MultHyFuel

Deliverable 3.6

Risk assessment review of critical scenarios and hazardous area classification

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Acronyms

CFE	Central Feared Event
CGH2	Compressed Hydrogen
CNG	Compressed natural gas
HAZID	HAZard IDentification
H_2	Hydrogen
HDV	Heavy Duty Vehicle
HRS	Hydrogen Refuelling Station
LDV	Light Duty Vehicle
LFL	Lower Flammability Limit
LPG	Liquefied petroleum gas
MAHB	Major Accident Hazards Bureau
PFD	Process Flow Diagram
PhD	Dangerous Phenomena
SEI	Thresholds of irreversible effects (in French "*Seuil des effets irréversibles*")
SEL	Lethal effects thresholds (in French "Seuil des effets léthaux" SEL)
SELS	Thresholds of significant lethal effects (in French "*Seuil des effets léthaux significatifs*" SELS)
TPRD	Thermal Pressure Relief Device
TT	HSE Test identification
UVCE	Unconfined Vapour Cloud Explosion

1 REPORT

1.1 Context and study framework

The main goal of WP3 is to **develop good practice guidelines that can be utilized as a common approach to risk assessment** for **addressing the safe design of hydrogen refuelling stations in a multi-fuel context.** The fuels covered are hydrogen (only compressed gaseous hydrogen CGH2) and conventional fuels such as gasoline, diesel, LPG, CNG. The fuel dispensers are assumed to be co-located at the same refuelling station. This study is focused on the risks related to the hydrogen dispenser and its surroundings, but does not cover the hydrogen generation/ storage in the 'backyard' of the HRS.

The goals of task 3.6 are focused on the dispenser and its accessories:

- Refine the critical scenario risk assessment from task T3.5 based on experimental results from WP2
- Establish preliminary recommendations on separation distances and dispenser design
- Establish preliminary recommendations on Hazardous Area Classification (HAC)

In order to achieve these goals, the following topics are described in this document:

1. Benchmarking exercise on Hazardous Area Classification and separation distances
2. Comparison of experimental results with preliminary and detailed risk assessment
3. Likelihood of Hydrogen release
4. Consequence Modelling of Hydrogen releases
5. Design requirements on Hydrogen dispenser
6. Preliminary recommendations on separation distance around dispenser
7. Preliminary recommendations for hazardous area classification around H2 dispensers
8. Areas for further research

1.2 Benchmarking

1.2.1 Hazardous area classification

A number of different methodologies exist to establish hazardous areas and their extents in an outdoor environment. These are generally based on calculations using the pressure of the system and the anticipated size of the release. In order to achieve the benchmarking on leak size and approach, the main standards and guidelines reviewed are the following: IEC 60079-10-1:2020 [12], IP 15 (2005)/IE 15 (2015), IGEM SR/25 – NG and H2 Supplement, Supplement Blue Book (HRS), BCGN GN13, NFPA 2/NFPA 55, Cox et al. (1990).

In terms of the definition of the Hazardous Area classification , the main tools used and analysed are CFD, IEC 60079-10-1:2020 [12] with its annex B/C and D, Quadvent, E15 (source point /risk-based approach) and DNV's PHAST.

The full benchmarking is available in Appendix A.

To summarise our analysis:

- there are many different hole sizes referenced in literature, based mainly on non-hydrogen applications and for some of these, the technical justifications on their use are not clear

- IEC 60079-10-1:2020 is selected as it is the international document generally followed for hazardous area classification.
- A benchmarking exercise was implemented as part of the work, which references the standard hole sizes used for hazardous area classification, i.e. Table B.1 of IEC 60079-10-1:2020 [12].
- IEC 60079-10-1:2020 [12], PHAST and Quadvent have been used for the case study and allow comparison for hazardous area classification on a H_2 dispenser

1.2.2 Separation distances

The following references were reviewed for their approaches in determining minimum separation distances: ISO 19980-1:2020 "Gaseous hydrogen — Fuelling stations — Part 1: General requirements", NFPA 2 hydrogen technology, EIGA document 75/21 methodology for determination of safety and separation distances, BCGA Guidance Note 41 "Separation Distances in the Gases I" and IEA TCP task 43 related to hydrogen safety.
The full benchmarking is provided in Appendix B.
Separation distances methodologies are not prescribed at the European level, and different approaches will therefore be taken by the different countries. This includes the consideration of different hazard scenarios.

1.3 Comparison of experimental results with preliminary and detailed risk assessment

The points highlighted in Task 3.3 Preliminary risk assessment were compared against the experimental studies performed by HSE within WP2 (for details on the experiments, please see Deliverable D2.3), and further analyses using analytical simulations were carried out, in an attempt to understand the results.

These are the key findings:

- High pressure release from the **filling hose in the forecourt** is potentially the worst-case scenario
- Generally-speaking, the existing methodology for consequence modelling remains adequate
- **For the dispenser:**
  -> Assess accumulation for the most safety critical and probable release
  -> Assess consequences of a **deflagration**
  -> Limit the internal overpressure at 200 mbar by decreasing H_2 build-up and/or with explosion venting panels
- **For the forecourt**
  - ➔ **Assess immediate ignition of the jet (i.e. flame) due to hose release**
  - ➔ **Limit the release**
- **H_2 accumulation in confined space: Linden** is a relevant approach, but will **overestimate** the concentration in most cases, giving conservative hazard distances
- **Deflagration in confined space:** FM Global approach or Molkov approach can be used for conservative results (these models can overestimate overpressure)
- **Flame:**
  - ➔ **Shefer approach** can be used, but this method assumes constant flowrate

➔ Constant flow rate can sometimes not be achievable in practice, specifically when the hydrogen source is finite.

1.4 Likelihood of Hydrogen releases

- **Numerous probability data sources exist**: formulae from expert judgment, generic data from past accidents and from different databases, *etc*.
- The evaluation carried out in the example case study include those based on initiating events as developed in Deliverable D2.1 plus the Central Feared Events (CFEs) as developed in Deliverable D3.4.
- The different approaches to estimating the probability exemplified in MultHyFuel have their own strengths and weaknesses.
- The mechanical probabilistic approach presented in WP2.1 develops a detailed analysis of the potential **degradation modes depending on the components present**. This approach still **requires further research before deployment at a larger scale**.
- At this stage of the project, it is proposed to **use data from generic databases such as BEVI, SANDIA or Oreda** because these were derived from industry experience and lessons learned from incidents, combined with potential modification factors based on expert judgement. However, the working group is aware that the **use of generic data presents a degree of uncertainty for the configurations studied.**

1.5 Hydrogen consequence modelling

From the comparison of experimental results with preliminary and detailed risk assessment within Tasks 3.3 and 3.4 respectively, the following were established for the modelling of consequences:

- The modelling tools tested within the project provided conservative estimates of hazard extents
- The correct **definition of source terms is key.**
- Take into consideration, **environment and local weather conditions** (wind) for Hazardous Area Classification and separation distance determination
- Assume **the worst-case conditions for the hydrogen: highest pressure and lowest H2 temperature** to remain conservative
- Assume the highest ambient temperature to allow conservative estimation of the flammable cloud extent

1.6 Dispenser design requirements

Through the comparison of WP2 experimental results with preliminary and detailed risk assessments within Tasks 3.3 and 3.4 respectively, some sensitivity studies were achieved with regard to ventilation, H2 inventory release, and the influence of explosion panels. From these analyses, the following are project findings on hydrogen dispenser design good practice:

- **Openings for natural ventilation** and wind-reinforced ventilation can reduce H2 accumulation

- **Horizontal ventilation apertures** allow dilution benefits offered by the wind, whatever the wind orientation
- **H_2 detection inside the dispenser** with associated emergency protocol and actuation in case of detection and alarm at a preset threshold
- **(Automatic) Excess flow valves** and shut-off valves to stop flow in case of catastrophic release
- Dedicated **explosion panels**
    - A panel with a surface area of **½ of the footprint** of the enclosure helps reduce damage in case of internal deflagration
- **Smart location of apertures**, specifically for large openings and other openings dedicated to explosion venting, **to direct the hazard** and limit damage and injuries (openings located in the upper segment of the dispenser and orientated away from the customer refueling the vehicle)
- **Early detection of releases** from filling hose and associated efficient **emergency protocol** (requirement: 2 - 5 s after detection)
- **Use of flow restrictor** upstream of the hose to limit the flow rate in case of full-bore rupture, but compliant with vehicle filling requirements
- **Use of breakaway coupling** to isolate the system and limit hydrogen inventory release in case of full bore rupture on hose filling
- **Limit ignition sources and combustible materials** on the forecourt in a 6 m radius around the dispenser. Installation of electrical equipment must follow the Hazardous Area Classification of the installation.
- Ensure **grounding of H2 equipment**
- **Canopy structure should be designed** in a way that avoids accumulation of any hydrogen release (e.g. inclined canopy roof; as well as sufficient distance between dispenser roof and canopy; individual canopies per dispenser so any potential collapse is localised)

1.7 Preliminary recommendations on separation distances

Based on WP2's experimental results and Task 3.4's detailed risk assessment, a number of safety barriers (flow restrictor, venting panel) and their impact on consequence distances were analysed. The following were established within MultHyFuel's scope, for the separation distances around hydrogen dispenser:

- High pressure release from the **filling hose in the forecourt** is potentially the worst-case scenario
- In the event of a release inside the dispenser, with sufficient openings for natural ventilation AND dedicated explosion venting panels, if ignited, the effects will potentially be contained within the dispenser with no or limited propagation outside the dispenser
- **Breakaway and Restriction Orifice** can strongly reduce the hazard extents of a hose rupture.
- **From the work conducted within MultHyFuel, there was no evidence to suggest larger separation distances than Compressed Natural Gas(CNG)**

- Calculations with Shefer approach show that – considering maximum delivery pressure, specific nozzle diameter for each fuel and ensuing jet fire due to hose full bore rupture with immediate ignition – flame lengths and associated **effects are significantly higher for CNG compared to H2** (around 40% higher).
- The most severe consequence does not come from an explosion inside the dispenser **if explosion venting panels are fitted**. **Jet fire is potentially the worst scenario upon which the basis of safety should be designed**.
- Hence, considering jet fire scenario, **larger separation distances for H2 than those existing for CNG are possibly not necessary, if ignition probability and minimum ignition energy are not taken into account** (this preliminary recommendation will still need to be refined in deliverable 3.7)
- A **separation distance of 6 m** seems to be adequate, provided industry good practice, i.e. relevant safety features are adopted.

1.8 Preliminary recommendations on Hazardous Area Classification

- The extent of a flammable cloud is recommended to be calculated as the distance to reach a **concentration of 50% LFL H_2** in order to consider, uncertainties with respect to dispersion and ignition. Modelling gives an average value of concentration over time and there is variability in the instantaneous concentration of the gas.
- **Local conditions of wind and temperature** need to be taken into consideration because they have a significant influence on Hazardous Area Classification, specifically for the zoning of enclosures.
- For a naturally-ventilated dispenser considered in the experimental work (WP2) and theoretical analysis performed in this WP, a minimum of **zone 1 with natural ventilation inside dispenser was determined.** For each application, an assessment of ventilation and release rate should be performed to consider a different type of zone.
- **Non-hazardous zone inside dispenser is not possible (for the theoretical work on this WP)** due to high pressure inside dispenser but zone 2 can only be reached with mechanical ventilation at high flow rate. Mechanical ventilation at high flow rate within the dispenser will need to be demonstrable by the duty-holder/ operator.
- **Hole size selection and justification for H2 technologies require further research and analysis.** Small hole sizes 0.025 mm2 (0.18 mm) for H2 fittings need to be justified and used with caution. It is recommended that at the very minimum, **pressure integrity checks in the dispenser are performed regularly, including all the fittings** that can potentially generate a release.
- **Frequent maintenance and inspection on H_2 fittings** are required especially with the uncertainty surrounding hole size assumptions in the calculations for the zoning related to hazardous area classification.
- The estimated extent of the zone is directly dependent on the assumed hole size generating such releases. For instance, for hole sizes of 0.025 mm^2, a hazardous zone ranging between 1.5 m to 2 m, depending on the dispersion tool used, would be obtained. However, if the type of elements, installation and operation would not allow the justification of a 0.025 mm^2 hole, but a larger hole size is more

representative instead, for example 0.1 mm^2, the estimated hazard extent could increase to approximately 3 m.

- Within such hazardous zones, operators must strongly consider the of **control of ignition sources** and implement restrictions/ safety procedures and protocol around the dispenser within these zones in order to limit the presence of ignition sources.
- For external releases, several variables should be considered for the assessment, for example the **wind conditions or potential physical obstructions that would result in an impeded jet**.
- **The methodology in Annex D of IEC 60079-10-1:2020 [12] is not recommended for Hazardous Area Classification around Hydrogen vents** for the conditions of the Hydrogen Refuelling Station **(elevated pressure and release rates)** because it is not possible to extrapolate and often the release rate will not be within the lines for jet, diffusive and heavy gas of the figure C.1 of the standard. So, **the extent cannot be determined using this methodology.**
- The only dispersion tool in this work that considers the **effect of the wind is Phast or equivalent 2D-tools** that can take into consideration weather and wind.

1.9 Further research and investigation identified

The research carried out within the confines of the MultHyFuel project led to the identification of gaps of knowledge in the following:

Safety barriers inside the dispenser:

- Verification of the best **response time achievable on hydrogen gas sensors** or Low-Low Pressure measurement.
- Experimentation to **evaluate the performance of various safety barriers** on cloud flammable formation inside and outside the dispenser.
- Evaluation of impact of controls increasing on likelihood (Record of fueling cycles and alarm when the maximum number of cycles is nearly reached).
- Estimate the Confidence Level or **SIL requirement** for these safety barriers in order to reduce the likelihood of these scenarios.

Hazardous Area Classification

- Reference values of hole sizes are based on gases with different properties from hydrogen and the technical basis behind them is not well understood. **Hole size selection and justification for H2 technologies require further research and analysis.**

2 APPENDIX A – Benchmarking on Hazardous Area Classification

2.1 Introduction

A number of different methodologies exist to establish hazardous area extents in an outdoor environment. These are generally based on calculations using the pressure of the system and the anticipated size of the release.

2.2 General description of hazardous area classification

To comply with directive 99/92/EC (also known as ATEX 137 or the ATEX Workplace Directive) related to the health and safety protection of workers who are potentially at risk from explosive atmospheres, different standards can be used. The main standard used is IEC 60079-10-1:2020 [12], which can be used for the classification of hazardous areas indoors and outdoors and establishing the extent of these hazardous areas.

Published UK based guidance can be obtained from IP 15 and British Compressed Gas Association (BCGA) recommended Codes of Practice. BCGA CP4, CP33 and GN13 are especially pertinent for the hydrogen refueling station.

2.3 Type of releases (IEC 60079-10-1:2020 – EI 15)

The IEC 60079-10-1:2020 [12] standard gives the following short definitions for the type of release:

- **Continuous** – releases which are continuous, or expected to occur **frequently or of long duration of time**.
- **Primary** – releases **expected** to occur **periodically or occasionally under normal operating conditions.**
- **Secondary** –releases **not expected to occur during normal operation**, but which occur infrequently and for **limited duration time** if they do happen.

Some examples of each type of releases are:

- Continuous: H_2 facilities could release H_2 for long duration of time through venting during commissioning phases or start up for large scale facilities
- Primary: Clause B2.3 describes the following examples: either valves if release of flammable substance during normal operation is expected; sample points which are expected to release flammable substance into the atmosphere during normal operation, venting of analysis gas, venting during regeneration of drying columns or before maintenance, at start-up/shutdown ; or relief valves, vents and other openings which **are expected to release flammable** substance into the atmosphere during normal operation.
- Secondary: For instance, Clause B2.4 describe the following examples: compressors and valves where release of flammable substance during normal operation of the equipment is not expected; or flanges, connections and pipe fittings, where release of flammable substance is not expected during normal operation; or sample points which are not expected to release flammable substance during normal operation; or relief valves, vents

and other openings which **are not expected to release** flammable substance into the atmosphere during normal operation.

Energy Institute EI 15 [1] gives the following short definitions for the type of release:

- **Continuous grade release:** A release that is continuous or nearly so, or that occurs frequently and for short periods.
- **Primary grade release:** A release that is likely to occur periodically or occasionally in normal operation (i.e. release which, in operating procedures, is anticipated to occur.
- **Secondary grade release:** A release that is unlikely to occur in normal operation and, in any event, will do so unfrequently and short periods (i.e. operator error or foreseeable equipment failure, such as a leak resulting from failure of flange gasket or seal on a pump or valve).

2.4 Definition of zones (0, 1, 2) – Equivalent USA (NFPA 70/497)

The IEC 60079-10-1:2020 [12] standard gives the followings short definitions for HAC zones:

- **Zone 0** – flammable atmosphere present continuously, frequently or for long periods.
- **Zone 1** – flammable atmosphere likely to occur occasionally under normal operation.
- **Zone 2** – flammable atmosphere not likely to occur during normal operation, but will be of limited duration if a release does occur.
- **Negligible Extent (NE)** – can be applied to any of the three zone classifications when ignition of the gas/air mixture would result in potentially negligible consequences.

The European directive on ATEX [2] gives the following regulated definition:

- **Zone 0** - A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is present continuously or for long periods or frequently.
- **Zone 1** - A place in which an explosive atmosphere consisting of a mixture with air or flammable substances in the form of gas, vapour or mist is likely to occur in normal operation occasionally.
- **Zone 2** - A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

These definitions are not so clear especially due to the lack of values for the definitions of time frame: e.g. frequently; occasionally; short period. Some references give additional input e.g. German guide ATEX from VBG of the statutory accident insurance: [3] ; that gives the following interpretations:

- **Zone 0**: The term "frequently" is to be used in the sense of "mostly in terms of time", which means that potentially explosive areas are assigned to Zone 0 if an explosive atmosphere prevails for more than 50% of the operating time of a system.
- **Zone 1**: If the presence of an explosive atmosphere exceeds a period of around 30 minutes per year or occurs occasionally, for example daily, but is less than 50% of the operating time of the system, zone 1 is generally considered to be present.
- **Zone 2**: The general consensus among many experts is that the term “short-term” corresponds to a period of around 30 minutes per year. Furthermore, it is stated that an explosive atmosphere is not normally to be expected in normal operation. If an explosive atmosphere occurs for a short time once a year, the affected area should already be classified in Zone 2.

So, there is no common agreement on that, however some definitions have been proposed by HSE [4] or EI 15 [1]; but have not been adopted by international standards. The most common values used in industry are:

- **Zone 0**: Explosive atmosphere for more than 1000h/yr
- **Zone 1**: Explosive atmosphere for more than 10, but less than 1000 h/yr
- **Zone 2**: Explosive atmosphere for less than 10h/yr, but still sufficiently likely as to require controls over ignition sources.

Note that in the United States National Electrical Code NFPA 70 [5] , another classification is also in force:

- Class I for locations for flammable gases and flammable liquids that produce vapours,
- Class II for combustible dusts,
- Class III for combustible fibres or flyings

Each class is subdivided into Division 1 and Division 2, depending on the frequency of presence of an explosive atmosphere:

- **Division 1 encompasses zones 0 and 1** for gases
- **Division 2 corresponds to zone 2** for gases

According to NFPA 497 [6] and NFPA 70 [5] a **Division 1 location** is a location

(1) In which ignitable concentrations of flammable gases, flammable liquid–produced vapors, or combustible liquid–produced vapors can exist under normal operating conditions,

or

(2) In which ignitable concentrations of such flammable gases, flammable liquid–produced vapors, or combustible liquids above their flash points may exist frequently because of repair or maintenance operations or because of leakage,

or

(3) In which breakdown or faulty operation of equipment or processes might release ignitable concentrations of flammable gases, flammable liquid–produced vapors, or combustible liquid–produced vapors and might also cause simultaneous failure of electrical equipment in such a way as to directly cause the electrical equipment to become a source of ignition.

