HYDROGEN PRODUCTION BY ELECTROLYSIS

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1.0 SCOPE

This data sheet applies to large-scale hydrogen generation plants using water electrolysis processes. It provides loss prevention recommendations for hydrogen generation using current commercially available technologies such as Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE), as well as for associated manufacturing and storage areas.

The recommendations in this data sheet are intended to prevent or minimize the effects of fires, explosions and equipment failures related to manufacturing and storage operations of both gaseous and liquid hydrogen. In addition to the recommendations in this data sheet, see data sheet 7-111, *Chemical Process Industries,* for basic physical and human element programs that may be applicable.

The guidance in this data sheet applies to hydrogen storage areas that exceed the storage quantities in Data Sheet 7-91, *Hydrogen*.

This data sheet does not cover:

- Hydrogen systems for dispensing, end-use equipment, laboratories, refueling stations, and skid-mounted and packaged electrolyzer systems (less than 5 MW total capacity). See Data Sheet 7-91, *Hydrogen*.
- Solid oxide water electrolyzer (SOWE) and Anion Exchange Membrane (AEM) technologies

1.1 Hazards

The main hazards in this occupancy involve fires and explosions related to the production of hydrogen. Hydrogen is a highly flammable material and can form flammable or explosive mixtures with air at low concentrations. For additional information on the hazards of gaseous and liquid hydrogen, see Section 3.1.

Failures in the electrolysis process, such as membrane damage, high current density, high differential pressure, etc., can lead to hydrogen/oxygen crossover, creating explosion hazards in downstream tanks and equipment. Additionally, fires and explosions can occur due to leaks in the electrolyzer or piping and equipment containing hydrogen. Since hydrogen is a small molecule, it can easily escape through tiny cracks or seals and can affect the mechanical properties of most materials.Specifically for steel, hydrogen reduces fracture toughness and increases the rate of fatigue crack growth. When subjected to rapid pressure cycling, permeable materials (such as those found in seals) can deteriorate due to hydrogen gas expansion within the material.

1.2 Changes

October 2025. This is the first publication of this document.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 Introduction

Use FM Approved equipment, materials, and services whenever they are applicable and available. For a list of products and services that are FM Approved, see the *Approval Guide*, an online resource of FM Approvals.

2.2 Construction and Location

2.2.1 General

2.2.1.1 Conduct a comprehensive facility siting study in accordance with Data Sheet 7-14, *Fire Protection for Chemical Plants*. Ensure the study includes, but is not limited to:

A. Evaluation of safe space separation distances for lower/different hazard operations (offices, general manufacturing buildings, etc.) and critical infrastructure/equipment

B. Firefighting activities

C. Equipment spacing for maintenance and replacement activities

2.2.1.1.1 Provide adequate separation or barriers between transformers and buildings in accordance with Data Sheet 5-4, *Transformers.*

2.2.1.2 Utilize noncombustible or FM Approved Class 1 construction materials for all important buildings and productions areas. Ensure building construction is suitable for the environment, considering such things as corrosion resistance and compatibility of materials.

2.2.1.3 When feasible, locate hydrogen production and handling areas in outdoor open structures with minimal confinement. Where needed, provide freeze protection according to Section 2.9.1. If an outdoor location is not possible, see Section 2.2.2 for guidance on indoor areas as defined in Appendix A.

2.2.2 Indoor Areas

2.2.2.1 Construct indoor hydrogen production and handling areas using lightweight construction or explosion venting panels designed to fail at 20 psf (0.96 kPa) or less. Higher pressures can be utilized if required for wind rating of walls or roof. Ensure all interior partition walls are rated for a pressure resistance of at least 50 psf (2.4 kPa) above the venting pressure.

2.2.2.2 Construct indoor areas to minimize congestion of piping and equipment, and of ceiling concealed spaces where hydrogen can accumulate.

2.2.2.2.1 Where possible, locate hydrogen piping outdoors or at high points where hydrogen can be more easily exhausted from the area in the event of a release.

2.2.2.3 Provide continuous and emergency ventilation according to Section 2.5.6.

2.3 Process Safety

2.3.1 Develop and implement a comprehensive process safety program that incorporates all the elements in accordance with Data Sheet 7-43, *Process Safety*. Ensure the following considerations are included and thoroughly evaluated:

A. Process Hazard Analysis (PHA). Evaluate all modes of operation including normal, startup, shutdown, emergency, idle and maintenance. Ensure the analysis includes, but is not limited to:

- Inerting, purging, venting and/or flaring
- Sudden upset conditions or loss of critical utilities and controls (power, process and cooling water, nitrogen, etc.)
- Gas permeation and crossover
- Safe operating windows (included but not limited to voltage, pressure, temperature, flow, etc.)
- Hydrogen release and explosion hazards, including ventilation assessment
- Cryogenic hazards, if applicable

B. Asset Integrity. Implement a robust asset integrity program that addresses the following components:

- Positive Material Identification (PMI) to ensure materials are according to specifications.
- ·Control of replacement material, such as gaskets, valves, etc., to confirm they are suitable for their intended service
- Monitoring and management of hydrogen degradation for vessels and piping
- Interlocks and safety devices credited in the PHA as layers of protection. Ensure they are included in the Inspection, Testing and Maintenance (ITM) program and are serviced at the frequency required to maintain the reliability level established during design.

2.4 Protection

The most effective and safest approach to handling a hydrogen fire is to allow it to burn in a controlled manner until the hydrogen supply can be safely shut off. Due to the invisible nature of hydrogen flames, extinguishing the flame prematurely may bring other hazards, such as the potential of hydrogen gas accumulation.

Water spray systems can be used to manage secondary fires and provide cooling to nearby equipment; however, avoid spraying pressure-relief devices to prevent ice formation.

2.4.1 Provide sprinkler protection to areas with combustible construction, ductwork and equipment according to Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies*, using a Hazard Category HC-3.

2.4.2 Provide protection for transformers according to Data Sheet 5-4, *Transformers.*

2.4.3 Provide protection for compressors in accordance with Data Sheet 7-95, *Compressors.*

2.4.4 Provide fire detection systems that are capable of detecting hydrogen fires in areas with the potential for leaks, spills or hydrogen accumulation where the use of a gas detection is not practical according to Section 2.5.5.

2.4.4.1 Interlock the fire detection system to initiate equipment shutdown or activate automatic shutoffs, and alarm to a constantly attended location.

2.5 Equipment and Processes

2.5.1 General

2.5.1.1 Select construction materials for piping and equipment to be compatible and suitable for service. Consider specific process and environmental conditions when selecting materials and alloys.

2.5.1.1.2 Do not use gray, ductile or cast iron in hydrogen service.

See Section 3.5 for additional information.

2.5.2 Electrolyzers

2.5.2.1 Provide electrolyzers with process controls and interlocks to prevent process upsets and maintain process operation within safe limits. Ensure the following critical parameters are included, at a minimum:

A. Voltage

B. Current

C. Temperature

D. Differential pressure between the cathode and anode

E. Electrolyte flow and purity for the AWE process. Water flow and purity for the PEM process.

2.5.2.2 Provide electrolyzers with an emergency shutdown system to be activated upon process upset or conditions outside the safe operating window. Ensure all the following conditions are included:

A.The system is designed to override all other control system commands, take precedence over normal operational controls and initiate a controlled emergency shutdown sequence as determined by a PHA.

