ANALYSIS AND COMPARISON OF HYDROGEN GENERATORS SAFETY MEASURES ACCORDING TO INTERNATIONAL REGULATIONS, CODES AND STANDARDS (RCS)

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ABSTRACT

Climate change has prompted the international community to invest heavily in renewable energy sources in order to gradually replace fossil fuels. Whilst energy systems will be increasingly based on non-programmable renewable sources, hydrogen is the main player when it comes to the role of energy reserve. This change has triggered a fast development of hydrogen production technologies, with increasing use and installation of hydrogen generators (electrolyzers) in both the civil and industrial sector. The implementation of such investments requires the need for accurate design and verification of hydrogen systems, with particular attention on fire safety. Due to its chemical-physical characteristics, hydrogen is highly flammable and is often stored at very high-pressure levels. ISO 22734 and NFPA 2 are the main international standards which are currently available for the design of hydrogen generators and systems, both of which include fire safety requirements. This paper analyses the main existing Regulations, Codes and Standards (RCS) for hydrogen generators with the purpose of evaluating and comparing fire safety measures, with focus on both active protection (detection systems, extinguishing systems) and passive protection (safety distances, separation walls). The scope of the paper is to identify safety measures which can be considered generally applicable and provide a reference for further fire safety regulations. The analysis carried out identifies potential gaps in RCS and suggests areas for potential future research.

NOMENCLATURE

DS	Data Sheet
ESD	Emergency Shutdown Device
ESS	Emergency Shutdown System
GH2	Gaseous Hydrogen
HEE	Hydrogen Equipment Enclosure
HSE	Health and Safety Executive
IPG	Installation Permitting Guidance
ISO	International Standard Organization
LEL	Lower Explosive Limit
LH2	Liquid Hydrogen
NFPA	National Fire Protection Association
NTP	Normal Temperature and Pressure
RCS	Regulations, Codes and Standards
SOV	Shut Off Valve
UEL	Upper Explosive Limit

1.0 INTRODUCTION

Climate change has led international policies to important investments aimed at replacing current fossil fuels with renewable sources. Green hydrogen, obtained through electrolysis processes from renewable sources, can become an important support in decarbonization. Due to its flexibility, hydrogen is the main candidate to play the role of energy reserve in the long run as it has high energy density; however, its low volumetric density reduces its use in transportation applications. To date, the production of green hydrogen is still very limited (lower than 1 % of total hydrogen production) but this is going to change through a radical acceleration in the coming years. A rapid development of hydrogen technologies is already underway, and an adequate infrastructure is needed to enable widespread use of hydrogen for both stationery and transportation applications.

The implementation of these measures and the development of related projects require design and safety verification tools that are currently (in many cases) being defined. The purpose of this paper is to analyze the main existing Regulation, Codes and Standards (RCS) related to hydrogen production with a focus on fire safety aspects, in order to highlight common parts and to evaluate measures that can be considered typically valid, regardless of the technology adopted or the country in which the plant is to be built.

Research and development activities for civil and industrial applications are currently focusing on gaseous hydrogen (GH_2); although liquid hydrogen (LH_2) has some advantages related to lower operating pressure, its handling involves the use of cryogenic equipment and is currently mainly used in space and aeronautics industry. This paper analyzes only safety aspects related to GH_2.

In the paper it will be briefly resumed the state of the art on hydrogen generation systems, their hazards and main RCS (Chapter 2); relevant RCS will be analyzed to evaluate and compare fire safety measures, with a focus on active, passive, and preventive measures. The result of the comparison will identify safety measures which can be considered generally applicable to all contexts regardless of the specific characteristics of the installation and site, which could provide a reference for further fire safety regulations (Chapter 3). The analysis carried out will also identify potential gaps in RCS and suggest areas for potential future research (Chapter 4).

2.0 STATE OF THE ART OF HYDROGEN GENERATORS

2.1 Main hazards

Electrolyzers are devices that produce hydrogen through electrolysis, a chemical process that uses electricity to separate water molecules into hydrogen and oxygen atoms. The produced hydrogen can be stored as GH_2 or LH_2 and can be used in different appliances within industrial or automotive appliances (fuel cells can power transport vehicles).