According to NFPA 497 [6] and NFPA 70 [5], a **Division 2** location is a location

(1) In which volatile flammable gases, flammable liquid–produced vapors, or combustible liquid–produced vapors are handled, processed, or used, but in which the liquids, vapors, or gases will normally be confined within closed containers or closed systems from which they can escape only in case of accidental rupture or breakdown of such containers or systems or in case of abnormal operation of equipment,

or

(2) In which ignitable concentrations of flammable gases, flammable liquid–produced vapors, or combustible liquid–produced vapors are normally prevented by positive mechanical ventilation and which might become hazardous through failure or abnormal operation of the ventilating equipment,

or

(3) That is adjacent to a Class I, Division 1 location, and to which ignitable concentrations of flammable gases, flammable liquid–produced vapors, or combustible liquid–produced vapors above their flash points might occasionally be communicated unless such communication is prevented by adequate positive-pressure ventilation from a source of clean air and effective safeguards against ventilation failure are provided.

2.5 Release estimation

2.5.1 Hole size - Benchmarking

2.5.1.1 IEC 60079-10-1:2020

Release rate is proportional to the square of the equivalent hole radius. A modest underestimate of this equivalent hole size will therefore lead to a gross underestimate of the calculated value for the release rate.

The representative hole size estimation would depend on the type of the release (definitions detailed in section2.3). For **continuous** and **primary grades** of release, the equivalent hole sizes are defined by the size and shape of the release orifice. For example, for venting it is related to its outlet. For **secondary grade** releases, a guide of equivalent hole sizes is suggested in Table B.1 of the standard. This is reproduced as Table 1 below.

- Lower values in a range: for ideal conditions, e.g. Operating at well below design ratings
- Higher values: when operating conditions are close to design ratings, or adverse conditions.

Simultaneous releases:
In indoor areas with more than one release source, the releases might be summated depending on the type of release:

- **Secondary grade release:** These releases are not expected in normal operation and therefore it is unlikely that more than one secondary source would release at any one time, only the largest secondary release should be considered.
- **Primary grade release**: These releases occur in normal operation but it is unlikely that all of them will be releasing simultaneously. Therefore, the maximum number of primary grade releases that can release at the same time should be determined from knowledge and experience of the installation.
- **Continuous grade release**: Due to the permanent release expected for these sources, all continuous grade releases should be summated.

Table 1 - Range of leak size cross section per source of release from IEC 60079-10-1:2020 [12] (Table B.1)

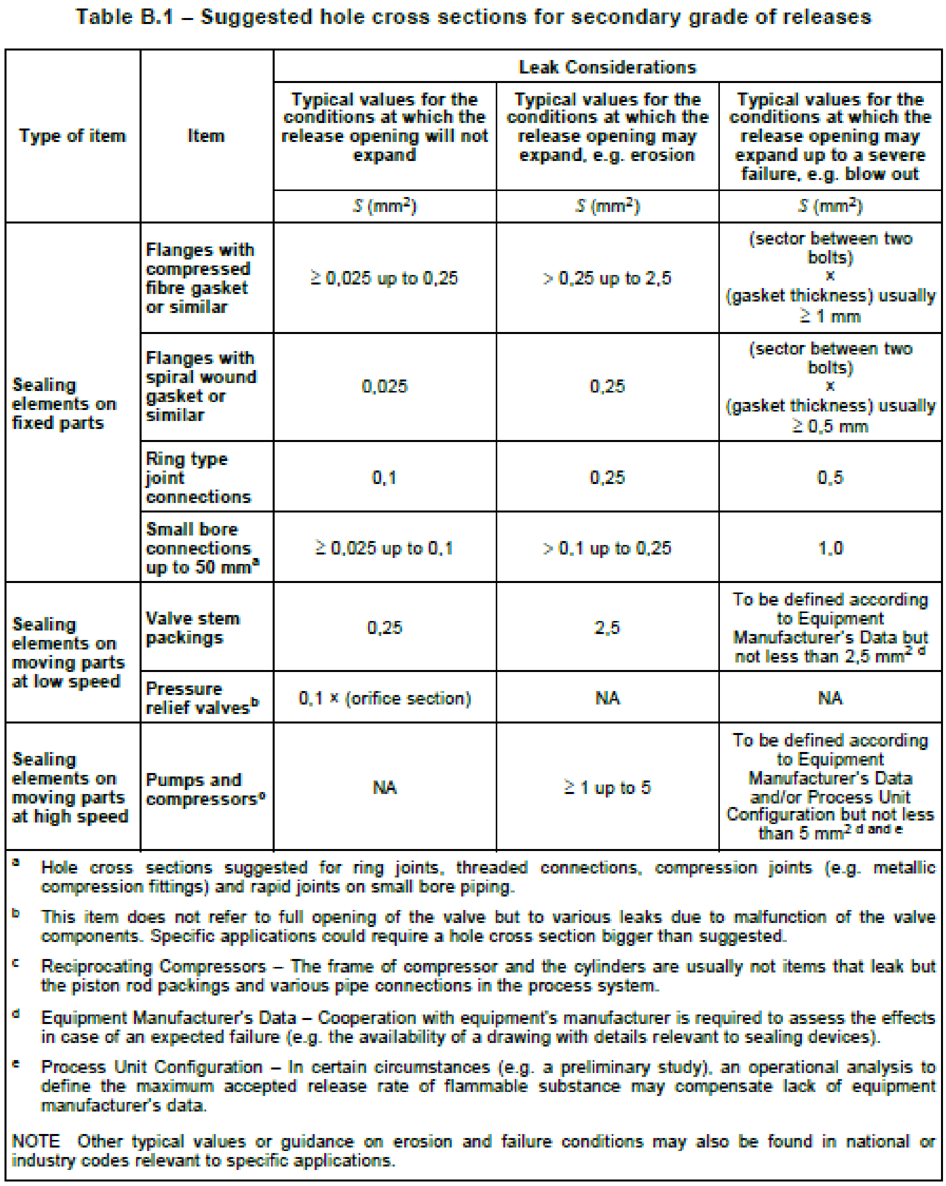


Table B.1 – Suggested hole cross sections for secondary grade of releases

Type of item	Item	Leak Considerations		
		Typical values for the conditions at which the release opening will not expand	Typical values for the conditions at which the release opening may expand, e.g. erosion	Typical values for the conditions at which the release opening may expand up to a severe failure, e.g. blow out
		S (mm^2)	S (mm^2)	S (mm^2)
Sealing elements on fixed parts	Flanges with compressed fibre gasket or similar	≥ 0,025 up to 0,25	> 0,25 up to 2,5	(sector between two bolts) x (gasket thickness) usually ≥ 1 mm
	Flanges with spiral wound gasket or similar	0,025	0,25	(sector between two bolts) x (gasket thickness) usually ≥ 0,5 mm
	Ring type joint connections	0,1	0,25	0,5
	Small bore connections up to 50 mm[a]	≥ 0,025 up to 0,1	> 0,1 up to 0,25	1,0
Sealing elements on moving parts at low speed	Valve stem packings	0,25	2,5	To be defined according to Equipment Manufacturer's Data but not less than 2,5 mm^2 [d]
	Pressure relief valves[b]	0,1 × (orifice section)	NA	NA
Sealing elements on moving parts at high speed	Pumps and compressors[c]	NA	≥ 1 up to 5	To be defined according to Equipment Manufacturer's Data and/or Process Unit Configuration but not less than 5 mm^2 [d and e]

[a] Hole cross sections suggested for ring joints, threaded connections, compression joints (e.g. metallic compression fittings) and rapid joints on small bore piping.

[b] This item does not refer to full opening of the valve but to various leaks due to malfunction of the valve components. Specific applications could require a hole cross section bigger than suggested.

[c] Reciprocating Compressors – The frame of compressor and the cylinders are usually not items that leak but the piston rod packings and various pipe connections in the process system.

[d] Equipment Manufacturer's Data – Cooperation with equipment's manufacturer is required to assess the effects in case of an expected failure (e.g. the availability of a drawing with details relevant to sealing devices).

[e] Process Unit Configuration – In certain circumstances (e.g. a preliminary study), an operational analysis to define the maximum accepted release rate of flammable substance may compensate lack of equipment manufacturer's data.

NOTE Other typical values or guidance on erosion and failure conditions may also be found in national or industry codes relevant to specific applications.

2.5.1.2 Cox et al. (1990) – Classification of Hazardous Locations

Methods used in industrial codes or in-house practices for determining zone dimensions generally utilise hole sizes which are based partly on engineering considerations and partly on expert judgement.

It was considered useful to collect information on the hole sizes used in industrial work on hazardous area classification and to derive from these, a set of standard hole sizes. A set of hole sizes, or classes, has been defined, applicable to all types of equipment, which covers the sizes used in industrial codes and practices. Then, for a given type of equipment, one or more of these hole classes have been assigned.

The authors have had access to a number of in-house methods for zone sizing. The hole sizes given in these methods range from 0.25 mm^2 or less up to 250 mm^2. The approach taken by Cox et al. [7], is based on a set of hole sizes (or classes) covering the range of sizes used in industry codes and practices, which were mainly applicable for oil and gas applications.

The most straightforward form is the actual hole area. In this case, it is necessary to apply a coefficient of discharge. In some cases, the area quoted already incorporates the coefficient of discharge. This is referred to as 'modified area' by Cox et al..

For seals on shafts, the area may be determined if an annular hole or clearance is assumed. Often the clearance is itself taken to be proportional to the shaft diameter, so that in effect the hole size becomes proportional to the square of the diameter.

FLANGE GASKET LEAKS

For a leak in a gasket, the principal severe leak considered is usually the loss of a section of the gasket between two bolts. Information is required on flanges and associated bolts for different pipe sizes.

COMPRESSOR SEAL LEAKS

The leak size is usually quoted in terms of the shaft diameter. A typical relationship is

$$A = \pi l d$$

Where d is the shaft diameter (mm), l the clearance (mm). In other cases (other technology than centrifugal compressor), the hole area is determined by

$$A = k\pi d$$

Where k is a constant (the constant k is simply equivalent to the clearance l or whether it also incorporates a coefficient of discharge – See Annex 7 of Cox et al. [7]).

DRAIN AND SAMPLE POINT LEAKS

A typical sample point diameter is 20 mm. Drain sizes are rather wider in range (with typical diameters of 15, 25, 40 and 50 mm).

STANDARD HOLE SIZE AREA CLASSES PROPOSED BY COX *et al*.

FLANGES

Principal types of Flanges:

- Compressed Asbestos Fibre (CAF)
- Spiral Wound Joint (SWJ)
- Metal-to-Metal ring type (RTJ)

A typical thickness of a CAF gasket is 1.6 mm. Other thicknesses include 0.6 and 3 mm. The aperture given by a leak from SWJ and RTJ flange is much less: a typical effective thickness being about 0.05 mm.

The hole size in a gasket failure may be that due to the complete section between bolt holes or something much smaller. In a metal-to-metal joint, the hole may be due to scoring or pitting and is unlikely to extend over a whole section.

In industrial practice, the hole size for a complete section failure of a gasket is usually calculated using the actual gasket thickness and sector between bolt holes.

For lesser holes (interpreted as cases that are not complete section failure), a typical value for a CAF gasket is 2.5 mm^2 and for RTJ is 0.25 mm^2, SWJ gasket being the intermediate between these.

For a CAF gasket, the hole width is taken as 1 mm, and then the hole size is determined using the sector between two bolts. For instance, if the arc is of 50 mm, the hole size would be 50 mm^2. A smaller leak is taken as 2.5 mm^2.

For an SWJ gasket, the hole width is taken as 0.05mm. Then, for the same example, the hole size would be 2.5 mm^2. A smaller leak is taken as 0.25 mm^2.

For an RTJ, a smaller leak is taken as 0.1 mm^2.

VALVES

The hole size values adopted by Cox et al., are 0.25 mm2 for normal duty valves and 2.5 mm2 for severe duty valves and large valves (>150mm). The hole sizes used in industrial practice are typically 0.25 mm2 but with 2.5 mm2 for more severe cases.

RECIPROCRATING COMPRESSORS

In industrial practice, typical values of hole sizes for the various release points on reciprocating compressors tend to lie in the range **1 to 5 mm^2**.

CENTRIFUGAL COMPRESSORS

In industrial practice, the hole size for a leak from a compressor seal is generally determined in a manner similar to that for pump seals.
Seals may be purged labyrinth seals or floating ring seals. The latter tend to give a smaller hole size, the reduction factor typically being about 6. For the Cox et al. study, a 150 mm shaft compressor is taken as the base case, resulting in the following hole sizes:
Purged labyrinth --> 250 mm^2
Floating ring seal --> 50 mm^2
For other shaft sizes, the hole size is taken as proportional to the square of the diameter.

SMALL BORE CONNECTIONS

For small bore connections, the hole sizes used in industrial practice tend to lie in the range 0.1 - 1 mm^2. For the Cox et al. study, the hole size adopted for a small bore connection is **0.25 mm^2**.

2.5.1.3 IP Model Code - Part 15 (IP15 - 2005)

The Hazardous Area Classification based on the process fluids and conditions and the type and location of equipment, must be carried out before the choice of appropriately certified equipment is made.

Hazardous area approaches:

1. Direct example approach: Some arrangements of generic industrial equipment handling common flammable materials may be classified directly from typical examples.
2. Point source approach: Individual assessment of release and extent.

3. Risk based approach: For systems where the release rate is of an unknown, unspecified and of variable quantity, the risk-based approach is proposed to determine the hole size to be used for a secondary release.

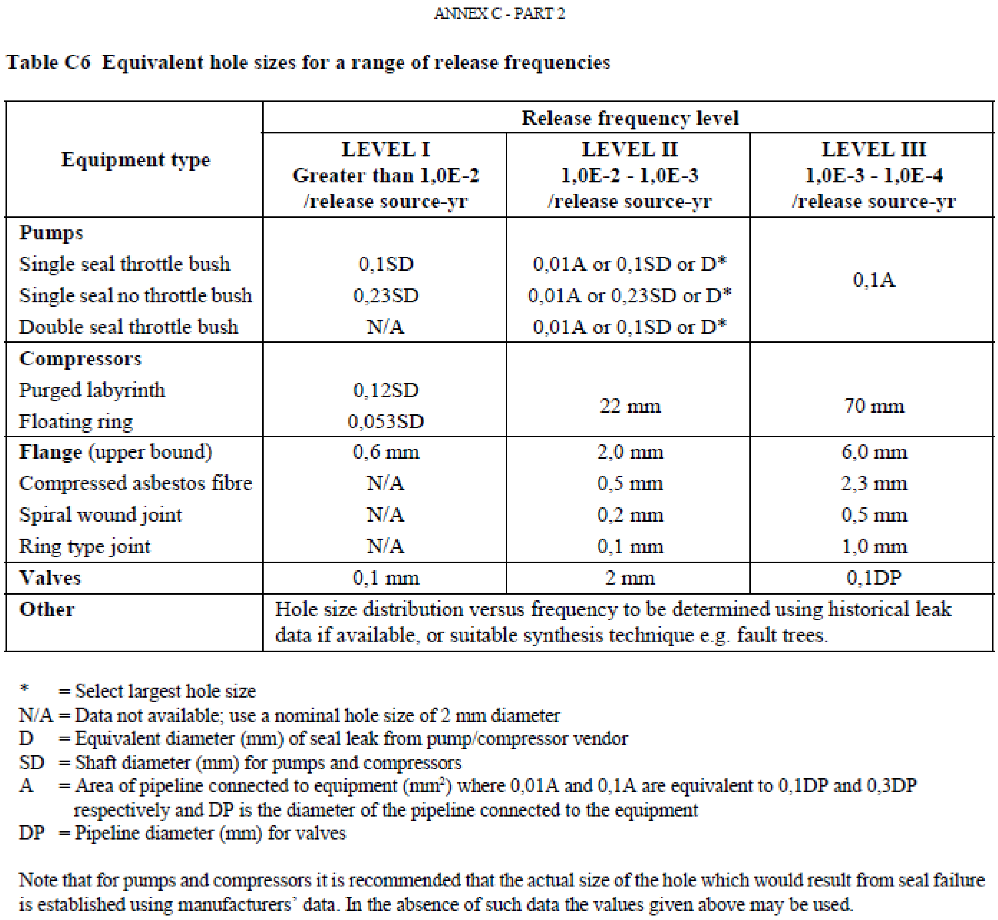
PIPING SYSTEMS

For both flanges and valves, the likelihood of release from an individual item is very small and so it may not warrant classification as generating a hazard if a risk-based approach is followed, particularly if it is not operated at high pressures or temperatures. Only where there are a number of possible leak sources close together, should this area be classified. As a guide, where there are more than 10 leak sources within close proximity, the area should be classified as Zone 2.

Specific hole sizes for flanges and valves are given in Table C6 in Annex C Part 2, for the appropriate level (LEVEL I, II or III) of release frequency (reproduced as Table 2).

The more recent version of this document, EI15: 2015 (Revision 4), however, suggests much larger hole sizes (starting from 1mm in diameter, see Table 6), which are considerably bigger than other references used for Hazardous Area Classification. For some specific cases, the proposed sizes are bigger than the pipework size used for the installation.

Table 2 - Equivalent hole size for a range of release frequencies from IP15 (Table C6)



ANNEX C - PART 2

Table C6 Equivalent hole sizes for a range of release frequencies

Equipment type	**Release frequency level**		
	LEVEL I **Greater than 1,0E-2** **/release source-yr**	**LEVEL II** **1,0E-2 - 1,0E-3** **/release source-yr**	**LEVEL III** **1,0E-3 - 1,0E-4** **/release source-yr**
Pumps			0,1A
Single seal throttle bush	0,1SD	0,01A or 0,1SD or D*	
Single seal no throttle bush	0,23SD	0,01A or 0,23SD or D*	
Double seal throttle bush	N/A	0,01A or 0,1SD or D*	
Compressors		22 mm	70 mm
Purged labyrinth	0,12SD		
Floating ring	0,053SD		
Flange (upper bound)	0,6 mm	2,0 mm	6,0 mm
Compressed asbestos fibre	N/A	0,5 mm	2,3 mm
Spiral wound joint	N/A	0,2 mm	0,5 mm
Ring type joint	N/A	0,1 mm	1,0 mm
Valves	0,1 mm	2 mm	0,1DP
Other	Hole size distribution versus frequency to be determined using historical leak data if available, or suitable synthesis technique e.g. fault trees.		

* = Select largest hole size
N/A = Data not available; use a nominal hole size of 2 mm diameter
D = Equivalent diameter (mm) of seal leak from pump/compressor vendor
SD = Shaft diameter (mm) for pumps and compressors
A = Area of pipeline connected to equipment (mm^2) where 0,01A and 0,1A are equivalent to 0,1DP and 0,3DP respectively and DP is the diameter of the pipeline connected to the equipment
DP = Pipeline diameter (mm) for valves

Note that for pumps and compressors it is recommended that the actual size of the hole which would result from seal failure is established using manufacturers' data. In the absence of such data the values given above may be used.

COMPRESSORS

The distances recommended in IP15 assume that failure of joints and nozzles due to vibration are considered separately.

