Hidrogén töltőállomás tűz- és robbanásvédelmi megoldásai

Fire and explosion protection solutions for hydrogen fuelling station

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Abstract
Hydrogen fuelling stations will soon replace conventional fuel fuelling stations, but systems that meet the highest performance and safety standards are still needed. The safety challenges and risks associated with hydrogen will vary depending on the specific design of the hydrogen fuelling station and will need to be addressed differently. The fire and explosion risks and hazards of hydrogen fuelling stations can be minimised by appropriate precautions and devices.

Keywords: hydrogen, leak detection, invisible fire, flame detection, safety distance

1. HYDROGEN FUELLING STATIONS IN EUROPE AND ACCIDENTS

Since 2015, the total number of hydrogen fuelling station in Europe has grown at an accelerated pace to 187 operational and publicly accessible hydrogen fuelling station by the summer of 2024. Most hydrogen fuelling station are located in Germany (86), followed by France (27) and the Netherlands (24). The vast majority of the hydrogen fuelling station have dispensers for refuelling of cars at 700 bar. About one in two hydrogen fuelling station have dispensers that allow buses or cars, or both, to refuel at 350 bar [5]. Between 2006 and 2019, there were 13 incidents at hydrogen fuelling stations, the most recent of which was on June 10, 2019, a hydrogen fuelling station for fuel cell vehicles exploded in the Norwegian town of Sandvika. The explosion was caused by a poorly installed connector on one of the tanks, which allowed hydrogen to leak. This then mixed with oxygen in the air to create a highly explosive detonating gas, which ignited. To prevent similar incidents, the fuelling station manufacturer has ordered new assembly, inspection, and documentation procedures for its fuelling equipment. The cause of 13 incidents can be traced back to leaks, which occurred due to fitting failures or improper valve use and loosening.

2. DETECTION OF HYDROGEN LEAKAGE

Several levels of detection methods can help to significantly reduce the extent of the hazard, which ranges from leakage to gas dispersion and then ignition to possible explosion. Installing an early detection system will improve hazard management. Detectors should be used to detect invisible flames. The integration of reliable safety sensors and detectors is necessary for condition monitoring, fire detection and to minimise emissions from storage tanks. The requirements for safety systems such as reliability, speed, early detection, monitoring are all important for safety. If not detected, gas leaks can cause catastrophic fires and explosions. Because hydrogen is stored at extremely high pressures at the fuelling station and leaks can occur relatively easily due to the small molecular size of hydrogen, leaks must be detected extremely quickly to ensure an adequate safety response. Conventional gas detectors do not detect a gas leak until a gas cloud is formed and reaches the gas detector after a certain time. Hydrogen has highly flammable properties and can ignite even before the cloud is formed. It is essential that the sensors are fail-safe, require minimal maintenance, use little energy and have a long lifetime. They should be simple to use, easy to install and test. For this reason, a combination of gas detection and flame detection technologies is essential to provide effective levels of protection as a comprehensive safety solution. The following hydrogen detection devices provide an immediate alarm in the event of a dangerous leak:

- Dräger Point Gard 2200 fixed gas detector;
- Dräger Polytron 8200 installed gas detector;
- Dräger Polytron 8900 UGLD ultrasonic acoustic gas leak detector;
- Dräger Safety PAC 8000 portable hydrogen gas detector;
- Dräger X-am 8000 multi-gas detector;
- MSA Altair 4XR gas detector;
- Honeywell BW Ultra gas detector [6] [7].

2.1. Invisible flame detection

The hydrogen flame is very difficult to detect unless it is contaminated. Hydrogen burns with a very faint blue flame that is invisible in daylight, making it difficult to detect visually. Because it emits little visible light and infrared radiation, it is more difficult for humans to detect. However, the hydrogen flame emits significant ultraviolet (UV) radiation in the wavelength range between 2 and 4 µm, which can produce effects similar to solar radiation. Direct contact with hydrogen flame can cause various degrees of burns. Special UV-sensitive flame detectors, thermal imaging cameras and ultrasonic cameras can be used to detect invisible flames:

- Dräger Flame 2700 (Multi-IR) flame detector;
- Det-Tronics X3302 MIR flame detector [2];
- Dräger Flame 1750 hydrogen flame detector;
- BOSCH GIS 1000 C Professional portable thermal imaging camera;
- CS Instruments LD500 and LD 510 ultrasonic camera.

