ZONE NEGLIGIBLE EXTENT: EXAMPLE OF SPECIFIC DETAILED RISK ASSESSMENT FOR LOW PRESSURE EQUIPMENT IN A HYDROGEN REFUELLING STATION

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ABSTRACT

The MultHyFuel project aims to develop evidence-based guidelines for the safe implementation of Hydrogen Refueling Stations (HRS) in a multi-fuel context. As a part of the generation of good practice guidelines for HRS, Hazardous Area Classification (HAC) methodologies were analyzed and applied to case studies representing example configurations of HRS. It has been anticipated that Negligible Extent (NE) classifications might be applicable for sections of the HRS, for instance, a hydrogen generator. A NE zone requires that an ignition of a flammable cloud would result in negligible consequences. In addition, depending on the pressure of the system, IEC 60079-10-1:2020 establishes specific requirements in order to classify the hazardous area as being of NE. One such requirement is that a zone of NE shall not be applied for releases from flammable gas systems at pressures above 2000 kPag (20 barg) unless a specific detailed risk assessment is documented. However, there is no definition within the standard as to the requirements of the specific detailed risk assessment. In this work, an example for a specific detailed risk assessment for the NE classification is presented:

- Firstly, the requirements of cloud volume, dilution and background concentration for a zone of NE classification from IEC 60079-10-1:2020 are analyzed for hydrogen releases from equipment placed in a mechanically ventilated enclosure.
- Secondly, the consequences arising from the ignition of the localized cloud are estimated and compared to acceptable harm criteria, in order to assess if negligible consequences are obtained from the scenario.
- In addition, a specific qualitative risk assessment for the ignition of the cloud in the enclosure was considered, incorporating the estimated consequences and analyzing the available safeguards in the example system.

Recommendations for the specific detailed risk assessment are proposed for this scenario with the intention to support improved definition of the requirement in future revisions of IEC 60079-10-1.

1.0 INTRODUCTION

The MultHyFuel project aims to contribute to the effective deployment of hydrogen as an alternative fuel by developing a common strategy for the implementation of Hydrogen Refueling Stations (HRS) in a multi-fuel context [1]. In order to provide harmonized guidance, the project developed risk assessments and documentation addressing the gaps on HRS', using three configurations for the study [1 - 3]. As part of drafting the good practice guidelines, Hazardous Area Classification (HAC) methodologies were analyzed for 3 configurations representative for HRS. It has been anticipated that Negligible Extent (NE) classification might be able to be to equipment sections of the HRS, for instance a hydrogen electrolyser, as analyzed as part of configuration 2 in the project (Figure 1). The standard IEC 60079-10-1:2020 defines a Zone NE as a zone such that if an ignition did occur, it would have negligible consequences. A zone of negligible extent would imply either a negligible release or a negligible release quantity considering the volume of dispersion [4]. An example of a zone of negligible extent for natural gas is detailed in clause 4.4.2 of the standard and the extrapolation to hydrogen is detailed in section 3 of this paper. Depending of the pressure of the system, IEC 60079-10-1:2020 establishes specific requirements to classify the extent of a zone as NE. For instance, for pressures above 2000 kPag (20 barg), Zone NE shall not be applied unless a specific detailed risk assessment can document otherwise [4]. For pressures between 1000 kPag (10 barg) and 2000 kPag (20 barg), consideration shall be given to a specific risk assessment. However, there is no definition within the standard as to the requirements of the specific detailed risk assessment. In addition to the specific requirements, IEC 60079-10-1:2020 indicates that an ignition would not result in harm from overpressure effects in case of explosion and would not result in sufficient heat to cause harm or escalation in case of flash or jet fire [4].

This work aims to develop an example of a specific detailed risk assessment for a simplified example of an artificially ventilated enclosure of an on-site electrolyser. The enclosure characteristics, conditions of operation and installed safeguards are described in section 2.The requirements of cloud volume, degree of dilution and background concentration for a classification of NE are analyzed in section 3. A specific detailed risk assessment is performed in section 4, by estimating the potential consequences of the ignition of the cloud volume for negligible extent and considering the available safeguards described in the example.

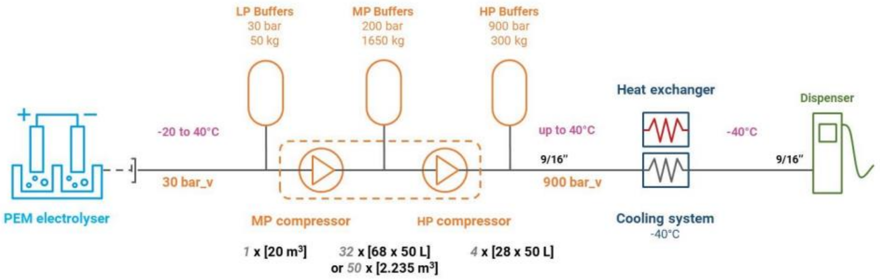


Figure 1. Simplified Process Flow Diagram for “On-site H_2 production” HRS(Configuration 2) studied in the MulHyFuel Project [1, 2, 3]

2.0 HYDROGEN ELECTROLYSER EXAMPLE

In this work, a simplified example of an enclosure for a hydrogen electrolyser is analyzed.