It is recommended that the manufacturers' data for seal failure leak rates are used to establish the hazard radii equivalent to a Level I release.

Data in Table 2 (Table C6 - LEVEL I from Cox et al.), 0.12 SD for purged labyrinth and 0.053SD for floating ring seal. SD--> Shaft diameter. Having determined hole size, radii can be determined using Table 5.3 (reproduced as Table 3 below)

Table 3 - Example of leak hole size compressor and hazard radius from EI15 (Table 5.3)

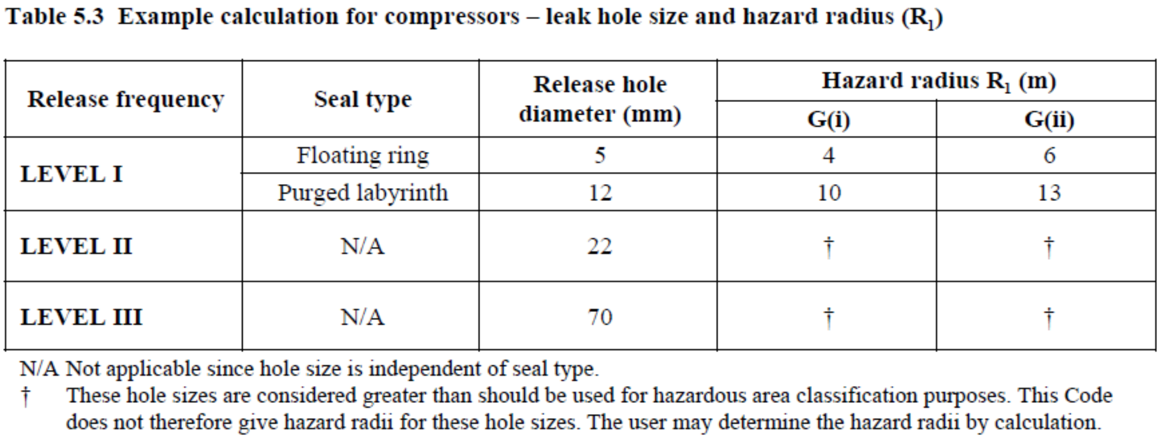


Table 5.3 Example calculation for compressors – leak hole size and hazard radius (R_1)

Release frequency	Seal type	Release hole diameter (mm)	Hazard radius R_1 (m)	
			G(i)	G(ii)
LEVEL I	Floating ring	5	4	6
	Purged labyrinth	12	10	13
LEVEL II	N/A	22	†	†
LEVEL III	N/A	70	†	†

N/A Not applicable since hole size is independent of seal type.

† These hole sizes are considered greater than should be used for hazardous area classification purposes. This Code does not therefore give hazard radii for these hole sizes. The user may determine the hazard radii by calculation.

2.5.1.4 EI 15 (2015)

Equipment where release hole size is known to be independent of release frequency

Equipment Drains and Liquid Sample Points

Gaseous sample points or drain points from gas systems should be considered as vents. Good practice is to prevent abnormal release following a failure of the sampling system.

For the determination of primary releases from drains and sampling points, the flow area is the key factor rather than the hole size, as a quarter turn valve on a sample point is likely to be cracked open rather than fully opened. The flow rate is determined using Tables C.1 and C.4 from EI 15 (reproduced as Table 4 and Table 5 below), based on the type of fluid, the pressure and the size of the point.

For secondary releases, the release size should be identified by analysing the likely failure modes. It is recommended that as many of these failure modes are mitigated against as possible through the use of sprung valve handles, double valves and the positioning of sample points above appropriate drains.

Table 4 - Fluid category according to composition and LFL from EI (Table C1)

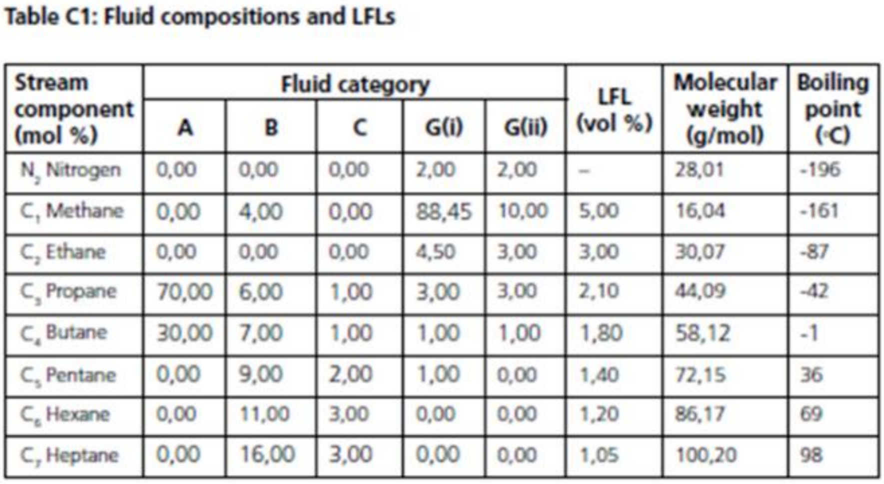
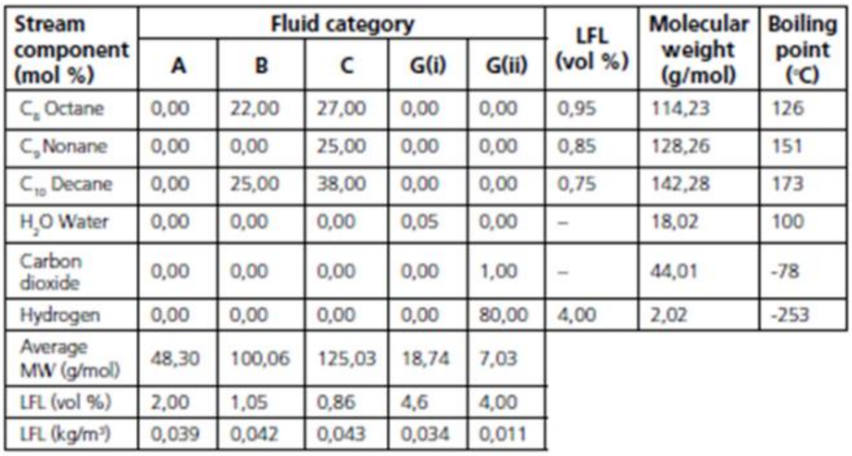


Table C1: Fluid compositions and LFLs

Stream component (mol %)	Fluid category					LFL (vol %)	Molecular weight (g/mol)	Boiling point (°C)
	A	B	C	G(i)	G(ii)			
N_2 Nitrogen	0,00	0,00	0,00	2,00	2,00	–	28,01	-196
C_1 Methane	0,00	4,00	0,00	88,45	10,00	5,00	16,04	-161
C_2 Ethane	0,00	0,00	0,00	4,50	3,00	3,00	30,07	-87
C_3 Propane	70,00	6,00	1,00	3,00	3,00	2,10	44,09	-42
C_4 Butane	30,00	7,00	1,00	1,00	1,00	1,80	58,12	-1
C_5 Pentane	0,00	9,00	2,00	1,00	0,00	1,40	72,15	36
C_6 Hexane	0,00	11,00	3,00	0,00	0,00	1,20	86,17	69
C_7 Heptane	0,00	16,00	3,00	0,00	0,00	1,05	100,20	98



Stream component (mol %)	Fluid category					LFL (vol %)	Molecular weight (g/mol)	Boiling point (°C)
	A	B	C	G(i)	G(ii)			
C_8 Octane	0,00	22,00	27,00	0,00	0,00	0,95	114,23	126
C_9 Nonane	0,00	0,00	25,00	0,00	0,00	0,85	128,26	151
C_{10} Decane	0,00	25,00	38,00	0,00	0,00	0,75	142,28	173
H_2O Water	0,00	0,00	0,00	0,05	0,00	–	18,02	100
Carbon dioxide	0,00	0,00	0,00	0,00	1,00	–	44,01	-78
Hydrogen	0,00	0,00	0,00	0,00	80,00	4,00	2,02	-253
Average MW (g/mol)	48,30	100,06	125,03	18,74	7,03			
LFL (vol %)	2,00	1,05	0,86	4,6	4,00			
LFL (kg/m^3)	0,039	0,042	0,043	0,034	0,011			

Table 5 - Hazard radii for pressurised releases from EI (Table C4)

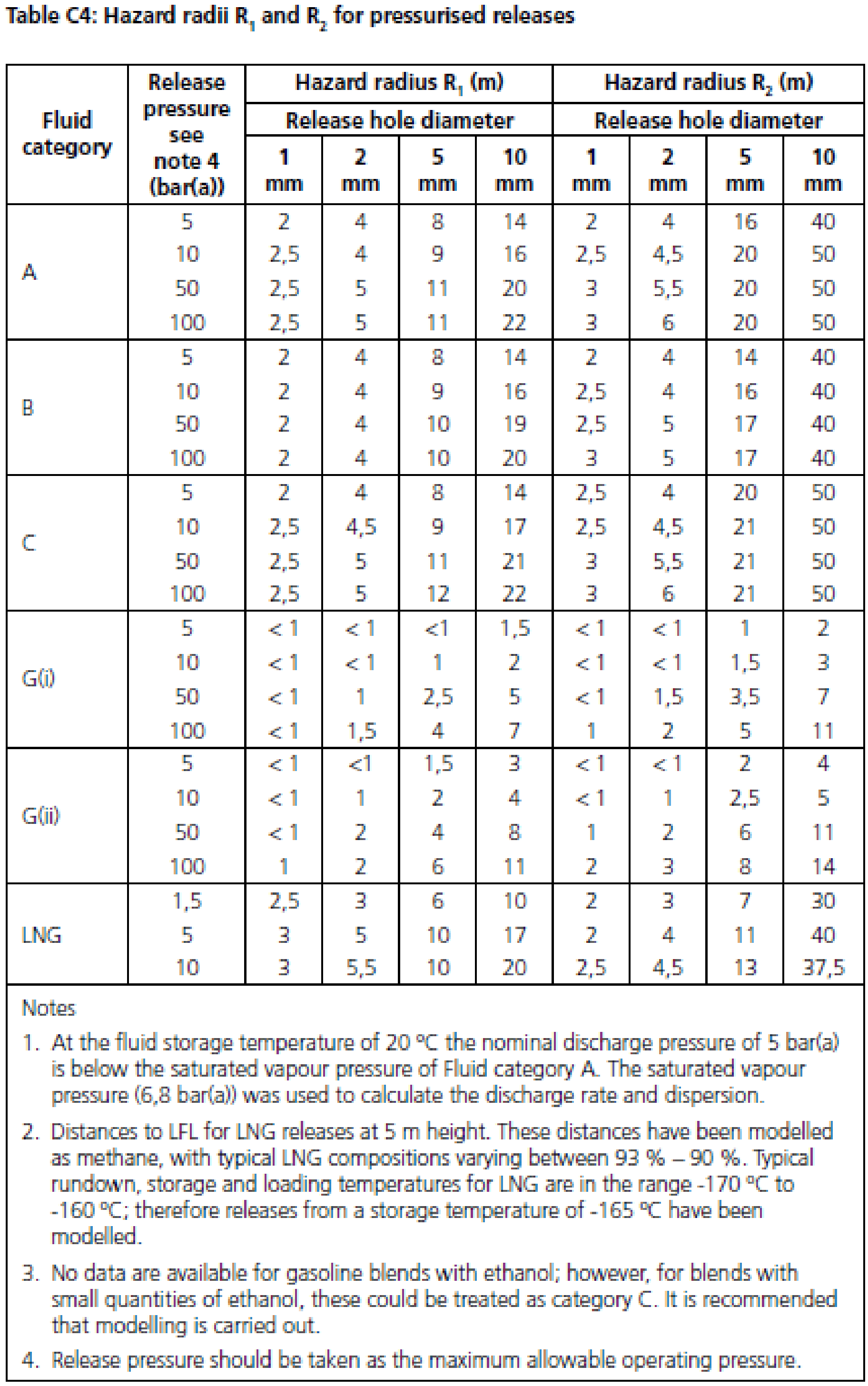


Table C4: Hazard radii R_1 and R_2 for pressurised releases

Fluid category	Release pressure see note 4 (bar(a))	Hazard radius R_1 (m)				Hazard radius R_2 (m)			
		Release hole diameter				Release hole diameter			
		1 mm	2 mm	5 mm	10 mm	1 mm	2 mm	5 mm	10 mm
A	5	2	4	8	14	2	4	16	40
	10	2,5	4	9	16	2,5	4,5	20	50
	50	2,5	5	11	20	3	5,5	20	50
	100	2,5	5	11	22	3	6	20	50
B	5	2	4	8	14	2	4	14	40
	10	2	4	9	16	2,5	4	16	40
	50	2	4	10	19	2,5	5	17	40
	100	2	4	10	20	3	5	17	40
C	5	2	4	8	14	2,5	4	20	50
	10	2,5	4,5	9	17	2,5	4,5	21	50
	50	2,5	5	11	21	3	5,5	21	50
	100	2,5	5	12	22	3	6	21	50
G(i)	5	< 1	< 1	<1	1,5	< 1	< 1	1	2
	10	< 1	< 1	1	2	< 1	< 1	1,5	3
	50	< 1	1	2,5	5	< 1	1,5	3,5	7
	100	< 1	1,5	4	7	1	2	5	11
G(ii)	5	< 1	<1	1,5	3	< 1	< 1	2	4
	10	< 1	1	2	4	< 1	1	2,5	5
	50	< 1	2	4	8	1	2	6	11
	100	1	2	6	11	2	3	8	14
LNG	1,5	2,5	3	6	10	2	3	7	30
	5	3	5	10	17	2	4	11	40
	10	3	5,5	10	20	2,5	4,5	13	37,5

Notes

1. At the fluid storage temperature of 20 °C the nominal discharge pressure of 5 bar(a) is below the saturated vapour pressure of Fluid category A. The saturated vapour pressure (6,8 bar(a)) was used to calculate the discharge rate and dispersion.
2. Distances to LFL for LNG releases at 5 m height. These distances have been modelled as methane, with typical LNG compositions varying between 93 % – 90 %. Typical rundown, storage and loading temperatures for LNG are in the range -170 °C to -160 °C; therefore releases from a storage temperature of -165 °C have been modelled.
3. No data are available for gasoline blends with ethanol; however, for blends with small quantities of ethanol, these could be treated as category C. It is recommended that modelling is carried out.
4. Release pressure should be taken as the maximum allowable operating pressure.

<u>Equipment where hole size is frequency dependent</u>

Larger releases resulting in a seal failure: are covered by secondary releases using Table C.13 of the guidance, reproduced as Table 6.

Table 6 - Equivalent hole sizes for a range release frequency from EI (Table C13)

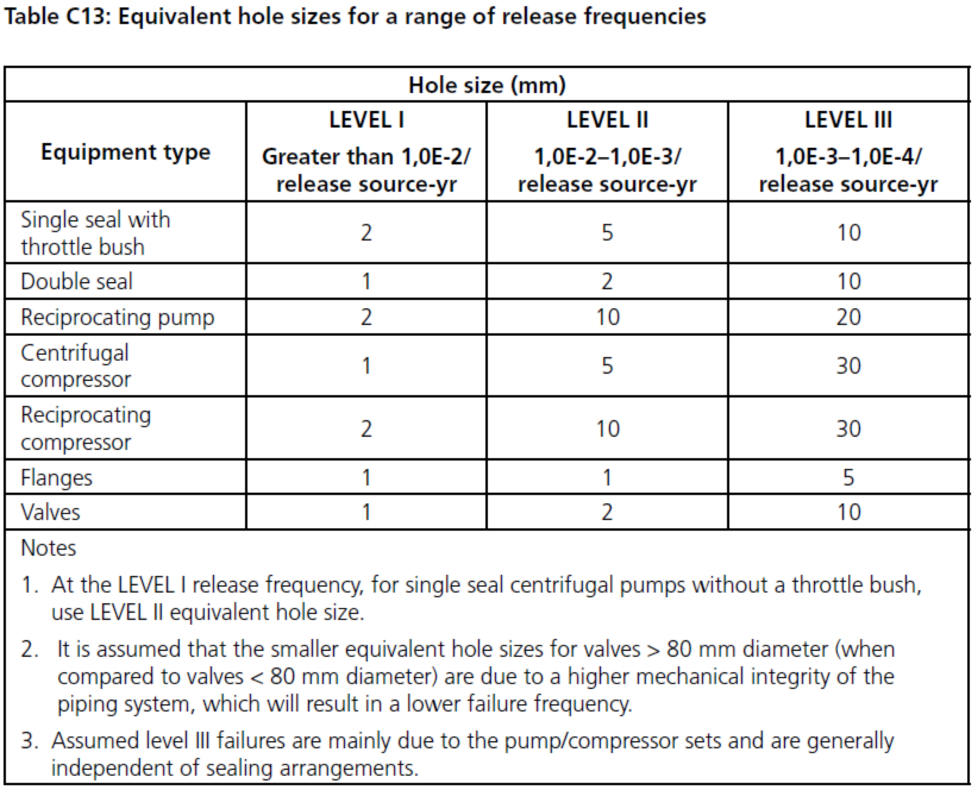


Table C13: Equivalent hole sizes for a range of release frequencies

Equipment type	Hole size (mm) LEVEL I Greater than 1,0E-2/ release source-yr	 LEVEL II 1,0E-2–1,0E-3/ release source-yr	 LEVEL III 1,0E-3–1,0E-4/ release source-yr
Single seal with throttle bush	2	5	10
Double seal	1	2	10
Reciprocating pump	2	10	20
Centrifugal compressor	1	5	30
Reciprocating compressor	2	10	30
Flanges	1	1	5
Valves	1	2	10

Notes

1. At the LEVEL I release frequency, for single seal centrifugal pumps without a throttle bush, use LEVEL II equivalent hole size.
2. It is assumed that the smaller equivalent hole sizes for valves > 80 mm diameter (when compared to valves < 80 mm diameter) are due to a higher mechanical integrity of the piping system, which will result in a lower failure frequency.
3. Assumed level III failures are mainly due to the pump/compressor sets and are generally independent of sealing arrangements.

<u>COMPRESSORS</u>

Piping on compressor systems are subject to vibration. The hazard radii recommended in the section 3.7.2 of EI 15 assume that failure of joints and nozzles due to vibration are considered to be catastrophic failures, and hence outside the scope of EI 15.

<u>Estimation of leak hole size and determination of hazard radii:</u> If available, manufacturer data for seal failure leak rates should be used to establish the hazard radii equivalent to a LEVEL I release. If manufacturer data are not available, Table C13 of the guidance (see Table 6 above) should be used. Having determined the hole size, the hazard radius (R1) (and, where required, R2) may be determined using Table C4 in Annex C Part 1 of EI 15.

<u>PIPING SYSTEMS</u>

Pipework designed and constructed to ISO 15649 Petroleum and natural gas industries – Piping, ANSI/ASME B31.3 Process piping, or equivalent that is fully welded should not be considered as a source of release.

Leakage is unlikely on infrequently used valves and these should therefore be regarded as sources of secondary grade releases. On frequently used valves (including control valves) with packed glands, where leakage is more likely due to wear on the packing, these should be regarded as producing an additional primary grade release with a nominal radius of 0.3 m. This value is fixed whatever the pressure.

Hole sizes for flanges and valves are given in Table C13 in Annex C Part 2 of EI 15. Having determined the hole size, the hazard radius (R1) may be determined using Table C4 in Annex C Part 1.