Hydrogen, as well as any other flammable gas, needs an oxidizer and a source of ignition to cause a fire or an explosion. Considering that hydrogen/oxidizer mixtures need a very low energy level to ignite (it has a wide flammability range with a Lower Explosive Limit LEL set at 4% concentration in air and an Upper Explosive Limit UEL at 77 %) and that air is a largely available oxidizer for standard applications, prevention is the most reliable method for hazard reduction. Separation of hydrogen from the oxidizers is the primary explosion protection measure.

In addition, hydrogen production systems have further specific risks related to the possibility of directly producing hydrogen-oxidizer mixtures in case of failure (with mechanical and chemical related risks). This can lead to an uncontrolled combustion of hydrogen and high-energy releases that can develop as a fire (non-premixed combustion) or an explosion (deflagration and detonation). For hydrogen-air mixtures, deflagrations can produce pressures up to 8 times the initial pressure, detonations up to 20 times the initial pressure (but for shorter durations) and with reflection pressures can reach up to 50 times the initial pressure.

2.2 Regulations, Codes and Standards (RCS) for hydrogen generators

There are several hydrogen production technologies, mostly developed since 20th century, and technical standards for systems and components dealing with hydrogen that have been issued for decades, both by internationally recognized standardization bodies and by private entities. A useful reference can be found in *https://h2tools.org/fuel-cell-codes-and-standards*.

The fast development of hydrogen production technology and research has led to the development of innovative systems that in many cases are not covered by existing RCS. As a result, manufacturers and installers of hydrogen systems often need to design their systems by analogies or conduct in-depth analyses in order to place them on the market.

In this paper, among many existing RCS, it has been chosen to focus on the most widely used ones in industrial and fuel cells applications which contain safety recommendations; this doesn’t exclude the possibility that further useful guidance can be found in other existing RCS. Safety measures will be directly compared to assess whether and how the analyzed RCS differ.

RCS that have been analyzed in this paper are:

- ISO 22734 “Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications” [1]; it establishes criteria for the construction, safety and performance of hydrogen generators by electrolysis, and it mainly covers electrolyzers and auxiliary equipment (fans, pumps, heat exchangers, compressors, etc.) but it doesn’t include other plant elements such as storages and dispensing or LH2 equipment;

- NFPA 2 “Hydrogen Technologies Code” [2]; specifies safety measures for the generation, installation, storage, and distribution of GH2 and LH2, including dispensing;

- Health and Safety Executive “Installation permitting guidance for hydrogen and fuel cell stationary applications” [3] (hereafter referred to as HSE IPG); it provides best practices for the installation of hydrogen systems, including fuel cells, giving guidance on the main preventive and protective measures to be provided;

- CAN/BNQ 1784-000/2022 “Canadian Hydrogen Installation Code” [4]: it provides guidance on the installation of hydrogen generators, dispensing, storage and piping, and it applies to both GH2 and LH2;

- FM Global Property Loss Prevention Data Sheet 7-91 “Hydrogen” [5] (hereafter referred to as FM GLOBAL DS 7-91); it includes measures for both GH2 and LH2 storage and dispensing systems, but it doesn’t include electrolyzers.

The analyzed RCS have different scopes; therefore, the analysis will be limited to common and directly comparable aspects. Additional useful safety information about hydrogen systems can be found in ISO/TR 15916 “Basic considerations for the safety of hydrogen systems” [9].

3.0 COMPARISON OF HYDROGEN GENERATORS SAFETY MEASURES

3.1 Active protection

3.1.1 Detection and alarm systems

Gaseous hydrogen is colorless, odorless and it burns with an almost invisible flame (particularly during daylight hours) that emits little radiant heat and no smoke; therefore, a hydrogen fire may be difficult to detect. To detect a hydrogen flame, it is generally necessary to use infrared cameras and ultraviolet detection systems. On the other hand, flammable gas detection systems can be provided to detect hydrogen leaks, with a large variety of available technologies; detectors must be placed above possible leak points and where hydrogen may accumulate (i.e., roof inside a room, intake of ventilation ducts). Since a hydrogen fire doesn't produce smoke itself, a smoke detection could be useless in some circumstances; however, smoke detection could be useful where a fire could ignite nearby combustible materials (which could instead generate smoke).