The hazardous area classification for the enclosure with only natural ventilation must first be assessed. For this example, a Zone 1 classification internal to the enclosure can be assumed. Mechanical ventilation can be applied to reduce the risk of a flammable atmosphere inside the enclosure and support the use of equipment inside the enclosure that is not rated for hazardous areas. Such ventilation and safeguards are accepted subject to the control measures meeting IEC 60079-13 for the desired level of reduction in the hazardous area classification, and, the ventilation system provides sufficient control of any flammable gas leak such that, with the ventilation system running, the local area to a leak source can be considered as non-hazardous or Zone NE. If both requirements are met then the enclosure can be assessed as protected by ventilation Ex “v”.

2.1 Description of the enclosure

Hydrogen is generated within an enclosure using PEM electrolysis in three separated stacks (Figure 2). The equipment required for the treatment of the water fed to the stacks and for conditioning of the hydrogen are assumed to be external to the enclosure and hence not considered within the risk assessment. Hydrogen and oxygen are produced from the electrolysis of water and separated by the membrane in the stacks. Hydrogen is generated at a pressure of 3000 kPag (30 barg), for which metallic tubing is used to transport the gas outside the enclosure. Compression fittings are used for the hydrogen pipework, which are installed in front of the door louvres to promote the exposure of potential leak points to incoming air into the enclosure. In addition, installation of hydrogen bearing pipework is avoided in locations where reduced ventilation effectiveness is anticipated, i.e. corners or spaces between equipment and walls. Furthermore, in the pressurized pipework within the enclosure, moving parts from which leaks could be anticipated are placed outside the enclosure, as for example pneumatic valves used for shutdown scenarios.

The hazardous area classification inside the enclosure will depend on the dimensions and type of ventilation. For the calculations, it is assumed that the free internal volume of the enclosure is 10 m^3, with a horizontal cross-sectional area equal to 3.4 m^2. The enclosure is artificially and continuously ventilated by an extraction fan in the roof of the enclosure to provide optimum efficiency for hydrogen as a lighter than air gas. The flow is monitored using a pressure differential instrument across the fan correlating to the minimum acceptable air flow in the enclosure. Two doors cover 80% of the area of one enclosure wall. A louvre is installed in each door, covering most of its surface. However, the effective open area is estimated to be approximately 50% of each of the door, due to the structure of the louvres. The ventilation velocity and direction at different locations of the enclosure depend on the position of the extraction fan, dimensions and position of the air inlet openings, dimensions and positions of the equipment placed inside the enclosure. All these variables shall be considered in the assessment for the determination of the ventilation and cross-sectional area perpendicular to the flow to be used in the hazardous area classification assessment. For purposes of the simplified example, it is assumed that the air flow is predominately directed upwards, with a minimum air flow equal to 1.5 m^3/s. Although this example is based on a number of assumptions, the objective of the current work is to provide an approach for the development of a hazardous classification assessment and “specific detailed risk assessment”. When put into practice and in order to validate the minimum flow rate of the application (by experimental measurement or computational simulation), the assessments should consider in detail the ventilation characterization, as for example: potential locations where hydrogen could accumulate due to the location of fittings, and any variable that could reduce the effectiveness of the ventilation.

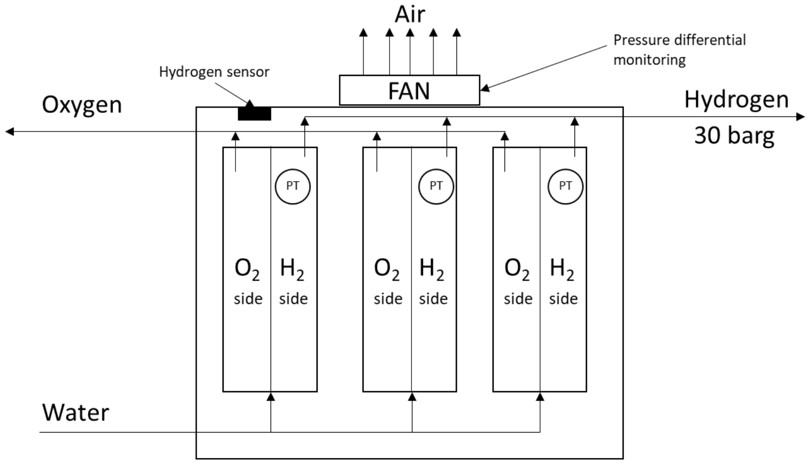


Figure 2. Example of hydrogen generator room

Table 1 summarizes the installed safeguards to detect potential leaks in the hydrogen pipework and reduce the potential for hydrogen accumulation in the enclosure. When shutdown is activated, generation of hydrogen is stopped, followed by depressurization of the entire system and de-energization of all elements not required to put the system in a safe state. If the system is pressurized, the ventilation is monitored and maintained all the time (it is not possible to work with a system under pressure if the artificial ventilation of the system is not in operation). The ventilation will start several minutes before the system is pressurized. Equipment required for a safety function is rated for hazardous area allowing for a scenario without artificial ventilation, for example, hydrogen sensor, pressure sensors and fan in accordance IEC 60079-13:2017 [5].