2.5.1.5 ISO 19880-1 Gaseous Hydrogen Fuelling Stations (2020)

From ISO 19880-1 [8] , some elements are mentioned in relation to Hazardous Area Classification such as:

- **shelter or a canopy** with a flat roof surface and with the sides sufficiently open to allow free passage of air through all parts should be considered well-ventilated and may be treated as an outdoor area (i.e. "medium" degree and "good" availability). If the canopy is within the height of the hazardous area, the hazardous area should extend to the border of the canopy (Section 7.4 A)
- Area classification around **venting system** outlets should be defined on the basis of a foreseeable flow rate, under normal operating conditions, but also considering reasonable potential upset or fault conditions with the exception of fire conditions and voluntary, manually initiated response to emergency conditions.

Moreover, in the section §8.4.4 of ISO 19880-1 [8] (Hazardous area around the dispenser), the hydrogen fuelling process is a “closed system” as there is no hydrogen vented to open air in the dispensing area. Per the design qualification procedures in the referenced standards of this section, the **allowable leakages from the dispensing system and fuelling assembly under normal operation are very small and not ignitable**. Even during the uncoupling of the nozzle from the receptacle on the vehicle, **the quantity of hydrogen released in the dispensing area is also insignificant**.

Additionally, the probability of a potentially hazardous leak is reduced by the utilization of the mitigation measures listed in Sections 8.2.1.6, 8.2.2.5 and 8.2.2.6 of ISO 19880-1 [8].
According to these elements, this standard assumes that the **presence of a flammable atmosphere in the dispensing area is therefore not expected during normal operation**, and the need to classify portions fuelling area should be established by risk assessment based on the likelihood and extent of component failures and mitigation measures being used (see 5.3.5.2 of the standard).

2.5.1.6 Supplement of Blue Book for Hydrogen Refuelling Stations

The Energy Institute produced the document “Guidance on Hydrogen delivery systems for refuelling of motor vehicles, co-located with petrol filling stations” or commonly known as ‘Supplement to the Blue Book’.

It is indicated that area classification for the hydrogen refuelling activities shall be carried out and it shall identify the applicable Gas Group and Temperature Class requirements. In addition, some examples are presented in Section 4.3 implementing some assumptions on the release, however, it is indicated that a Hazardous Area Classification should be calculated for the design and based on the methodologies developed in IEC 60079 or EI 15.

<u>Dispenser – Pressurised but not in use (idle):</u>
The dispensing equipment shall be identified by the dispenser manufacturer for the specific model proposed in accordance with the equipment's ATEX certification. Figure 1 shows the default zoning diagram for the dispenser when idle, however, where an equipment manufacturer supplies an alternative zoning diagram assessed as part of ATEX certification, this may be used. Information from operators suggest that couplings around breakaways can leak and therefore, **a Zone 2 of 1.5m was estimated by using a 0.1 mm diameter hole at a maximum operating pressure of 875 barg**.

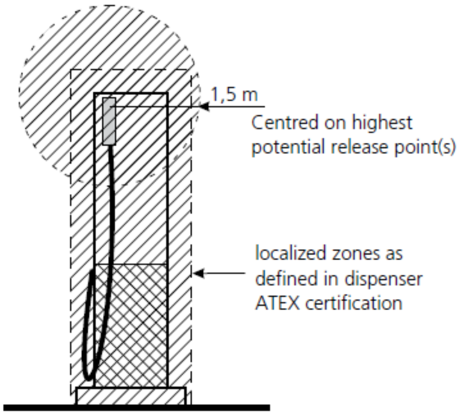


Figure 1 - Hazardous area classification of a hydrogen dispenser when not in use but pressurised (idle)

Figure 2 shows the hazardous area zoning around the dispenser when fuelling the vehicle, which is based on a failed hose in service (from a previous incident). It was assumed that the possibility of full pressure release is limited by the full pressure test, and by a pressure detection system within the dispenser. On this basis, **a Zone 2 of 1.5 m has been included using a 0.1 mm diameter hole size at the maximum operating working pressure of 875 barg**. There can be a small lower pressure puff of hydrogen when the nozzle is disconnected, however, due to the limited volume it will only result in a very small, if not negligible, Zone 1 around the nozzle.

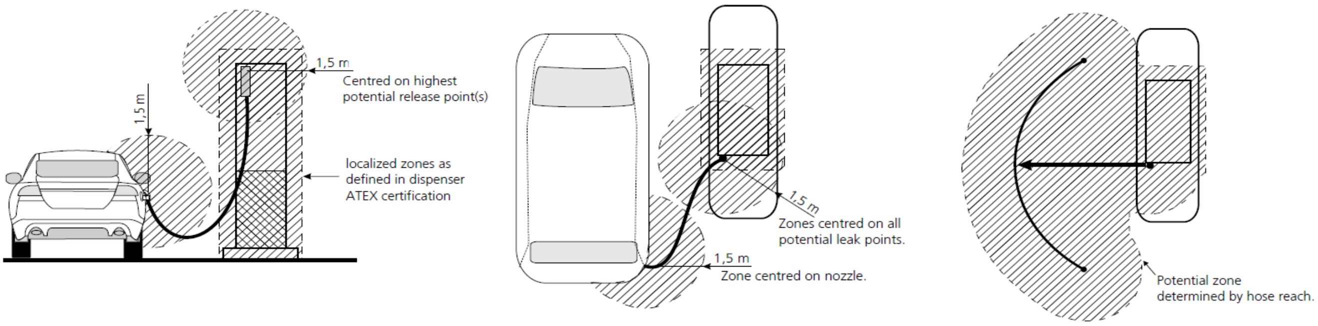


Figure 2 - Hazardous area classification of a hydrogen dispenser when refuelling the vehicle

Canopies installed on fuel dispensing sites typically contain electrical equipment that is not ignition-protected and enclosed areas where lighter-than-air gases could be trapped and accumulate. For most sites, the canopy will be outside of the hazardous area generated by a hydrogen dispenser and normal vehicle filling operations. Site designers should carry out assessments of the suitability of existing canopies in a large release situation when it is proposed to locate hydrogen dispensing equipment under them.

2.5.1.7 IGEM SR 25

IGEM/SR/25 takes a pragmatic approach to the determination of safe dispersion distance and represents the results in the form of tables. The dispersion of a natural gas release is determined by the interaction of the momentum and buoyancy forces of the release and the atmosphere within which it is dispersing.

A place in which an explosive atmosphere may occur to such an extent as to require special precautions to protect the health and safety of workers concerned (or the public) is deemed to be hazardous within the scope of DSEAR and must be assessed.

Secondary grade release:

A secondary grade release is defined as a 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 periods.

A. The following items shall be considered as sources of secondary grade releases with a nominal hole size of 0.25 mm^2
    - Pairs of flanges
    - Screwed fittings
    - Joints
    - Distribution regulators
    - Valve glandes

Note 1: The 0.25 mm^2 hole size assumes that the fuel is clean, dry natural gas in non-vibratory equipment. Otherwise, a 2.5 mm^2 hole size is applied.

Note 2: For metering installations and installation pipework with inlet pressures not exceeding MOP 100 mbar a hole size of 0.025 mm^2 can be considered.

B. The following shall be considered as sources of secondary grade release that are specific to the particular item of equipment and which in general are significantly larger than 0.25 mm^2 (based on natural gas installation as per IGEM/SR/25)
    - Small holes in the shell crown of watersealed gasholders
    - The outer seal on watersealed gasholders where prevention of overfilling cannot be ensured.
    - The cup and grip seals on watersealed gas holders where the integrity of the seal cannot be ensured.
    - The piston seal within waterless gas holders
    - Purge vents, drains and sample points if operating infrequently
    - Relief valve vents when operating
    - Process, machinery and instrument vents, if operating infrequently
    - Shaft seals on compressors and boosters/pumps

In certain circumstances (low pressures), secondary grades of release can be deemed to be from a nominal hole size of 0.025 mm^2 rather than 0.25 mm^2 or 2.5 mm^2. This, in turn, will often lead to a classification of Zone 2 NE.

Good maintenance that quickly identifies any potential or actual leakage sources is essential to maintain Zone 2 NE status.

Installation pipework

In un-obstructed locations, the areas around joints with an **operating pressure not exceeding 100 mbar** may be classified as Zone 2 NE, provided they are in a space having **ventilation above 0.25 air changes per hour**.

In obstructed locations that are congested or confined locations, the areas around new joints shall be classified as Zone 2 with a discrete zoning distance. The areas around the existing joints may need to be allocated a Zone 2 classification, unless additional measures are taken to permit a Zone 2 NE classification, such as increasing the artificial ventilation with flow interlocks and shut-off valves, the provision of gas detection systems or monthly checks of the environment for lack of gas leakage with combustible gas tester.

Primary grade release:

A primary grade release is defined as a release which can be expected to occur periodically or occasionally during normal operation.

The following items shall be considered as sources of Primary grade release:

- Purge vent pipe terminations, drain and sample points, if operating frequently
- The valve seat of closed purge vent pipes, drains and sample points, if not capped when not used
- The valve seat of relief valves that are not operating
- Process, machinery and vents, if operating frequently

Continuous grade release:

A continuous grade release is defined as a release which is continuous or is expected to occur frequently or for long periods.

Supplement for Hydrogen

The supplement is to be read in parallel with IGEM/SR/25 Edition 2 - with Amendments August 2013. The supplement outlines where there are differences in the approach for Hazardous Area Classification of installations handling hydrogen and blends of 20% hydrogen in volume in natural gas.

It is recommended that the shapes of zones around fixtures and fittings remain the same for hydrogen and blends as those used currently in IGEM/SR/25 for natural gas.

In clause 4.4.1 of the main standard, the nominal hole sizes were described for different conditions (normal and adverse conditions + low pressure installations). In the Supplement section 4, it is indicated that all statements made for natural gas in Section 4 of the main standard apply for hydrogen and blends up to 20% H2 in volume. In addition, Section 5 is recalculated for certain conditions (especially for hydrogen) using the same nominal hole size but considering the properties of hydrogen or hydrogen blend.

2.5.1.8 NFPA 2 – hydrogen technologies code

NFPA 2 [9] list extents of the zones around the dispenser in Table 10.4.6.1, reproduced in Table 7, however, the assumptions on hole diameter and pressure of the release are unknown. In addition, electrical area classification for gaseous hydrogen bulk storage are shown in Table 7.3.2.3.1.7.1 of the code and included in Table 8 of this document.

Table 7 - Dispenser area classification indicated in NFPA 2, clause 10.4.6

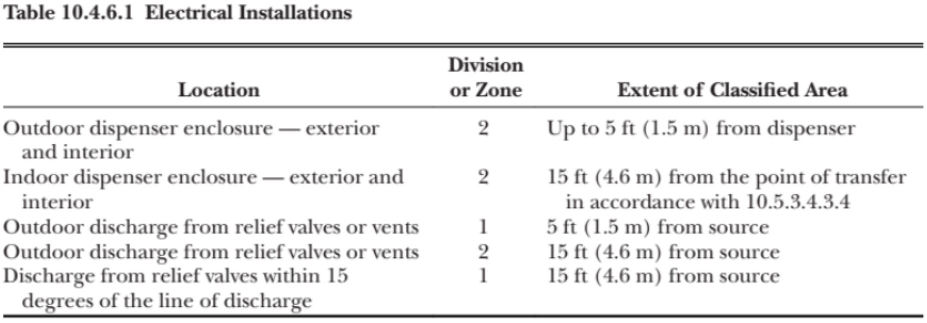


Table 10.4.6.1 Electrical Installations

Location	Division or Zone	Extent of Classified Area
Outdoor dispenser enclosure — exterior and interior	2	Up to 5 ft (1.5 m) from dispenser
Indoor dispenser enclosure — exterior and interior	2	15 ft (4.6 m) from the point of transfer in accordance with 10.5.3.4.3.4
Outdoor discharge from relief valves or vents	1	5 ft (1.5 m) from source
Outdoor discharge from relief valves or vents	2	15 ft (4.6 m) from source
Discharge from relief valves within 15 degrees of the line of discharge	1	15 ft (4.6 m) from source

Table 8 - Electrical area classification of Gas Hydrogen bulk storage NFPA 2, clause 7.3.2.3.1.7

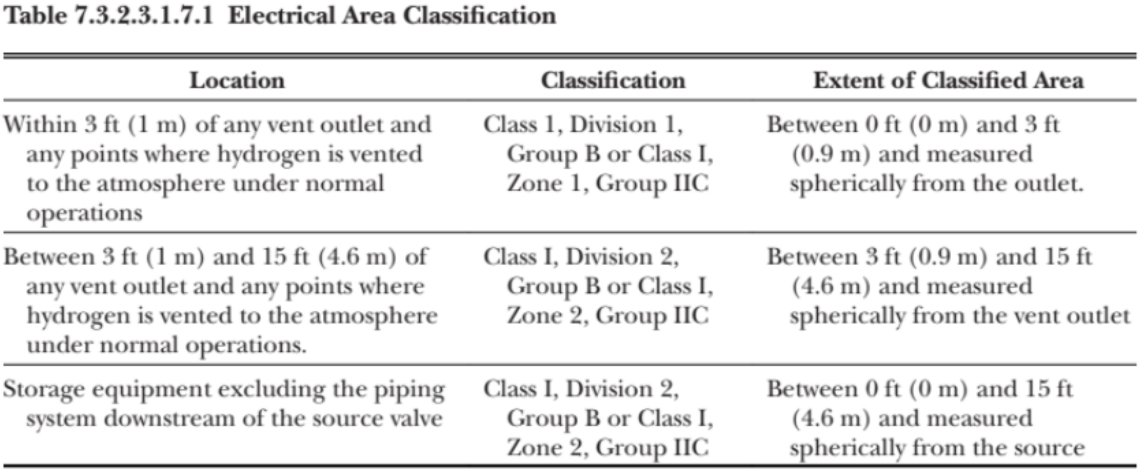


Table 7.3.2.3.1.7.1 Electrical Area Classification

Location	Classification	Extent of Classified Area
Within 3 ft (1 m) of any vent outlet and any points where hydrogen is vented to the atmosphere under normal operations	Class 1, Division 1, Group B or Class I, Zone 1, Group IIC	Between 0 ft (0 m) and 3 ft (0.9 m) and measured spherically from the outlet.
Between 3 ft (1 m) and 15 ft (4.6 m) of any vent outlet and any points where hydrogen is vented to the atmosphere under normal operations.	Class I, Division 2, Group B or Class I, Zone 2, Group IIC	Between 3 ft (0.9 m) and 15 ft (4.6 m) and measured spherically from the vent outlet
Storage equipment excluding the piping system downstream of the source valve	Class I, Division 2, Group B or Class I, Zone 2, Group IIC	Between 0 ft (0 m) and 15 ft (4.6 m) and measured spherically from the source

In addition, NFPA 2 present separation distances to different group exposures based on parameters on leak area and distance to the lower flammable limit (see section 3.2) as shown in Table 8.

2.5.1.9 BCGA Documentation

The British Compressed Gas Association published the Guidance Note 13 regarding the DSEAR Risk Assessment [10], aiming to act as guide for the generation of DSEAR Assessment for customer applications following the Dangerous Substances and Explosive Atmospheres Regulation 2002 (DSEAR Regulations).

In this document, examples of release calculations, dispersion calculations and risk assessment are shown, which are based on the nominal hole size from IP15 2nd Edition of **0.1 mm.**

2.5.2 Quantification of mass release rate (chocked/non-chocked flow)

Before calculating the release, it should be known whether the flow will be choked or not. The velocity of released gas is choked if the pressure inside the gas container is higher than the critical pressure ($p > p_c$) – this can be calculated using Equation 1:

$$p_c = p_a \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{(\gamma-1)}}, \qquad \text{(Equation 1)}$$

Where P_0 is the atmospheric pressure and γ is the polytropic index of adiabatic expansion.

For a non-chocked flow, the mass release rate can be estimated as follows using Equation 2:

$$W_g = C_d \times S \times p \times \sqrt{\frac{M}{ZRT} \times \frac{2\gamma}{\gamma-1} \times \left[1 - \left(\frac{p_a}{p}\right)^{\frac{(\gamma-1)}{\gamma}}\right]} \times \left(\frac{p_a}{p}\right)^{\frac{1}{\gamma}}, \qquad \text{(Equation 2)}$$

Where C_d is the coefficient of discharge, S is the surface of the opening, M is the molar mass of the gas, R is the universal gas constant, T is the temperature, P is the gas pressure and Pa is the atmospheric pressure.

For the case of choked flow, the mass flow rate could be estimated by the following Equation 3:

$$W_g = C_d \times S \times p \times \sqrt{\gamma \frac{M}{ZRT} \times \left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{(\gamma-1)}}}, \qquad \text{(Equation 3)}$$

2.6 Type of ventilation

Air movement due to natural or artificial ventilation will promote dispersion. As defined in guidance for H_2 delivery systems for refuelling of motor vehicles [11], ventilation indicate air movement and replacement by fresh air and can be natural or artificial. Natural ventilation refers to ventilation caused by wind or convection effects whereas artificial ventilation refers to ventilation caused by air purges or mechanical means such as fans.

2.6.1 Natural ventilation

For natural ventilation, if we consider area outside in open air, air movement due to wind can be sufficient to ensure dispersal of any explosive gas atmosphere which arises in the area. Table C.1 of IEC 60079-1 2021 provides guidance on wind speed for outdoor situations and give indicative values for outdoor ventilation velocities. For example, for hydrogen, the velocities recommended by the standard IEC goes from **0.5m/s to 2m/s** depending on the obstruction degree of the area and on the elevation from ground level.

On the other hand, the natural ventilation of enclosed area is driven primary by two forces: the atmospheric wind outside the enclosure, which gives rise to pressure distribution around the external faces of the enclosure, and buoyancy forces, which result from temperature differences between the inside and outside of the enclosure. The flow rate of air into and out of enclosed area due to natural ventilation can be predicted using a range of approaches, from simple analytical approaches to complex CFD simulations to tracer measurement [1].
Hereafter, some examples of natural ventilation for building IEC 60079-1 2020 [12]:

- an open building which, having regard to the relative density of the gases and/or vapours involved, has openings in the walls and/or roof so dimensioned and located that the ventilation inside the building, for the purpose of hazardous area classification, can be regarded as equivalent to that in an open-air situation;
- a building which is not an open building but which has natural ventilation (generally less than that of an open building) provided by permanent openings made for ventilation purposes.

Moreover, as mentioned in IEC 60079-1 2021, some elements to have in mind for natural ventilation inside enclosures:

- The indoor temperature must be higher than the outdoor temperature to achieve the necessary conditions for buoyancy induced ventilation. During periods of high outdoor ambient temperatures, the indoor temperature may become lower than the outdoor unless there is some heat source indoors. Temperature gradients are also affected by the substance of the building and for some constructions the indoor temperature may be lower than the outside temperature under certain conditions.
- The greater the vertical distance between the midpoints of the lower and upper openings, the more effective the natural ventilation will be. For buoyancy induced ventilation, the most desirable position for the inlet openings is at the bottom of the opposite walls and for outlet openings, at the roof top. However, where this is not feasible, the inlet and outlet openings should be positioned at the opposite walls to provide for air movement across the whole area.

Clause C.5.3 develops a methodology for the estimation of ventilation due to buoyancy effect, considering the effective area and the difference of temperature.