ISO 22734 indicates the need for hydrogen detectors to the manufacturer's risk assessment and it doesn't indicate the need for smoke or flame detectors. Regarding alarm systems, the standard deals with process alarms specifying that, when provided, they can be provided locally, remotely, or both; however, no guidance is given about fire alarms to be installed in the plant.

NFPA 2 indicates that hydrogen and fire detectors are required for hydrogen generation systems. The need to provide a manual alarm system serving the plant is also stated.

HSE IPG indicates that production units should be preferably located in a room equipped with fire detection and alarm systems. Hydrogen detection is suggested and the document gives reference on the alarm activation level (≤ 10% of LEL).

CAN/BNQ 1784-000 requires hydrogen detection system for indoor installations, with alarm set point at 25 % of LEL, which activates audible and visible alarm, closes SOVs, deactivates hydrogen-dispensing equipment and shuts off the hydrogen supply. Fire detection is required for indoor storages, with maximum activation temperature set at 110 °C and leading to the venting of outdoor hydrogen storages.

FM GLOBAL DS 7-91 indicates to provide hydrogen detection systems for hydrogen cylinders not installed in indoor gas cabinets, connected to emergency ventilation and shut-off systems, to be activated when 25% of LEL is reached.

3.1.2 Emergency Shutdown System

In the event of accidents or process malfunctions in industrial plants, it is common practice to provide an Emergency Shutdown System (ESS, also referred to as ESD), the main function of which is to shut down plant operation if anormal and potentially dangerous conditions are detected. The possible actions taken by the system are related to the specific characteristics of the process, and different causes can lead to the activation of the system.

ISO 22734 indicates that the hydrogen generator must be equipped with an emergency shutdown function (ESS) that must stop hydrogen production and initiate safeguard actions such as the depressurization to a safe location and the deactivation of unclassified electrical equipment. The causes that must activate the ESS system are: exceeding 50% of the LEL; malfunction of the mechanical ventilation system; differential pressure inside the cells (stack) between oxygen and hydrogen beyond the limits specified by the manufacturer; high pressure and high temperature at compressors outlet; low suction pressure at compressors inlet. Emergency stop buttons (ESD) may also be provided.

NFPA 2 for Hydrogen Equipment Enclosure (HEE) indicates the need for an emergency shutdown system (ESS), the activation of which must: de-energize unclassified electrical equipment; close all SOVs valves on piping connected to areas where hydrogen equipment is located; stop of all compressors; isolate hydrogen storages. HSE intervention should be linked to the following cases: hydrogen detection above 25 % of LEL, fire alarm, shutdown or lack of mechanical ventilation; manual activation of an ESD.

HSE IPG indicates that in case of alarm activated by hydrogen detection (with activation level as low as possible, the standard indicates 10% of LEL) shutdown should intervene as fast as possible, with the following automatic actions: start of forced ventilation, isolation of electrical components, isolation of hydrogen storages and auto-shutdown. The shutdown should also intervene in the case of ventilation failure.

CAN/BNQ 1784-000 indicates the need to provide an ESS that causes the (partial or complete) shutdown of the plant in the event of hazardous conditions. In particular, the ESS must intervene when hydrogen detectors reach 40% of LEL and must shut down the electrical power supply to non-essential equipment, shutdown hydrogen supply, close all SOVs and shut down hydrogen generation. ESD must also be provided within 3 meters from hydrogen systems and with remote activation.

FM GLOBAL DS 7-91 indicates an emergency shutoff that stops hydrogen flow if 25% of LEL is reached. An ESD system is required for dispensers, which must contain SOVs and hydrogen and flame detectors in the dispensing area; it can be activated manually or automatically, and must interrupt hydrogen supply following an accidental release during refueling.