Table 1. List of safeguards and actions in the example of generator room

Safeguard	Set-Point/Action
Engineering controls	
Gas sensor generating shutdown of the system	Warning at 10% LFL and alarm plus shutdown at 25% LFL.
Pressure differential to monitor fan flow to the room	Shutdown of the system in case of ventilation flow below requirements (Set point not detailed in the example, dependent on the design of the generator)
Interlock to the doors to avoid access to the enclosure when system is pressurized	Shutdown of the system in case of door opening
Pressure monitoring of the system	Shutdown of the system in case of low-low pressure (Set point not detailed in the example, dependent on the design of the generator)
Recurrent automatic pressure drop test	Leak detection approach, initiating shutdown of the system. The pressure hold test consists in stopping generation and isolating the system, followed by monitoring of the pressure for a short duration of time. (Interval of test, duration and set point, not detailed in the example, dependent on the design of the generator and sensitivity of the detection)
Procedural controls	
Trained operators: Access to the enclosure forbidden when pressurized as documented in equipment procedures.	
Recurrent inspection and maintenance of the system (Interval to be determined by the designer and manufacturer of the equipment)	

2.2 Methodology of the assessment

The methodology is divided in two parts:

- a validation of negligible extent classification for the characteristics of the enclosure
- the development of a detailed risk assessment due to the operational pressure of the system.

Firstly, a hazardous area classification assessment is performed for the example with the described characteristics, following an accepted approach from the standard IEC 60079-10-1:2020. The classification is performed for secondary grade releases as defined by the standard: “release which is not expected to occur in normal operation, and, if it does occur, is likely to do so only infrequently and for short durations of time” [4]. Therefore, the secondary releases considered in this work are leaks in which the release is detected sufficiently early such that timely mitigation measures are initiated to isolate the release. As the secondary grade releases are not expected during normal operation, multiple releases are not expected at the same time and only the largest release is considered [4]. In case that multiple releases are expected during normal operation, the release shall be treated as primary grade and the maximum number of releases under the worst conditions should be considered in the assessment. The expected leak rate shall be defined from the representative hole cross sectional area that would be expected in the system. As described in section 2.1, the pressurized hydrogen system is composed of compression fittings with no moving parts, which will not move after testing (pressure and leak testing). This piping is also subjected to automatic pressure drop test at each start-up and recurrent test if continuous operation, allowing the detection of any leak before it can expand to a bigger leak. In addition, a hydrogen sensor is installed in the room and connected to the safety system, generating a shutdown in case of detection of concentrations equivalent to 25% LFL before expansion of the leak. The high-pressure fittings, ranging between 12 to 25 mm OD, are operating at a pressure well below the rating of each element (rated pressures ranging between 160 and 400 barg). For these reasons, a representative hole size of 0.025 mm^2 has been selected for the assessment from Table B.1 of the standard IEC 60079-1-10:2020. In addition to the hole area, the leak flow rate for the assessment will depend on the temperatures of the gas and of the enclosure. The temperature of operation of the stacks is well above 298.15K (25°C), however, at lower temperatures the leak flow rate increases, therefore, this value is used in this work to obtain a conservative estimation of the release rate. Regarding the enclosure temperature, the highest possible temperature of the enclosure will result in a bigger flammable cloud. For this reason, a maximum temperature of 338.15K (40°C) for the enclosure has been used for the analysis.

In order to validate the Negligible Extent classification, a comparison between the estimated flammable cloud volume for hydrogen is compared using one of the methodologies described in IEC 60079-10-1:2020. Furthermore, the consequences in case of ignition of such cloud are estimated and incorporated as part of the qualitative risk assessment of this specific scenario.

3.0 HAZARDOUS AREA ASSESSMENT

The methodology used in this work follows an approach in the standard IEC 60079-10-1:2020 [4]. The classification of the enclosure with the ventilation system running is performed by estimating the dilution degree of the room and the availability of ventilation. Firstly, the dilution degree of the system during operation is determined by estimating the volumetric release characteristic of the source (Q_c) and the ventilation velocity (u_w) within the enclosure. The characteristic flow rate is approximated from the mass flow rate of the leak, which is determined using the choked flow equation (Equation 1) due to the working pressure, i.e. 3101 kPa.a above the critical pressure (Pc = 192 kPa.a) for hydrogen.