B.Upon activation, the system immediately de-energizes or isolates the electrolyzer and its associated subsystems such as power supplies, hydrogen compression units and related hazardous energy sources.

C.The system is designed to remove or minimize hazards by stopping hydrogen production, venting or purging gases safely, and depressurizing critical components if necessary.

D.The emergency shutdown circuit is integrated into the safety-related control system and designed to a Safety Integrity Level (SIL) or Performance Level (PL) suitable for the identified risk, as determined by a PHA.

2.5.2.3 In addition to Section 2.5.2.2, provide electrolyzers with manual means (e.g. E-Stop button, switches, etc.) to initiate a controlled emergency shutdown. Ensure this manual approach is accessible during normal and emergency operations or at constantly attended remote locations such as control rooms. Include a monitoring system to verify activation from the control room.

2.5.3 Separators (H_2-Water and O_2-Water)

2.5.3.1 General

2.5.3.1.1 Provide H_2-Water and O_2-Water separators with water level and pressure monitoring systems.

2.5.3.2 H_2-Water Separators

2.5.3.2.1 Provide a continuous oxygen monitoring system interlocked to initiate emergency shutdown when 50% or less of the limiting oxygen concentration (LOC) is detected. Evaluate if oxygen concentrations of less than 50% of the LOC may result in temperature excursions in the deoxidizer, and adjust the interlock setpoint accordingly.

2.5.3.3 O_2-Water Separators

2.5.3.3.1 Provide a continuous hydrogen monitoring system in the O2-Water separator, interlocked to initiate emergency shutdown when 50% or less of the lower explosive limit (LEL) is detected.

2.5.4 Deoxidizer

2.5.4.1 Provide deoxidizers with a temperature monitoring system to detect temperature conditions outside the safe operating limits (low and high).

2.5.5 Hydrogen Gas Detection Systems

2.5.5.1 Provide a hydrogen detection system interlocked to initiate equipment shutdown, activate automatic shutoffs, activate emergency ventilation and alarm remotely to a constantly attended location if hydrogen levels exceed 25% of the LEL.

2.5.5.2 Ensure the following considerations are included in the selection of a hydrogen detection system:

A. Required speed of detection

B. Detection limits. See Section 2.5.5.1.

C. Location – indoor or outdoor

D. Cross-sensitivity

2.5.5.3 Locate detectors strategically to capture the hydrogen as close as possible to potential release points. In general, locate detectors above potential release points to account for buoyancy. Follow the manufacturer’s recommendations for installation and spacing. Consider ventilation effects and airflow in the area.

2.5.6 Ventilation

2.5.6.1 Continuous Ventilation

2.5.6.1.1 Provide continuous mechanical or fixed, natural ventilation with an average fresh airflow rate of at least 1 cfm/ft^2 (0.30 $\text{m}^3\text{/min per m}^2$) of floor area in all indoor areas where hydrogen may be present.

2.5.6.1.1.1 For small, enclosed areas (less than 100 ft^2 [9.3 m^2]) ensure a minimum flow rate of 100 cfm (2.8 $\text{m}^3\text{/min}$) is provided.

2.5.6.1.2 For continuous mechanical ventilation systems, interlock hydrogen production equipment to the ventilation system to ensure ventilation is activated prior to startup operations and the equipment is shut down if ventilation is lost.

2.5.6.2 Emergency Ventilation

2.5.6.2.1 Provide an emergency ventilation system in any unclassified indoor area where a hydrogen release could potentially exceed the lower explosion limit (LEL). Ensure a minimum ventilation rate of 2.5 cfm/ft^2 (0.75 $\text{m}^3\text{/min per m}^2$) of floor area can be provided. Interlock the system with a hydrogen detection system designed in accordance with Section 2.5.5.

2.5.6.2.2 Design the emergency ventilation system, considering all the following:

A. In addition to automatic activation, provide accessible local and remote manual activation.

B. Exhaust 100% to outdoors.

C. Ensure the average hydrogen concentration in the exhaust air is limited to no more than 50% of the LEL (2%).

2.5.7 Compressors

2.5.7.1 Select compressors that are suitable for hydrogen service, pressure and temperature process conditions.

2.5.7.2 Locate and protect compressors according to Data Sheet 7-95, *Compressors*.

2.5.7.3 Arrange compressors to shut down upon hydrogen detection in the area (see Section 2.5.5).

2.5.8 Transformers and Rectifier Transformers

2.5.8.1 Provide transformers and rectifier transformers with protective interlocks and condition monitoring according to Data Sheet 5-4, *Transformers*.

2.5.9 Vent and Flare Systems

The necessity of a vent or flare system should be determined through a comprehensive process hazard analysis where specific process configurations and potential release scenarios are evaluated. For example, in certain configurations—especially those involving systems with the potential for significant releases of more than 0.5 lb/s (0.2 kg/s) and where a steady flow can sustain ignition—a flare system may be justified. For design considerations of vents and flare systems, refer to Sections 2.5.9.1 and 2.5.9.2, respectively.

2.5.9.1 Vent Systems

2.5.9.1.1 Design vent systems according to CGA G-5.5, *Standard for Hydrogen Vent Systems* and NFPA 2, *Hydrogen Technologies Code*.

2.5.9.1.2 Locate vent stacks outdoors, away from ignition sources, air intakes, and building openings. Ensure vent systems are provided with an unobstructed flow path of gases to a safe release location (i.e., an above roof location or remote area).

2.5.9.1.3 Provide vents with weather protection.

2.5.9.2 Flare Systems

2.5.9.2.1 Design and install flare systems in accordance with API 537, *Flare Details for Petroleum, Petrochemical, and Natural Gas Industries*. Ensure a flare header sizing study is performed, considering all points of release and the maximum flow conditions expected under all modes of operation. Ensure revalidation is performed after changes.

2.5.9.2.2 Design the system with the appropriate safety combustion controls that include, but are not limited to, pilot ignition and warning systems for flameout.

2.5.9.2.3 Ensure hydrogen flow through the flare stack is provided at an adequate velocity for stable combustion.

2.5.9.2.4 Ensure the flare system is provided with vent line purging and a robust knockout drum to remove liquids.

2.5.10 Overpressure Protection

2.5.10.1 Design and install pressure relief devices in accordance with Data Sheet 7-49, *Emergency Venting of Vessels*.

2.5.11 Storage Vessels

2.5.11.1 Hydrogen Gas (GH_2)

2.5.11.1.1 Design and construct pressure vessels in accordance with ASME Boiler and Pressure Vessel Code, Section VIII. Ensure construction materials are suited for their service.

2.5.11.1.2 Provide pressure relief devices in accordance with Section 2.5.10.

2.5.11.2 Liquid Hydrogen (LH_2)

2.5.11.2.1 Design and construct the inner vessel according to ASME Boiler and Pressure Vessel Code, Section VIII. Ensure construction materials are suitable for liquid hydrogen service at cryogenic conditions. Design the outer vessel (vacuum jacket) to withstand the maximum internal and external pressure to which it will be subjected during normal and emergency conditions.