Following the selection of the listed sensors, it is important to consider their location and coverage, which is guided by the manufacturer's application instructions, and may also be influenced by specific operating parameters, environmental conditions and gas mapping. The Dräger Polytron 8200 and Dräger Polytron 8900 gas detectors and the Dräger Flame 1750 hydrogen flame detector are graphically illustrated in Figure 1 for their possible installation locations for hydrogen storage facilities and hydrogen compressors [6].

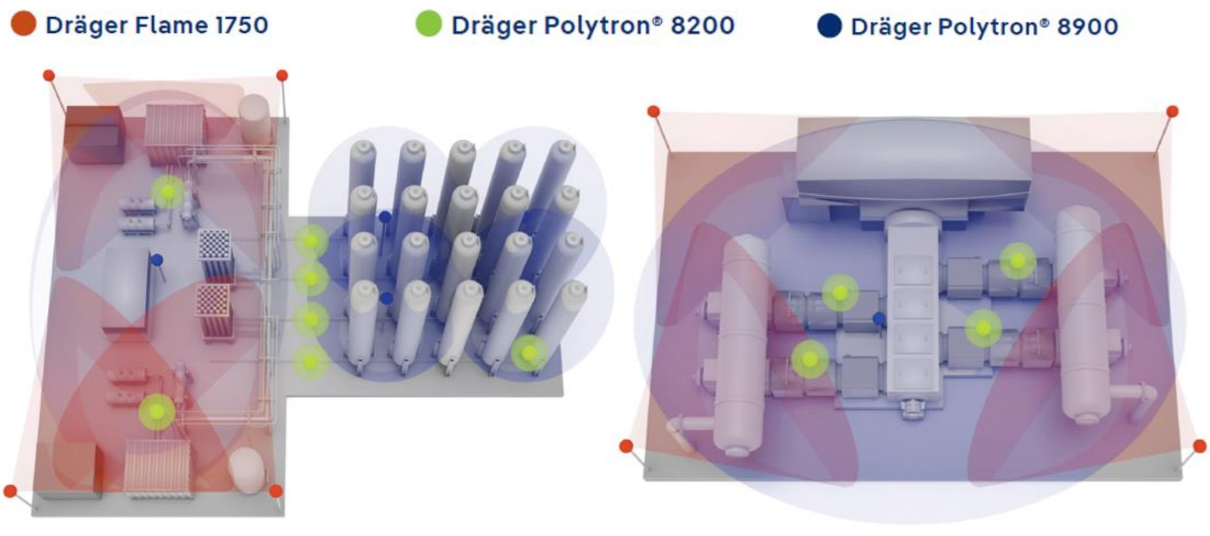

Figure 1: Location and coverage of gas detectors and flame detectors [6]

Because of the explosive environment, it is advisable to use remote-controlled robots to protect human life during firefighting operations. The specific characteristics of the hydrogen flame justify the use of a thermal imaging camera for fire brigades, which must also have explosion-proof protection due to the special environment. The solution is a new PYROLATER explosion-proof fire brigade thermal imaging camera, developed and manufactured in-house, which is capable of measuring objects with temperatures from -40 °C up to 800 °C. In addition to ATEX compliance, the thermal imaging camera is ESD protected and can be used for data and image recording and transmission [3]. The introduction of leakage mitigation measures is also essential for the safe operational status of a hydrogen fuelling station, such as the introduction of inspection and integrity testing on high-pressure storage units with connectors to verify the success of repairs. In order to ensure the tightness of the system components, it is necessary to design the system with welded joints with as few connections as possible. Measuring and control devices are as essential for the reliable and safe operation of hydrogen fuelling stations as pressure and safety relief valves, pressure regulating valves, flow regulators, solenoid valves, temperature gauges, level gauges. It is important to distinguish control valves from conventional shut-off valves because, due to their function, control valves operate virtually continuously depending on their control characteristics and the sensitivity of the sensors. The inner space of the control valve is considered as zone 0, while the sphere of 1 m radius from the valve stem is zone 1. The environment and traffic routes in the direction of the blowdown of the blast pressure relief surfaces shall be protected.