$$W_g = C_d S p \sqrt{\gamma \frac{M}{ZRT} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}, \tag{1}$$

where W_g (kg/s) is the mass flow rate, C_d is the coefficient of discharge, S (m^2) is the representative cross sectional area of the source, p (Pa) is the pressure of the system, M (kg/kmol) is the molar mass of the system, γ polytropic index of adiabatic expansion, Z is the compressibility factor, R is the universal gas constant (J/kmol/K) and T (K) is the temperature of the gas. The secondary grade release is expected to be leaks in fittings rather than rounded orifices, hence a coefficient of discharge for sharp orifice equal to 0.75 is used, as suggested in Annex B of IEC 60079-10-1:2020 [4]. Calculation 1 results in a release rate of 3.6×10^{-5} kg/s at 3000 kPa.g and 298.15 K (25°C) for a hole cross-sectional area of 2.5×10^{-8} m^2 (0.025 mm^2).

The volumetric characteristic release of the source is estimated using Equation 2, where ρ_g (kg/m^3) is the density of the gas and LFL is the lower flammability limit (4% H_2 in air at ambient temperature). IEC 60079-10-1:2020 notes that a safety factor is not included in the formula and a safety factor should be determined by the designer of the application [4]. In this study, a safety factor of 2 is applied for the determination of the volumetric characteristic release for a secondary grade release, resulting in the use of 50% LFL (2% v./v. H_2 in air).

$$Q_C = \frac{W_g}{\rho_g \times 0.5 \times LFL}, \tag{2}$$

The gas density is calculated using Equation 3, where p_a (Pa) is the atmospheric pressure, T_a (K) is the ambient temperature.

$$\rho_g = \frac{p_a \times M}{R \times T_a}, \tag{3}$$

For the operational conditions discussed in section 2.2, a density of the gas of 0.078 kg/m^3 is calculated, resulting in a volumetric characteristic release equal to $Q_c = 0.022$ m^3/s.

The ventilation velocity is estimated from the minimum ventilation flow rate in the vertical direction and the effective free cross-sectional area of the enclosure, as shown in Equation 4:

$$u_w = \frac{1.5\,m^3/s}{3.4\,m^2} = 0.44\,m/s, \tag{4}$$

The degree of dilution is estimated from Figure C.1 of IEC 60079-10-1:2020 [4] using the estimated volumetric release characteristic of the release and the estimated ventilation velocity, which is shown in Figure 3. IEC 60079-10-1:2020 [4] indicates that the red line of Figure C.1 represents a flammable volume of 100 m^3, while the blue line represents a flammable volume of 0.1 m^3. Therefore, any intersection to the left of the blue line would have a smaller cloud volume. The dotted black lines in Figure 3 show that the dilution in the enclosure could be classified as high. In addition, a mass flow rate of 5.49×10^{-5} kg/s (equivalent to Q_c = 0.032 m^3/s) would still result in an assessment of high dilution degree for the same ventilation velocity, represented with the dotted red lines in Figure 3. In order to validate the degree of dilution for the specific application, the background concentration must also be assessed to verify that the concentration does not exceed 25% LFL, otherwise, the dilution should be considered as low.

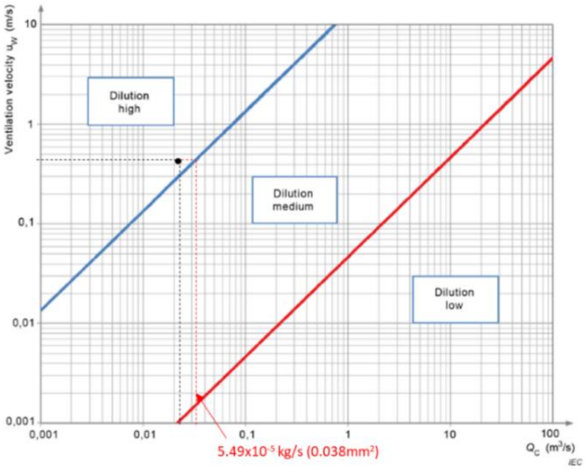


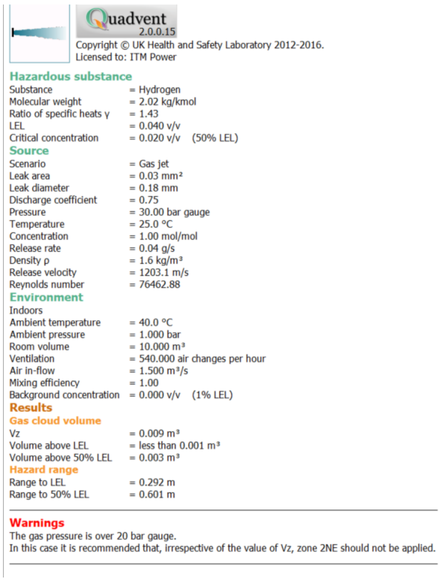
Figure 3. Dilution level for the release in the example using Figure C.1 from IEC 60079-10-1:2020 [4]