3.1.3 Extinguishing systems

The most effective way to extinguish a flammable gas fire is to interrupt the flow of gas. For this purpose, the generally adopted solution is to provide a SOV on piping, connected to ESD buttons or to automatic detection systems. When preventive actions are not enough, it is necessary to provide fire extinguishing and control systems to limit fire spread. Given the characteristics of hydrogen, the most common measure used is water in order to cool equipment containing pressurized GH2. Extinguishing systems are not generally provided for HEE production areas because incidents are more likely to be lead to explosions, for which such systems are useless.

ISO 22734 doesn’t provide guidance on automatic or manual extinguishing systems to be provided within the electrolyzer enclosure, as it only analyzes electrolyzers and related auxiliary systems.

NFPA 2 states that gas fires should be extinguished by shutting off the source of the gas; in case of intervention, fires should not be extinguished before the hydrogen supply has been shut off due to re-ignition or explosion risks. Water systems should be provided to cool vessels containing compressed GH2 in order to reduce the likelihood of a release and its consequences. Small hydrogen fires can be extinguished using chemical powder or carbon dioxide extinguishers. Alternative extinguishing systems, such as dry-chemical or gaseous agent systems, cannot be used as an alternative to water because they do not guarantee the cooling of the equipment; despite this indication, the standard does not provide further details about alternative extinguishing systems, not even excluding their use.

HSE IPG indicates that in extinguishing gas fires no action should be taken until the gas flow has been stopped. The main measure is to provide sprinkler systems capable of delivering large quantities of water to cool nearby elements and to prevent fire spread, protecting hydrogen tanks, grouped piping and pumps. Small hydrogen fires can be extinguished using powder or carbon dioxide chemical extinguishers.

CAN/BNQ 1784-000 provides similar guidance to NFPA 2: hydrogen fires should not be extinguished until the hydrogen supply is interrupted; in the event of a fire, large quantities of water should be used to cool nearby equipment.

FM GLOBAL DS 7-91 indicates the need for sprinkler protection in all areas where hydrogen-containing equipment is located. It also indicates the need for hydrants with a performance adequate to the risk classification of the area.

3.1.4 Active protection measures comparison

Table 1. Active protection measures comparison

	ISO 22734 [1]	**NFPA 2 [2]**	**HSE IPG [3]**	**CAN/BNQ 1784-000 [4]**	**FM GLOBAL DS 7-91 [5]**
Hydrogen detectors	According to manufacturer's risk assessment	For hydrogen generator	Yes	In indoor areas	In indoor areas (if hydrogen cylinders are not installed in gas cabinets)
Fire detectors	-	For hydrogen generator	For hydrogen generator	For indoor storage	-
Fire alarm	-	Manual	For hydrogen generator	Yes	-
ESD	Start at: 50% LEL, ventilation malfunction	Start at: 25% LEL, fire alarm, ventilation malfunction, ESD activation	Start at: 10% LEL, ventilation malfunction	Start at 40% LEL	Start at 25% LEL, release in dispensing areas
Automatic extinguishing systems	-	Sprinkler for hazardous occupancies	Water spray for storage, grouped piping and pumps	Water spray	Sprinkler for dispensing areas and HEE
Fire hydrants	-	-	-	-	Yes

3.2 Passive protection

3.2.1 Fire resistance and fire reaction

Where prevention measures are not enough, it is necessary to rely on passive protection to reduce the effects of a fire or explosion toward nearby vulnerable elements. The main passive protection measure is fire resistance, which can be applied to various plant elements (vessel supports, walls, floors, etc.), and which can be realized with fire compartments or fire walls to reduce fire radiation.

Given the high flammability of hydrogen and the consequent possibility of propagation of fires, fire reaction is a complementary measure to fire resistance (actually being more a preventive measure rather than a protective one) that should always be considered; in fact, it is essential that materials have an adequate fire reaction class in order to delay ignition of other combustible materials and to reduce the possibility of fire spread.

ISO 22734 indicates compartmentation among the measures to limit fire spread, without providing guidance on minimum fire-resistance classes or duration to be ensured for enclosures. For hydrogen generator enclosure, thermal insulating materials and partition walls must provide adequate fire reaction in order to not accelerate combustion, without specific fire reaction classes indications. In any case, the standard emphasizes more on fire reaction then on fire resistance, as it does not address other plant components besides electrolyzers (e.g., storages).

