Safety in Classified Areas for Hydrogen Storage

Abstract

This technical paper addresses the challenges and safety measures associated with storing hydrogen, a highly flammable and potentially dangerous substance. Hazardous area classifications specific to hydrogen storage will be discussed, along with the precautions needed to ensure the safety of workers and facilities. Topics covered include the safe design of storage facilities, adequate ventilation systems, leak prevention, gas detection, requirements for explosion-proof equipment, fire suppression systems and emergency procedures. Best practices for preventive maintenance, regular inspections and proper employee training will also be explored, as well as relevant safety guidelines and regulations.

Introduction

The storage of hydrogen presents particular challenges due to its highly flammable and potentially dangerous nature. This paper aims to explore the safety measures needed to ensure the protection of workers and facilities in areas where hydrogen is stored. The classifications of hazardous areas will be discussed, as well as the appropriate precautions and procedures to minimise the associated risks.

1. CLASSIFICATION OF HAZARDOUS AREAS

1.1. HYDROGEN STORAGE AREA CLASSIFICATIONS

The classification of hazardous areas for hydrogen storage is based on specific standards and regulations:

1. NFPA 55: The NFPA 55 (National Fire Protection Association) standard establishes requirements for the storage, use and handling of compressed and liquefied gases, including hydrogen. It provides guidelines for classifying hazardous areas based on the amount of hydrogen present and the likelihood of its release.

2. IEC 60079-10-2: The IEC 60079-10-2 standard (International Electrotechnical Commission) deals with the classification aspects of explosion-risk areas in electrical installations. It addresses the classification of areas where flammable gases may be present, including hydrogen.

3. ISO 14691: The ISO 14691 standard establishes guidelines for the safe storage and handling of compressed hydrogen in fixed installations. It provides guidance on the classification of hazardous areas and specific safety measures for the storage of hydrogen.

4. CSA B108.1-18 (Canadian Standards Association): Canadian standard that defines technical requirements for underground hydrogen storage system installations, including pipework, sensors, and equipment.

5. DOE Technical Standard DOE-STD-1158-2016 (U.S. Dept. of Energy): Provides design, construction, operation, and maintenance guidelines for underground hydrogen storage tanks.

6. ISO/TS 19880-1: (International Organisation for Standardization): Establishes general principles and safety requirements for underground compressed hydrogen storage units.

7. ASME BVPC Section XII (American Society of Mechanical Engineers): Standard covering the design, manufacture, and inspection of underground storage tanks for both liquid and gaseous hydrogen.

8. ASME B31 (American Society of Mechanical Engineers): Integrity code for pipework structures. Defines design and inspection parameters for hydrogen systems.

9. Government regulations: In addition to the technical standards mentioned above, it is important to note that different countries may have specific regulations for storing hydrogen in hazardous areas. For example, in the United States, the Occupational Safety and Health Administration (OSHA) establishes regulations relating to workplace safety, including the storage of flammable substances such as hydrogen.

10. ATEX Directive 2014/34/EU (EUROPEAN UNION): Addresses explosive areas, citing technical characteristics for equipment and installations.

11. Recommendations from professional associations: Professional associations such as the American Society of Safety Professionals (ASSP) and the International Association for

Hydrogen Safety (IAHydrogenS) can offer additional recommendations and resources on the safe storage of hydrogen in hazardous areas.

12. Association for Hydrogen Safety (IAHydrogenS)

- Safety of hydrogen systems (Manual): Comprehensive guidelines on storage systems, pipework, refuelling stations and associated equipment.
- Risk assessment (Technical publications): Methodologies and recommended practices for assessing and managing risks in hydrogen projects and applications.
- Stationary tank systems (Technical manual): Requirements for the engineering, design, manufacture, and operation of stationary tanks.
- Transport (Publications): Guidelines on safety in the transport of gaseous and liquefied hydrogen by road, ship, and pipeline.
- Accident analysis (Reports): Analyses of accidents that have occurred with the aim of disseminating lessons learnt.

1.2. IDENTIFYING RISK ZONES

Hydrogen storage areas require special care due to the risks inherent in handling and storing this highly flammable substance. In this context, the correct identification of risk zones is a fundamental aspect for the safety of installations and workers.

Zone classification must follow international standards and guidelines, such as the NFPA hazardous area classification or **IEC 60079** electrical zoning. This makes it possible to stratify areas according to factors such as maximum expected gas concentration, potential ignition sources, ventilation, etc.

After classification, each zone must be clearly signposted using signs, colours, symbols and other visual identification elements. Warning signs at strategic points alert you to the level of danger, the need for PPE and the procedures to be followed.

Colour coding is also important, where more critical areas are given warning colours such as red. Less dangerous areas can be signposted in yellow, for example.

International icons such as the **NFPA 704** diamond describe the risks of flammability, reactivity, and other hazards in the presence of hydrogen in a standardised way.

In addition, equipment, and devices in special areas such as outdoor pipework are further labelled with information about the fluid being transported.

Effective signalling makes it easier to guide the movement of personnel and also to identify deviations from the usual procedures, helping to ensure a high level of safety on site.

1.3. ACCESS CONTROL REQUIREMENTS

Access control requirements are fundamental to ensuring the security of hydrogen storage areas. They help prevent unauthorised access and reduce the risk of incidents or malicious activities. Here are some important aspects related to access control requirements:

1. **Physical access control systems**: This includes the implementation of physical measures, such as gates, fences, railings, and locks, to restrict access to hydrogen storage areas. These physical barriers are designed to prevent unauthorised access and provide a first layer of protection.

2. **Prior authorisation**: People wishing to access hydrogen storage areas must generally obtain prior authorisation. This may involve issuing identification badges, access cards or other forms of authentication to confirm that the person is authorised to enter the area. Prior authorisation can be based on criteria such as appropriate training, specific certifications, or security clearance.

3. **Access log**: It is important to keep an accurate record of all people entering and leaving hydrogen storage areas. This makes it possible to track who has had access to the facilities at certain times and can be useful for investigation purposes in the event of incidents or safety violations.

4. **Monitoring and surveillance**: Hydrogen storage areas must be adequately monitored and guarded to ensure compliance with access control requirements. This may include the use of security cameras, alarm systems, intrusion detection systems and the presence of trained security personnel.

5. **Training and awareness**: All employees and contractors who have access to hydrogen storage areas must receive adequate training on access control and security procedures. This includes raising awareness of the importance of access control, identifying unauthorised persons, and properly reporting any suspicious activity.

It is essential to follow the relevant standards, regulations, and guidelines, as well as implementing good industrial practice, when establishing access control requirements in hydrogen storage areas. This will help ensure the safety and integrity of these facilities.