The background concentration is estimated using Equation 5, where Q_g (m^3/s) is the volumetric flow rate of flammable gas from the source, Q_2 (m^3/s) is the total volumetric flow rate leaving the room and f is an inefficiency of ventilation. Q_g (m^3/s) is defined as the ratio between the mass flow rate of the leak and the gas density ρ_g (kg/m^3).

$$X_b = \frac{f \times Q_g}{Q_2}, \tag{5}$$

The background concentration has been calculated using two values for the inefficiency of mixing: a perfect mixing factor (f = 1) and a very inefficient mixing factor (f = 5). For a volumetric flow rate Q_g = 4.59×10^{-4} m^3/s and a total volumetric flow rate of 1.5 m^3/s (due to the fact that $Q_2 >> Q_g$), the background concentration is equal to 3.06×10^{-4} for f=1 (0.76% LEL) and 1.53×10^{-3} for f=5.(3.75% LEL) Both results are well below the threshold for a low dilution degree, i.e. a concentration of 0.01 for hydrogen (25% LFL).

For comparison, Quadvent software [6] was used to estimate the mass flow rate, the background concentration and the volume of the cloud with an average concentration of 50% LFL (*Vz*). Figure 4 shows that the results using Quadvent generally agree with the estimations obtained by following the approach used from IEC 60079-10-1:2020 [4].



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Hazardous substance
Substance                   = Hydrogen
Molecular weight            = 2.02 kg/kmol
Ratio of specific heats γ   = 1.43
LEL                         = 0.040 v/v
Critical concentration      = 0.020 v/v   (50% LEL)
Source
Scenario                    = Gas jet
Leak area                   = 0.03 mm²
Leak diameter               = 0.18 mm
Discharge coefficient       = 0.75
Pressure                    = 30.00 bar gauge
Temperature                 = 25.0 °C
Concentration               = 1.00 mol/mol
Release rate                = 0.04 g/s
Density ρ                   = 1.6 kg/m³
Release velocity            = 1203.1 m/s
Reynolds number             = 76462.88
Environment
Indoors
Ambient temperature         = 40.0 °C
Ambient pressure            = 1.000 bar
Room volume                 = 10.000 m³
Ventilation                 = 540.000 air changes per hour
Air in-flow                 = 1.500 m³/s
Mixing efficiency           = 1.00
Background concentration    = 0.000 v/v   (1% LEL)
Results
Gas cloud volume
Vz                          = 0.009 m³
Volume above LEL            = less than 0.001 m³
Volume above 50% LEL        = 0.003 m³
Hazard range
Range to LEL                = 0.292 m
Range to 50% LEL            = 0.601 m

Warnings
The gas pressure is over 20 bar gauge.
In this case it is recommended that, irrespective of the value of Vz, zone 2NE should not be applied.
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Figure 4. Quadvent simulation for the example of a hydrogen generator room

In order to classify the room, Table D.1 of IEC 60079-10-1:2020 is used as reference as shown in Figure 5 for secondary grade releases and with a high degree of dilution. From Figure 5, the enclosure can be classified as Zone 2 NE (Non-hazardous) for the conditions assessed as providing high dilution and with the ventilation assessed as at least fair. However, the classification will depend on the assurance of the required air flow rate and the limited release rate, i.e. only one leak point with the estimated release area or if multiple releases are present, the total mass flow rate of hydrogen is below the value used in the estimate above.

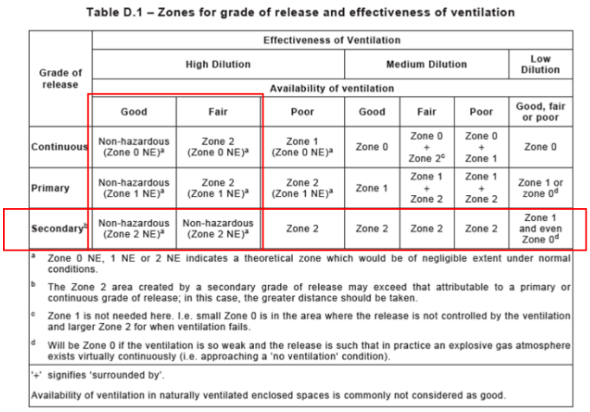


Table D.1 – Zones for grade of release and effectiveness of ventilation

Grade of release	Effectiveness of Ventilation						
	High Dilution			Medium Dilution			Low Dilution
	Availability of ventilation						
	Good	Fair	Poor	Good	Fair	Poor	Good, fair or poor
Continuous	Non-hazardous (Zone 0 NE)[a]	Zone 2 (Zone 0 NE)[a]	Zone 1 (Zone 0 NE)[a]	Zone 0	Zone 0 + Zone 2[c]	Zone 0 + Zone 1	Zone 0
Primary	Non-hazardous (Zone 1 NE)[a]	Zone 2 (Zone 1 NE)[a]	Zone 2 (Zone 1 NE)[a]	Zone 1	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1 or zone 0[d]
Secondary[b]	Non-hazardous (Zone 2 NE)[a]	Non-hazardous (Zone 2 NE)[a]	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 and even Zone 0[d]

[a] Zone 0 NE, 1 NE or 2 NE indicates a theoretical zone which would be of negligible extent under normal conditions.