3. MATERIALS SELECTION FOR HYDROGEN TECHNOLOGY SYSTEM COMPONENTS

The materials of the fuelling station components shall be suitable for the operating conditions, compatible with the operating environment, corrosion resistant and resistant to hydrogen embrittlement. The material selected shall also be resistant to exposure to high temperatures caused by hydrogen fire, to changes in properties at the hydrogen temperature and to thermal contraction. The choice of material depends on the specific operating conditions. Insulation of the hydrogen system is also important and requires the selection of an appropriate thermal insulation material, taking into account the moisture barrier, the lack of which due to low temperatures can lead to ice formation, energy and evaporation losses and ultimately corrosion. Insulation may be applied in multiple layers of polyisocyanurate (PIR) and polyurethane (PUR) insulation foam, in which case it must comply with EN 13165:2012+A2:2016 Thermal insulation products. The austenitic stainless steels and aluminium alloys, copper alloys are satisfactory for the conditions of the hydrogen fuelling station. Non-stabilised austenitic stainless steel may become martensitic when loaded towards the yield point at low temperatures, which reduces the ductility of the steel. Iron, low alloy steels, zinc, chromium, cubic crystal metal are not acceptable for use at cryogenic temperatures. The use of elastomers and plastics should be limited in seals because they can cause hydrogen leakage. In the selection of sealants, silicone rubber sealants should be avoided and preferred:

- silicone-free NBR (nitrile rubber);
- FPM/FKM Viton;
- IIR butyl rubber;
- SBR neoprene;
- Graphite sealing compounds.

It is important that the permanently sealed condition of hydrogen systems cannot be restored after maintenance due to ageing of the sealant, and leakage control after sealant replacement is the final task of maintenance. Welds in any hydrogen environment are susceptible to hydrogen embrittlement. Hard spots, residual stresses and a microstructure favourable to brittleness are often formed in the heat affected weld zone. Post-weld annealing may be necessary to restore the favourable microstructure. The effect of contact with hydrogen shall be taken into account when determining the permissible stress of hydrogen systems. The permissible stress of containers and piping used for hydrogen systems shall be set at a maximum of 50% of the minimum yield strength of the substance at ambient temperature as an additional safety factor. Asbestos and Teflon impregnated asbestos were previously recommended for hydrogen technologies, but are prohibited due to the carcinogenicity of asbestos.

4. EXCLUSION OF IGNITION SOURCES

The hydrogen fuelling station may contain a highly flammable and explosive gas medium, which is a condition for an explosion. Another condition for an explosion is the presence of oxygen in the air around the emission sources, and the third condition is the presence of ignition sources. According to EN 1127-1:2019, an ignition source is a process or object from which the energy for ignition is derived. The basic principle of explosion protection is to avoid the simultaneous presence of an explosive medium and ignition sources and to protect against the expected effects of an explosion. The risk can be eliminated or reduced by using a combination of primary, secondary and tertiary protection measures.

- Primary protective measure: avoid formation of explosive atmosphere, reduce leakage of combustible material, dilution by ventilation,

- Secondary protective measure: avoid ignition source,
- Tertiary protective measure: limiting the consequences of an explosion to acceptable levels by means of design protection measures.

Priority should be given to preventing the formation of explosive atmospheres, as the greater the likelihood of an explosive atmosphere occurring, the more comprehensive the measures against the ignition sources. In the case of hydrogen fuelling stations, the ignition sources to be taken into account are those distinguished by the standard:

4.1. Hot surface

When the explosive medium comes into contact with a hot surface it can ignite. The ignition capability of hot surfaces depends on the type of material and the concentration of combustible material in its mixture with air, and the temperature at which ignition occurs depends on the dimensions and shape of the hot body. The minimum ignition temperature for tubes increases with decreasing diameter. Easily identifiable hot surfaces such as radiators and filaments can be easily eliminated, but hot surfaces caused by friction, e.g. the mechanical brake components of a vehicle, do not facilitate isolation.