2. SAFE DESIGN OF STORAGE FACILITIES

2.1. STRUCTURAL AND ELECTRICAL ENGINEERING DESIGN

The structural design of hydrogen storage facilities requires attention to specific technical requirements in order to guarantee the safety of the buildings and installed systems.

The structure must be designed to withstand the internal pressures of the tanks and pipes, taking into account factors such as thermal expansion of pressurised equipment. In addition, it must be designed in suitable materials such as stainless steel or reinforced composites to resist corrosion.

Buildings also need to meet strict fire resistance criteria, since in the event of a fire it is necessary to contain the spread of flames and guarantee structural integrity long enough for evacuation.

Another important aspect is the containment design to support the tank and pipeline systems, in order to retain possible leaks within the facilities.

Finally, the structural design includes adequate dimensions for ventilation spaces and heat dissipation since hydrogen is stored at low temperatures.

In the electrical field, the parameters to be observed include the need for safe earthing systems, since hydrogen is highly flammable. In addition, equipment and devices in hazardous areas must be explosion-proof.

Therefore, the electrical design must minimise the risk of ignition from sparks or overloads, especially in the areas where the gas is most likely to be present. This is essential to guarantee the integrity of the installations and the electrical systems installed in them.

2.1.1 What are the most recommended materials for building hydrogen storage facilities?

The most commonly used and recommended materials for the construction of hydrogen storage facilities include:

- **Stainless steels:** Mainly austenitic stainless steels such as 304 and 316, due to their high resistance to corrosion. They are used in the manufacture of tanks, pipework and other equipment.
- **Aluminium and aluminium alloys:** For example, alloys 5083 and 6061, with good mechanical and hydrogen corrosion resistance. Used in tanks and light components.
- **Reinforced composites:** With glass, carbon or aramid fibre embedded in epoxy or vinyl resins. They provide high pressure resistance in complex tanks.
- **Reinforced concrete:** Can be used in civil works such as foundations and retaining walls, due to its lower cost, but requires a protective coating.
- **Glass fibre reinforced polyester (GRP):** Lightweight composite material for flexible pipes and internal tank components.
- **Borosilicate:** Special glass for building explosion-proof windows in storage buildings.

These materials therefore provide good mechanical strength and protection against hydrogen corrosion in its various physical forms and storage conditions.

Here are some other important points about materials for hydrogen storage facilities:

- In addition to corrosion resistance, it is essential that the materials are compatible with the low temperatures of liquid hydrogen, which can reach **-250°C**.
- Carbon steel is not recommended due to its greater susceptibility to hydrogen fracture. It can be used in complementary structures, but requires additional protection.

- Joints and connections also deserve attention, as they are critical leakage points. Stainless steel welds or ultrasonic beams in composites are preferable.
- Underground tanks generally use steel with cathodic protection to prevent corrosion. There are also specialised coatings.
- Galvanic compatibility between materials is essential to avoid corrosion by dissimilar pairs at the interfaces.
- Common plastic materials are not suitable as they can absorb hydrogen and become brittle.
- **ASME, NFPA** and **ISO** standards define minimum stress resistance parameters, permeability, and inspection requirements for each material.

Therefore, in addition to intrinsic strength, other construction aspects such as joints and corrosion protection also deserve attention in the design.

There are alternative materials under development that may be more suitable for the construction of hydrogen storage facilities.

Some alternative materials in the research and development stage that may become more suitable for building hydrogen storage facilities in the future:

- **Carbon nanotubes:** These can be used to reinforce composites, increasing mechanical strength, and reducing hydrogen permeability.
- **Advanced metal alloys:** Such as magnesium and aluminium alloys, which tend to be lighter and stronger than the steels currently used.
- **Functionalised ceramics:** With improved barrier properties against hydrogen permeation through surface engineering.
- **Intelligent polymers:** Capable of self-healing in the event of micro-cracks, preventing leaks. An example is functionalized polyolef.
- **Polymer nanocomposites:** For example, resins reinforced with graphene nanocargo or graphene oxide, providing greater mechanical strength.
- **High-performance fabrics:** Such as laser-produced high-modulus fabrics for use in lightweight fabric-covered tanks.

However, these materials still require more research before they can be adopted commercially. They could represent significant gains in safety and costs in the future.

2.2. THE IMPORTANCE OF AN ADEQUATE VENTILATION SYSTEM IN HYDROGEN STORAGE FACILITIES

Due to its high flammability potential, the presence of hydrogen gas requires efficient ventilation systems to ensure the safety of storage facilities.

Ventilation design must take into account factors such as the total hydrogen storage capacity of the tanks, the geography of the site and the construction characteristics of the building.

The system must be able to renew the ambient air to adequate levels in short periods of time. This is essential to quickly dilute any leaks and prevent the build-up of flammable concentrations that could pose a risk of explosion.

In addition, it must be sized to ensure rapid flows of the gas towards the outside in the event of the involuntary release of large volumes, so as to prevent it from spreading throughout the area.

It is also important to consider the installation of ducts, diffusers and registers that allow localised control of air circulation in the areas most at risk, such as near tanks.

Treatment plants can be added to the system to purify the air and remove traces of the gas before it is exhausted into the atmosphere.

Therefore, a well-dimensioned design guarantees rapid and efficient air renewal, which is fundamental to safety in hydrogen storage facilities.

2.2.1. What are the main requirements for an efficient ventilation system in hydrogen storage facilities?

The main requirements for an efficient ventilation system in hydrogen storage facilities include:

- Adequate air renewal rate, capable of quickly and effectively diluting and dispersing any leaks to below the Flammability Limits.
- Sizing with a safety margin, taking into account maximum instantaneous leakage volumes.
- Control and monitoring of air quality, with gas sensors at different points.
- Exhaust fans of sufficient number and power to meet specified air flows.
- Leak detection and alarm system.
- Ventilation ducts and grilles made of explosion-proof materials.
- Dampers and control valves in the duct network.
- Periodic maintenance to guarantee continuous performance.
- Recapture system with filters in case of toxic fumes.
- Monitoring of ventilation parameters (pressure, flows, etc).
- Protection against ignition sources entering the ducts.

The main safety criteria for the ventilation system in hydrogen storage facilities include:

- Being located in a safe area, away from possible leaks or ignition sources.
- Use explosion-proof ducts made of hydrogen-compatible materials.
- Protection against lightning and atmospheric discharges.
- Avoid the formation of bubbles or accumulation of gas in the ducts.
- Allow laminar and continuous air flow, without turbulence or dead zones.
- Have an alarm and detection system for ventilation deficiencies.
- Provide safe access for regular maintenance and cleaning of the ducts.
- Have more than one exhaust fan, with redundant equipment.
- Have filters and air treatment capable of removing traces of gas.
- Be monitored and have parameters controlled remotely.
- Be protected against obstructions in the ducts that could jeopardise the flow.
- Comply with specific standards and legislation for ATM systems.