2.5.11.2.2 Ensure the inner vessel is designed using a vapor-tight seal in the outer jacket to prevent air condensation and oxygen enrichment within the insulation.

2.5.11.2.3 Select insulation materials and arrangements of the outer vessel that provide thermal protection from ambient temperatures to minimize evaporation losses and pressure rise.

2.5.11.2.4 Provide vacuum level monitoring to the outer jacket to ensure adequate pressure is maintained within the annular space between the inner and the outer vessel.

2.5.11.2.5 Provide pressure relief devices for the inner vessel. To prevent the tank from being emptied when servicing the relief devices, install double relief devices with a selector valve. Configure the selector valve to prevent both relief devices from being isolated simultaneously, regardless of its position.

2.5.11.2.6 Ensure vessels are provided with shutoff valves on all connections, except for pressure relief devices, with the capability to be locally or remotely operated. Valves should be accessible and located as close as practical to the vessel.

2.5.11.2.7 Avoid any dike system that will contain spills close to the vessel. Diking or berms should be used to direct the spill away from the vessel.

2.5.12 Piping, Valves and Components

2.5.12.1 General

2.5.12.1.1 Design and install piping, tubing and fittings in accordance with ASME B31.12, *Hydrogen Piping & Pipelines* or an equivalent international standard. Ensure all piping and pressure-containing components are leak tested after installation.

2.5.12.1.2 Provide pressure relief devices on piping systems at points where blockages or potential pressure increases can be expected, according to a PHA. Design the pressure relief device based on Section 2.5.10.

2.5.12.1.3 Ensure gasket materials can withstand the maximum pressure and temperature conditions and maintain a seal under any credible condition to which it may be subjected in service.

2.5.12.1.4 Design and install piping systems with sufficient flexibility to prevent fatigue failures caused by thermal contraction or vibration. For vacuum-jacketed piping, the jacket must be designed to allow thermal contraction of the inner pipe. Ensure that expansion and contraction of piping connected to a pressure vessel is considered.

2.5.12.1.5 Provide adequate support for long runs of piping at intervals that allow for axial motion with transverse motion restraint.

2.5.12.2 Hydrogen Gas (GH_2) Systems

2.5.12.2.1 Use welded pipe for indoor hydrogen systems when possible. Ensure welding materials are compatible and suited for hydrogen gas services. Mechanical joints such as flanges should only be used for ease of installation, maintenance and other similar considerations.

2.5.12.2.2 Install an excess flow valve immediately downstream of the shutoff valve on hydrogen bulk storage that automatically closes in the event of a pipe failure.

2.5.12.3 Liquid Hydrogen (LH_2) Systems

2.5.12.3.1 Install vacuum-insulated piping to minimize heat gain, thereby reducing vaporization losses and avoiding ice formation. Ensure insulation is of noncombustible materials.

2.5.12.3.1.1 Separate the vacuum jacket system of piping from the vacuum systems of storage vessels and handling systems.

2.5.12.3.1.2 Provide the vacuum-insulation jacket with a pressure relief device to protect against overpressure scenarios that may be present due to insulation failures, leakage from the inner pipe or fire.

2.5.12.3.2 Install extended bonnet valves to prevent low-temperature contraction of nonmetallic seals. This method establishes a temperature differential between the valve stem packing and the fluid in the piping to avoid leakage, external icing or other heat flux problems.

2.5.12.3.3 Where liquid hydrogen can be trapped (e.g., in double-seated valves, or sections of piping between two isolation valves) and subjected to heating and consequent expansion, a means of pressure relief should be provided to avoid excessive pressure buildup.

2.5.12.3.4 Install an automatic shutoff valve in liquid hydrogen withdrawal piping as close to the vessel as practical. Ensure no connections, flanges, or other appurtenances (other than a welded manual shutoff valve) exist in the piping between the automatic shutoff valve and the tank.

2.5.12.3.5 Use valve types that do not permit any liquid hydrogen to be trapped inside upon valve closing.

2.5.12.3.6 Use pneumatic valve actuators to operate valves from a remote location, so that potentially close ignition sources are eliminated. If electrical actuators are utilized, they should be properly classified for use in a hydrogen environment.

2.5.12.4 Oxygen Systems

2.5.12.4.1 Use construction materials for oxygen piping and components that are compatible for the application, considering flammability and ignitability potential under operating conditions.

2.5.12.4.2 Use gaskets of compatible materials that have been cleaned for oxygen service. Ensure they are sized and installed to match the internal diameter of the pipe, thereby preventing free spaces where particles can accumulate.

2.5.12.4.3 Design piping and components to function without lubrication. For cases where a lubricant is necessary for assembly or functionality of the component or equipment, ensure the following:

A. Select lubricants that are compatible and acceptable for oxygen services.

B. Restrict the use of lubricants to minimum quantities.

2.6 Operation and Maintenance

2.6.1 Operation

2.6.1.1 Establish procedures for all operating modes, including normal startup and shutdown, process upsets, emergency shutdown and restart. Include activities to prevent hydrogen leakage, accumulation and explosions. Ensure procedures include clear instructions for the following cases:

A. Hydrogen isolation and equipment shutdown (see Sections 2.5.2.2 and 2.5.2.3).

B. Resetting the emergency shutdown, which requires a deliberate manual action, to ensure the system can only be restored after the hazardous condition has been resolved and the system is confirmed to be safe for restart.

C. Purging with inert gas before startup/restart operations and before and after maintenance activities.

2.6.2 Maintenance

2.6.2.1 Establish and implement an asset integrity monitoring program in accordance with Data Sheet 9-0, *Asset Integrity*.

2.6.2.2 Implement a positive material identification program (PMI) for new equipment or material to ensure that construction materials are adequate for service.

2.6.2.3 Develop and implement specific procedures for cleaning oxygen piping after maintenance activities. Ensure cleaning products and solvents are compatible for the operation.

2.6.2.4 Inspect, test and maintain safety controls, alarms and interlocks according to Data Sheet 7-45, *Safety Controls, Alarms and Interlocks (SCAI)*.

2.6.2.5 Perform inspection, testing and maintenance of rectifier transformers according to Data Sheet 5-4, *Transformers*.

2.7 Contingency Planning

2.7.1 Equipment Breakdown Spares

2.7.1.1 Equipment breakdown spares for hydrogen production are spares to be used during an unplanned outage of process equipment to reduce downtime and restore operations. Provide the following equipment breakdown spares:

A. Rectifier transformer – Maintain one full spare.

B. Electrolyzers stack spares - Maintain at least one spare stack. For larger facilities, maintain a minimum of 10% spare stacks.

2.7.1.2 Utilize an N+1 approach for the rectifier transformer equipment breakdown spare, so the transformer can be put directly into service if a breakdown of the in-service transformer occurs.

2.7.1.3 Maintain the rectifier transformer equipment breakdown spare viability per Data Sheet 9-0, *Asset Integrity*.

2.8 Ignition Source Control

2.8.1 Provide hazardous location-rated electrical equipment in areas with the potential for hydrogen release or accumulation points in accordance with Data Sheet 5-1, *Electrical Equipment in Hazardous Locations*. Ensure all electrical components within hydrogen process and storage areas are electrically rated. The following ratings are recommended:

A. Provide Class I, Div 2 (Zone 2), Group B for electrical equipment within 15 ft (4.6 m) of gaseous hydrogen equipment.

B. Provide Class I, Div 1 (Zone 0 where flammable material is present continuously or Zone 1 where present intermittently), Group B for electrical equipment within 3 ft (1 m) of a point where connections/disconnections are regularly performed.