4.2. Hot gas, flame

Open flames, even very small ones, are an ignition source. Hot gas, flame can be caused by gas compression, illicit behaviour by persons (smoking, discarded cigarette butts), cutting and welding of metals. These processes must be eliminated and banned. Lighters, tobacco products and electric cigarettes must not be brought into the service station area. The prohibition signs shall be clearly displayed. Electrical equipment of non-explosion-proof design must not be brought into the service station area.

4.3. Mechanically excited spark

It can be caused by impact or friction, where the pressure between two bodies hitting or rubbing against each other is taken up by small surface areas of material protruding from solid surfaces, where the high pressure creates high temperatures, these high temperature particles break off and can ignite the combustible gas by flying apart as glowing sparks. This can happen, for example, with tools that create sparks, so only tools, screwdrivers and wrenches that can be used in explosive atmospheres according to Annex A of EN 1127-1:2019 should be used during maintenance. A general prohibition of use applies to all types of steel tools in Zone 1.

4.4. Electrical products

Electrical equipment installed in potentially explosive atmospheres can become an ignition source. A distinction can be made between electrical sparks and electrical arcs, which can be generated when electrical circuits are opened and closed. Only electrical equipment with explosion-proof protection may be used in the charging station area. Because of the particular importance of the safety of products intended for use in potentially explosive atmospheres, all necessary information must be provided on the equipment and components. The product must also bear the 'CE' marking, which indicates that the manufacturer has declared that the product has been manufactured in conformity with the provisions and requirements of the Directive and has undergone a conformity assessment procedure. When selecting a device, care should be taken to ensure that it bears the manufacturer's identification data, the explosion protection distinguishing sign (EX) followed by the symbol for the application group and category of the equipment. For hydrogen fuelling stations, the gap size < 0,5 mm and the minimum ignition energy of 0,02 mJ, which are typical for hydrogen, allow the hydrogen fuelling station to be classified in gas group IIC. For this reason, only a device of explosion sub-group IIC may be used at the station. For the temperature class marking, the minimum temperature class may be a device marked T1, but devices with temperature class T2, T3, T4, T5, T6 are all appropriate. For the EPL (equipment protection level) value, Ga: Zone 0, 1, 2; Gb: Zone 1, 2; Gc: Zone 2 may be used. A device marked H2 may also be used, as this indicates that it is suitable for hydrogen.

Marking of appropriate devices:
Zone 0: (Ex) II 2G Ex e [ia] IIC T1 Ga
Zone 1: (Ex) II 2G Ex db [ib] IIC T3 Gb
Zone 2: (Ex) II 2G Ex nC [ic] IIC T5 Gc.

4.5. Static electricity

The positively and negatively charged particles that make up materials are equally numerous and equally distributed inside or on the surface of the materials. The breakdown of equilibrium, i.e. the separation of electric charges on the surface of an insulating material, due to various external influences, is called electrostatic charging. The discharge of conductive parts in a charged insulated arrangement can easily lead to an ignitable spark. The most important characteristic for the risk of fire and explosion caused by electrostatic discharges is the spark sensitivity of the material, which is determined by the minimum ignition energy of hydrogen (0,02 mJ), which places it in the group of gases with high spark sensitivity. As a protective measure, an equipotential bonding (EPH) network must be installed, to which all metallic bodies, metallic structures and earthing devices must be connected. Earthing shall be provided when tanker trucks are unloaded.

4.6. Lightning strike

When an explosive medium is struck by lightning it will always ignite, but there is also the possibility of ignition due to the intense heating of the lightning conductors. Large currents flow from the flash point and can cause sparks in the immediate vicinity of the flash point. Primary lightning protection against lightning strikes should be installed.