The main standards and legislation that regulate ventilation systems in hydrogen storage facilities are:

- **NFPA 2 (USA):** Safety code for gaseous fuel buildings and compressed air systems. Defines requirements for ventilation.
- **OSHA (USA):** Department of Labour regulations on ventilation in industrial environments.
- **IBC Code (USA)**: International Building Code, establishes ventilation sizing rules.
- **NFPA 55 (USA):** Standard focused on the storage, distribution, and commercial use of composite gases.
- **ISO 19880 (international)**: Part 1 and 2 specify ventilation requirements for mobile and stationary tanks.
- **ASME B31.12 (USA):** Code for hydraulic pipeline systems, includes section on H2.
- Local environmental legislation: Such as gas emissions and treatment of effluents from the system.
- **Fire brigade requirements:** Fire brigades may require ventilation system designs.

A few additional points on standards and ventilation systems in hydrogen storage facilities:

- Standards define parameters such as minimum air renewal rate (5x/h usually), flows in ducts and exhausts.
- Manuals such as the **Waterstof Platform (NL) and the Hydrogen Ventilation guide (UK)** should be followed.
- Ventilation projects must be approved by safety regulatory bodies.
- Requirements vary according to the risk class of the installation and the quantity stored.
- In fixed tanks, ventilation is natural. In mobile tanks, it needs to be forced by exhaust fans.

- Continuous monitoring of parameters is a growing requirement for early detection of problems.
- There are specific training courses for designers and operators of **H2** ventilation systems.
- Computer simulation technologies are already being used to model and optimise projects.
- Integration with other systems such as gas detection is essential to improve safety.

2.3. THE IMPORTANCE OF PREVENTING LEAKS AND DETECTING HYDROGEN IN STORAGE FACILITIES

Maintaining the tightness of hydrogen storage systems is essential to guaranteeing the safety of the installations.

To this end, designs must specify reliable components such as valves, fittings, and tank joints capable of withstanding high pressures over time. The use of suitable materials and controlled manufacturing processes is essential.

In addition, periodic preventive inspections must be carried out to diagnose and correct early signs of degradation. This scheduled maintenance prevents small defects from turning into significant leaks.

On the other hand, strategically distributed detection systems help to constantly monitor the presence of the gas. Sensors capable of detecting low concentrations ensure that alarms are triggered quickly if hydrogen is released.

This makes it possible to isolate the affected area and activate the ventilation system to dilute the gas before it reaches dangerous levels.

Therefore, maintaining the tightness of equipment combined with the early detection of leaks is fundamental to avoiding accidents in hydrogen storage facilities.

There are different technologies used in gas detection systems to monitor the presence of hydrogen in storage facilities:

- **Thermal conduction detectors** identify hydrogen by altering the sensor's ability to dissipate heat when exposed to the gas.
- **Catalytic detectors** take advantage of hydrogen's property of burning when in contact with catalytic metals, generating a detectable temperature increase.
- **Ionisation systems** use radioactive sources to ionise the air and create an electric field. Changes caused by hydrogen are identified.
- **Mass spectrometers** are more precise, separating molecules by mass-to-charge ratio and quantifying the concentration levels of each gas.
- **Wireless sensors** allow continuous monitoring at various points, with alarms triggered remotely.

They are usually installed in ducts, ventilation ducts, near valves and joints or inside tanks. Combining different technologies in the same system increases the reliability of leak detection.

2.3.1 What are the advantages and disadvantages of each of these gas detection technologies?

Some advantages and disadvantages of the main gas detection technologies:

Thermoresistance:

- Advantage: Simple, cheap, sensitive.
- Disadvantage: Can be affected by dust, humidity.

Catalytic:

- Advantage: Sensitive, fast, stable.
- Disadvantage: Can weaken over time, interfering gases.

Ionisation:

- Advantage: High sensitivity, long service life.
- Disadvantage: More expensive, can be affected by dust and humidity.

Mass spectrometry:

- Advantage: Extremely sensitive and precise, identifies gases.
- Disadvantage: Very expensive, complex, requires calibration.

Wireless:

- Advantage: Facilitates coverage of large areas, no wiring.
- Disadvantage: Batteries limit operating time, transmission may fail.

Hydrogen detection technologies can be integrated into automation systems as follows:

- Catalytic, thermoresistive and ionisation detectors can be installed at strategic points such as tanks, pipes, and ventilation ducts. These detectors transmit **4-20mA** analogue or digital signals to programmable logic controllers (PLCs) or supervisory control and data acquisition (SCADA) systems.
- In the PLC or SCADA, the detected hydrogen levels are monitored, and responses are programmed in the event of a leak, such as triggering alarms and automatically closing valves.

- Field communication: Wireless (WirelessHART, Bluetooth etc) or wired (Fieldbus, Modbus) protocols for transmitting data.
- Industrial communication protocols such as Fieldbus, Modbus, Profibus can be used to integrate the detectors into the automation system.
- Wireless detectors can transmit data to gateways and thus be supervised remotely.
- SIS (Safety Instrumented Systems) systems can be triggered in the event of high gas levels, stopping processes safely.
- Historical data collected by the system enables trend detection and preventive maintenance.

The main challenges in implementing hydrogen detection technologies in automation systems are:

- Interference from other gases such as carbon monoxide which can mask the presence of hydrogen.
- Difficulty in detecting small concentrations of the gas, close to flammability limits.
- Analogue or digital signal failures during data transmission from the detectors.
- Electrical compatibility between field devices and I&C equipment in **4-20mA** transmission.
- Integration between existing automation systems.
- Reconciliation of different industrial communication protocols.
- Availability and reliability of detectors in harsh environments such as high pressures and temperatures.
- Adequate preventive maintenance to guarantee the detectors' long-term performance.
- Correct interpretation of measured concentration levels to trigger safe responses.
- Confirmation of leaks by cross-referencing data from multiple detectors.

2.4. REQUIREMENTS FOR EXPLOSION-PROOF EQUIPMENT

In hydrogen storage and handling facilities, equipment presents in areas where gas can accumulate needs to meet strict construction requirements to prevent incidents from occurring. It is necessary to map the zones classified according to the expected concentration of gas, defining classes/zones as **0**, **1** or **2**.

Many items, such as electrical panels, motors and measuring instruments, must be certified for use in classified locations where there is a risk of explosive atmospheres. This explosion-proof equipment, known by the acronym **Ex**, has a specific design capable of preventing sparks or hot spots that could ignite hydrogen.