NFPA 2 provides guidance on the characteristics of electrolyzer enclosures (HEE), which must be made of non-combustible materials, without specific fire resistance requirements. Electrolyzers and other hazardous elements must be kept separate from hydrogen storage areas by walls with fire resistance of at least 60 minutes; where walls are provided for the purpose of reducing safety distances, they must have fire resistance of at least 120 minutes (the requirement may be reduced to 30 minutes for non-bulk storages, i.e., less than 141.6 Nm^3).

HSE IPG indicates that production facilities should preferably be located in a normally unoccupied room, within a non-combustible structure with at least 30 minutes fire resistance. In addition, storage tank supports should be made of non-combustible materials.

CAN/BNQ 1784-000 indicates that indoor storages containing less than 35 kg of hydrogen, rooms floor, walls, and ceiling shall be constructed of noncombustible materials, and interior walls require a fire-resistance rating of at least 120 minutes; when storages contain more than 35 kg of hydrogen, they must be in a dedicated separate building constructed of noncombustible materials.

FM GLOBAL DS 7-91 indicates that hydrogen production areas must be built within a non-combustible building, whose walls must have a fire resistance of at least 120 minutes. Hydrogen storage tank supports (on the assumption that they are made of steel and they are higher than 0.46 m), must be fireproofed in order to guarantee a fire resistance of 120 minutes. Hydrogen storage tanks are allowed indoors if they have a capacity of less than 57 m^3, in which case they must be located separately within non-combustible structures with fire resistance of at least 120 minutes.

3.2.2 Separation distances and fire barriers

One of the main passive protection measures is to provide separation distances between hydrogen plants and people (or buildings outside the plant), in order to reduce the effects of a fire or explosion; similarly, separation distances can be provided between critical equipment within the plant (e.g., between electrolyzer and storages).

Fire resistant walls (fire barriers) may also be interposed, with a dual function: reducing separation distances and limiting the projection of fragments and debris outside the plant. Walls should be designed with great care because confinement can trap the expanding reaction products and produce a bulk flow, (which in turn could propel the flame front more rapidly into the unburnt mixture, with an increasing burning rate, high overpressures and flame acceleration).

ISO 22734 doesn't provide guidance on separation distances or protective walls, as the standard specifically treats electrolyzers as individual equipment and not within a whole hydrogen plant.

NFPA 2 provides guidance on safety distances to storages, distinguishing between non-bulk (with volume lower than 141.6 Nm^3) and bulk storages. For non-bulk storages, safety distances are given depending on the volume stored and its exposures (e.g., other storages, roads, buildings, etc.), ranging from 1.5 m (5 ft) to 7.6 m (25 ft) m, which can be reduced to zero if fire walls with at least 120 minutes fire resistance are provided. For outdoors bulk storages, safety distances depend on pressure (between 1 and 1000 barg), piping diameter (from which the release can occur), and the exposures, with distances up to a maximum of 68 m. Furthermore, distances can be reduced by half in the case of fire with at least 120 minutes fire resistance. The configuration of fire walls shall be designed in order to prevent the accumulation of hazardous gas concentrations.

HSE IPG indicates that where is foreseeable a hydrogen release during normal operation, safety distances should be determined case-by-case. Blast walls are allowed in order to protect sensitive elements and to reduce the potential effects of explosions (pressure, debris projection).

CAN/BNQ 1784-000 gives a range of distances that should be maintained from outdoor hydrogen storages depending on the quantity stored and exposure (e.g., buildings, roads, other storages, etc.), with distances ranging from a minimum of 0 m to a maximum of 5 m and which may be reduced in presence of fire walls with a minimum of 120 minutes fire-resistance. The standard recommends that fire barriers configuration should allow natural ventilation and prevent the accumulation of flammable gas.

FM GLOBAL DS 7-91 provides separation distances (for outdoor storages) depending on the storage volume (referring to NTP, Normal Temperature and Pressure), with distances variable between a minimum of 4,6 m and a maximum of 30 m.