5. Fire safety

To avoid explosion, the injection of chemicals such as sodium bicarbonate ($NaHCO_3$), hydrogen bromide (HBr), sodium chloride (NaCl) can prevent combustion. There is evidence that the chance of explosion of hydrogen-air mixtures can be reduced. Specialised and highly effective fire fighting techniques are required at hydrogen fuelling stations. Water mist or spinkler systems emit small water droplets that absorb heat and displace oxygen, effectively reducing the temperature and depriving the fire of oxygen, thereby extinguishing the fire. Water mist systems are extremely effective in extinguishing hydrogen fires by minimizing the likelihood of rekindling, a common concern with hydrogen flames. Small leaks are a lower risk, but to keep leaks below the permissible level and prevent hydrogen fires from either electrostatic or ignition source sources, a safety margin should be maintained. Requirements for safety distances (Figure 2) are provided in the NFPA2 Hydrogen Code of Practice, which provides guidance.

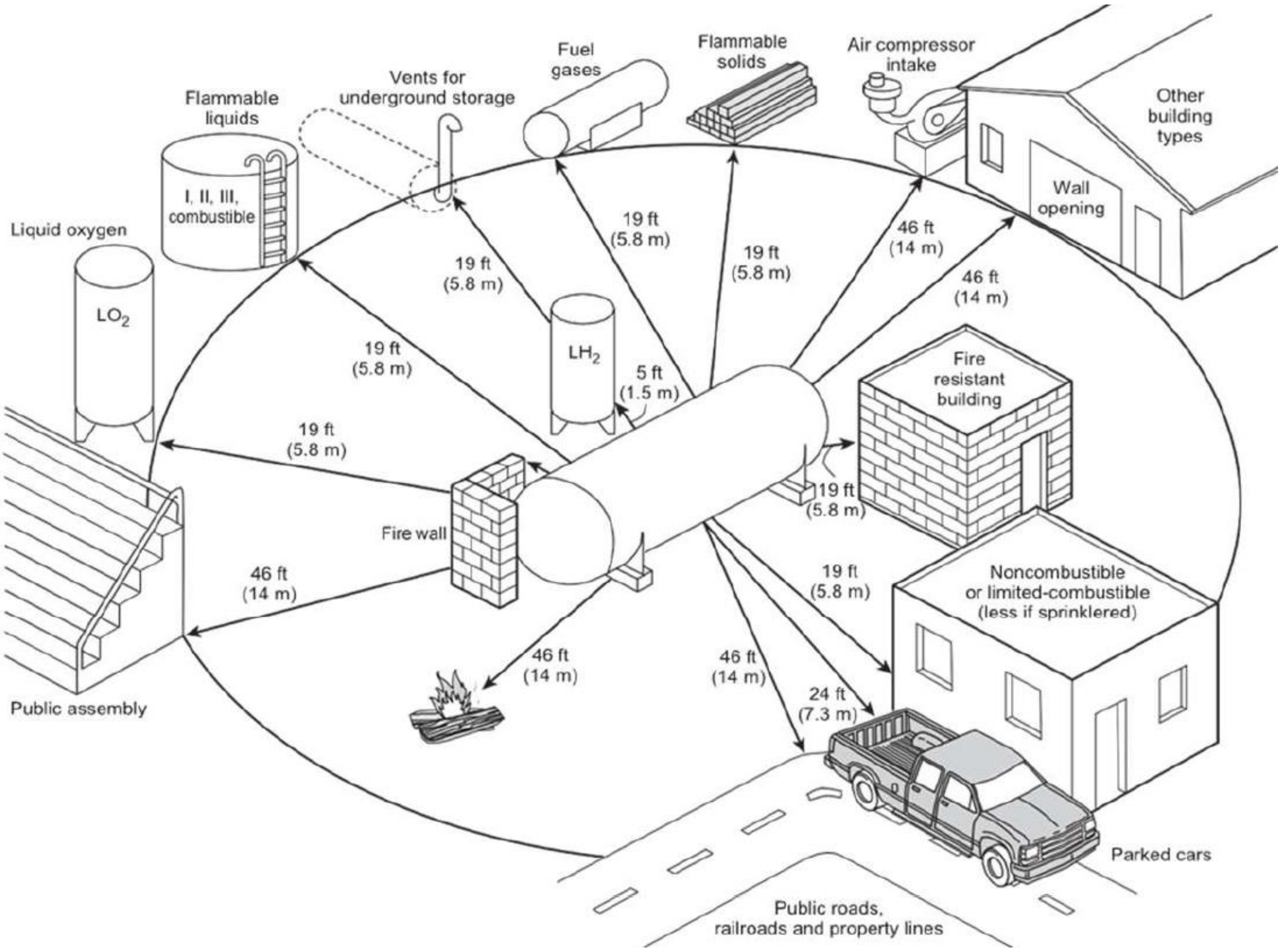

Figure 2: NFPA2 distances for hydrogen refuelling stations [4]

Inhibition of fire by chemical reactions such as injection of sodium bicarbonate prevents combustion. Gas extinguishing systems such as carbon dioxide reduces the oxygen concentration so that combustion is not possible, or FM-200 extinguishing gas, which eliminates the fire by a combination of chemical and physical mechanisms [1]. Further spread of fire must be prevented by fireproof masonry, which works through a process of heat absorption and insulation. This reduces the rate of temperature rise of the element to be protected. It also increases the stability of the building structure against the effects of fire and prevents further fire spread. Options include: fire barriers, cladding, cuffs, flame arresters or flame arrestors. Such an effective solution is the ISOLATIE Combinatie IGNIS-PFP panel, which has been tested for 2.5 hours according to ISO 22889-1:2013. This protection is mainly used against fires in the oil and gas industry. The panel is made of 316 grade austenitic chromium-nickel steel containing 2-3% molybdenum, providing excellent passive fire protection.