[b] The Zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

[c] Zone 1 is not needed here. I.e. small Zone 0 is in the area where the release is not controlled by the ventilation and larger Zone 2 for when ventilation fails.

[d] Will be Zone 0 if the ventilation is so weak and the release is such that in practice an explosive gas atmosphere exists virtually continuously (i.e. approaching a 'no ventilation' condition).

'+' signifies 'surrounded by'.

Availability of ventilation in naturally ventilated enclosed spaces is commonly not considered as good.

Figure 5. Hazardous zone classification depending on the grade of release and effectiveness of ventilation [4]

For the current example, the ventilation is initiated before generation of hydrogen can commence and is maintained permanently when the system is pressurized. For the reasons explained previously, the availability of ventilation can be defined as 'at least fair' for this analysis. Therefore, Figure 5 indicates that a Zone 2 NE extent might be able to be applied. However, section 4.4.2 of the standard also defines other requirements to be considered for a flammable cloud and specific requirements depending on pressure. IEC 60079-10-1:2020 [4] defines a cloud of negligible extent as: "An example of zone NE is a natural gas cloud with an average concentration that is 50 % by volume of the LFL and that is less than 0.1 m^3 or 1.0 % of the enclosed space concerned (whichever is smaller)". For other gases, the standard proposes to allow modification of the reference volumes used for methane based on the ratio between the properties of the particular gas and methane such as; the heat of combustion, maximum explosion pressure and the maximum rate of pressure rise [4]. Following this basis, Table 2 shows the ratio between methane and hydrogen in terms of heat of combustion, maximum explosion overpressure and maximum rate of pressure rise. The ratio of the maximum rate of pressure rise is analyzed in this study as it provides the most restrictive condition of volume. However, for a localized flammable cloud, the heat of combustion per volume of mixture could provide a comparison of the available energy for a specific scenario (jet fire or delayed ignition).

This results in the following requirement: gas cloud with an average concentration that is 50 % by volume of the LFL and that is less than $\underline{0.01\ m^3}$ or $\underline{0.1\ \%}$ of the enclosed space concerned. For the example analyzed in this work, 0.1% of the volume of the room is equal to $0.01 m^3$, therefore this volume of cloud is used to validate the classification of Negligible Extent. Figure 2 shows that the volume of the cloud with an average concentration of 50% LFL is estimated to be $0.009\ m^3$ using Quadvent.

Table 2. Hydrogen and methane properties

Material Property	Hydrogen H_2	Methane CH_4	Ratio CH_4/H_2
Heat of Combustion (MJ/kg) [7]	141.8	55.5	0.39
Max. Explosion Pressure (bar g) [8]	8.3	8.4	1.01
Max. Rate of Pressure Rise (bar m/s) [7]	550	55	**0.1**

In addition to the previous definitions, the classification of areas within the enclosure as a zone of Negligible Extent requires specific analysis due to the operating pressure of the system. These requirements are detailed in the following section.

4.0 SPECIFIC DETAILED RISK ASSESSMENT

Clause 4.4.2 of IEC 60079-10-1:2020 [4] indicates that a Zone of Negligible extent shall not be applied to gas distributed above 2000 kPag (20 barg) unless a specific risk assessment can document otherwise. In order to fulfil this requirement, it is proposed to firstly determine the consequences of ignition of a cloud equivalent to the negligible extent. Then, a qualitative risk assessment was performed, incorporating the estimated consequences and the effects of the installed safeguards.

4.1 Explosion severity of localized cloud ignition

In case of a leak in the enclosure following the estimation performed in section 3, a flammable cloud of $0.01\ m^3$ will be obtained. To analyze the consequence of ignition of a cloud equivalent to the definition of Negligible Extent, it is proposed to use the Equivalent Stoichiometric Volume Approach [9] to estimate the expected overpressure from a localized cloud explosion. Although the definition of a Negligible Extent zone is defined as $0.01\ m^3$ cloud (V_z) with an average concentration of 50% LFL, the expected overpressure is instead, calculated for a conservative scenario in which the cloud reaches an average concentration equal to the LFL (4% v./v. H_2) and compared to the minimum harm criterion. To estimate the Equivalent Stoichiometric Volume (V_{ESV}), the volume of the flammable cloud (V_{fuel}) is multiplied by the ratio between the concentration of the cloud (C) and the stoichiometric concentration of the mixture (ϕ = 29.5% v./v. H_2 in air), as shown in Equation 6.

$$V_{ESV} = V_{Fuel}\left(\frac{C}{\phi}\right) = 0.01m^3 \times \left(\frac{4\%}{29.5\%}\right) = 0.0014\ m^3, \tag{6}$$

From the Equivalent Stoichiometric Volume, the explosion overpressure (P) can be estimated by multiplying the maximum reported overpressure in closed conditions (P_{max}) for hydrogen in air at stoichiometric conditions with the ratio between the equivalent volume and the total volume of the enclosure (V), as shown in Equation 7.

