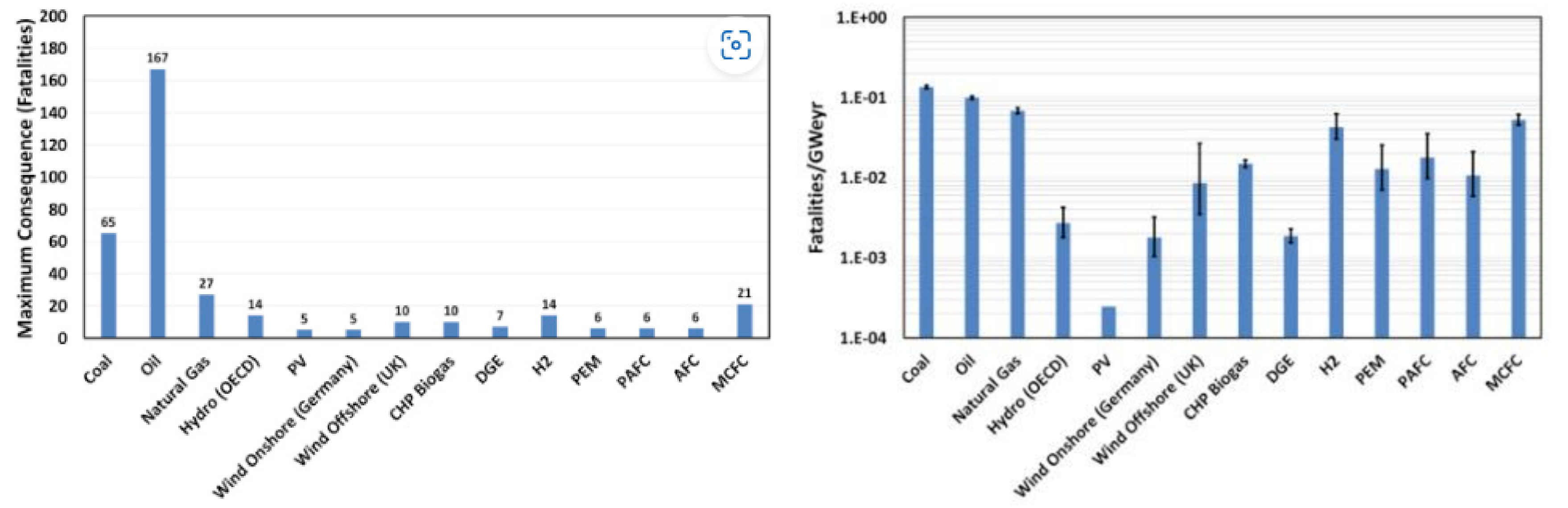

Figure 2. Diagrams showing maximum consequences and fatalities from incidents for several electricity generation technologies [5].

Components Risks

Each component in the fuel cell can generate different risks. If the incidents mentioned below is not noticed in time it can lead to critical accidents.

Membrane:
Mechanical: By assembling the membranes wrongly it can lead to increased membrane degradation due to exothermic combustion reactions between the oxidizing and reucing agents, witch can lead to cracks and tears of the membrane. By assembling the membranes carefully and with high accuracy this risk can be mitigated.
Thermal: If the fuel cells get a higher working temperature than 60-80°C there is a risk of glass transition of the polymers and since the humidity decreases with increased temperature and decreases the transfer through the membrane it hinders the perfomrance of the PEM fuel cell system.
Chemical/electrochemical: High exothermal combustion of oxidizing and reducing agent can result in pinholes of the membrane, potentially causing a failure of the system. The anode and cathode can produce peroxide and hydroperioxide radicals conditions through chemical reactions for example at low humidity and this can lead to degradation of the membrane. [6]

Electrocatalyst and Catalyst Layer
The material that electrocatalysts usually are made of are platinum and metal alloys of platinum and there is a risk that the catalyst gets contaminated by impurities from the supply system. This can get reduced by sintering or by deattaching the platinum particles on the carbon support. The durability can be increased by having a lower operating condition, low relative humidity, low temperature and steady state operation. [6]

Gas Diffusion Layer
The materials PTFE and carbon composites that are inside the gas diffusion layer are adoptive to chemical and electrochemical degradation as a result of peroxide formation and oxidation. The degradation of PTFE results in increased water retention inside the gas diffusion layer, higher mass transport losses and reduced efficiency. The fibers can be graphitized during the preparation of the gas diffusion layer to increase the stability of the gas diffusion layer. [6]