3.2.3 Passive protection measures comparison

Table 2. Passive protection measures comparison

	ISO 22734 [1]	**NFPA 2 [2]**	**HSE IPG [3]**	**CAN/BNQ 1784-000 [4]**	**FM GLOBAL DS 7-91 [5]**
Fire reaction	Enclosure and insulating materials with proper flammability classification	HEE of non-combustible materials	Vessel supports of non-combustible material	Hydrogen rooms of non-combustible material	HEE and storage support in non-combustible building
Fire resistance	-	From 30 to 120 minutes	30 minutes for HEE	120 minutes for indoor storage	120 minutes for HEE and storage supports
Separation distances	-	From 0 to 68 m	T.B.D. case-by-case	From 0 to 5 m	From 4,6 to 30 m
Fire barriers	-	From 30 to 120 minutes to reduce separation distances	Bast walls	120 minutes to reduce separation distances	-

3.3 Preventive measures

3.3.1 Explosive atmospheres

Given the ease of ignition of hydrogen/oxidizing mixtures, it is essential to rely on preventive measures to avoid accidents. The most effective preventive measure is to avoid and reduce the formation of explosive atmospheres (ATEX), where international standards and directives apply. An explosive atmospheres risk assessment is a fundamental requirement in these kinds of installations.

ISO 22734 provides guidance for protection against fire and explosion hazards. One of the main measures is to proceed to an hazardous areas classification in accordance with IEC 60079-10-1[6] and select electrical equipment accordingly; equipment that must remain under voltage in case of failure (e.g. hydrogen detection system and ventilation) shall be suitable for use in hazardous areas. Where hydrogen detectors are provided, the deactivation of non-ATEX classified electrical equipment shall occur when the hydrogen concentration of 25% of the LEL is exceeded.

NFPA 2 indicates the use of the NFPA 69 methodology as one of the possible explosion control methods [7].

HSE IPG indicates the need to proceed with hazardous areas classification according to IEC 60079-10 [6] and subsequent electrical equipment selection. In indoor areas, natural or forced ventilation is required to ensure that hydrogen concentration is normally maintained below 10% of LEL, with only occasional temporary increases to 25% of LEL.

CAN/BNQ 1784-000 requires hazardous areas classification according to IEC 60079-10-1 [6].

FM GLOBAL DS 7-91 indicates the need to select electrical equipment following the hazardous areas classification in accordance to Data Sheet 5-1 "Electrical Equipment in Hazardous (Classified) Locations" [8].

3.3.2 Ventilation systems

Among other preventive measures which may be effective in preventing the formation of explosive atmospheres, the main one is natural or mechanical ventilation, to ensure that hydrogen concentrations above LFL are not reached in closed areas.

ISO 22734 indicates that potentially explosive mixtures in the electrolyzer cabin must be prevented by maintaining hydrogen concentration below 25% of LEL; this can be achieved with various solutions, including: natural ventilation, process control (for example by shutdown when flow rate and pressure of gaseous hydrogen are outside the design parameters), continuous mechanical ventilation.

NFPA 2 requires a mechanical ventilation system for hydrogen production systems.

HSE IPG indicates that natural ventilation is preferred for its reliability and provides minimum ventilation surfaces (0.003 m^2/m^3 compared to the volume of the room). Where forced ventilation is used, the system shall be interconnected with process equipment and the shutdown shall be activated in the absence of ventilation. When explosive atmospheres cannot be avoided, the document suggests as possible mitigation measures: explosion venting, explosion suppression, isolation systems, containment systems, blast walls.

CAN/BNQ 1784-000 requires for cabinets, storage areas, enclosures or rooms containing hydrogen equipment to be ventilated with a minimum ventilation rate of six air changes per hour or 0.3 $m^3/min/m^2$, to prevent hydrogen concentration above 25% of LEL. Ventilation may be achieved by natural convection or by ventilation system interconnected to process equipment (to prevent the process equipment from working in the absence of ventilation).

FM GLOBAL DS 7-91 indicates the need for continuous mechanical ventilation for indoor installations.