2.6.2 Artificial or forced ventilation

As described in IEC 60079-10-1:2020 [12], air movement required for ventilation may be provided by artificial means, for example, fans or extractors. Although artificial ventilation is mainly applied inside a room or enclosed space, it can also be applied to situations in the open air to compensate for restricted or impeded air movement due to obstacles.

The artificial ventilation may be either general (e.g. a whole room) or local (e.g. extraction near a point of release) and for both of these, differing degrees of air movement and replacement can be appropriate.

With the use of artificial ventilation, it is sometimes possible to achieve:

- reduction in the type and/or extent of zones;
- shortening of the time of persistence of an explosive gas atmosphere;
- prevention of the generation of an explosive gas atmosphere.

IEC 60079-10-1:2020 [12] explains how artificial ventilation can provide an effective and reliable ventilation system in an indoor situation. The following considerations should be included for artificial ventilation systems:

a) classification of the inside of the extraction system and immediately outside the extraction system discharge point and other openings of the extraction system;
b) for ventilation of a hazardous area the ventilation air should normally be drawn from a non-hazardous area taking into account the suction effects on the surrounding area;
c) before determining the dimensions and design of the ventilation system, the location,

grade of release, release velocity and release rate should be defined.

In addition, the following factors will influence the quality of an artificial ventilation system:

a) flammable gases and vapours usually have densities other than that of air, thus they may accumulate near to either the floor or ceiling of an enclosed area, where air movement is likely to be reduced;
b) proximity of the artificial ventilation to the source of release; artificial ventilation close to the source of release will normally be more effective and may be needed to adequately control gas or vapour movement;
c) changes in gas density with temperature;
d) impediments and obstacles may cause reduced, or even no, air movement, i.e. no ventilation in certain parts of the area;
e) turbulence and circulating air patterns.

For more details, see Annex C of IEC 60079-10-1:2020 [12].

2.7 Zone of Negligible Extent

The standard IEC 60079-10-1:2020 [12] defines a Zone of Negligible (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. In such cases, the zone NE may be treated as a non-hazardous area.

An example of Zone NE is developed for natural gas, which is defined as a 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). However, for other gases, the standard proposes to allow modification of the reference volume used for natural gas 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.

The criteria for a Zone NE classification should be based on the following factors as indicated in IEC 60079-10-1:2020 [12]:

- Ignition would not result in sufficient pressure to cause harm wither due to the pressure wave or due to damage that could cause flying objects or particles.
- Ignition would not result in sufficient heat to cause harm or a fire from surrounding materials.
- For a gas distributed at pressures above 10 barg, consideration shall be given to a specific risk assessment.
- A zone NE shall not be applied to gas distributed at pressures above 20 barg unless a specific detailed risk assessment can document otherwise.

A case study of the classification of Zone of Negligible Extent in an electrolyser enclosure, including a proposed analysis for the specific detailed risk assessment, is detailed in Appendix C of this document.

2.8 Methodologies (Internal and External)

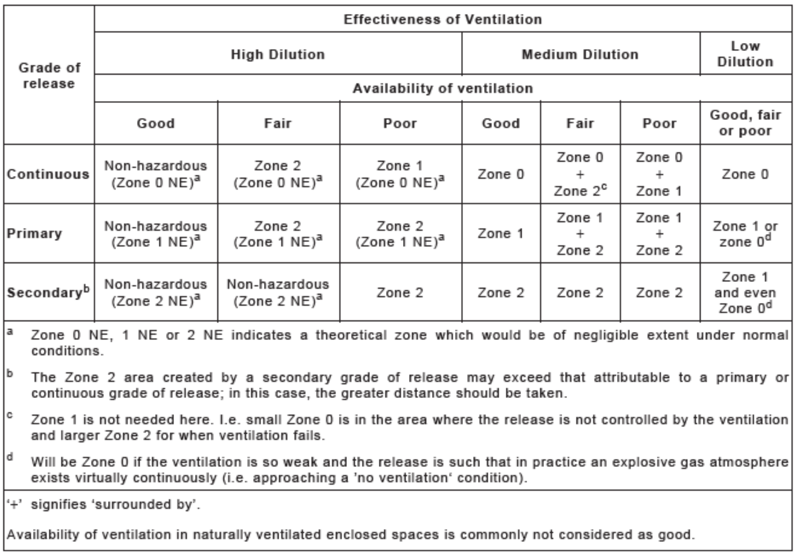
2.8.1 IEC 60079-10-1:2020: Annex B, C, D

Annex B, C and D of IEC 60079-10-1:2020 [12] provides guidance on the estimation and extent on the zone by considering the following factors:

- Type of release
- Ventilation characteristics: degree of dilution and effectiveness
- Availabitily of ventilation

Table D.1 of IEC 60079-10-1:2020 [12] suggest a classification of areas depending on the degree of dilution, release rate and type of release as illustrated in Table 9

Table 9 - Zones for grade of release and effectiveness of ventilation (table D.1 from [12])



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.

In Annex C3.5, the **degree of dilution** is defined as follows:

- High dilution: The concentration around the source decreases quickly and will be virtually no persistence after the release has stopped.
- Medium dilution: The concentration is controlled and results in a stable zone boundary. Whist the release is in progress and the explosive gas atmosphere does not persist after the release has stopped.
- Low dilution: There is significant concentration whilst the release is in progress and/or significant persistence of an explosive atmosphere after the release has stopped.

In Annex C, the standard IEC 60079-10-1:2020 [12] suggest that Figure C.1, Figure 3 in this report, may be used to determine the degree of dilution in the space under consideration. The dilution degree would be determined by estimating the volumetric release characteristic of the source (Q_c) and the ventilation velocity (u_w). Considerations for the determination of the ventilation velocity are detailed in clause C.3.4 of the standard. The characteristic volumetric release of the source is estimated from the mass flow rate of the leak (W_g), the lower flammability limit (LFL) and the density of the gas (ρ_g) as shown in Equation 4. IEC 60079-10-1:2020 [12] notes that a safety factor is not included in the formula and a safety factor should be determined by the designer of the application.

$Q_C = \frac{W_g}{\rho_g \times LFL}$, (Equation 4)

The gas density is calculated using Equation 5, where p_a (Pa) is the atmospheric pressure, T_a (K) is the ambient temperature.

$\rho_g = \frac{p_a \times M}{R \times T_a}$, (Equation 5)

The determination of the ventilation velocity is described in clause C.3.4 of IEC 60079-10-1:2020 [12]. For indoor scenarios, the flow or ventilation velocity may be based on the average flow velocity caused by the ventilation. This may be calculated as the volumetric air/gas mixture divided by the cross-section area perpendicular to the flow.

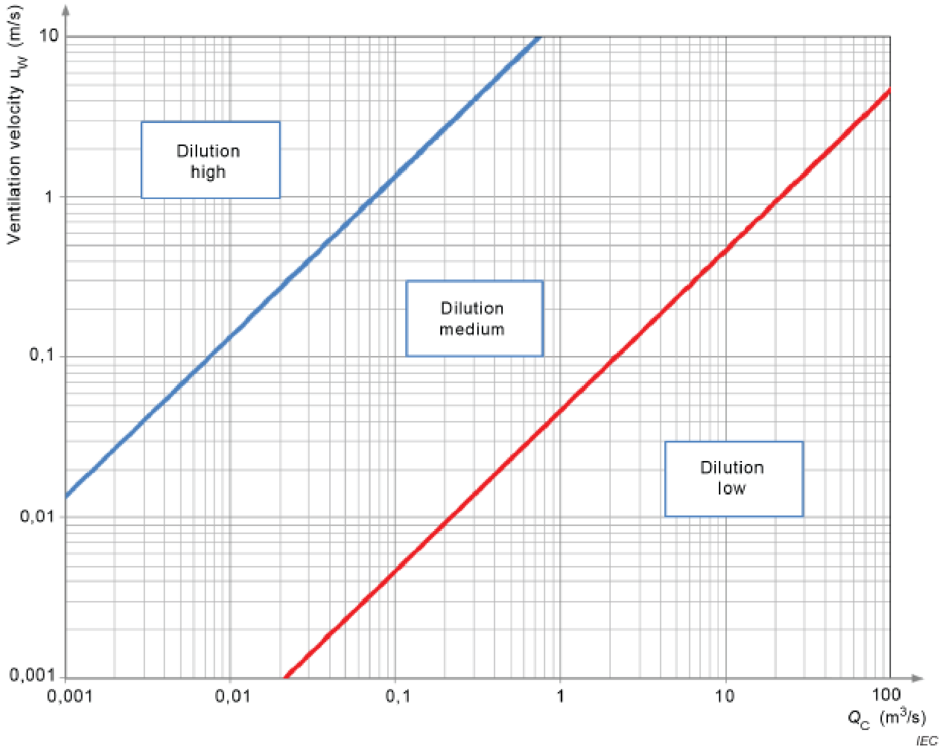


Figure 3 - Dilution level for the release in the example using Figure C.1 from IEC 60079-10-1:2020 [12]

Once the characteristic volumetric flow rate and ventilation velocity has been estimated, the degree of dilution can be determined using Figure C.1 of IEC 60079-10-1:2020 [12]. For indoor applications, clause C.3.6.2 of the standard indicates that 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. The background concentration may be assessed as:

$X_b = \frac{f \times Q_g}{Q_2}$, (Equation 6)

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). Q_2 can be calculated as follows:

$Q_2 = C \times V_0,$ (Equation 7)

Figure D.1 of IEC 60079-10-1:2020 [12] (Figure 4) may be used as for the determination of the extent of a hazardous area. The curves are based on a zero-background concentration and are not applicable for indoor medium and low dilution situations. The curves in chart of Figure D.1 (Figure 4) are based upon CFD simulations for different "ventilation velocities". The distances in the chart are given to be reasonably worst-case for the given release. This has been compared with CFD simulations and the distances given in reputable industry codes.

Extrapolation of the curves beyond the chart area shown in should not be undertaken due to other factors that will affect the assessment beyond the limits indicated, even though hazardous distances can be less than 1 meter as well as higher than those shown in Figure D.1 of the standard (see Figure 4). The appropriate line should be selected based on the type of release:

- Jet: Unimpeded release with high velocity (unobstructed releases at pressure)
- Diffusive: Low velocity jet (sub-sonic) or jet that loses its momentum due to the geometry or impingement of the jet
- Heavy gas: not applicable to hydrogen.

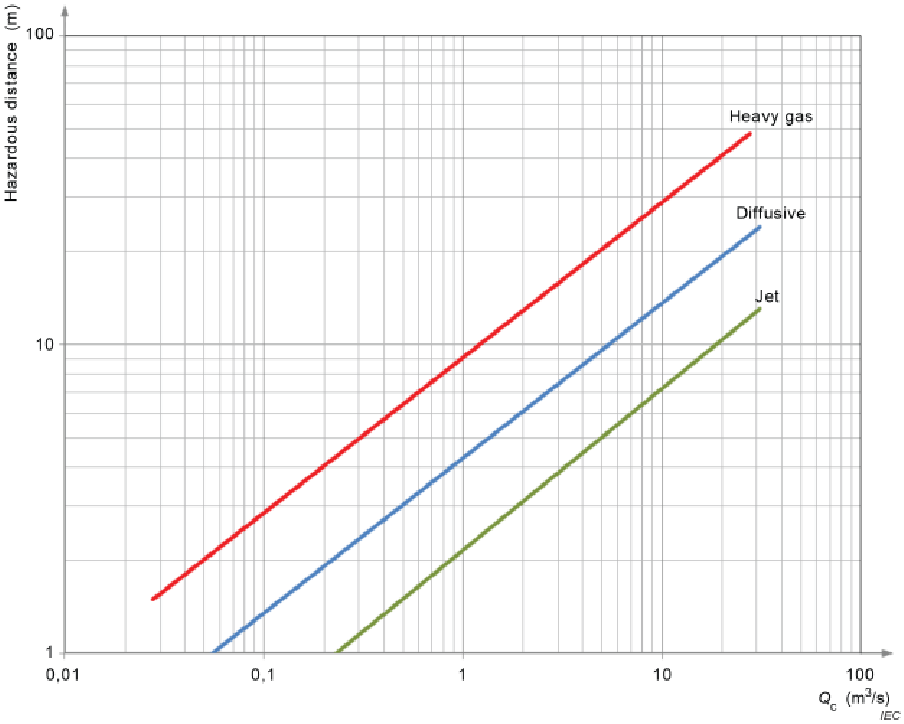


Figure 4 - Figure for estimating the extent of a Hazardous Area (Figure D.1, IEC 60079-10-1:2020 [12])

2.8.2 EI15 Code of Practice

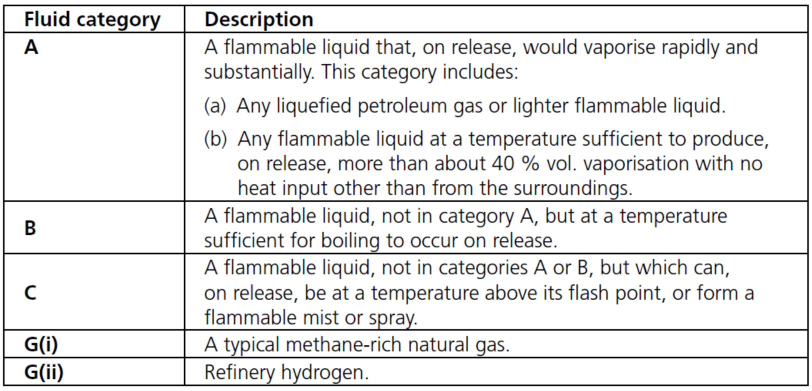
The EI15 Code of Practice presents three methodologies to be used in area classification. The extent of the hazardous area is performed in the document to the LFL limit, rather than ½ LFL.

2.8.2.1 Point Source approach

For cases in which the release rate, pressure and hole size are known, the point source approach can be implemented. The approach is based in the steps below:

- Identify point sources and release conditions
- Determine a grade of release (see Section 3.1.1.2 of EI15)
- Determine fluid category: For the determination of the extent of a release, tables of radii depending on the type of release, hole size and type of fluid are present in Section 3 and Annex C of the Code of Practice. The document divides the fluid in the categories shown in Table 10 where hydrogen is classified as G(ii).

Table 10 - Fluid categories as defined in EI 15 (2015)



Fluid category	Description
A	A flammable liquid that, on release, would vaporise rapidly and substantially. This category includes: (a) Any liquefied petroleum gas or lighter flammable liquid. (b) Any flammable liquid at a temperature sufficient to produce, on release, more than about 40 % vol. vaporisation with no heat input other than from the surroundings.
B	A flammable liquid, not in category A, but at a temperature sufficient for boiling to occur on release.
C	A flammable liquid, not in categories A or B, but which can, on release, be at a temperature above its flash point, or form a flammable mist or spray.
G(i)	A typical methane-rich natural gas.
G(ii)	Refinery hydrogen.

- Establish Zone classification: The zone classification must be determined from the grade of release, the duration of flammable atmosphere and the degree of ventilation.
- Determine hazard radii: The extent determination will depend on the grade of the release:

  - Continuous/Primary: Release rate are expected to be known, as they should have been anticipated in the design. If the process conditions for the equipment/arrangement are covered in Annex C of the document, the radius R_1 and/or R_2 can be determined using the information in Section 3 and Annex C. Otherwise, a dispersion modelling is required to determine the extent.
  - Secondary: For secondary releases if the process conditions and diameter is covered by Annex C (specifically Table C4) of the code of practice, R1 and R2 can be determined from the Table (covered in section 2.5.1.4 of this document). Otherwise, a dispersion modelling is required to determine the extent.

- Determine hazardous area: The hazardous area would be a three dimensional representation using the hazard radii estimated in the previous step, and considering the ventilation characteristics around the release.
- When appropriate, combine hazardous areas from different release sources.

2.8.2.2 Risk-based approach

For systems in which the release rate is of an unknown, unspecified and variable quantity, the risk-based approach is proposed to determine the hole size to be used. The risk-based approach provides a means of adjusting the release frequency and hence the hazard radii to a specific process.

The criterion adopted in the code of practice is that the total individual risk due to an ignited release should not exceed 1x10^{-5}/yr. The analysis will depend on the grade of the release:

- Continuous/Primary releases: The releases are known and the extent can be determined using dispersion models. The probability of a flammable atmosphere being present can also be determined. The main unknowns are the occupancy and the frequency of ignition.
- Secondary releases: As the size of the leak and release of rate are unknown, the aim of the approach is to determine the outer limit of the zone at which unclassified ignition sources may be located. Historical data have been used to develop a "leak vs frequency relationship". By setting values of ignition probability, individual exposure to a zone 2 and vulnerability to an ignited release, the leak size corresponding to the maximum frequency of release determining the Zone boundary may be established. A detailed description of the methodology is presented in Annex C -Part 2 of EI (2015).

2.8.2.3 *Direct example approach*

For arrangements of generic industrial equipment handling common flammable materials, direct examples presented in Annex D of the code can be applied for the classification. This approach should only be applied when the facility under consideration does not differ considerably from the example.

2.8.3 IGEM/SR/25 Edition 2 - Hazardous area classification of natural gas installations

The hazardous area classification depends on the grade of release, operating pressure, ventilation, environmental conditions, confinement and congestion. The following definitions are relevant for the classification of areas for IGEM/SR/25 [13]:

Ventilation

The ventilation is classified as follows:

- Natural ventilation: ventilation through enclosed space where the flow of air is generated by wind and/or buoyancy effect.
- Artificial ventilation: ventilation through an enclosed space where the flow of air is forced or induced by mechanical means.
- More than adequate ventilation: any means of ventilation is sufficient to ensure a gas concentration in excess of 10% LFL is unlikely outside of the classified zone.
- Adequate ventilation: any means of ventilation that is sufficient to ensure that a gas concentration in excess of 25% LFL is unlikely outside the classified zone.
- Inadequate ventilation: any lesser level of ventilation than that required to achieve the objective of adequate ventilation.
- Poor ventilation: levels lower than "inadequate ventilation".