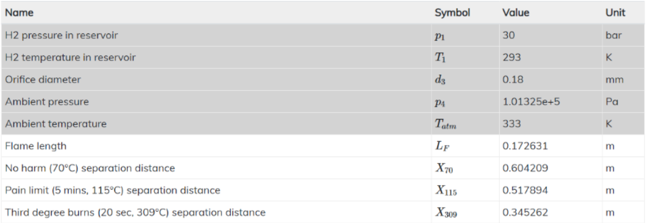
$$P = P_{max}\left(\frac{V_{ESV}}{V}\right) = 8.3\ barg \times \left(\frac{0.0014\ m^3}{10\ m^3}\right) = 1.13\ mbarg, \tag{7}$$

Such a cloud could generate an overpressure in closed conditions of 1.13 mbarg (113 Pa.g) as shown in the previous equation. There is not a unified minimum harm criterion for the effects due to overpressure, and different thresholds are used within the EU countries. In this work, the "No harm threshold for humans" of 13.5 mbarg (1.35 kPa.g) proposed as part of HyResponder project [10] is used as reference. The previous information suggests that the overpressure generated by a flammable cloud NE would be well below the harm threshold. In addition, the estimated overpressure is below the overpressure required to generate injuries from flying fragments, i.e. HyResponder [10] reported an overpressure of 3.0 kPa g (30 mbarg) to generate injuries from glass fragments. However, there are not windows in the enclosure and higher overpressures would be required to generate flying objects in case of explosion.

The previous calculation is considered conservative, as it assumes the generation of a stable localized cloud with an average concentration, while in case of such leaks being present, a small jet surrounded by cloud with a concentration gradient. The pressure rise of such small jet is expected to be lower than the estimated in this section.

4.2 Heat radiation – Jet fire scenario

In case of an immediate ignition, a jet fire can potentially be produced from the release and the criteria for a zone of NE should consider that there would not be sufficient heat to cause harm or to lead to a fire affecting surrounding materials [4]. For such small leaks, there is limited experimental data and a jet fire might not be stable, especially at such high ventilation levels. However, the jet fire properties were modelled using e-laboratory platform [12], based on Molkov and Saffers model [11], and the hazardous distances to "No harm" (70°C). "Pain limit" (5 mins @ 115°C) and "Third degree burns" (20 sec @ 309°C) were determined [10]. Figure 6 shows that estimated flame length for the conditions of the example would be 0.172 m, for which a distance of 0.604 m would be required to be below the "No harm limit". In this example, access is restricted when the system is at pressure, and in case of opening of the enclosure, the depressurization of the system would stop the release and any jet fire thus limiting exposure to personnel. In addition, the materials within the enclosure are selected to avoid propagation of a fire. In order to estimate the radiative heat from a jet fire with the leak properties of this study, DNV Phast has been used at different levels of ventilation. As shown in Figure 7, the maximum radiative heat from the jet fire would be below the threshold to generate significant damage to the equipment (37.5 kW/m^2 [17])



Name	Symbol	Value	Unit
H2 pressure in reservoir	p_1	30	bar
H2 temperature in reservoir	T_1	293	K
Orifice diameter	d_3	0.18	mm
Ambient pressure	p_4	1.01325e+5	Pa
Ambient temperature	T_{atm}	333	K
Flame length	L_F	0.172631	m
No harm (70°C) separation distance	X_{70}	0.604209	m
Pain limit (5 mins, 115°C) separation distance	X_{115}	0.517894	m
Third degree burns (20 sec, 309°C) separation distance	X_{309}	0.345262	m

Figure 6. Flame length correlation and hazardous distances using e-laboratory platform [12]

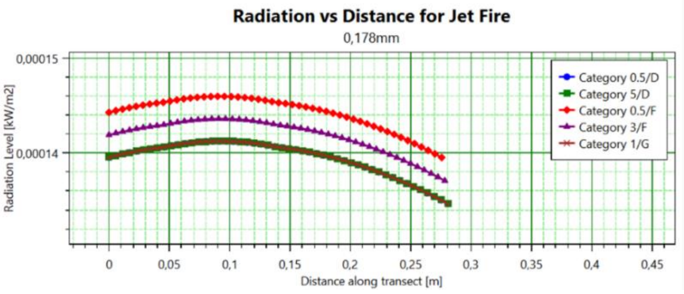


Figure 7. Results of radiative heat from a jet fire using DNV Phast 8.6.1 [13]

In case of an immediate ignition of the release studied in this work, a microflame would be expected, as the flowrate of the release is above the quenching limit for hydrogen in air (3.9 µg/s). However, the considerable ventilation velocity in the enclosure (0.44 m/s) is expected to perturb the flame and reduce the thermal effects to the materials around the release.