3.3.3 Materials

Materials subjected to high stresses and temperatures and exposed to contact with hydrogen are subject to hydrogen embrittlement, which is an increased susceptibility to corrosion, and which causes a decrease in the strength and ductility of metals. Embrittlement can manifest in various ways, such as blistering, cracking, hydride formation, and reduced ductility. This phenomenon is well known and typical of hydrogen applications and must be taken into account in materials choice for piping and vessel.

ISO 22734 provides generic guidance on materials to be used in hydrogen systems, stating that they must be suitable for use in hydrogen systems and to consider: hydrogen embrittlement and hydrogen-assisted corrosion, corrosion and wear resistance, aging resistance, galvanic corrosion, erosion, abrasion, corrosion or other chemical attack. For further details the standard gives reference to ISO/TR 15916 [9] and ISO 11114-4 [10].

NFPA 2 indicates that hydrogen piping, valves, and fittings from the electrolyzer to the hydrogen storage system shall be in accordance with ASME B31.12 "Hydrogen Piping and Pipelines" [11].

HSE IPG indicates that a proper material selection is required to prevent embrittlement, and that materials must be suitable for such application during the scheduled lifetime.

CAN/BNQ 1784-000 indicates that hydrogen piping materials shall comply with the requirements of Table GR-2.1.1-1 of ASME B31.12 [11] and ISO/TR 15916 [9].

FM GLOBAL DS 7-91 does not provide any indication, although it indicates that one of the possible causes of accidents is incompatible piping materials.

3.3.4 Preventive measures comparison

Table 3. Preventive measures comparison

	ISO 22734 [1]	**NFPA 2 [2]**	**HSE IPG [3]**	**CAN/BNQ 1784-000 [4]**	**FM GLOBAL DS 7-91 [5]**
Area classification	According to IEC 60079-10-1	According to NFPA 69	According to IEC 60079-10-1	According to IEC 60079-10-1	According to Data Sheet 5-1
Ventilation	Natural or mechanical	Mechanical for HEE	Natural or mechanical	Natural or mechanical	Mechanical
Materials	Suitable for hydrogen (ref. ISO/TR 15916 ISO 11114-4)	According to ASME B31.12	Suitable for hydrogen	According to ASME B31.12 and ISO/TR 15916	-

4.0 RCS COMPARISON AND GAP ANALYSIS

A direct comparison of the analyzed RCS reveals many similarities. Safety principles on which the various RCS are based on are common and well known; references can be found in ISO/TR 15916 [9]. However, some differences can be found and analyzed in order to highlight factors that can influence hydrogen systems and plants design.

Hydrogen detection systems are a common measure provided by all RCS. There is a large variety of available technologies and cross sensitivity of the sensors should be considered; useful references can be found in IEC 60079-29-1 [12] and IEC 60079-29-2 [13]. In contrast, not all RCS require flame and smoke detectors, but their presence could be useful as an additional risk reduction measure.

An ESS system is an indispensable measure common to all RCS, but its triggers and started actions are different. It is interesting to note that the threshold of hydrogen detectors (at which the ESS must be activated) varies from 10 % to 50 % of LEL. This is a sensitive choice the must be taken into high consideration, since lower thresholds may result in false alarms, and higher ones may cause late activation of ESS.

Regarding active protection systems, all RCS require water-based systems to cool equipment (mainly vessels) exposed to a fire. Only FM GLOBAL DS 7-91[5] indicates the need to provide a hydrant network; this measure could certainly be useful in all plants, but it should be specified that its presence could be prescribed according to local standards.

The opportunity to provide automatic extinguishing systems (sprinklers, inert gas, aerosols, etc.) within HEE is to be evaluated and is not mentioned by the analyzed RCS. Automatic water systems (sprinklers, deluge) within enclosures where there is risk of explosion could be useless in many cases, considering that such systems are called to intervene when a certain temperature is reached, therefore an explosion could significantly damage the system even before it is activated. Gas extinguishing systems might be more effective since they intervene before ignition (e.g., following the exceeding of a certain concentration of hydrogen in air) and they could therefore prevent the fire/explosion saturating the enclosure and avoiding the formation of explosive mixtures; this could present technical difficulties where forced ventilation systems are provided.