Explosion-proof means that the internal components are adequately insulated and ventilated to dissipate the heat generated, while the outer casing is sealed to prevent possible gas or dust leaks. This greatly reduces the risk of occurrences such as explosions or fires.

By following standards such as **NFPA 55**, **IEC 60079-10-2** and other applicable codes, it is possible to correctly size hazardous areas and specify compatible Ex equipment according to the class and risk zone present in each sector of the installation. This guarantees the safety of people and assets on site.

2.4.1. What are the main requirements for explosion-proof equipment used in hydrogen storage facilities?

The main requirements for explosion-proof equipment in hydrogen storage facilities include:

- Certification according to standards such as **ATEX, IECEx** or **NEMA**, certifying that the design is explosion safe.
- Ex marking with group, **category,** and zone of use, according to the hazardous area where it will be installed.
- Robust construction in hydrogen-inert materials such as stainless steel or aluminium.
- Watertight housing that prevents the entry of gases, dust, or liquids.
- Internal ventilation to dissipate heat generated by electrical/electronic components.
- Low emission of sparks, sparks, or surface temperatures capable of igniting the gas.
- Assembly of internal components to avoid contact with moving parts or spikes.
- Properly sealed cable inlets and outlets.
- Periodic maintenance and recording of the integrity of seals and gaskets to ensure gas-tight protection.
- Conditions for pressure testing and sealing when installing or repairing.

2.4.2. What are the most commonly used materials in the construction of explosion-proof equipment for hydrogen storage?

The materials most commonly used in the construction of explosion-proof equipment for hydrogen storage are:

- **Stainless steel**: corrosion-resistant alloy with low spark emission. 316 and 304 stainless steels are well suited.
- **Aluminium**: Lightweight and corrosion-resistant, good thermal conductor for heat dissipation. Requires corrosion protection in some environments.
- **Copper**: Excellent thermal and electrical conductor. Sensitive to corrosion and more expensive than steel and aluminium.
- **Bronzes**: Alloy of copper and tin, with high mechanical and corrosion resistance.
- **Brass**: Similar to bronzes, adding zinc to the alloy forms a protective layer.
- **Glass fibre reinforced polyester**: Lightweight composite material for housings, resistant to corrosion.
- **Elastomers**: Special rubbers for joints and seals, hydrogen-resistant and flexible.
- **Plastics**: Little used in internal layers but can make up external coatings.

The material is selected according to the chemical and physical conditions of the process and installation area.

There are other materials besides those mentioned above that are also frequently used in the construction of explosion-proof equipment:

- **Carbon steel:** A more economical alloy than stainless steel, but less resistant to corrosion. Can be used in non-aggressive environments.
- **Titanium:** Very resistant, light and chemically inert metal. However, it is expensive, which limits its use.
- **Nickel:** Highly resistant to corrosion, it is used in alloys such as Inconel and Hastelloy. However, it is also expensive.
- **Terpolymers:** Group of fibre-reinforced plastics, such as Kevlar, which provide mechanical resistance without the risk of sparks.
- **Graphite:** Conductive material used in O-rings and seals that require dry lubrication.
- **Ceramics:** Such as zirconia and alumina, for components that need to withstand high temperatures.
- **Carbon fibre:** Used in the lining of small equipment to dissipate static loads.

2.4.2.1. What are the advantages of using terpolymers in explosion-proof equipment?

The main benefits of using **terpolymers** in the manufacture of explosion-proof equipment include:

- **Mechanical resistance:** Terpolymers reinforced with fibres such as Kevlar provide superior resistance to impacts and loads.
- **No sparks:** Unlike metals, they do not emit sparks under impact or friction, eliminating the risk of ignition.
- **Lightweight:** Composite materials are lighter than metals such as steel or aluminium, making them easier to handle.
- **Cushioning:** They absorb vibrations and shocks, protecting fragile internal components.
- **Insulation:** They perform well as electrical and thermal insulators.
- **Durability:** They age well, maintaining their mechanical properties for long periods.
- **Chemical resistance:** They are stable in contact with many chemical products and environmental agents.
- **Cost:** Although higher than ordinary plastics, they are affordable compared to metals such as nickel.
- **Safety laws:** Their use in Ex equipment complies with regulations that prohibit the use of ferrous or conductive materials.

This allows them to be used in a variety of applications with strict safety requirements.

Some of the main industrial applications that benefit from the use of reinforced **terpolymers** in explosion-proof equipment are:

- Storage and transport of combustible gases such as hydrogen, natural gas, and LPG. Lightweight and resistant equipment in installations.
- Oil refineries. Components for areas at risk of hydrocarbon leaks.
- Chemical and petrochemical industry. Robust equipment in corrosive areas with solvents and reagents.
- Steel and metallurgical plants. Parts for areas subject to explosive metal dust.
- Industrial laundries. Laundry machinery for sites with suspended organic dust.
- Mining. Resistant equipment for processing ores and powdery substances.
- Fuel cell factories. Lightweight, non-conductive components in hydrogen power generation.
- Clean rooms and laboratories. Laboratory equipment in places with volatile solvent residues.

The mechanical performance and intrinsic safety of **terpolymers** make them ideal for many hazardous industrial environments.

3. FIRE SAFETY MEASURES

3.1. SUITABLE FIRE SUPPRESSION SYSTEMS

Install sprinklers (automatic showers) or another fire suppression gas system (**CO2**, **halon gas**, etc.), designed in accordance with **NFPA 55**, **FM**, **UL** standards, etc. This includes hydraulic sizing and defining the spacing and types of sprinklers according to the estimated fire loads. The sprinklers installed must be of the hydrogen-resistant type, made from materials such as stainless steel or plastic. Continuous monitoring of sprinkler conditions through automated supervision systems is recommended. The design must take into account the pressure and water flow required to control fires involving large quantities of hydrogen.

Carry out a detailed study to determine the appropriate sprinkler coverage in all risk areas, taking into account variables such as room heights, obstructed ceilings, places where gases or dust may accumulate, etc.

Install certified smoke and flame detectors in strategic locations such as hydrogen ducts, compressor rooms and control panels, ensuring effective detection coverage.

Keep dry chemical powder fire extinguishers of a type compatible with gaseous fuels in easily accessible and visible locations in the vicinity of possible ignition sources.

Carry out scheduled preventive maintenance on sprinklers and replace them every **5-10 years**, as recommended by the manufacturer, to ensure full operation in the event of an accident.