2.8.2 Provide direct-straight lightning protection in accordance with Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*, for all areas where hydrogen is processed or stored. Ensure all components and equipment in buildings are interconnected and grounded to prevent sparks between equipment during lightning strikes.

2.9 Natural Hazards

2.9.1 Freeze

2.9.1.1 Provide freeze protection according to Data Sheet 9-18, *Prevention of Freeze-Ups*, for all areas and equipment that can be exposed to freezing conditions. For indoor areas, ensure vents and ventilation exhaust to the outdoors.

2.9.2 Earthquake

2.9.2.1 Provide earthquake protection in accordance with Data Sheets 1-2, *Earthquakes* and 1-11, *Fire Following Earthquake*, to facilities located in FM 50- through 500-year earthquake zones.

2.9.2.1.1 Design and construct buildings, process structures, equipment, vessels and piping to resist earthquake forces, according to the latest seismic design codes and regulations. Provide all the necessary seismic anchorage, bracing, restraint and flexibility.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Hydrogen Hazards

3.1.1 Hydrogen Gas (GH_2)

Hydrogen is a colorless, odorless and non-toxic gas. It is the lightest of all gases and highly buoyant in ambient environments due to its low density, which is approximately one-fifteenth that of air.

Due to its small molecular size, hydrogen can easily pass through porous materials, causing leakage or embrittlement of metals.

3.1.2 Liquid Hydrogen (LH_2)

Liquid hydrogen is colorless and odorless, with a light-blue tint. Its density, approximately 4.4 lb/ft^3 (70.3 kg/m^3), is one-fourteenth that of water. It exists as a liquid at -423.17°F (-252.87°C) and quickly evaporates into gas when exposed to higher temperatures. One liter of liquid hydrogen expands to approximately 850 liters of gaseous hydrogen in ambient conditions.

Liquid hydrogen is noncorrosive. However, due to its extremely low temperatures, equipment should be designed and manufactured from materials suitable for operation at cryogenic temperatures.

Like hydrogen gas, liquid hydrogen is highly flammable and can form explosive mixtures with air.

3.1.3 Fire and Explosion Hazards

Hydrogen has several unique physical properties that make it significantly different from other common flammable gases, based on fire and explosion hazards. Understanding these properties is important to properly assess the consequences and potential likelihood of these events.

Due to hydrogen’s low density, it is highly buoyant, which can significantly reduce accumulation when released outdoors. Indoors however, buoyancy has the potential to enhance mixing and create a larger flammable cloud. In addition, this low density significantly increases its volumetric release rate for a given leak size or orifice. Finally, to compensate for hydrogen’s low density, it is often stored at higher pressures, further increasing the potential release rate and severity of an accidental release.

Hydrogen also has several properties that increase the likelihood of a fire or explosion event. Hydrogen has a wide flammability range, from 4% to 75% by volume, allowing it to easily form an explosive mixture when released. For additional flammability limit values of hydrogen-oxygen-nitrogen mixtures, refer to Data Sheet 7-91, *Hydrogen*.

Hydrogen has a very low ignition energy, approximately 0.02 mJ, which is about one tenth of the ignition energy required for methane. This makes hydrogen more susceptible to ignition when released. In certain scenarios, hydrogen can even spontaneously ignite, reducing the effectiveness of ignition source control and electrically classified environments. While hydrogen’s tendency to ignite can potentially decrease the likelihood of explosions (if the mixture ignites before accumulating), it can also increase the risk of jet fires. Additionally, hydrogen burns with a pale blue flame that is difficult to detect in bright light.

From an explosion severity standpoint, hydrogen has several properties that significantly increase the hazard it presents. First, hydrogen has a much higher laminar burning velocity than most flammable gases. As a result, gas explosions involving hydrogen can produce significantly higher overpressures. They require much less congestion and confinement to generate damaging overpressures in a vapor cloud explosion. Even the delayed ignition of a free hydrogen jet has the potential to generate damaging overpressures without congestion or confinement. In addition, hydrogen has a very small detonation cell size, making it much easier to undergo a transition to detonation over a wide range of concentrations. These effects make it challenging to fully protect against a hydrogen-air release within an enclosure using traditional means like deflagration venting. Nevertheless, deflagration venting can provide a significant benefit for lean hydrogen releases.

3.2 Process Overview

Hydrogen production by water electrolysis is an electrochemical process that uses water and electricity to produce hydrogen and oxygen through electrolyzer units. In this reaction, each mole of water introduced produces one mole of hydrogen and half a mole of oxygen:

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

An electric current is passed between two electrodes through a conductive medium or electrolyte, such as a solid membrane (PEM) or an alkaline solution (AWE). During this process, hydrogen gas is generated at the negative electrode (cathode), while oxygen is produced at the positive electrode (anode).

As large-scale hydrogen production plants continue to emerge, their designs vary considerably due to the wide array of electrolyzer and balance-of-plant (BOP) manufacturers entering the market. Despite these differences, most designs incorporate scalable approaches, allowing for flexibility and adaptation to various production needs and capacities.

Typically, a hydrogen production plant begins with a central water treatment area that supplies all downstream electrolyzers. This setup ensures the deionized water used for PEM electrolyzers, or potassium hydroxide/ sodium solution for alkaline water electrolyzers, is of proper quality. Figures 3.2-1 and 3.2-2 present typical flow diagrams for Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE) processes, respectively.