Adverse conditions

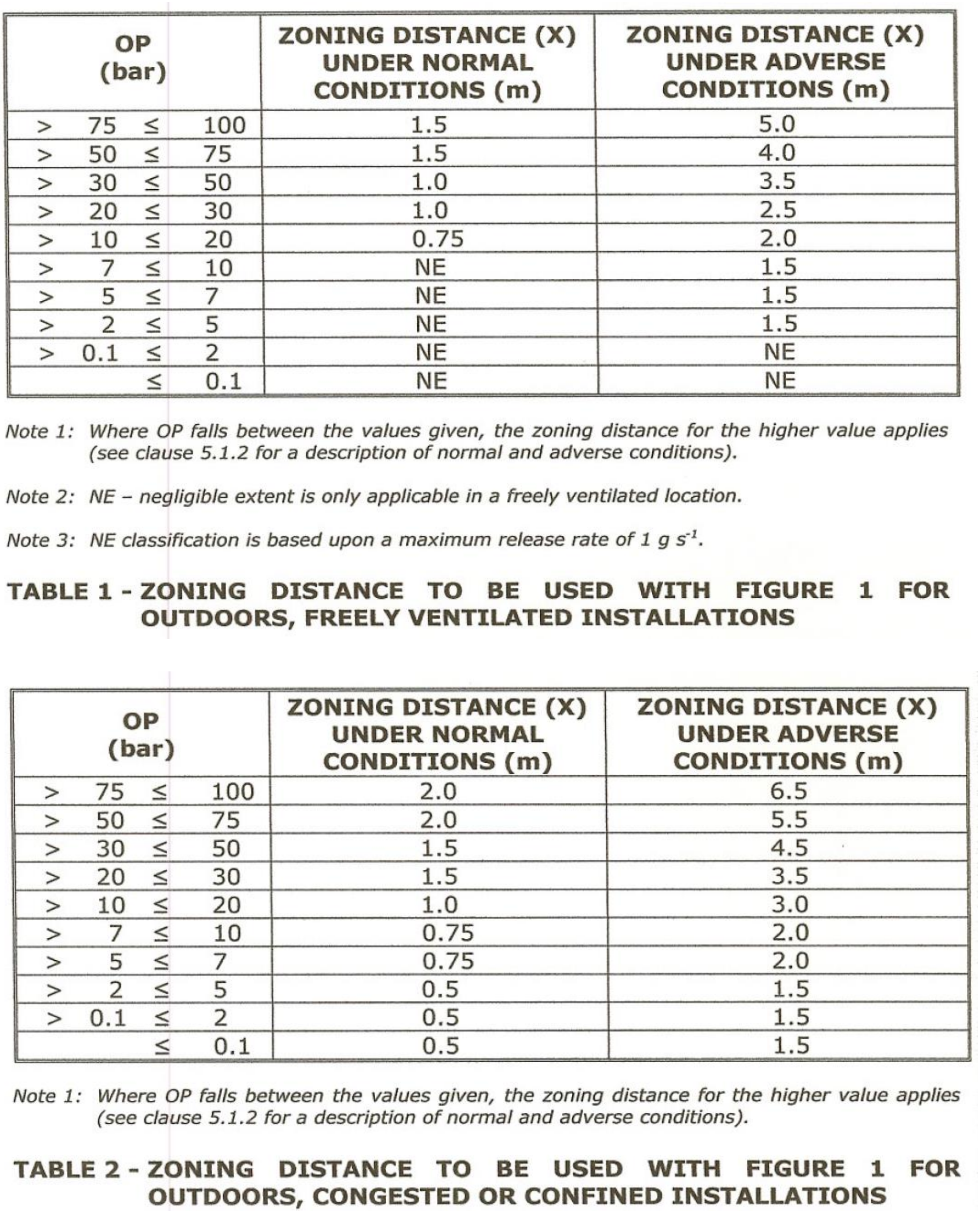
The gas is not clean or not dry, or is contained in vibrating equipment, or is contained in plant which is sited in a corrosive atmosphere, which will include coastal sites.

Confinement and congestion

A potential leak area around which there are obstructions to the air flow such as large items of plant, a high density of pipework, or the proximity to the floor, wall or ceiling.

2.8.3.1 Outdoors

For flanges, screwed fittings, joints, regulators valve connections and valve glandes, IGEM/SR/25 (and for hydrogen IGEM/SR/25 Hydrogen Supplement), the extent are tabulated in tables and should be used with Figure 5 of this report, taken from the standard for the representation of the zone.



OP (bar)	ZONING DISTANCE (X) UNDER NORMAL CONDITIONS (m)	ZONING DISTANCE (X) UNDER ADVERSE CONDITIONS (m)
> 75 ≤ 100	1.5	5.0
> 50 ≤ 75	1.5	4.0
> 30 ≤ 50	1.0	3.5
> 20 ≤ 30	1.0	2.5
> 10 ≤ 20	0.75	2.0
> 7 ≤ 10	NE	1.5
> 5 ≤ 7	NE	1.5
> 2 ≤ 5	NE	1.5
> 0.1 ≤ 2	NE	NE
≤ 0.1	NE	NE

Note 1: Where OP falls between the values given, the zoning distance for the higher value applies (see clause 5.1.2 for a description of normal and adverse conditions).

Note 2: NE – negligible extent is only applicable in a freely ventilated location.

Note 3: NE classification is based upon a maximum release rate of 1 g s^{-1}.

TABLE 1 - ZONING DISTANCE TO BE USED WITH FIGURE 1 FOR OUTDOORS, FREELY VENTILATED INSTALLATIONS

OP (bar)	ZONING DISTANCE (X) UNDER NORMAL CONDITIONS (m)	ZONING DISTANCE (X) UNDER ADVERSE CONDITIONS (m)
> 75 ≤ 100	2.0	6.5
> 50 ≤ 75	2.0	5.5
> 30 ≤ 50	1.5	4.5
> 20 ≤ 30	1.5	3.5
> 10 ≤ 20	1.0	3.0
> 7 ≤ 10	0.75	2.0
> 5 ≤ 7	0.75	2.0
> 2 ≤ 5	0.5	1.5
> 0.1 ≤ 2	0.5	1.5
≤ 0.1	0.5	1.5

Note 1: Where OP falls between the values given, the zoning distance for the higher value applies (see clause 5.1.2 for a description of normal and adverse conditions).

TABLE 2 - ZONING DISTANCE TO BE USED WITH FIGURE 1 FOR OUTDOORS, CONGESTED OR CONFINED INSTALLATIONS

Figure 5 - Tables from IGEM/SR/25 for determination of the zone extent for outdoors installations (Natural gas)

2.8.3.2 Within buildings

For releases within buildings, the assessment is based on the determination of the level of ventilation, for which the estimation of the total release rate is very important.

Total gas release rate

The total release rate of gas (G) within an enclosed space is the sum of the total release from all sources of Continuous grades of release, the largest total release of any combination of Primary grade of release likely to be released simultaneously, and the release rate from Secondary grades of release that are likely to be released simultaneously.

The total release rate (G) is defined below from primary (G_P) and secondary releases (in Normal - G_{SN} and Adverse conditions - G_{SA})

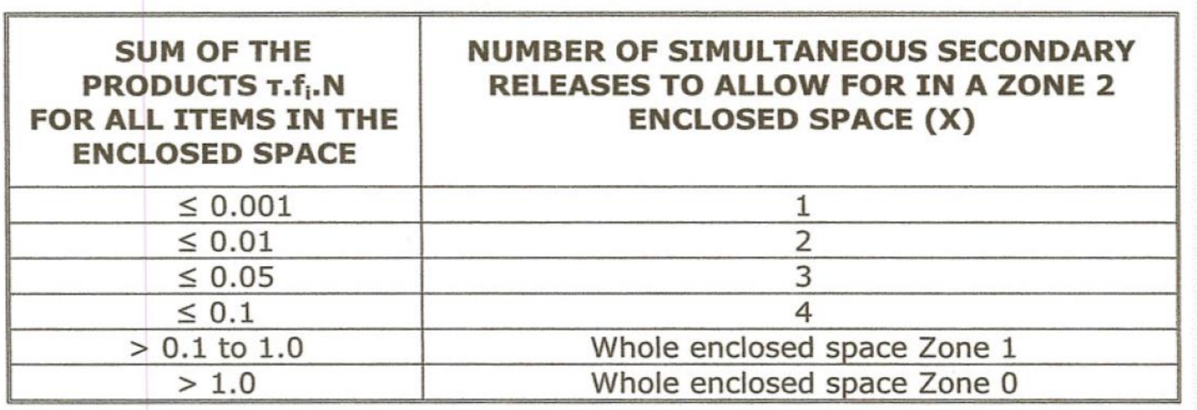
$G = G_P + G_{SA} + G_{SN}$

For secondary releases, the number of releases at both normal (N_{SN}) and adverse (N_{SA}) conditions need to be counted. In addition, the shortest time between inspections for the sources (T_{SN} for normal conditions and T_{SA} for adverse conditions), In order to determine the number of releases that are likely to be present at the same time, the factor of the inspection period, number of releases and frequency of failures per year needs to be estimated.

$T_{SN} \times f_i \times N_{SN}$ and $T_{SA} \times f_i \times N_{SA}$

For hydrogen applications, an additional factor should be incorporated as indicated in Table 6BH of the IGEM/SR/25 supplement. In order to determine the number of simultaneous releases, the factor $T \times f_i \times N$ should be added for each type of fitting and the resultant value should be compared with Table 7 of the standard, provided below in Table 11.

Table 11 - Simultaneous secondary release from IGEM/SR/25 (Table 7)



SUM OF THE PRODUCTS $\tau.f_i.N$ FOR ALL ITEMS IN THE ENCLOSED SPACE	NUMBER OF SIMULTANEOUS SECONDARY RELEASES TO ALLOW FOR IN A ZONE 2 ENCLOSED SPACE (X)
≤ 0.001	1
≤ 0.01	2
≤ 0.05	3
≤ 0.1	4
> 0.1 to 1.0	Whole enclosed space Zone 1
> 1.0	Whole enclosed space Zone 0

The flow rate from individual releases is calculated for hydrogen using equations S5.1H or S5.2H depending on the operational pressure.

Determination of level of ventilation

Natural ventilation can be divided into buoyancy driven and wind driven ventilation. The determination of the level of ventilation (more than adequate, adequate, inadequate and poor) can be determined from the vertical distance between openings and the total release rate using the correlations of Annex A7.2 of the standard.

For hydrogen releases, an additional factor F shall be used in the correlations as per IGEM/SR/25 Hydrogen supplement (S7.2), where F is 6.3 to hydrogen and 1.1 for the blend. An example of the equations for the case the ventilation is provided in two walls, the buoyancy driven ventilation is "more than adequate" if A $\geq A_{b,10}$ (A is the total free ventilation area of cross section area)

IGEM/SR/25	Hydrogen Supplement
$A_{b,10} = 7762\ G\ L^{-0.5}$	$A_{b,10} = 7762\ F\ G\ L^{-0.5}$

2.8.4 Dispersion models

2.8.4.1 Quadvent

Quadvent software has been developed by the Health and Safety Executive (HSE) to be used as a tool to perform Hazardous Area Classification, however, a specific standard or guidance would need to be followed for the classification. Quadvent models a gas jet (1D), a two-phase jet or a buoyant plume release into a ventilated room (naturally/artificially) or outdoors. The turbulent jet or plume entrains air containing a background concentration gas, and becomes more diluted as it gets further from the source. If the jet is outdoors, then no background concentration builds-up, and the hazardous volume is defined by the size of the jet/plume.

In indoor conditions, air enters the room through ventilation openings, and a mixture of gas + air leaves through other openings. The mean background concentration is determined by the balance of the source rate of flammable gas and the ventilation rate with which air enters and mixture leaves the room.

Webber *et al*., (2011) and Santon *et al*., (2012) describe assumptions and equations solved for the dispersion calculations of jet and plume releases. It is based on 1-dimensional steady-state flow equations considering momentum, mass balance and "contaminant" mass balance for sub-sonic jets and plumes, which are calculated for a pseudo-source in a chocked flow scenario.

Equation	Jet	Plume
Momentum	$\frac{d(\rho u^2 A)}{dz} = 0$	$u = u_a$
Mass	$\frac{d(\rho u A)}{dz} = (2\pi r)\rho_b u_E$	$\frac{d(\rho u A)}{dz} = (2\pi r)\rho_b u_E$
Contaminant	$\frac{d(CuA)}{dz} = (2\pi r)C_b u_E$	$\frac{d(CuA)}{dz} = (2\pi r)C_b u_E$

The model is completed by the sub-model for entrainment of Ricou and Spalding (1961) and its use is as described in Equation 8:

$$u_E = \alpha \sqrt{\frac{\rho}{\rho_b}} u \qquad \text{(Equation 8)}$$

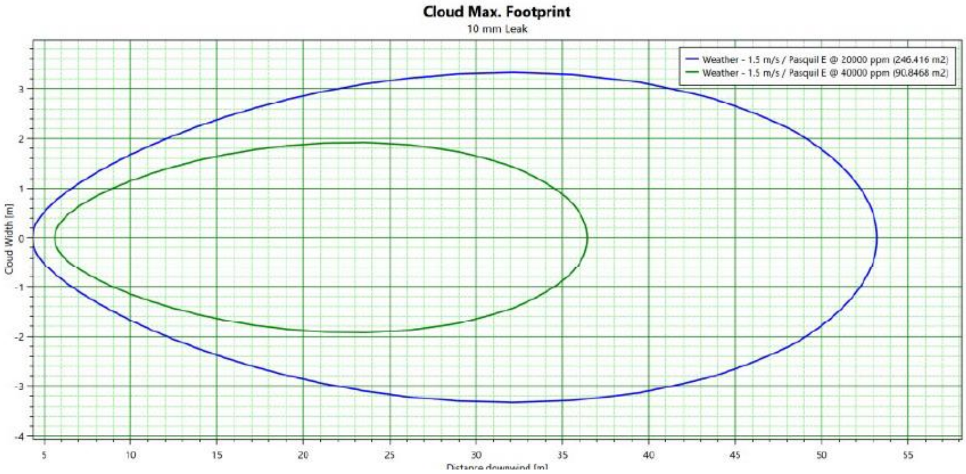
2.8.4.2 PHAST

PHAST (Process Hazard Analysis Software Tool) is a commercially-available analysis tool to examine consequences associated with a hazardous scenario, from the initial release to far field dispersion of a toxic and/or flammable gas. PHAST is able to simulate various release scenarios such as leaks, line ruptures, long pipeline releases and tank roof collapse in pressurised and unpressurised vessels or pipes. PHAST encompasses:

- dispersion modeling using the similarity laws described
- explosion models using an empirical approach for consequence determination

For our application of Hazardous Area Classification, we will use only the dispersion modelling module and sequence.

PHAST, after the definition of the accidental scenario, allows to establish the maximum extent of the flammable plume in the surrounding environment as a function of time. Usually the hydrogen's lower flammability limit is considered equal to a value between 40,000 ppm and 80,000 ppm using an engineering approach. Dispersion charts, as a function of the hydrogen concentration, the plume width, height and distance downwind as a function of time.



The dispersion charts are computed using the Unified Dispersion Model [14] based on similarity law profiles (described in the subsection 2.8.4.3).

Then, the concentration profiles of the flammable cloud are used to determine the flammable mass of the fuel-air mixture in the volume considered to contribute to the explosion, which is calculated by integrating the cloud volume part, whose concentration is within the flammable range (i.e. between the LFL (lower flammable limit, 4 %) and UFL (upper flammable limit, 75 %).

For the determination of Hazardous Area Classification we are inclined to use **20 000ppm (50% LFL H2) as the concentration to determine the ATEX zoning**.

2.8.4.3 Molkov – e-laboratory

Molkov (2012) presents a similarity law for estimating the concentration decay in under-expanded H_2 jets. The model can be used to determine distances to H_2 concentrations of interest, such as the LFL or ½ LFL of H_2 in air. The model is based on the original concentration decay law proposed by Chen and Rodi (1980) for expanded jets. In comparison to experimental data, the model gives conservative estimates of the distance to a given concentration.

In the similarity law for concentration decay, Equation 9 is used to determine the distance, X, to a given concentration of interest, C, on the jet centreline. Here, ρ is the density with the subscripts N and S representing conditions at the nozzle and in the surrounding fluid, respectively, and D is the nozzle/leak diameter.

$$X = \frac{5.4D}{C}\sqrt{\frac{\rho_N}{\rho_S}} \qquad \text{(Equation 9)}$$

2.8.4.4 HYRAM+ – Hydrogen Plus Other Alternative Fuels Risk Assessment Models

According to [15], HyRAM+ is a software toolkit that provides a basis for quantitative risk assessment and consequence modelling for hydrogen infrastructure and transportation systems. HyRAM+ integrates validated, analytical models of hydrogen behaviour, statistics, and a standardized QRA approach to generate useful, repeatable data for the safety analysis of various hydrogen systems.

The HyRAM toolkit uses deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterising the impact of hydrogen hazards, including dispersion of hydrogen, thermal effects from jet fires and overpressure effects from deflagration. HyRAM incorporates models for the impact of heat flux on humans and structures, with computationally and experimentally validated models of various aspects of gaseous hydrogen release and flame physics.

The equation of state used for hydrogen is based on CoolProp [16] library to perform several thermodynamic calculations [16]. The property calculations are based on a Helmholtz energy function, and account for the real gas behavior at high pressures. For hydrogen, the relationships and energy functions are detailed in Leachman *et al*. [17] These thermodynamic calculations are used to calculate leak rates and are used in mass, momentum, and energy balances in regions close to the leak point.

HyRAM+ assumes that fluids flow isentropically through an orifice. CoolProp [16] is used to calculate the entropy and enthalpy of the fluid upstream of an orifice, using the specified pressure and temperature; notional nozzle models are used to calculate the effective diameter, velocity, and thermodynamic state after the complex shock structure of an under-expanded jet. In HyRAM+, a notional nozzle model is used if the pressure at the orifice is above atmospheric pressure; There are five different notional nozzle models in HyRAM+, with each model conserving mass between flow through the real orifice and flow through the notional nozzle : Yüceil and Ötügen [18] Birch *et al*. (1987) [19], Birch *et al*. (1984) [20], Ewan and Moody [21] , Molkov *et al* [22].

The flows are all assumed to be plug flows, where the properties (e.g., velocity, density) are constant across the entire cross-section of the flow. However, jets, plumes, or flames from a pure source are well-known to have Gaussian profiles of their properties (e.g., velocity, density, mixture fraction) in the downstream regions [23] [24]. The final model for developing flow describes the transition from plug flow to the Gaussian profile that is used as an input to a one-dimensional system of ordinary differential equations that describes unignited dispersion or a diffusion flame.

For a jet or plume unignited hydrogen release, HyRAM+ follows the one-dimensional model described by Houf and Winters [25] . While the model only considers one dimension, this dimension is along the streamline, and the jet/plume can curve due to buoyancy effects (or wind, although this aspect is not currently included).

2.9 Zones from Vents (shutdown lines or PRVs)

In a Hydrogen Refuelling Station (HRS), equipment for compression, storage and distribution have installed emergency depressurisation systems, Pressure Relief Valve vents and maintenance vent. Releases of hydrogen through those vents can potentially generate a hazardous zone around the release point. The grade of the release would depend on the type of vent line, as shut-off valve vents could be used during normal operation of the system, e.g. depressurisation line of a compressor. On the other hand. Pressure Relief Valves are usually the last protective layer and are not expected to open in normal operation, therefore they are usually considered as a secondary release.

2.9.1 Determination of extent using IEC 60079-10-1:2020, Quadvent or Phast

The extent of the hazardous zones can be determined using the methodology and dispersion models detailed in section 2.8.4 for the conditions of release or release rates from manufacturers (for instance, for pressure relief valves). Although, most of them are transitory releases, the use the described methodologies will be based on the assumption of a steady-state release rate.

2.9.2 EI 15 (2015)

VENTS TO ATMOSPHERE
In Section 3.4 of the EI 15 document, are typical hazard radii (R_1) for different equipment and arrangements, including vents.

It is recommended that specific dispersion modelling of actual process fluids and venting conditions is used to determine the vertical and horizontal extent of the hazardous area.

- Low pressure tank vents: Hazardous area is dependent on the vapour emission (or filling rate) and the vent diameter. For very low or zero wind conditions, material may flow down the outside of the vent pipe, therefore it may be appropriate to extend the zone as Zone 2.
- Low pressure process vents: The extent is estimated from the type of gas (lighter or heavier than air), the diameter of the vent and the release rate. A matrix of distances is shown in Table 3.2 of the EI 15 document, and depending on the height of the release, the effect of the ground would need to be considered.
- Instrument vents: The diameter of the smallest item on the vent line should be used to determine the hazardous zone. Gas samples should be designed so that the flowrate is less than 10 m^3/hr under ambient conditions.
- Pressure relief valves: PRVs lifting at their design condition are covered under area classification, with any discharge being a secondary release. To cover any fugitive emission that may occur, **a zone 1 of nominal 1 m radius** should be placed around the end of any discharge point. Where a process relief valve lifts at its design intent, the extent of the resultant Zone 2 should be determined.