The main challenges in implementing fire suppression systems in hydrogen storage facilities include:

- Sizing to control fires involving large quantities of hydrogen, which disperses quickly and can recombine in secondary flames.
- Use of hydrogen-compatible materials in pipes, sprinklers and other exposed components that do not cause sparks or corrosion.
- Early detection of the presence of hydrogen, as it diffuses quickly and forms atmospheres that are not visible.
- Design for different tank configurations and gas storage and supply systems.
- Operation in the wide pressure and temperature ranges in which hydrogen can be handled.
- Integration with other safety and leak detection systems in the installation.
- Brigade training to deal with the risks associated with hydrogen, such as flammability over a wide range of concentrations.
- Preventive maintenance considering the corrosiveness of the environment in the presence of the gas.

There are a number of alternatives to conventional sprinkler systems that can be used to suppress fires in hydrogen storage facilities:

- **Inert gas systems**: Pipe networks with **CO2** or **Argon** that can be activated in a localised or general way to reduce the oxygen content in the environment.
- **Dry chemical powder systems**: Use class D powder extinguishers directed by hoses or robots to safely extinguish ignition sources.
- **Foam system**: Flame-retardant foam can be projected by cannons or launchers through ducts close to possible fire outbreaks.
- **Mixed system**: Intelligent combination of sprinklers in specific areas with flame detection coupled with automatic inert gas release for large areas.
- **Immersion system**: underground tanks or protected chambers that can be quickly flooded in the event of an emergency.
- **Early detection and automatically activated valves**: To isolate sectors and reduce available fuel before the fire spreads.

The choice depends on the characteristics of the installation and the risks identified in the fire safety project.

3.1.1. Are there any specific regulations for fire suppression in hydrogen storage facilities?

There are important standards and regulations that specifically address the requirements for fire suppression systems in hydrogen storage and utilisation facilities:

- **NFPA 2 (USA):** Fire Code for Gaseous Fuel Facilities and Hydrogen Storage Systems.
- **NFPA 55 (USA):** Code for compressed, liquefied and cryogenic combustible gas storage systems.
- **NFPA 850 (USA):** Recommendations for safe hydrogen storage, use and handling facilities.

- **ISO/TC 197:** Series of standards dealing with the safe storage, transfer, and utilisation of hydrogen.
- **IEC 60079-10-1 (IEC):** Requirements for the design, inspection, and maintenance of electrical equipment in hazardous locations.
- **ABNT NBR 13777 (Brazil):** Design and installation of hydrogen and biodiesel equipment.
- **EN 14470-1 (Europe):** Requirements for automatic fire suppression sprinkler systems. Defines risk classes and technical specifications.
- **EN 15004 (Europe):** Design, installation, inspection, and maintenance of fixed gas fire suppression systems. Details requirements for **CO2**, **Argon** and other inert gases.
- **AS 5149.1 (Australia/New Zealand):** Requirements for the design, installation, and maintenance of fixed fire extinguishing gas systems.
- **NFPA 2001 (USA):** Fire protection standards for fuelled vehicle transport systems.
- **ISO 14520 (International):** General requirements for the design, selection, installation, and maintenance of fixed fire extinguishing gas systems.
- **EN 12845 (Europe):** Automatic sprinkler systems for fire protection. Requirements and recommendations for design, installation, and maintenance.

3.2. FIREFIGHTING TRAINING

- Train all employees in the correct use of emergency equipment, such as fire extinguishers, breathing masks and personal protective clothing. This should include regular practical training.
- Train procedures for evacuating the affected area and incipient firefighting, taking advantage of its early stages. It is important to rehearse escape routes and meeting points.
- Simulate different hypothetical accident and emergency scenarios every year to test the effectiveness of the company's response plan. Evaluate possible points for improvement.
- Ensure a permanent team of in-house firefighters who are properly certified and regularly trained to act in the first few minutes of an accident, with appropriate equipment.
- Training should review protocols for action and provide for situations such as hydrogen leaks, fires in confined areas and activation of sprinklers or remote suppression systems.

The main emergency equipment that employees of hydrogen storage facilities should know how to use correctly after training include:

- **Class D fire extinguishers -** For use in the initial fight against hydrogen fires.
- Respiratory masks - Protection in the event of leaks or contaminated environments. Must be seal-tested.
- **Full protective clothing -** Protective equipment for firefighters in higher risk scenarios.
- **Portable gas detectors -** For quickly mapping leaks or checking the composition of gas bubbles.

- **Signalling equipment -** Cones, siding, and reflective signs to isolate areas until they are cleared.
- **Leak sealing kit -** For emergency use of hoses, tapes, and foams to contain leaks.
- **Hoses and equipment for use with CO2 -** For remote activation of inert gas suppression systems.
- **Emergency telephones and alarms -** Rapid communication in the event of accidents in the installation.

The main risks associated with handling emergency equipment in hydrogen storage facilities include:

- Lack of familiarity with the equipment, which can lead to it being used incorrectly and unsafe.
- Use of unsuitable equipment or equipment in a poor state of repair, making it less effective in an emergency.
- Electrostatic discharges generated by contact or friction with certain materials, which can cause ignitions.
- Limitations on the use of equipment in environments with dangerous concentrations of hydrogen or other toxic substances.
- Failures in the sealing and protection offered by masks and clothing, exposing the user to risks.
- Ergonomic risks associated with weight, balance, and mobility with full protective equipment.
- Communication difficulties between teams in poorly visible or noisy environments.
- Lack of coordination between firefighters, which can aggravate the emergency scenario.

Therefore, specific training to deal with these risks systematically and safely is crucial.

3.3. EMERGENCY PROCEDURES IN THE EVENT OF FIRE

- Immediately activate the sound and light alarm of the fire protection network, setting off the warning signal for the entire installation.
- Contact the Emergency Brigade by telephone or radio, giving details of the nature, exact location, and apparent characteristics of the incident (smoke, flames, crackling, etc.).
- If it is safe and you have the skills, you can start fighting the fire using hoses and portable class D extinguishers, following a safe use procedure and away from the source of ignition.
- Otherwise, isolate the area in accordance with emergency signs and training, switching off non-essential electrical or mechanical equipment and installations to prevent spread.
- Wait for instructions from the fire brigade by tuning into a radio/communicator channel or outside the building at a predefined meeting point.
- Only return to the incident area after authorisation from the fire brigade and checking that there is no longer any danger, receiving information about the damage and repair/standardisation procedures.