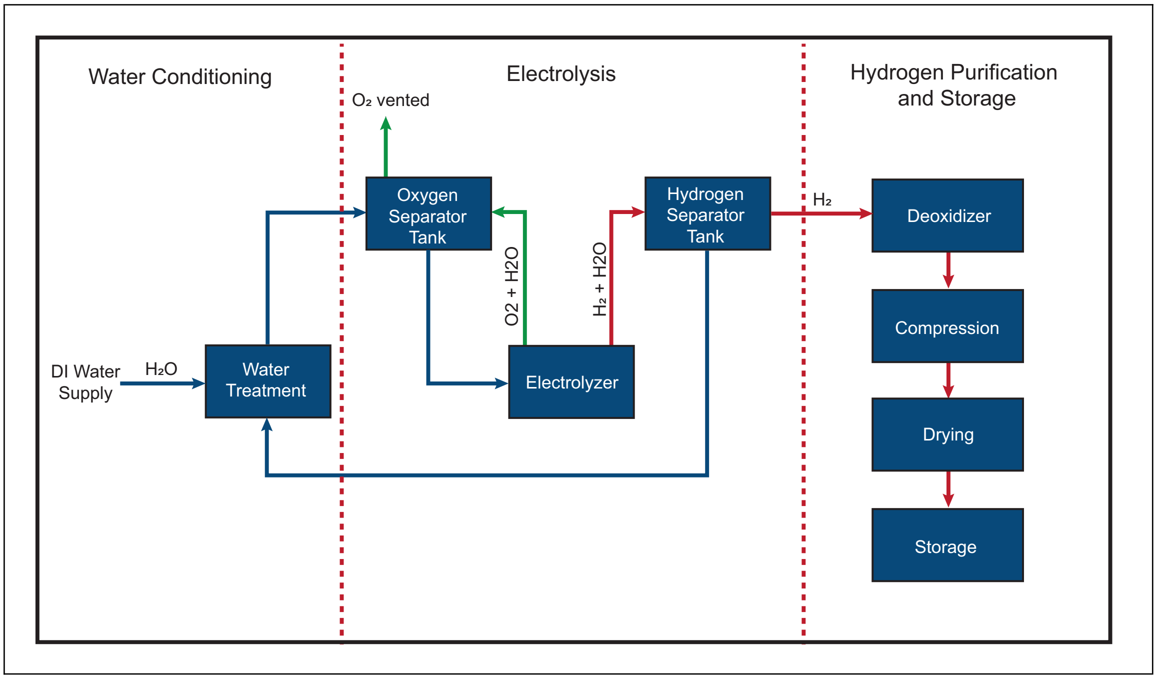

Fig. 3.2-1. Typical flow diagram of a PEM electrolytic process

Most manufacturers use a modular approach for electrolysis. The splitting of the electrolyte into hydrogen and oxygen gas occurs in individual cells, which are part of a larger stack consisting of plates and membranes. These stacks are often assembled into larger modules with a set production capacity. For example, cells might be combined into a 1 MW stack, with five stacks grouped into a single 5 MW module (Figure 3.2-3). To achieve a total production of 30 MW, six modules would be installed. Depending on the climate and manufacturer, individual modules might be built as small, detached units with most piping outdoors, or housed in one large common electrolyzer hall.

When leaving the stack, the gas-water mixture is sent to oxygen-water and hydrogen-water separators. These separators remove the gas and allow the water or electrolyte to be recycled back to the electrolysis modules. Different manufacturers adopt various designs for this stage: some provide separators for each module, while others use a common separator for all modules. In the previous example, either six smaller oxygen- and hydrogen-water separators would be needed or just one of each.

The oxygen is often discharged into the atmosphere, while the hydrogen is purified in the deoxidizer and then moves to compression. The compression step may involve one large compressor or multiple smaller units. After compression, the hydrogen is dried and either sent to storage as a high-pressure gas or proceeds to a liquefaction step if stored in liquid form.

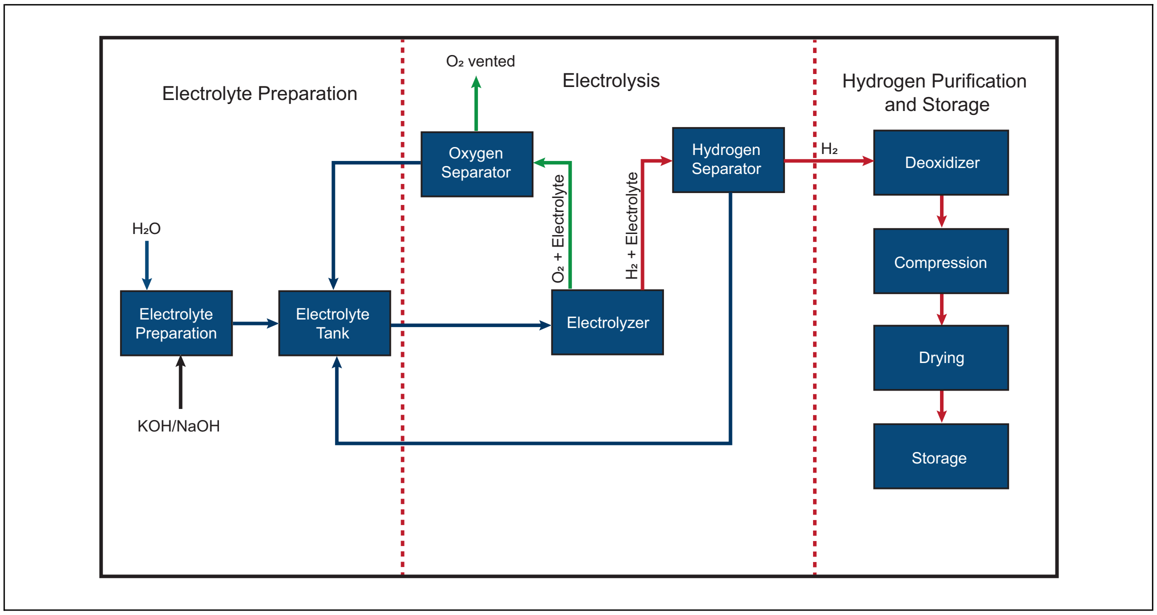

Fig. 3.2-2. Typical flow diagram of an AWE electrolytic process

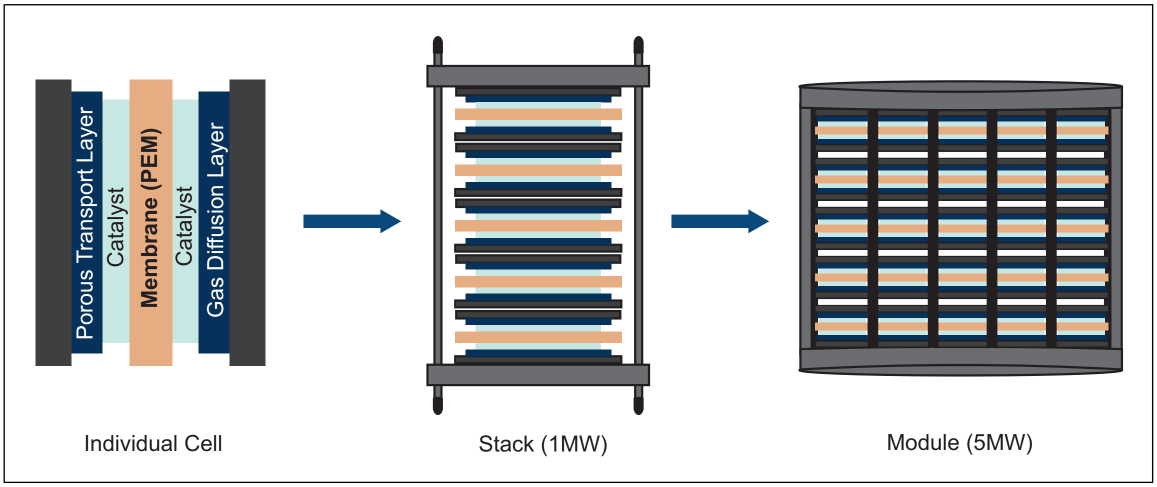

Fig. 3.2-3. Typical arrangements for electrolysis units and systems

3.3 Electrolyzers

3.3.1 Proton Exchange Membrane (PEM) Electrolyzers

A Proton Exchange Membrane (PEM) Electrolyzer is a device that uses electricity to split water into hydrogen and oxygen. This process occurs in a cell equipped with a solid polymer electrolyte, known as the proton exchange membrane. The membrane is crucial; as it conducts protons, separates the product gases, and electrically insulates the electrodes. PEM electrolyzers are often designed in modular, stackable units.