2.9.3 NFPA 497:2024

The extent distances presented in Figure 6 are for combustible materials with low lower flammability limits. The extent of the classified area can be determined by using sound engineering judgement to apply the considerations of the methodology of Clause 5.6.2 of NFPA 497:2024 and the diagrams of its Sections 5.10 and 5.11. The extent can be modified by considering the following:

- Whether an ignitable mixture is likely to occur frequently due to repair, maintenance or leakage.
- Where conditions of maintenance and supervision are such that leaks are likely to occur in process equipment, storage vessels and piping systems containing combustible material.

- Whether combustible material could be transmitted by trenches, pipes, conduits or ducts.
- Ventilation or prevailing wind in the specific area, and the dispersion rates of the combustible materials.

Hydrogen vent stacks are presented in NFPA 497's Section 5.10 (Class I, Division classification) and 5.11 (Zoning classification), however, the conditions for the determination of the extent are not detailed. The illustration of these hazardous area classification around GH2 vents are shown on Figure 6.

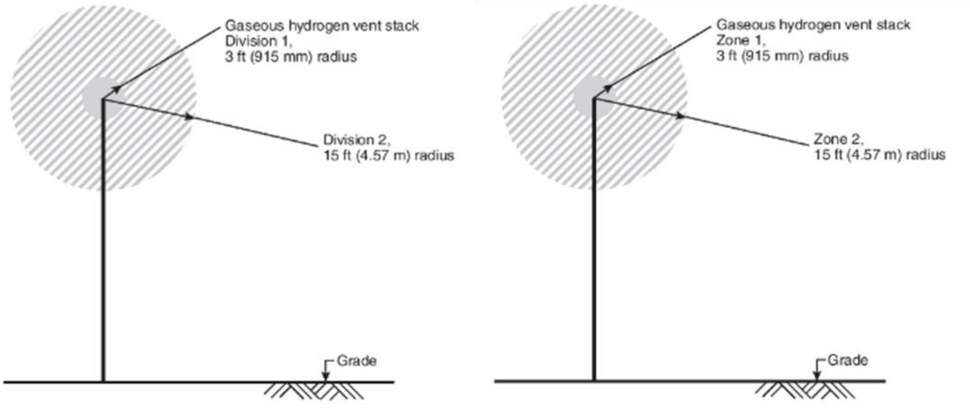
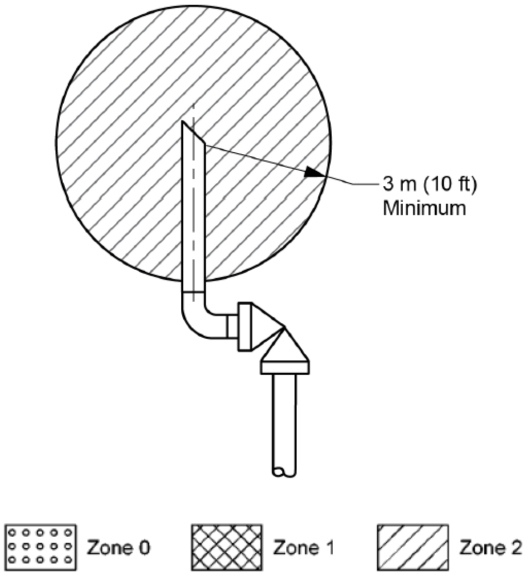


FIGURE 5.10.8(d) Gaseous Hydrogen Vent Stack. **FIGURE 5.11.8(d)** Gaseous Hydrogen Vent Stack.

Figure 6 - Hazardous area classification around GH2 vent stack from NFPA 497 (Figures 5.10.8 & 5.11.8)

2.9.4 API RP 500/505

Section 8 of API RP 505 [26] presents examples developed by experience in industry and are applicable to most petroleum and petrochemical facilities but not specific to hydrogen Application of the examples to similar but not identical configurations should be made with sound engineering judgement employing information in recommended codes of practices. The section on vent lines assumes that the process equipment and instrument and control devices vent sources are continuous. If the grade of release is not continuous, good engineering judgement normally would dictate a lesser hazardous location.



[1] The interior of the vent piping above the relief valve is Zone 2. Cross hatching has been omitted for drawing clarity.

Figure 7 - Example of zoning around pressure relief valve from API 505

API RP 505 Section 8.2.3.4 provides an example of a relief valve in a non-enclosed and adequately ventilated area (see Figure 7). As a consequence of the influence of multiple parameters in the extent, individual engineering judgment is required for each specific case.

2.9.5 Technical note – DVGW G (442): Potentially Explosive Atmospheres at Exhaust Openings of venting lines at gas plants or systems

This German document [27] applies to systems with lines to atmosphere that are operated with gases from the 2nd gas family according to DVGW

- Gas pressure regulating and metering stations.
- Compressor systems according DVGW CP G497.
- Natural gas filling stations according to DVGW G641/VdTUV bulletin 510.

The procedure in determining Ex-areas is only applicable for vertically upward and horizontal blowers. The procedure is only applicable if there are no other influences, i.e. by buildings and plant components.

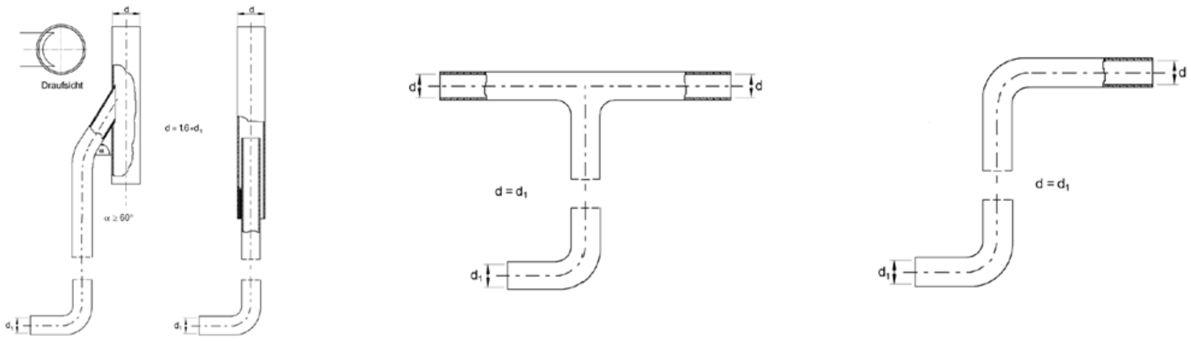
The calculation method presented is mainly suitable for pressure relief systems whose **pressure in the reservoir does not exceed 100 barg.**

In principle, released gas quantities must be discharged without causing danger. Calculations have shown that a steady state is reached after a very short time. Therefore, the steady-state is used as a basis for determining the Ex-areas.

Blow-off lines are lines to atmosphere through which gas quantities released from automatic blow-off devices are discharged.

Breathing lines: When determining potentially explosive atmospheres on breathing lines, diaphragm rupture must be considered when determining appropriate measures. If the occurrence of a hazardous explosive atmosphere can be demonstrated to be preventable by technical or organisational measures, zones need not be defined.
Permanently installed lines to atmosphere for manual gas release: If the gas is released manually, this may only be done by appropriate, qualified personnel. A corresponding area must be defined for the duration of the expansion process, which must be free of ignition sources. The protection can be achieved by both technical and organisational protection measures.

DVGW G (442) Section 5 presents a calculation method that can be used to determine the Ex-areas for simple pressure-relief systems in a predominantly graphical manner. A detailed description of the calculation procedure is given in its Appendix A, where the tables and diagrams required for the calculation are also given (reproduced in this report as Figure 8). The procedure presented in the document is applicable for vertically upward or horizontally directed blowing, e.g. by means of the blower types A to C.



Type A **Type B** **Type C**

Figure 8 - Typical configurations of vent releases

The results of the calculation method are only applicable if there are no other influences, e.g. from buildings or external walls. For the calculation of the table values given in DVGW G (442) Appendix A, the gas was assumed to be ideal. In Appendix A of the document, a graphical methodology for the determination of the size and extent through H and R (as described in Figure 10) of the zone is detailed by the determination of dimensionless ratios of the venting system, relative overpressure and auxiliary parameters (X, K (G/B)). The calculations are based on the simplified system shown below in Figure 9:

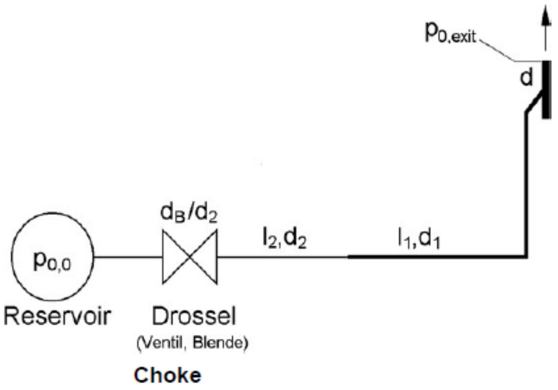


Figure 9 - Simplified diagram for calculation of vent release from [27]

Considering the relevant regulations, the outer limits of the Ex-areas are where the gas concentration falls below a **limit of value 2% v./v. H_2 (50% LEL).**

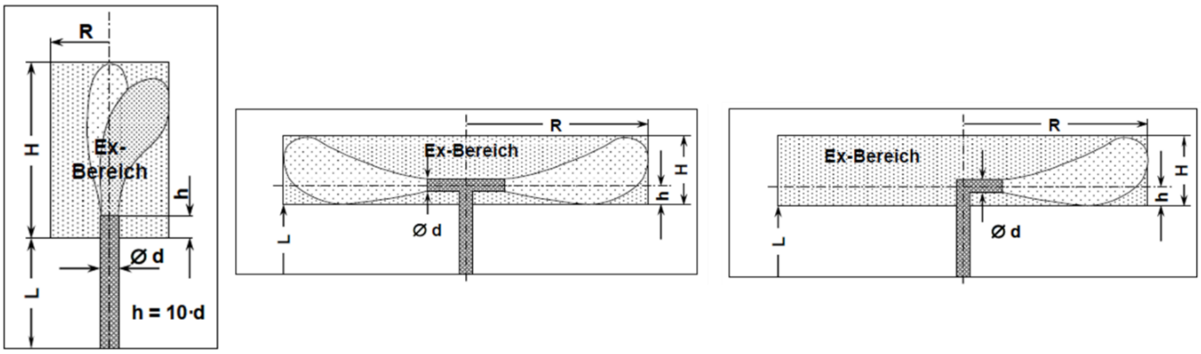


Figure 10 - Shape and size of hazardous area extent for vent outlet [27]

Considering the relevant regulations, the outer limits of the Ex-areas are where the gas concentration falls below a limit of value 2% v./v. H_2 (50% LEL).

Cylindrical hazard areas are defined for both vertical and horizontal blow-outs. The height of the Ex-area H in this case results from the vertical extension of the gas column up to ½ LEL concentration contour, with negligible crosswind. The largest radial expansion of the area with concentrations > ½ LEL is not always achieved at the wind speed of 15 m/s considered to be the maximum. The stronger deflection of the jet at higher wind speeds competes with the minimum reduction of the jet length due to simultaneously-occurring better mixing with the surrounding air. The lower limit of the hazardous area above ground is designated as L.

For horizontal releases, if one side is blown out horizontally, the potentially explosive area also has the shape of a solid cylinder, which considers the drifting of the gas when there is a headwind.

2.9.6 IGEM SR 25/H2

The British standard, related to natural gas initially, has a complement for hydrogen purpose [28]. It summarises the several vent terminations used in the gas industry into two basic types i.e. “ideal” and “non-ideal”. The terminations considered in the standard are:

- Ideal
- Non-ideal
    - Impeded
    - Upward pointing and angled
    - Downward pointing
    - Other vent pipe terminations

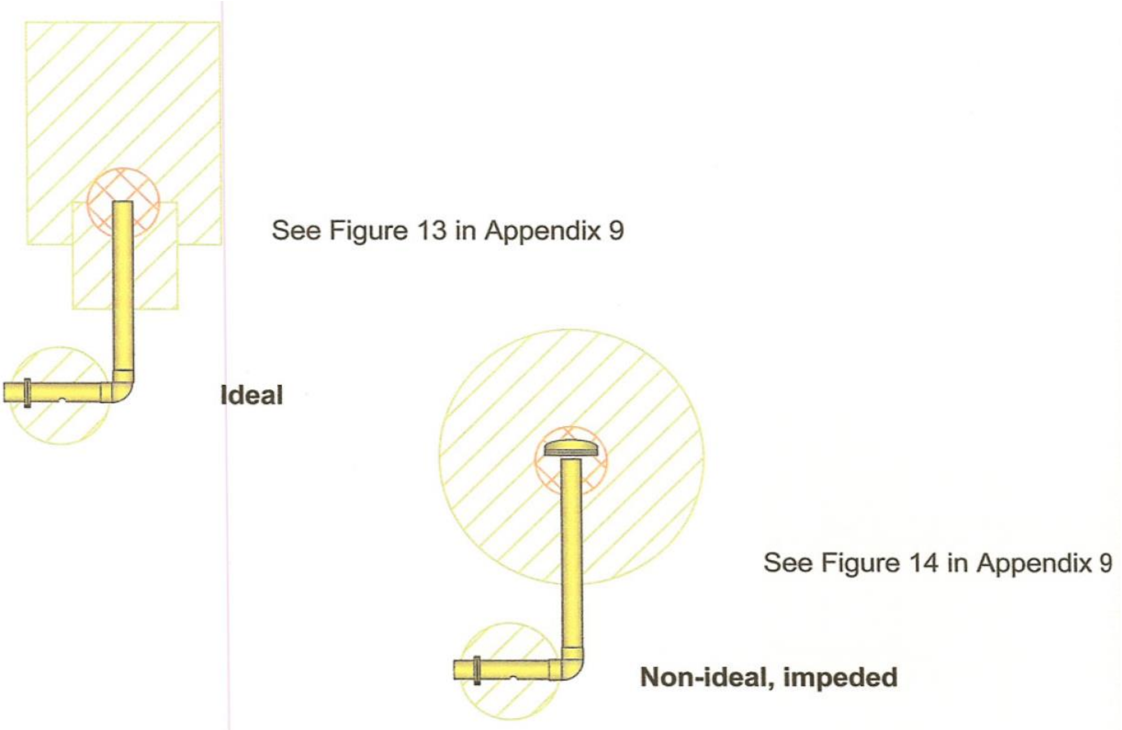


Figure 11 - Vent pipe termination: ideal and non-ideal impeded (IGEM/SR/25)

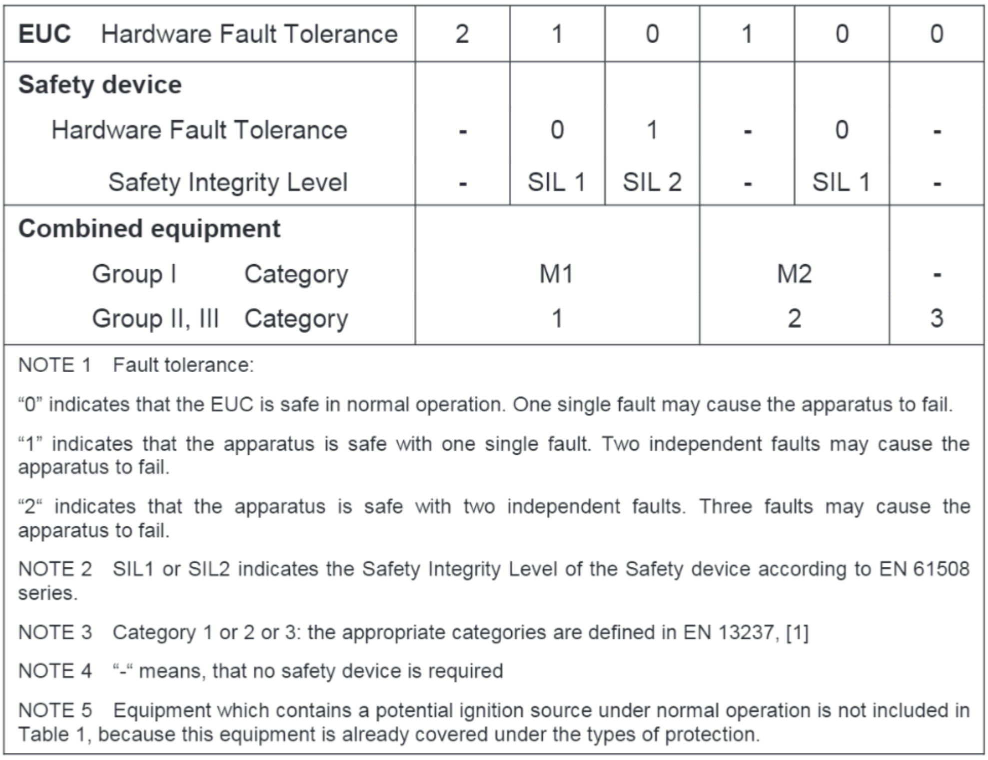
The extent of the zones depends on the flow rate, which are determined using equations S5.1H or S5.2H in IGEM SR 25/H2 DTB, depending on the operational pressure. The downward dispersion can be estimated using the equations presented in sections 5.2.2.3 and 5.2.2.4 of the standard. Figure 11, reproduced from the standard illustrates the vent pipe termination mentioned.

2.9.6.1 Reliability considerations

BS EN 50495:2010 [29] specifies the requirements of electrical safety devices, which are used to avoid potential ignition sources of equipment in explosive atmospheres. Electrical equipment, which may rely on the correct operation of safety devices which for example maintain certain characteristics of the equipment within acceptable limits. The following definitions are very important for the understanding of the requirements of the standard:

- Equipment under control (EUC) is defined as equipment, machines, apparatus or components which contain potential ignition source which is controlled by the safety device.
- Hardware Fault Tolerance is defined as the ability of a safety device to perform a required function in presence of faults.

Table 12 - Minimum requirement of Safety Integrity Level depending on the EUC fault tolerance and the category of the equipment (Table 1 from BS EN 50495)



EUC Hardware Fault Tolerance	2	1	0	1	0	0
Safety device						
Hardware Fault Tolerance	-	0	1	-	0	-
Safety Integrity Level	-	SIL 1	SIL 2	-	SIL 1	-
Combined equipment						
Group I Category	M1			M2		-
Group II, III Category	1			2		3

NOTE 1 Fault tolerance:

“0” indicates that the EUC is safe in normal operation. One single fault may cause the apparatus to fail.

“1” indicates that the apparatus is safe with one single fault. Two independent faults may cause the apparatus to fail.

“2“ indicates that the apparatus is safe with two independent faults. Three faults may cause the apparatus to fail.

NOTE 2 SIL1 or SIL2 indicates the Safety Integrity Level of the Safety device according to EN 61508 series.

NOTE 3 Category 1 or 2 or 3: the appropriate categories are defined in EN 13237, [1]

NOTE 4 “-“ means, that no safety device is required

NOTE 5 Equipment which contains a potential ignition source under normal operation is not included in Table 1, because this equipment is already covered under the types of protection.

Table 1 of BS EN 50495:2010 shows the minimum requirement of Safety Integrity Level depending on the EUC fault tolerance and the category of the equipment (reproduced as Table 12). An example is presented in the document, where if an equipment shall be classified in Category 1, even rare incidents to the equipment must be considered. Hence, the equipment must:

- Either be safe with 2 faults occurring independently in the equipment. If a type of protection is only safe up to one fault, the fault tolerance of the equipment may be enhanced by the control with an appropriate safety device.
- Or, in the event of one means of protection fails, provide at least an independent second means to ensure the requisite the level of protection. For this purpose, also, a suitable safety device can be used.