The main firefighting techniques currently used include:

- **Direct attack:** Direct application of water, foam, or extinguishing agent directly on the fire, preferably in the early stages.
- **Indirect attack:** Use of jets to cool the hot zone above the fire and create a firebreak, preventing spread.
- **Aftermath:** Application of foam or powder to cool and completely isolate the area, preventing re-ignition.
- **Controlled ventilation:** Occasional opening of windows/doors to safely remove smoke and toxic gases.
- **Flank technique:** Attack the lateral edges of the fire, preventing it from spreading beyond the initial area.
- **Pincer technique:** Two simultaneous attacks on the flank and in front of the fire to surround it.
- **Trench technique:** Forming a wet channel around the fire, releasing water in a V-shape.
- **Thermal monitoring:** Special cameras identify residual heat spots after the fight.

Training and making the most of the terrain are fundamental to efficiently applying these modern extinguishing techniques.

The main firefighting techniques involving **hydrogen** are:

- Use of class D dry chemical powder extinguishers, which form an insulating layer over the hydrogen, depriving it of oxygen.
- Targeted application of inert gases such as carbon dioxide or Argon to quickly reduce the O2 concentration below the lower flammable limit of hydrogen.
- Cooling by irradiation with water jets or aqueous solution with additives, lowering the temperature of the zone to below the ignition point of the gas, in conjunction with the application of thermal inertisation.
- Blocking the flow of hydrogen to the burning area, using physical barriers such as rapid containment or foam-expanding materials.
- Thermal isolation of the original heat source that triggered the hydrogen explosion or ignition, prioritising removal of the cause.
- Controlled ventilation to dilute and disperse the flammable gas cloud away from the hot zone, preventing re-ignition.
- Constant post-fire monitoring to identify any remaining outbreaks or accumulation of pockets of hydrogen that are still flammable.
- Fully enclosed protective clothing with its own air supply (**SCBA - Self Contained Breathing Apparatus**).
- Portable and fixed gas detectors for constant monitoring of H2 levels and toxic substances.
- Rapid barriers and containments to isolate the area and block the flow of gas.
- Strict coordination and communication protocols between firefighting teams.
- Extended post-fire monitoring with infrared and remote detection of **H2** pockets.

The main risks associated with fighting fires involving hydrogen include:

- Formation of pockets or clouds of flammable hydrogen that can ignite again.
- Explosions if the gas accumulates in concentrations of **4-75%** in the air in confined environments.
- Contamination through inhalation of toxic gases from hydrogen combustion, such as nitrogen oxide.
- Burns from contact with equipment or surfaces heated to high temperatures.
- Static electrical discharges capable of causing new ignitions in the gas.
- Fractures or leaks in tanks under high pressure from the heat of the fire.
- Difficulty in detecting hydrogen leaks, as it is colourless and dissipates quickly.
- Lack of visibility due to dense smoke, especially from burning plastic components.
- Ergonomic risks of protective equipment in hot, low-visibility environments.

3.3.1. What are the recommended safety procedures when fighting hydrogen fires?

Here are some of the main safety procedures recommended for fighting fires involving hydrogen:

- Use appropriate personal protective equipment (PPE) such as waterproof clothing, boots, gloves, goggles and breathing masks.
- Work in teams, with at least one member on standby outside the risk zone to provide assistance.
- Assess risks before taking any action, monitoring hydrogen levels, temperature, and toxic gas concentrations.
- Prioritise control techniques that allow a safe distance from the fire, such as remote application of inert gases.
- Respect fences and signs to isolate the incident area.
- Maintain constant communication with other firefighters and support bases by radio or mobile phone.
- Act in a methodical and coordinated manner, following pre-established protocols.
- Withdraw immediately if loss of PPE, sudden increase in risk or collapse of facilities is detected.
- Carry out a prolonged aftermath, monitoring residual outbreaks for at least 24 hours after the incident.

The main personal protective equipment (PPE) recommended for fighting fires involving hydrogen includes:

- Respiratory mask with pressurised air supply (SCBA): Protects the airways against inhalation of toxic gases.
- Fully sealed and waterproof chemical protective clothing: Insulates the body from thermal radiation and protects against burns.

- Waterproof safety boots: Prevent accidents from sharp objects and protect feet from chemical splashes.
- Leather or nitrile gloves: Resist heat and provide electrical insulation, protecting the hands.
- Safety glasses or face shield: Shield eyes and face from splashes, embers, and radiation.
- Equipment belt: Secures secondary items such as torches, gas detectors and whistles.
- Communication devices: Radios or headsets are essential for verbal contact between brigades.
- Personal alarm: An acoustic device triggers a distress signal if the firefighter remains motionless.

The main procedures to be carried out for the aftermath of a fire in hydrogen installations are:

- Controlled ventilation of the area to completely disperse the gas, ensuring safe levels before the aftermath.
- Constant monitoring with portable gas detectors to check for concentrations of hydrogen, monoxide, and carbon dioxide.
- Cooling down the structures and equipment affected by the fire, to prevent re-ignition. This can be done with water jets, foams, or powders.
- Applying an insulating covering to hot surfaces, such as sand, powders, or special foams. This ensures controlled cooling.
- Methodical inspection of the entire affected area with thermal cameras or other residual heat detectors.
- Isolation of the scene for a minimum of 24 hours after the aftermath, with constant monitoring.
- Interaction with the technical team to assess the equipment and report on the possibility of returning to operation.
- Detailed reports on damage, causes, procedures adopted, and lessons learnt to improve future protocols.

Safe aftermath requires special care due to the risks of reignition with hydrogen.

The main risks associated with the aftermath of fires in hydrogen installations include:

- Presence of pockets or invisible accumulations of still-flammable hydrogen inside structures.
- Dangerous levels of monoxide and carbon dioxide due to incomplete aftermath of materials.
- Heated internal surfaces that can cause new explosions or re-ignitions.
- Weakened structures at risk of collapse during procedures.
- Damaged equipment that may leak hydrogen inadvertently.
- Pressure escaping from tanks when they are abruptly cooled.
- Electrical risks from exposed cables and wiring damaged by fire.

- Fatigue or inhalation of toxic fumes due to long exposure of firefighters.
- Ventilation failures that leave pockets of stale or flammable air.
- Accidents due to falls on slippery floors or incorrect use of PPE.

The aftermath therefore requires maximum precautions to ensure the safety of the teams.

3.4. MAIN CHALLENGES ASSOCIATED WITH HYDROGEN STORAGE IN HAZARDOUS AREAS

One of the main challenges faced is preventing and containing hydrogen leaks. This substance is extremely light and can quickly diffuse into structures. To deal with this, it is crucial to use resilient tanks and pipework, with leak-proof joints and systems for constantly monitoring the integrity of the systems. Accurate leak detection is key to ensuring safety by preventing the uncontrolled release of gas.

In leak situations, rapid dispersal or confinement of the hydrogen is essential to avoid the formation of explosive atmospheres. The accumulation of the gas in enclosed spaces must be avoided, as this can lead to explosions. To do this, it is essential to have specific training in emergency scenarios and the implementation of automated fire detection and suppression systems. In this way, any ignition can be extinguished immediately, and the large-scale spread of hydrogen prevented.