6. Summary

Hydrogen technology is an exciting piece in the puzzle of the future of renewable energy. High levels of hydrogen security are essential to green the energy sector. Building trust between users is important for the integration of charging stations. It is important to effectively address fire and explosion safety issues in hydrogen technologies to ensure that the risks associated with hydrogen technologies are at least equivalent, if not lower, than those of established energy technologies. Recent safety-related events show that more effort is needed to embed a new culture in this fast-growing sector. Leak detection and flame detection devices and the development of a spark-free zone are of paramount importance for the sophisticated and safe introduction of this technology. The fire protection solutions - active, passive fire protection, safety distance - all contribute to a quick and efficient response to a potential incident.

References

[1] Matteo Genovese, David Blekhman, Petronilla Fragiacomo 2024: An Exploration of Safety Measures in Hydrogen Refueling Stations: Delving into Hydrogen Equipment and Technical Performance, *Hydrogen* **2024/5**, 102-122; MDPI AG, https://doi.org/10.3390/hydrogen5010007

[2] Michael J. Hosch 2019: Hydrogen and fire safety: Detecting the most flammable element on earth, *International Fire Protection,* **AR-1132, 2019/Marc,** 54-56; Detector Electronics Corporation, AR-1132-Hydrogen-and-fire-safety.pdf (det-tronics.com)

[3] Dr. Nagy Tamás, 2025: Hazai fejlesztés, gyártás: Pyrolater robbanásbiztos kivitelű tűzoltósági hőkamera, *Tűzvédelem – tűz- és katasztrófavédelmi folyóirat* **2025. 32. évfolyam, 1. szám**, 51-52; Rádiós és Infokommunikációs Országos Egyesület

[4] NFPA 2, Hydrogen Technologies Code: **2023 Edition**, National Fire Protection Association

Internet

[5] Internet_1:https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/distribution-and-storage/hydrogen-refuelling-stations

[6] Internet_2:https://www.draeger.com/hu_hu/Safety/Clean-Energy-Solutions/Hydrogen-Safety-for-the-Industry

[7] Internet_3:https://www.sensorcontrol.hu/%C3%89rt%C3%A9kes%C3%ADt%C3%A9s/msa-altair-4xr