In a PEM, electrolyzer water is supplied to the anode side, where the water is oxidized by an electrolytic process to produce oxygen (O_2), protons (H^+), and electrons (e^-) as indicated in the below reaction:

$$H_2O \rightarrow \tfrac{1}{2}\, O_2 + 2H^+ + 2e^-$$

The generated protons pass through the proton exchange membrane to the cathode side, where the protons combine with electrons to form hydrogen gas (H_2):

$$2H^+ + 2e^- \rightarrow H_2$$

Figure 3.3.1 shows a schematic view of the PEM water electrolysis working principle.

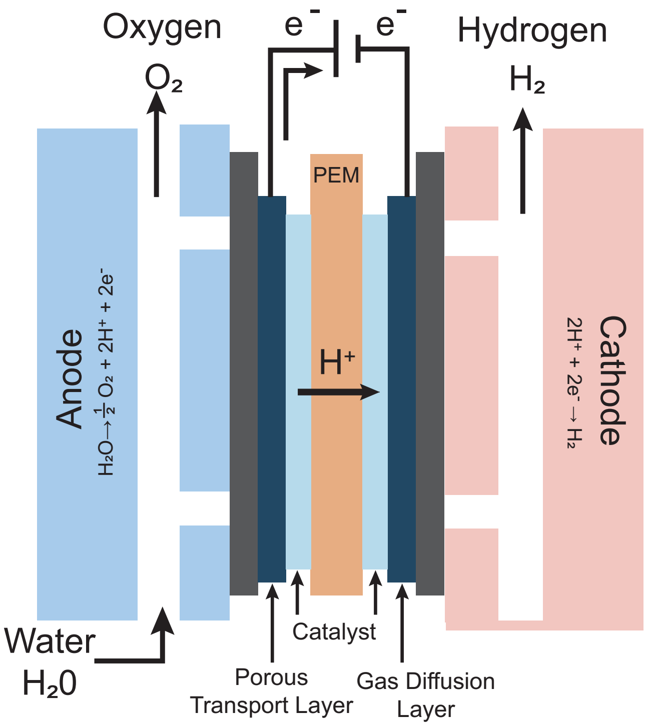

Fig. 3.3.1. PEM water electrolysis working principle

The specific characteristics and operating conditions of PEM electrolyzers can vary significantly, depending on the manufacturer and the size of the equipment. Table 3.3.1 provides a summary of some typical characteristics of these electrolyzers.

Table 3.3.1. Typical Characteristics of a PEM Electrolyzer

Typical Characteristic	*Description*
Electrolyte/Membrane Material	Solid polymer (e.g., Nafion, Fumapem, etc.)
Working Fluid	Deionized or Distilled Water
Bipolar/Separator Plate Material	Titanium or gold and platinum-coated titanium
Catalyst Material	Anode: Iridium (Ir), Platinum (Pt) or Ruthenium (Ru) Cathode: Platinum (Pt) or Platinum on Carbon
Operating Temperature	50-80°C
Stack Pressure	Up to 30 bar
Current Density	0.6-10.0 A/cm²
Cell Voltage	1.75-2.20 V
Power Density	Up to 4.4 W/cm²
Specific Energy Consumption (Stack)	4.2-5.6 kWh/Nm³
Specific Energy Consumption (System)	4.5-7.5 kWh/Nm³
Cell Voltage Efficiency	67-82%
Stack Lifetime	Less than 20,000 hours
System Lifetime	10-20 years
Degradation Rate	Less than 14 µV/h

3.3.2 Alkaline Water Electrolyzers (AWE)

An Alkaline Water Electrolyzer (AWE) is a device that uses an alkaline solution and electricity to split water into hydrogen and oxygen. This process occurs in an electrolytic cell containing an alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH). The electrolyzer consists of two electrodes (anode and cathode) immersed in the alkaline solution, separated by a diaphragm or membrane that allows water molecules and hydroxide ions to pass through, preventing hydrogen and oxygen from being mixed.

The alkaline water electrolysis process initiates at the cathode side, where two molecules of alkaline solution are reduced to one molecule of hydrogen (H_2) and two hydroxyl ions (OH).

$$2H_2O+2e^- \rightarrow H_2+2OH^-$$

The produced H_2 is eliminated from the cathode surface to recombine in a gaseous form. The electrical circuit transfers the hydroxyl ions (OH) from the cathode, through the porous diaphragm to the anode, where half a molecule of oxygen (O_2) and one molecule of water (H_2O) are produced.

$$2OH^- \rightarrow ½\, O_2+H_2O+2e^-$$

Figure 3.3.2 shows a schematic view of the AWE working principle.

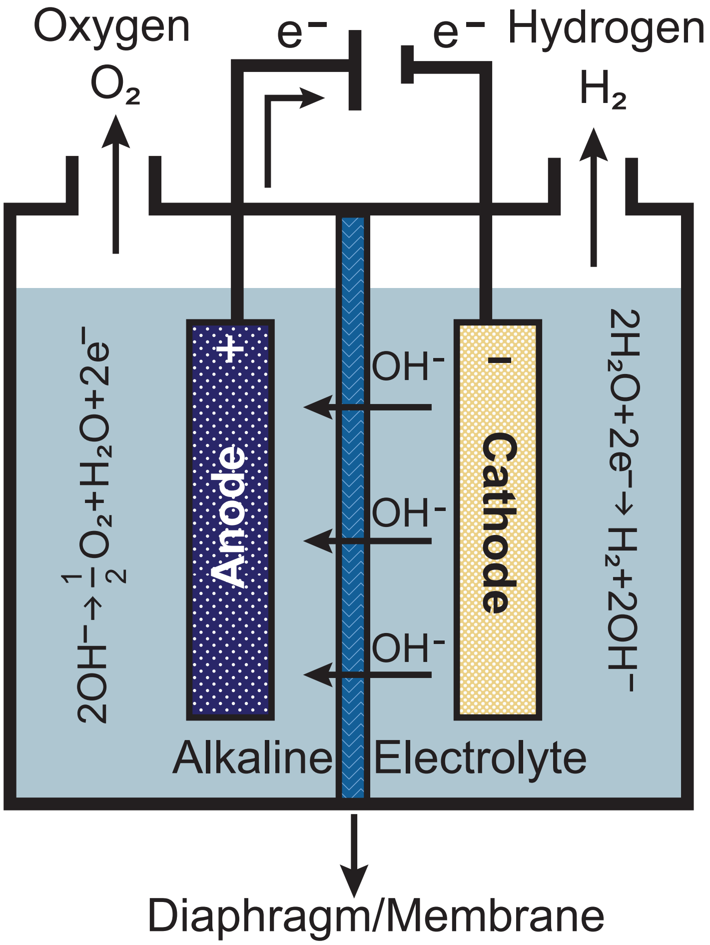

Fig. 3.3.2. AWE Working principle

The specific characteristics and operating conditions of alkaline water electrolyzers (AWE) can vary significantly depending on the manufacturer and the size of the equipment. Table 3.3.2 provides a summary of some typical characteristics of these electrolyzers.