Another important point is the access and operation of the Emergency Brigade. Buildings designed for classified areas must follow safety specifications, including containment zones and protection against deflagrations. The brigade needs to be familiarised with the facilities and personal protective equipment suitable for operating in these controlled, high-risk environments. The ability to respond quickly and efficiently is essential to minimise damage in the event of incidents.

In addition, it is essential to invest in continuous training, addressing the particularities of hydrogen as an extremely flammable substance in different conditions. With each simulated or real incident that takes place, it is important to incorporate new techniques and learnings to improve safety and response capacity.

By tackling these challenges, it is possible to ensure a safer and more secure hazardous area hydrogen storage environment. Awareness, proper training, and the adoption of preventive measures are essential to mitigate the risks associated with storing this highly flammable substance.

The challenges associated with storing hydrogen in hazardous areas:

- **Detecting subtle leaks:** Hydrogen is colourless and diffuses quickly, making it challenging to detect beforehand. A sensitive system with multiple measuring points is required.
- **Managing explosive zones:** Zones classified according to their potential for forming explosive atmospheres must be strictly defined and monitored in accordance with standards such as **NFPA 495**.

- **Controlled ventilation:** Air renewal systems need to be designed to prevent accumulations of gases and keep zones within safety limits, even if there is a leak.
- **Isolation of ignition sources:** It is essential to map and isolate all points capable of causing a spark or thermal spark within hazardous areas.
- **Safety signs:** Signs, colours, clear demarcations and constant training help prevent risks during maintenance or emergency operations.
- **Active monitoring:** Fixed detectors combined with check rounds are needed to monitor conditions in real time.
- **Containment of leaks:** Containment bars, tunnels or galleries prevent the spread of gas outside the designed zones.
- **Explosion resistance:** Buildings, pipework and tanks need to withstand shock waves within controlled levels.

Systemic management and engineering precautions are essential to meet these challenges. These challenges require careful approaches to the design, maintenance, and operation of hydrogen storage facilities, as well as compliance with specific safety regulations and guidelines to ensure adequate protection.

4. PREVENTIVE MAINTENANCE AND REGULAR INSPECTIONS

4.1 IMPORTANCE OF REGULAR MAINTENANCE

Scheduled maintenance of equipment is essential to ensure that it functions correctly and to identify possible damage or early wear. Following preventive replacement schedules for components such as gaskets, sensors and valves helps to avoid failures and leaks. This regular maintenance contributes to the safety of hydrogen storage in hazardous areas, minimising the associated risks. By carrying out thorough periodic inspections, it is possible to detect small abnormalities that, when neglected, can lead to accidents.

4.2 SAFETY INSPECTIONS AND EQUIPMENT TESTS

In-depth inspections must be carried out periodically by specially trained and qualified personnel. These inspections are essential to ensure the safety of hydrogen storage in hazardous areas.

During the inspections, rigorous tests are conducted on the control, monitoring, detection, and emergency response systems. The tests cover leak detection methods, alarm systems, sprinklers, inertisation, emergency lighting and escape routes.

It is essential to guarantee the accuracy and sensitivity of all fixed and portable sensors, as they provide crucial information about the presence of leaks or dangerous concentrations of hydrogen. The proper calibration of sensors is crucial to ensure that alarms are triggered at the right time, allowing for a quick and effective response by the emergency team.

In addition, during inspections, controlled simulations are carried out of various critical scenarios, such as leaks at different points and fires in storage areas. These simulations help validate the efficiency of active protections, such as fire suppression systems and emergency ventilation.

The effectiveness of the emergency plan is also checked, such as the response time of the teams, the flow of communications and the compliance of escape routes and meeting points. It is important to ensure that all safety measures are in perfect condition and ready to be activated in the event of a real incident.

These periodic tests are fundamental to identifying possible flaws in the systems and continually improving safety procedures, contributing to the safe storage of hydrogen.

4.3. CONTINUOUS MONITORING OF THE SECURITY SYSTEM

Using advanced technologies such as smart sensors, the Internet of Things, cloud computing and artificial intelligence, it is possible to monitor critical equipment parameters online in real time. This makes it possible to identify corrective or preventive maintenance needs in advance, detect small variations in patterns that may indicate premature wear and constantly monitor the performance of detection and emergency response systems. The use of machine learning algorithms allows AI to self-monitor the system, learning its normal operating patterns and warning of possible deviations or incipient failures.

4.3.1 Some examples of technologies that can be used for online monitoring of equipment parameters in hydrogen storage systems:

- **Sensors and IoT devices -** Sensors installed in the equipment measure parameters such as pressure, temperature, flow, leaks, etc. and transmit the data wirelessly via IoT.
- **Cloud platforms -** Sensor data is stored, viewed, and analysed on cloud-based monitoring platforms for 24-hour remote supervision.
- **Machine learning algorithms -** ML models can detect abnormal patterns, predict failures, and help determine maintenance needs.
- **Computer vision technologies -** CCTV cameras equipped with image recognition software visually monitor equipment for defects or problems.
- **Drones -** Drones with thermal cameras and sensors periodically inspect facilities for possible problem areas.
- **Process historians -** Systems capture plant hierarchies, process flows and historical data markings for recording and analysis.
- **Supervised control systems** - SCADA/DCS interact remotely with equipment controls and trigger alerts for parameter deviations.
- **Analytical dashboards -** Intuitive dashboards present KPIs, live data trends and exceptions to operators on mobile/desktop devices.

Real-time monitoring using these technologies enables early detection of anomalies for proactive maintenance and improved safety.

4.3.2. What are the main advantages of online monitoring of equipment parameters in hydrogen storage systems?

The main advantages of online monitoring of equipment parameters in hydrogen storage systems are:

- **Early detection of faults or deviations:** Allows problems to be identified early before they cause major damage.
- **Predictive maintenance:** It makes it possible to programme maintenance predictively, based on monitored wear and tear trends.
- **Improved safety:** A system that is always supervised presents fewer risks, as any faults are quickly detected.
- **Operational availability:** With constant monitoring, equipment works with greater uptime and there are fewer unscheduled stops.
- **Performance analysis:** Using the data collected, it is possible to analyse energy efficiency and points for performance improvement.
- **Decision-making support:** Real-time information supports better decisions by the operations team.
- **Reduced costs:** Reduces the cost of corrective and unforeseen maintenance, favouring preventive maintenance.
- **Compliance:** Monitored systems easily meet regulatory safety and inspection requirements.