4.3 Qualitative Risk assessment of the localized cloud ignition

A Qualitative risk assessment was performed for the specific scenario of a small leak within the enclosure with the characteristics used for the hazardous area classification. The assessment follows the methodology and risk ranking used for the analysis of the configurations studied in MultHyFuel project [2,15, 16].

Table 3 summarizes the risk assessment for the specific scenario of a small leak in the enclosure, presenting the main causes producing the loss of containment and the dangerous phenomena identified for this scenario. It was identified that the loss of containment can potentially create a confined explosion or a jet fire depending on the delay time of the ignition. Based on the calculations performed in section 4.1, the overpressure estimated for the localized cloud is below the minimum harm criteria for humans, therefore it was considered that the overall risk is within the tolerable range, with minor effects to humans. Regarding the jet fire sub-scenario, the risk is considered tolerable, based on the restricted access and depressurization of the hydrogen containment system when the doors of the enclosure are opened.

Table 3. Risk assessment of the specific scenario: small leak in the enclosure.

Central Feared Event (CFE)	**Causes**	**Existing Prevention barriers**	**Dangerous phenomena (DPh)**	**Existing protection Barriers**	**Observations**
Loss of H_2 containment - small leak equivalent to Negligible Extent cloud (0.025 mm^2 - ~0.18 mm) on H_2 piping (fittings/seals)	a) Equipment failure (Erosion, corrosion, metal embrittlement due to hydrogen, Weld failure, cycle fatigue, vibrations)	a) Compliance with PED regulations and specific standards in the choice of materials and welding (where applicable) a) maintenance and inspection of H_2 piping/accessories a) Procedure of controls: lSO 22734:2019 [14] - Type and routine tests	No Ignition: No Consequence	-Automatic pressure drop test (details in Table 1) - Forced ventilation (section 3) with pressure differential on the fan to initiate shutdown in case of loss of ventilation - H2 detection initiating shutdown (details in Table 1) Calibration and inspection to follow the manufacturers operating procedures.	Asphyxiation not credible for the leak size and ventilation degree. In addition, no personnel in the room when the system is pressurized
	b) malicious act (very unlikely due to containerized configuration	b) locked container and restricted access to the process area authorized persons b)interlock in the doors to initiate	Delayed ignition: Confined explosion (ignition of		With the incorporation of the barriers (active pressure drop detection, forced ventilation, etc), the explosion severity is estimated to be below the

	with locked access)	shutdown in case of opening during generation.	localized cloud)	Exiting protection barriers to avoid ignition: - Equipment required to act in case of leak is rated for hazardous areas for a scenario without artificial ventilation. - Prohibition of smoking , mobile	required pressure to generate failure of the weakest part of the system (see section 4.1)
	c) Human error during maintenance (check not done, part missing, inadequate sealing following maintenance)	c) Training / maintenance procedures before starting (pre-checks, four eyes controlling of the installation before re-start) c) management of changes (For example: see references [18, 19])	Immediate ignition: Jet fire		Estimations of jet fire suggest limited radiative heat and temperatures (see section 4.2) affecting the materials inside the room (material are unlikely to promote a fire). No access to the room when pressurised, and shutdown would stop jet fire.

Although the risk in this case was assessed as tolerable, the study was based on a simplified generalized example and not based on a specific design. For this reason, the team identified during the risk workshop some important points to be considered during design to ensure that the accumulation of hydrogen is kept to a negligible extent and to improve the reliability of the control measure in case of loss of containment. For instance, an evaluation of the sensitivity of the pressure drop test should be considered in order to ensure the early detection of leaks in the system. In addition, an assessment of the potential leak points and detailed analysis of the ventilation distribution should be performed to validate the high dilution within the enclosure. Moreover, it was recommended to analyze the methods of detection in case of a jet fire considering the type of sensor and position adapted for the application (i.e. hydrogen and localized flames).

5.0 CONCLUSIONS

An example of a specific detailed risk assessment applied to an enclosure for an electrolyser, classified as a zone of negligible extent, has been proposed in this work. The Zone NE conditions for a hydrogen leak have been validated for the enclosure and the consequences of a jet fire and explosion have been estimated, showing negligible consequences in case of ignition of a localized scenario. In addition, a qualitative assessment has been performed, considering the safeguards detailed in the example, and the quantification of consequences for the specific flammable hydrogen cloud. Due to the assumptions made to describe a simplified generic example, this work has not covered certain points that are considered necessary as part of the “specific detailed risk assessment”. For example, a detailed characterization of the ventilation within the enclosure, the number and location of fittings affecting the area classification, the reliability of the ventilation and the positioning of hydrogen detectors. When put into practice, and in order to validate the minimum flow rate of the application (by experimental measurement or computational simulation), the assessments should consider all aspects in further detail. The proposed methodology and recommendations are intended to support the development of improved descriptions in IEC 60079-10-1 when considering the application of Zone NE concepts.

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