Table 3.3.2. Typical Characteristics of an Alkaline Water Electrolyzer (AWE)

Typical Characteristic	*Description*
Electrolyte	20-30% KOH or NaOH solution
Electrode Material (Anode/Cathode)	Nickel-based alloys
Diaphragm/Membrane Material	Asbestos or polymer-based separators
Operating Temperature	60-80°C
Operating Pressure	Up to 30 bar
Current Density	0.2-0.4 A/cm²
Cell Voltage	1.8-2.4 V
Stack Lifetime	60,000-90,000 hours
System Lifetime	20-30 years
Degradation Rate	Less than 10 µV/h

3.4 Hydrogen Embrittlement

Hydrogen embrittlement refers to the degradation of fracture toughness or ductility in certain metallic materials due to the presence of atomic hydrogen. This hydrogen can cause intergranular or transgranular cracking and brittle fractures without warning. Metals can experience significant deterioration in mechanical properties when exposed to hydrogen. Whether used structurally or as sensing elements, metals for hydrogen service must be evaluated based on material properties, hydrogen exposure and applied stress.

For hydrogen embrittlement to occur, hydrogen must first permeate the metal. This complex process begins with the absorption of a hydrogen molecule on the metal surface, which then dissociates into atomic hydrogen. Once hydrogen ions are formed, they diffuse through the metal crystal lattice due to their small size. The interaction between hydrogen and metals can lead to the formation of solid solutions of hydrogen in metals, solid compounds such as hydrides, molecular hydrogen, or gaseous compounds with other elements in the metal. Susceptibility to hydrogen embrittlement increases with alloy strength.

Hydrogen embrittlement can be classified into three broad categories:

A. Hydrogen Environmental Embrittlement. Occurs when certain mechanical properties of metals and alloys degrade under conditions of plastic deformation in a gaseous hydrogen environment. Crack initiation often begins as surface defects and leads to surface cracks. It reduces ductility and fracture stress, making it more vulnerable to cracking. This situation is commonly observed in pressurized fittings, lines and vessels.

B. Internal Hydrogen Embrittlement. Results from the unintentional introduction of hydrogen into susceptible metals, typically during forming or finishing operations. Hydrogen sources include the decomposition of water from the atmosphere or organic contaminants on weld joints. The hydrogen is absorbed into molten metal during welding or casting. As the metal cools, excess hydrogen that cannot be accommodated leads to embrittlement. Hydrogen can also react to form molecular hydrogen, which collects at grain boundaries and defects, leading to internal fissuring and premature failures.

C. Hydrogen Reaction Embrittlement. Occurs when absorbed hydrogen chemically combines with elements or compounds within the metal to form brittle hydrides. This situation is common at elevated temperatures and pressures but can also occur at lower temperatures. Materials like titanium, zirconium and some steels are susceptible. For example, hydrogen can react with iron carbides to form methane, which promotes brittle rupture by forming voids and micro-cracks.

Hydrogen embrittlement has been observed over a wide temperature range, with internal and environmental hydrogen embrittlement peaking between -100 to 80 °F (-73 to 27°C). Hydrogen reaction embrittlement is associated with higher temperatures.

Some of the operational concerns with hydrogen and the potential effects of hydrogen embrittlement include:

- Permeation. Leakage rates through pipes and joints may be greater than other fuels because hydrogen molecules are smaller.

- When subject to rapid pressure cycling, permeable materials (such as those found in seals) will undergo deterioration due to hydrogen gas expansion within the material.
- Reactions between hydrogen and steel can make metal brittle, resulting in cracked pipelines. Both metallic and nonmetallic material are subject to embrittlement.
- Frequent fluctuations of pressure in transmission or distribution pipes can reduce the threshold cycling stress intensity factor and expose pipes to accelerated fatigue cracking, especially in carbon and low-alloy steel applications.
- Crack growth from existing defects can be exacerbated by introducing hydrogen, due to the reduced ductility of steel.

3.5 Construction Materials

Material selection, testing (i.e., direct exposure of the material to hydrogen) and analysis should be conducted to ensure the material will perform as expected at planned operating conditions and in worst-case scenarios. If testing is not practical, referring to existing material selection guidance found in the literature may provide the needed assurance.

For ambient temperature hydrogen systems, austenitic stainless steel is frequently used. Type 316 austenitic stainless steel is most common due to its high resistance to hydrogen embrittlement, good ductility and ability to withstand the high pressures involved in hydrogen storage and transportation. It is ideal for components like pipes, tanks and fittings in hydrogen systems. Key points about austenitic stainless steel for hydrogen applications include:

- Low hydrogen diffusion: Austenitic stainless steel has a lower rate of hydrogen diffusion compared to other steel types (like ferrite or martensite), which significantly reduces the risk of hydrogen embrittlement.
- Cryogenic compatibility: Austenitic stainless steel can handle very low temperatures, making it suitable for liquid hydrogen storage.
- High ductility: This property ensures good resistance to cracking under pressure, a crucial factor in hydrogen applications.
- Preferred grades: Type 316L and 316LN are preferred due to their excellent corrosion resistance and good mechanical properties.

Metals that are less resistant to deterioration when exposed to hydrogen may still be used when analysis of pressure containing components shows that the mechanical loading is acceptable. The generally accepted demonstration method is fracture mechanics.

Consideration of toughness at low temperature is essential for liquid hydrogen service. Industry uses the Charpy impact test, which measures the amount of energy absorbed by a material during fracture, to judge a material’s fracture toughness at the cold condition. Additional information is provided in ANSI/AIAA G-095A-2017, *Guide to Safety of Hydrogen and Hydrogen Systems*.

3.6 Hydrogen Detection Systems

3.6.1 Gas Detection Systems

Hydrogen is a highly flammable gas that can form explosive mixtures at low concentrations. Due to its small molecular size, gaseous hydrogen is prone to leaks, making early detection crucial to prevent fires or explosions.

To mitigate the risks associated with hydrogen leaks, many detection systems are integrated with automatic shutdown mechanisms. Several conventional, commercially-available technologies are used for detecting hydrogen. These include high-temperature semiconductor sensors (e.g., metal oxide sensors), catalytic combustion sensors, and heat conduction sensors such as thermoconductivity sensors. Additionally, hydrogen can be readily detected by electrochemical sensors and sensor platforms that utilize palladium thin films, where the adsorption of hydrogen changes the electrical and optical properties of the thin film.

Beyond conventional technologies, several emerging technologies are being developed for hydrogen detection. These include fiber optic sensors, ultrasonic detection and Schlieren imaging. Each of these technologies has its own advantages and disadvantages in terms of use and application.

3.6.2 Flame Detection Systems

Flame detection is another technology available for hydrogen. However, detecting hydrogen flames can be challenging due to their unique characteristics. Hydrogen burns with a pale blue flame that is almost invisible in daylight. If impurities are present in the air, the flame may appear yellow. Additionally, a pure hydrogen flame does not produce smoke and emits very little radiant heat.

Currently, the two main categories of flame detection systems are thermal fire detectors and optical sensors. Thermal fire detectors are further classified into rate-of-temperature-rise and overheating detectors. They are designed to detect changes in temperature and should be positioned very close to the potential site of a fire. While effective for direct detection, their effectiveness can be limited by their proximity requirements.