Online monitoring therefore provides greater efficiency, availability, and safety in operation.

5. EMPLOYEE TRAINING AND AWARENESS

5.1 TRAINING AND CAPACITY BUILDING

In addition to comprehensive initial training on the properties of hydrogen and the risks inherent in its storage, it is crucial that the teams directly involved in the safe storage and handling of this high fuel undergo constant training updates.

This includes the use of modern, immersive resources such as virtualised simulations in virtual and augmented reality. In these simulations, various critical scenarios related to hydrogen operations can be replicated in an extremely realistic way, such as emergencies due to leaks, fires in pressurised tanks, failures in detection systems, among others.

These trainings, when well-designed and conducted by specialised instructors, help ensure that the safety standards and protocols implemented in storage facilities are always reviewed and improved in the light of experience. They also ensure that all professionals involved in the chain are fully trained and able to respond practically, quickly, and effectively to any emergency situation or accident that may occur on site.

The training and qualification of workers to work in explosion-risk environments involves different aspects:

- Theoretical training on the properties of flammable gases and vapours, explosion phenomena, classified zones, and requirements for explosion-proof equipment.
- Practical training in safe working procedures, such as energy isolation, sealing tanks, use and testing of certified equipment, measures in the event of an emergency.
- Simulations of risk situations to consolidate concepts and train responses.
- Theoretical and practical exams to prove learning.
- Issuance of certificates with defined validity, requiring periodic retraining.
- Recording in the worker's single document of qualification for an explosion-risk environment.
- Only duly qualified technicians can carry out services on Ex equipment, such as maintenance, repairs, and modifications.

Training is conducted by professionals certified by specialised bodies, following programmes approved by the regulatory bodies in the area.

Safety in hydrogen operations depends crucially on the continuous preparation of teams through realistic and immersive training.

5.2. What modern resources are used in virtual and augmented reality training?

The main modern resources that can be used in virtual and augmented reality training for the safe storage of hydrogen include:

- **VR goggles and helmets**: allowing users to visualise realistic scenarios in an immersive way.
- **Haptic controls**: providing tactile feedback, such as resistance in valves or vibrations in the event of faults.
- **Virtual object handling**: realistically simulating maintenance and emergency operations.
- **Markers or cameras**: for body tracking and gesture recognition in augmented reality.
- **Interactive holograms**: representing equipment and systems dynamically in the environment.
- **Virtual triggers**: activating events such as alarms, leaks, or fires during the simulation.
- **Physiological monitoring**: measuring user responses such as heart rate during stressful scenarios.
- **Metrics recording**: evaluating parameters such as reaction time and performance during training.
- **Mixed reality**: combining real and virtual elements for greater training fidelity.

The adoption of these modern resources makes it possible to simulate complex scenarios in a dynamic way, guaranteeing immersive learning and the adequate preparation of teams.

5.3. SAFE WORKING PROCEDURES AND RECOMMENDED PRACTICES FOR HAZARDOUS AREAS WITH HYDROGEN STORAGE

The safe storage of pressurised hydrogen in hazardous areas requires strict working procedures and constant training for teams. Some crucial aspects involve:

- Access Permission: controlled entry by means of credentials and supervision, with maximum limits on the number of people in hazardous areas.
- Personal Protective Equipment (PPE): mandatory use of items such as waterproof clothing, anti-static boots, goggles, and respiratory protection masks.
- Risk signalling: danger signs at visible points, specifying the type of gas and associated risks.
- Checking for leaks: use of portable detectors and periodic inspections of the integrity of tanks and pipework. Daily inspections with calibrated portable detectors capable of detecting minimum concentrations of 0.001% H_2 in air.
- Energy release: gas purging and dilution procedures before maintenance, shutdowns, or transfers.
- Communication During Emergencies: training to activate alarms, activate protection systems and contact the incident response plan coordinator.
- Documentation: The entire system must have manuals with technical information, operating standards, flowcharts, and emergency plans.
- Isolation of ignition sources: There should be no equipment capable of generating sparks or hot surfaces in places with flammable gases/vapours.
- Route signalling: Bright colours and arrows clearly indicate access/exit routes during emergency evacuations.
- Meeting point: Pre-determined safe place where the team should meet after leaving the risk area.
- Scheduled maintenance: Prevents accidents due to wear and tear by calibrating/replacing equipment such as valves and sensors.
- Protection against discharges: All electrical equipment must have earthing and lightning/overvoltage protection devices.
- Control of chemical substances: Store compatible and labelled products to avoid dangerous reactions.
- Rescue training: Simulations to use rescue equipment for spillages/fires in a coordinated and rapid manner.
- Periodic audits ensure full compliance with these regulations, taking into account factors such as quantity limits, distance between tanks, fire protection, training, and technical documentation. This is crucial for obtaining certifications and operating licences.

Strict adherence to these procedures and the use of appropriate PPE, combined with constant training, are fundamental to guaranteeing safety during hydrogen operations in classified industrialised environments.

6. CONCLUSION

Safety in hazardous areas for hydrogen storage is extremely important due to the flammable and dangerous nature of this substance.

Some of the techniques and procedures on the subject have been presented here, with the aim of training and demonstrating the importance of safety in hazardous areas for hydrogen storage and the measures needed to guarantee a safe environment in these facilities. Through the rigorous application of preventive measures, such as the safe design of installations, advanced leak detection and prevention systems, equipment compatible with the needs of this activity and qualified employee training, it is possible to significantly minimise risks and guarantee a protected working environment.

However, it is essential that these procedures are constantly improved, keeping up with technical developments in the sector and new occurrences that may indicate opportunities for improvement. In this sense, research, and development into innovative technologies for the safe storage, handling and monitoring of hydrogen should be encouraged. In addition, safety guidelines and standards need to be periodically updated to ensure that installations comply with the highest standards of protection.

Co-operation between stakeholders and ongoing training of professionals are also key to continued safety in hydrogen storage areas. Only by strictly complying with current regulations, combined with preventive maintenance and regular inspections, will it be possible to minimise the risks inherent in this activity and guarantee a protected working environment for the workers involved, as well as for the community around these facilities. In conclusion, the responsible adoption of best engineering and occupational safety practices is essential if hydrogen storage is to take place in an increasingly safe manner.

It should be noted that the procedures and safety measures described in this paper do not exhaust all possible techniques and approaches to guaranteeing safety in hydrogen storage, but rather represent the most widely accepted and recommended practices by the international standardisation bodies that set the technical standards for this activity. New solutions and adaptations may emerge as research in the sector continues to advance. However, the rigorous adoption of the guidelines presented, based on the highest levels of current knowledge, ensures a proven level of protection against the risks inherent in handling this flammable and volatile substance.

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