Bipolar Plates
The characteristics of the bipolar plates are that the conductivity should be high, have a high corrosion resistance, a low gas permeability and a low thermal resistance. The bipolar plates are typically constructed of either graphite or metal. The graphite has high corrosion and chemical resistance but metals has favorable mechanical characteristics. There can be a risk to apply protective coatings to the bipolar plates when the operating conditions increases. In these cases there is a risk of microcracks due to thermal expansion and the metal ions can then move to the membrane and reduce the cell performance. A solution for this risk is to have an intermediate layer between the bipolar plate and the coating layer. [6]

Sealing Gasket
Materials that usually are used are silicone and EPDM. Due to electrical fields can silicone sealing gasket be observed in the anode and cathode layers. This is a result of degradation of the sealing gasket and this can result in gas and coolant leakage and crossover, which eventually can lead to short circuiting. The degradation can also lead to lower hydrophobicity of the electrodes that leads to platinum catalyst poisoning. The sealing gasket degradation can also affect the polymer electrolyte membrane by reducing the conductivity and mechanical characteristics which result in shorter life time of the cell. It is therefore important to chose the material of the sealing gasket according to mechanical and chemical properties of the surrounding materials. [6]

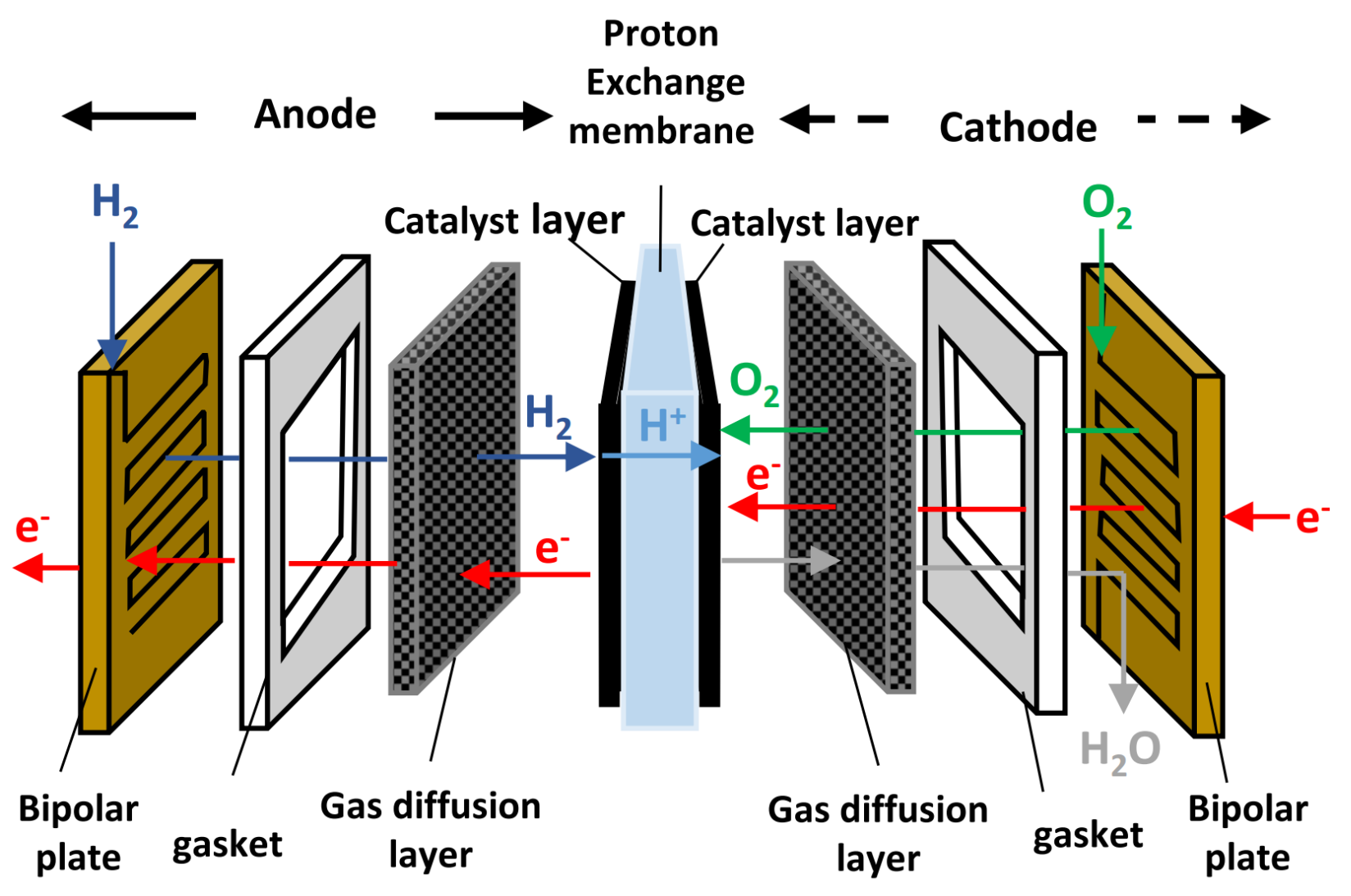

Figure 3. Illustration of the components inside a fuel cell [7].