Optical sensors operate in two primary spectral regions: ultraviolet (UV) and infrared (IR). UV sensors are highly sensitive to the presence of flames and can provide rapid detection. However, they are prone to false alarms due to environmental factors like fog and can be blinded under certain conditions. IR sensors are typically used for detecting hydrocarbon fires and are less sensitive to hydrogen flames. As hydrogen fires emit less infrared radiation, these sensors may not be suitable for hydrogen-specific applications. However, to address the limitations of single-spectrum sensors, dual-band systems have been developed. These systems utilize both UV and IR detection, incorporating logic to minimize false alarms. They are designed to quickly detect UV signals but only trigger an alarm when corresponding IR bands are also detected, thereby enhancing accuracy.

Systems should be designed to minimize false alarms caused by external factors such as sunlight, lightning, welding, artificial lighting, etc. In addition, because hydrogen flames are invisible in daylight, specialized imaging systems are necessary to accurately determine the size and location of a flame.

3.7 Ventilation

Hydrogen production facilities have equipment that contains large quantities of hydrogen at high pressures, where even small leaks indoors have the potential to generate flammable mixtures. Ventilation systems must be designed to dilute and disperse these releases to prevent hydrogen accumulation and ensure the concentration stays below the lower flammable limit (LFL). Two main types of ventilation systems are found at these facilities:

A. Natural ventilation

B. Mechanical or forced ventilation

Designing effective ventilation systems may require the use of specific evaluations and tools, such as Computational Fluid Dynamics (CFD) modeling, which can accurately simulate hydrogen releases and dispersion behaviors. Ventilation simulations can identify areas of low ventilation velocities or dead spots where gas may accumulate.

Considerations for designing the ventilation system should include identifying credible release scenarios, the layout and size of the production area, cost implications and ease of integration with current systems. Additionally, ensuring compliance with safety regulations and industry standards is crucial when selecting and implementing an effective ventilation solution.

3.7.1 Natural Ventilation

Natural ventilation in buildings is generated by pressure differences induced by the wind, temperature gradients and buoyancy. Natural ventilation may be effective for certain indoor situations to prevent the accumulation of hydrogen caused by a small leak. Natural ventilation should be arranged to promote dispersion and dilution. The buoyancy of hydrogen requires natural ventilation, so consider locating vent inlets at ground level and outlets as close to the ceiling as possible. The location of inlets and outlets should be designed to prevent short circuiting and promote crossflow through any potential leak points.

3.7.2 Mechanical or Forced Ventilation

Mechanical systems can precisely control the direction and speed of airflow, ensuring a hydrogen release is diluted and removed from the facility before accumulating. Unlike natural ventilation, mechanical systems provide consistent and reliable ventilation, regardless of external weather conditions. These systems should be designed to target specific areas where hydrogen leaks are likely to occur.

Considerations for mechanical ventilation systems should include:

- Proper electrical classification inside and immediately outside the extraction system discharge point and other openings
- Ventilation air should normally be drawn from a non-hazardous area.
- Before determining the dimensions and design of the ventilation system, the location, grade of release, release velocity and release rate should be defined.

3.7.3 Emergency Ventilation

For larger hydrogen releases, mechanical ventilation can be integrated with detection systems and automatic shutoffs. Increasing the ventilation rate can significantly reduce the time during which a dangerous accumulation of hydrogen is present indoors.

4.0 REFERENCES

4.1 FM

Data Sheet 1-2, *Earthquakes*
Data Sheet 1-11, *Fire Following Earthquake*
Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies*
Data Sheet 5-1, *Electrical Equipment in Hazardous (Classified) Locations*
Data Sheet 5-4, *Transformers*
Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*
Data Sheet 7-14, *Fire Protection for Chemical Plants*
Data Sheet 7-43, *Process Safety*
Data Sheet 7-45, *Safety Controls, Alarms and Interlocks (SCAI)*
Data Sheet 7-49, *Emergency Venting of Vessels*
Data Sheet 7-55, *Liquefied Petroleum Gas (LPG) Storage in Stationary Installations*
Data Sheet 7-91, *Hydrogen*
Data Sheet 7-95, *Compressors*
Data Sheet 7-111, *Chemical Process Industries*
Data Sheet 9-0, *Asset Integrity*
Data Sheet 9-18, *Prevention of Freeze-Ups*
Data Sheet 12-2, *Vessels and Piping*

4.2 Other

API 537, *Flare Details for Petroleum, Petrochemical, and Natural Gas Industries*

CGA G-5.5, *Standard for Hydrogen Vent Systems*

NFPA 2, *Hydrogen Technologies Code*

ASME Boiler and Pressure Vessel Code, Section VIII

ASME B 31.12, *Hydrogen Piping and Pipelines*

ANSI/AIAA G-095A-2017, *Guide to Safety of Hydrogen and Hydrogen Systems*

APPENDIX A GLOSSARY OF TERMS

Electrolyte: In hydrogen production using electrolysis processes, the electrolyte facilitates the movement of ions (like hydroxide ions in alkaline electrolysis or protons in Proton Exchange Membrane (PEM) electrolysis) between the electrodes, allowing the electrical current to drive the water splitting reaction.

In a PEM electrolysis process, the electrolyte is a solid material, typically made of Nafion or similar proton-conducting polymers. This membrane acts as a selective barrier, allowing only positively charged hydrogen ions (protons) to pass through, while preventing the mixing of hydrogen and oxygen gases.

For alkaline water electrolysis, the typical electrolyte is a 20-30% potassium hydroxide (KOH) or sodium hydroxide (NaOH) solution.

Electrolyzer Unit (PEM): A PEM electrolyzer unit is a device that uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) through electrolysis, employing a proton exchange membrane (PEM) as the electrolyte. Depending on the manufacturer, these units can vary in architecture, capacity, and size, based on the number of cells and stack arrangements. The terms ″cell″ and ″stack″ refer to different levels of the system’s architecture:

- **Cell:** The cell is the basic functional unit of an electrolyzer. It consists of electrodes (anode and cathode), a proton exchange membrane (PEM), and flow fields or bipolar plates that distribute water and collect gases. Each individual cell carries out the electrochemical reaction. However, a single cell typically produces only small amounts of hydrogen, insufficient for practical hydrogen production at scale.
- **Stack:** A stack is composed of multiple cells connected electrically in series and hydraulically in parallel. This configuration increases the total voltage and hydrogen output. Stacks typically share common manifolds for water input and gas output and are enclosed in a frame with compression hardware to ensure proper contact and sealing. Multiple electrolyzer cells are combined to form a stack.

Electrolyzer Module: Electrolyzer modules are units that can be enclosed spaces (box-type) or non-enclosed structures that house the core components necessary for water electrolysis processes. These components may include electrolyzer cell stacks (where the electrochemical reaction occurs), pumps, power supply units, gas-liquid separators, control systems, and sometimes auxiliary elements such as water purification systems and small buffer storage tanks. The module is designed to operate as a self-contained unit or as part of a larger electrolyzer system for scalable hydrogen production.

Indoor Areas: In this data sheet, an indoor area refers to a space that is enclosed and protected from the elements by walls, floors and a ceiling. This area can be a building, a room, a hallway or any enclosed space within a structure.

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

October 2025. This is the first publication of this document.