All RCS agree on the need for adequate materials fire reaction properties, but without providing guidance on minimum classes to be ensured. Clearly, materials choice should be carefully considered, preferring where possible noncombustible materials or at least high fire reaction classes. For materials selection, therefore, reference can be made to local regulations (which may give minimum performance requirements) and international standards (which define reaction classes and related performances).

Fire resistance is discussed in RCS mainly in relation to the fire barriers characteristics in order to reduce separation distances, and their fire resistance requirements range from a minimum of 30 minutes to a maximum of 120 minutes. The RCS also show some differences for HEE fire resistance, which in some cases is not required (while in others is required up to 120 minutes). Given the possible explosions scenarios and the characteristics of plants (where most equipment is generally located outdoors or within its own enclosure), providing fire resistance for enclosures may not always be efficient.

Although it is generally possible to determine a fire load for some equipment (e.g., by estimating the mass amount contained within a vessel), conventional methods for determining fire resistance refer to static fires. If designed to provide fire resistance, walls should be designed even taking into account possible jet fire scenarios; useful reference can be found in ISO 22899-1:2021 “Determination of the resistance to jet fires of passive fire protection materials - Part 1: General requirements” [14].

Regarding separation distances, RCS provide significantly different indications in some cases. Simplifying, and considering the maximum separation distance provided by the RCS (most severe case), it ranges from a minimum of 5 m for CAN/BNQ, going through the 30 m of FM GLOBAL DS 7-91 and up to a maximum of 68 m for NFPA 2. Considering that all the RCS deal with systems with pressures up to and over 1000 bar, these differences can be attributed to distinct release conditions. RCS seem not to take into proper account delayed ignition of hydrogen jets, which can generate flammable clouds and blast waves. It is useful to always proceed with a specific Quantitative Risk Analysis for each project in order to assess the possible scenarios effects and evaluate proper separation distances.

Hazardous areas classification is one of the fundamental measures to be considered during design for all RCS. A correct analysis and choice of electrical equipment allows to reduce the risk of explosions, and having a preventive character is to be preferred over active and passive measures. There are two main references for areas classification: IEC 60079-10-1 and NFPA 69; although different, these two standards have the same explosion risk theory and can be considered equivalent.

Ventilation of indoor areas is one of the main prevention measures that can be implemented to prevent explosive atmospheres. Some RCS allow natural ventilation, while others require a mechanical ventilation system. Natural ventilation has the advantage of being reliable, but performance is generally more difficult to ensure and depending on weather conditions; mechanical ventilation, if provided, becomes a fundamental safety element and in case of malfunctions or reduced performance must cause the intervention of the ESS system.

About materials selection, the main standards given by the RCS are ASME B31.12 [11] and ISO/TR 15916 [9]. Since ISO/TR 15916 is a technical reference and not acquired as a standard, a further development in this area is desirable.

5.0 CONCLUSIONS

In this paper, hydrogen production systems and facilities RCS have been analyzed and compared in order to highlight their common active and passive protection systems and their main differences.

Comparing the analyzed RCS, some measures are always provided and can therefore be considered standard for these types of plants, regardless of the electrolyzer technology and the characteristics of the specific project (hydrogen quantities, pressures, process, etc.). These common measures are: hydrogen detection, Emergency Shutdown System, sprinklers to protect hydrogen-containing vessels, materials fire reaction properties, fire resistance of HEE and vessel supports, separation distances from storages, hazardous area classification and ventilation.

There are further measures that are provided only by some RCS that can be evaluated by designers. These measures are: smoke and flame detectors, fire hydrant network, fire barriers.

Considering the rapid development of hydrogen projects and appliances, there are some gaps within the RCS that could require further study in order to provide clear references to designers and authorities. Methods for determining safety distances are not explained in the RCS: it would be useful to examine the most used methods in industry. Finally, instructions for the design of fire barriers in terms of geometry and structure characteristics would be helpful as well. None of the RCS gives indications about gas extinguishing systems within HEE or other enclosed areas containing hydrogen: these systems could be a useful measure regardless of the application.

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