How To Prevent Accidents

To prevent accidents related to fuel cell operation the focus should be on "every day" risks, operator errors and handling due to man-made related accident factors. Using H_2, ammonia, methane or methanol requires extra safety measures regarding tight seals, leak monitoring, quick safety system shutdown and adequate ventilation in case of leaked fuels. The components prone to leakages (e.g. pressure relief devices and check valves) are important to place in well ventilated areas without the risk of fuel accumulation. Efforts should be on inspection, monitoring, and maintenance of fuel storage and delivery systems. [1] [8]

Below is a list of guidelines that should be followed when designing a system:

1. **Prevent Leak**: Material Selection (e.g. stainless steel), Physical protection (components constructed for hydrogen) and maintenance (regularly controls)
2. **Isolate Leak:** Detection (e.g. gas sensors, handheld hydrogen detectors and bubble spray) and isolation of valve
3. **Minimize Accumulation:** small pipes or flow restriction in pipes and ventilation (e.g. passive ventilation and active ventilation in terms of fans)
4. **Prevent Ignition:** ATEX-rated (e.g. ATEX approved components, tools and equipment)
5. **Prevent Flame Acceleration:** Layout (e.g. double walled piping)
6. **Prevent Pressure Buildup:** Pressure relief (e.g. Both in system and TPRD), water mist, aerosols and inert gas. [9]

Conclusion

With hydrogen there comes a risk, but if handled according to its unique properties it can be as safe as other fuels. Most fuel cell related risks seems to be related to fuel leakage and ignition, where hydrogen is the most common fuel and most prone to leakage due to its small molecular size. The reason behind these events are usually associated with handling, installation, weak points, material compability or stress. Prevention measures of these events should focus on the design of the system and the surrounding space, including safety systems, to reduce risk of leakage.

References:
[1] X. Wen et al, "Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database", *Science Direct* [Online]. May. 2022. https://www.sciencedirect.com/science/article/pii/S0360319922012976
[2] Bultel et al, "Risk Analysis on a Fuel Cell in Electric Vehicle Using the MADS/MOSAR Methodology", *Science Direct* [Online]. 2007. https://www.sciencedirect.com/science/article/abs/pii/S0957582007714155
[3] Kumar Sharma el al, "Corrosion behaviour of high temperature fuel cell: issue for materias selection", *Metallurgija vol. 58 (2019) 3-4, pp. 347-351*. https://hrcak.srce.hr/file/318866
[4] S.Kazula, S. De Graaf, L. Enghardt, "Review of fuel cell technologies and evaluation of their potential and challenges for electrified propulsion systems in commercial aviation", *ResearchGate* [Online]. February. 2023. https://www.researchgate.net/publication/368397235_Review_of_fuel_cell_technologies_and_evaluation_of_their_potential_and_challenges_for_electrified_propulsion_systems_in_commercial_aviation
[5] M. Spada, P. Burgherr, P. Boutinard Rouelle, "Comparative risk assessment with focus on hydrogen and selected fuel cells: Application to Europe", *Science Direct* [Online]. May. 2018. https://www.sciencedirect.com/science/article/abs/pii/S0360319918310899
[6] Penga et al, "Degradation Mechanisms in Automotive Fuel Cell Systems", *Giantleap Deliverable D1.3.* December. 2017.
[7] Nishimura et al, "Proton Exchange Membrane Fuel Cell Bipolar Plate Analyses by GD-OES and Raman", *Horiba Scientific* [Online]. (n.d). https://static.horiba.com/fileadmin/Horiba/Application/Energy/Hydrogen/Documents/Scientific/GD-RA-01-Proton-Exchange-Membrane-Fuel-Cell-Bipolar-Plate-Analyses-by-GD-OES-and-Raman.pdf
[8] Xing et al, "Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives", *ResearchGate* [Online]. January. 2021. https://www.researchgate.net/publication/348776154_Fuel_Cell_Power_Systems_for_Maritime_Applications_Progress_and_Perspectives
[9] M. Runefors, "Safety of hydrogen and fuel cell systems", *Lecture Notes Chalmers* [Online]. January. 2024.