2.9.6.2 Considerations when using combustible gas detection equipment (API RP 505)

API RP 505 :2018 [26] present the requirements of combustible gas detectors in order to:

a) Designate an inadequately ventilated Zone 1 area containing equipment that could release flammable gas or vapour as suitable for Zone 2 electrical equipment. The documentation shall include the basis for installing electrical equipment for Zone 2 in the Zone 1 area.
b) Designate the interior of a building that does not contain a source of flammable gas or vapour but is located in a Zone 2 area as an unclassified location, provided that the building is of a type of construction that is essentially vapour-tight.

The requirements for the gas detection system are listed below:

- The gas detectors are stationary type and permanently mounted.
- Combustible gas detectors that have been evaluated for explosion in Class I hazardous atmospheres and the risk of the fire and electric shock shall also include performance testing for the specific gas listed and safer operation of the instrument in the presence of flammable or explosive mixtures of representative gases with air.
- An adequate number of sensors is installed to ensure the sensing of flammable gas or vapor in the building in all areas where such gas might accumulate.
- Sensing a gas concentration of 20% LFL (or less) should activate a local alarm.
- Sensing a gas concentration of 40% LFL has different requirement depending on the scenarios above (a or b):
    - Where all equipment is required to be suitable for Zone 2, sensing a gas concentration of 40% LFL or a gas detection system malfunction should activate an alarm.
    - For case b), sensing a gas concentration of 40% LFL or gas detector system malfunction should both activate an alarm and initiate automatic disconnection of power from all electrical devices.
    - In applying a) or b), the case of sensing 40% LFL or a gas detection system malfunction, corrective action to reduce the gas concentration should be initiated immediately.
- The gas detectors should be calibrated at a frequency in accordance with the manufacturer’s recommendations, but at least once every three months.

3 APPENDIX B – benchmarking on separation distances

3.1 General description

Separation distances methodologies are not prescribed at the European level, and different approaches will therefore be taken by the different countries. This includes the consideration of different scenarios.

AFIR prescribes that the EU HRS shall be compliant with the standard EN 17127 for technical specifications in HRS [30] and ISO 19880-1:2020 [8] for safety related issues. ISO 19880-1:2020 defines the minimum design, installation, commissioning, on-site-approval, operation, inspection and maintenance requirements, for safety. This document only gives minimum requirements for HRS, hence additional safety considerations are usually applied by HRS manufacturers and operators as well as local regulators. Basically, all these inputs can significantly change the associated separation distances.

Several EU countries use the methodology developed for CNG for the definition of the hydrogen safety distances. Since hydrogen and CNG have very different properties (flammability limits, viscosity, molar mass, ignition energy, *etc.*) we do not consider the ‘adapted CNG’ safety distances as an appropriate approach.

ISO 19980-1:2020 “Gaseous hydrogen — Fuelling stations — Part 1: General requirements” suggest the use of risk assessment analysis “to flexibly define station-specific mitigations that achieve an equal or lower level of risk to those of prescriptive recommendations or to relax existing prescriptive mitigation measures as long as the total system risk remains below the selected tolerability threshold (risk acceptance criteria).” ISO 19980-1:2020 suggests in its Chapter 5.2 to carry out a quantitative and/or semi-quantitative risk assessment instead of implementing prescriptive requirements. Risk assessment should consider (i) the nature of the hazards, (ii) the behaviour of hydrogen under the design and operating conditions, (iii) equipment design and operating conditions, (iv) installation design and location, including protection measures as well as (v) specific targets (e.g., person, property, equipment) which are being protected from effects of potential hazards. Chapter 5.3 of the standard also explains mitigation barriers and how they can influence the separation distance. ISO 19980-1:2020 also states that quantitative risk assessment (QRA) and/or semi-quantitative can be used for the definition of safety distances instead of prescriptive requirements.

The British Compressed Gases Association has specific guidelines for the design, construction, maintenance and operation of filling stations dispensing gaseous fuels, but no standard procedure is yet in place [31].

Arrete 1416 (France) “refuelling stations, open or not to public, where gaseous hydrogen is transferred into vehicle tanks and where the daily distributed quantity is superior or equal to 2 kg/day” [32]. gives some separation distances related to hydrogen dispenser and some conditions (safety barriers) to avoid or reduce separation distances requirements.

3.2 NFPA 2 – hydrogen technologies code

NFPA 2 [9] is a code related to the safety of hydrogen technologies, edited by the National Fire Protection Association in USA. It provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen.
The methodology utilized by NFPA 2 [9] takes a percentage of the flow area of the pipeline / manifold, of 3 % (seemingly irrespective of the component from which the leak initiates)

In the code, no difference was observed in the leak size for hazardous area classification and for separation distance.
In order to determine an area for the leak size, a risk-informed analysis was implemented. Component leak frequencies as a function of leak size were generated for several hydrogen components. The hydrogen specific leakage rates were used to estimate the leakage frequency for four example systems used as the basis for the risk evaluation. The cumulative probability for different leak sizes was then calculated to determine what range of leaks represents the most likely leak sizes. The results of the analysis showed than 0.1% of the flow component flow area represents 95% of the leakage frequency for the example system. Leak areas less than 10 percent of the flow area estimated to result in 99% of the leaks that could occur based on the results of the analysis.
The risk resulting from different size leaks were also evaluated for four standard gas storage configurations. The risk evaluations indicate that the use of 0.1% of the component flow area as the basis for determining the separation distances in risk estimates that significantly exceed the $2\text{x}10^{-5}$/yr. On the other hand, use of a leak size equal to between 1 and 10% of the component flow area results in risk estimated that are reasonably close to the risk guidelines.
Based on the results of both the system leakage frequency evaluation and the associated risk assessment, the diameter of 3% of the flow area corresponding to the maximum internal pipework downstream of the highest pressure source in the system. The use of 3% leak area result in capturing an estimated of 98% of the leaks that have been determined to be probable.

Effective leak diameters were analyzed at different pressure ranges based on the characteristic pipe diameter, where the leak flow area was taken as 3% of the flow area of the pipe. For a round leak diameter is:

$$d_{leak} = (0.03)^{1/2} d_{pipe(ID)}$$

OD	ID	D_{leak} (3% of the flow area)	$Area_{leak}$
12 mm	10 mm	1.73 mm	2.35 mm^2
18 mm	15 mm	2.60 mm	5.30 mm^2
25 mm	21 mm	3.64 mm	10.4 mm^2

In Annex E - Edition 2023, a detailed description of the review of separation distances using the latest information on hydrogen storage systems. As part of the work, the thresholds for the determination of separation distances, e.g. distance to reach 4% mole fraction of hydrogen, were reviewed as well.

Based on the latest work in NFPA 2, the task group decided that adjusting to a diameter of 1% value instead of 3% would remove excess of conservatism from the input model. The 1% value accounts for 95% of the leakage frequency.

$$d_{leak} = (0.01)^{1/2} d_{pipe(ID)}$$

OD	ID	D_{leak} (1% of the flow area)	$Area_{leak}$
12 mm	10 mm	1.0 mm	0.78 mm^2
18 mm	15 mm	1.5 mm	1.76 mm^2
25 mm	21 mm	2.1 mm	3.46 mm^2

This seems to change the distances of exposure group 1 from Edition 2016 to Edition 2020/2023

2023

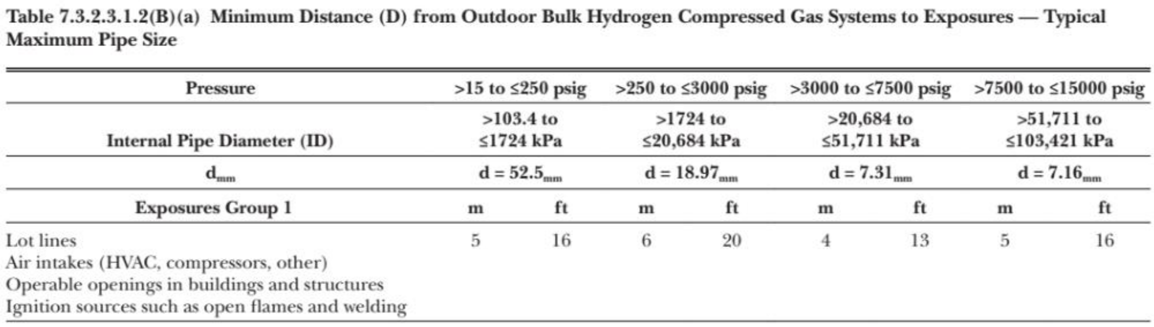


Table 7.3.2.3.1.2(B)(a) Minimum Distance (D) from Outdoor Bulk Hydrogen Compressed Gas Systems to Exposures — Typical Maximum Pipe Size

Pressure	>15 to ≤250 psig		>250 to ≤3000 psig		>3000 to ≤7500 psig		>7500 to ≤15000 psig	
Internal Pipe Diameter (ID)	>103.4 to ≤1724 kPa		>1724 to ≤20,684 kPa		>20,684 to ≤51,711 kPa		>51,711 to ≤103,421 kPa	
d_{mm}	$d = 52.5_{mm}$		$d = 18.97_{mm}$		$d = 7.31_{mm}$		$d = 7.16_{mm}$	
Exposures Group 1	m	ft	m	ft	m	ft	m	ft
Lot lines Air intakes (HVAC, compressors, other) Operable openings in buildings and structures Ignition sources such as open flames and welding	5	16	6	20	4	13	5	16

2016

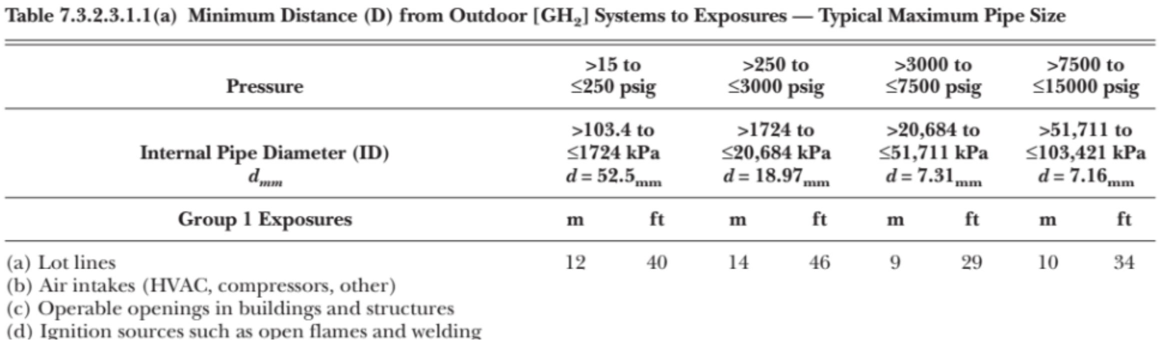


Table 7.3.2.3.1.1(a) Minimum Distance (D) from Outdoor [GH_2] Systems to Exposures — Typical Maximum Pipe Size

Pressure	>15 to ≤250 psig		>250 to ≤3000 psig		>3000 to ≤7500 psig		>7500 to ≤15000 psig	
Internal Pipe Diameter (ID) d_{mm}	>103.4 to ≤1724 kPa $d = 52.5_{mm}$		>1724 to ≤20,684 kPa $d = 18.97_{mm}$		>20,684 to ≤51,711 kPa $d = 7.31_{mm}$		>51,711 to ≤103,421 kPa $d = 7.16_{mm}$	
Group 1 Exposures	m	ft	m	ft	m	ft	m	ft
(a) Lot lines (b) Air intakes (HVAC, compressors, other) (c) Operable openings in buildings and structures (d) Ignition sources such as open flames and welding	12	40	14	46	9	29	10	34

3.3 EIGA 75 (2021)

EIGA document 75/21 [33] methodology for determination of safety and separation distances describes the basic principles to calculate appropriate safety and separation distances for the industrial gases industry. The document recommends following 4 steps:

1. Identify the hazard sources and events, for example release of gas, taking into account the likelihood.
2. Calculate the effects on neighbouring objects, and population taking into account mitigating factors.

3. Determine the safe distance to each object or population to meet the minimum hazard criteria.
4. Consider additional prevention or mitigating factors and re-calculate safe distance.

The safety and separation distances are not intended to provide protection against catastrophic events or major releases, these should be addressed by other means to reduce the frequency and / or consequences to an acceptable level.
The safety distance is a function of the following:

- The nature of the hazard, for example toxic, flammable, oxidising, asphyxiant, explosive and overpressure.
- The equipment design and the operating conditions, for example pressure and temperature and / or physical properties of the substance under those conditions.
- Any external mitigating protection measures, for example fire walls, blast walls, dikes, deluge system, that reduces the escalation of the incident.
- The object that is protected by the safety distance; that is the harm potential, including for example, people, exposure time, environment or equipment.

An assessment of the frequency of the event and the potential consequence is necessary to understand which risks can be reasonably mitigated by a safety distance. If the safety distance is too large, additional mitigating or prevention measures should be considered and the safety distance re-calculated.

The risk from a hazardous activity should not be significant when compared with risk in everyday life.

The individual harm exposure threshold, defined as Ft, for determining safety distances is proposed as:

$Ft =< 3.5 \times 10^{-5}$ per annum.

For events where the risk of harm is below Ft, no safety distance criteria is required. For deviations, which are likely to occur during the life of the equipment or occur during normal operation, for example venting, then the safety distance should be calculated, or mitigation provided to produce a no harm effect. The safety distances determined on the basis of tables are intended to safeguard against or mitigate harm of such leaks but do not generally safeguard against catastrophic leaks.

The document suggests a methodology for the evaluation of the safety distance:

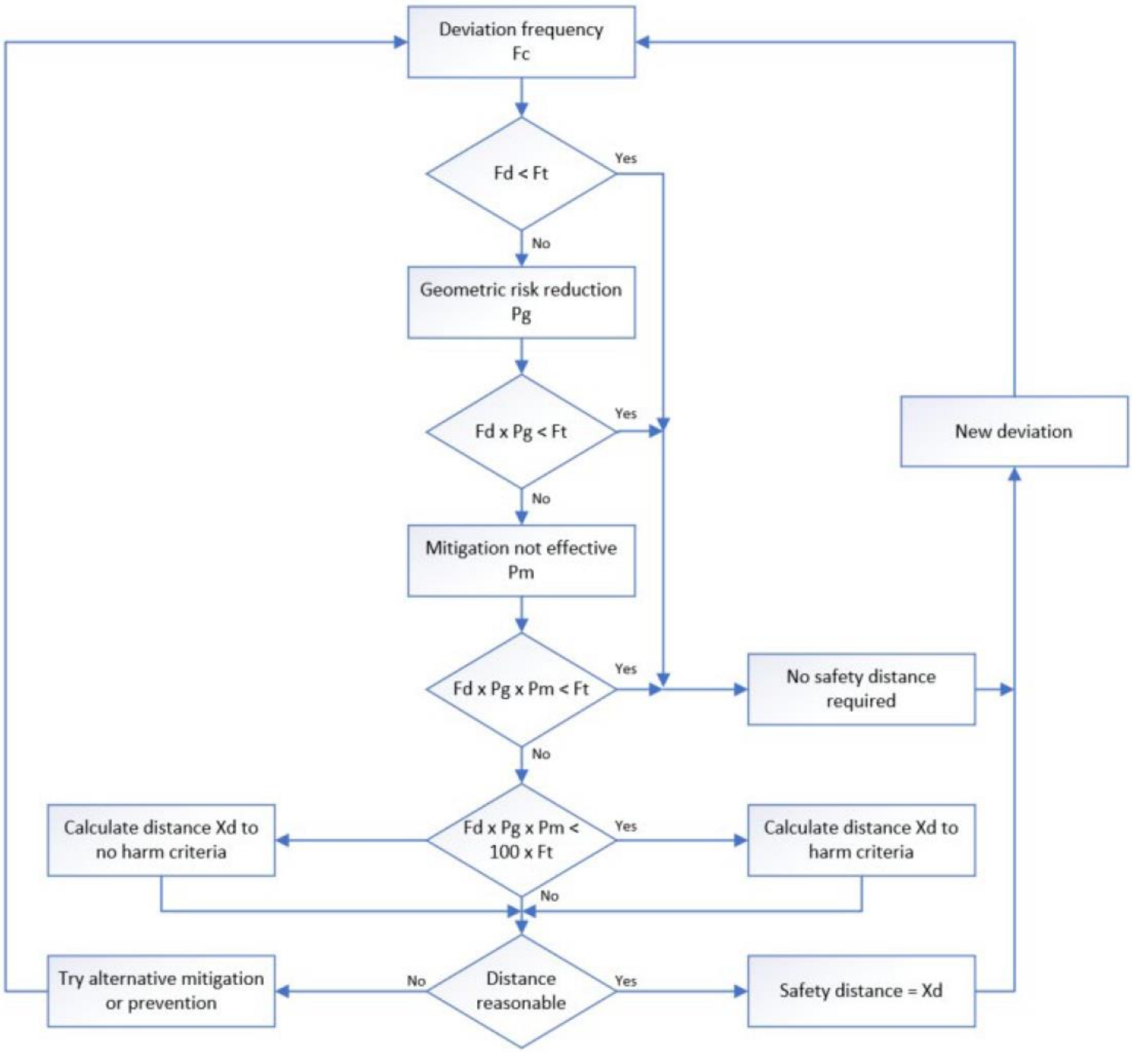


Figure 12 - Methodology for the evaluation of the safety distance from EIGA 75/21

On Figure 12 related to Methodology for the evaluation of the safety distance from EIGA 75/21, here Fd is the frequency of the process deviation, Pg is the geometric risk reduction, Pm represents the probability of failure of mitigating measure in terms of probabilities.

The objective of safety distances is to provide protection by ensuring that the effects of an event do not cause a risk of injury to people or failure of equipment. In order to calculate a safety distance, an assumption is to be made for the threshold level of the effect that can cause a defined severity of failure or injury. These thresholds are very dependent on the local regulator assumptions.

In order to calculate the hazardous effects, there is a requirement to consider the series of physical effects that could occur, including:

- rate of release of the substance including flashing, aerosol and evaporation effects;
- gas dispersion;
- fires or explosions;
- exposure to cryogenic temperatures;
- exposure to heat radiation; and
- exposure to toxics.

EIGA 75/21 gives a list of the of leak sources (Table 2, in Section 5 of EIGA 75/21) which should be used for initiating events, any of which can give rise to different discharges for gas, liquid and two-phase flow.

For the calculation of thermal effects, EIGA 75/21 recommends to consider the following types of fires:

- pool fire;
- flash fire;
- jet fire.

Fireball is typically excluded as it is a very low probability event.

EIGA 75/21 considers typical explosions experienced in the industrial gases industry:

- Rapid chemical reactions;
- Unconfined vapour cloud explosions;
- Confined explosions, where a rapid chemical reaction takes place inside the vessel, process or congested area;
- Physical explosions, where the stored energy of the system is released by rupture. This can include a Boiling Liquid Expanding Vapour Explosion (BLEVE).

The result is usually examined in terms of a shockwave although projectiles can be a major threat from physical or confined explosions.

The document also gives a list of the potential mitigation barriers, which can help to significantly reduce the risk of the installation and hence the safety distances in terms of the probability of the event and its consequences.

3.4 BCGA

British Compressed Gas Association (BCGA) developed a comprehensive document defining separation distances: GUIDANCE NOTE 41 SEPARATION DISTANCES IN THE GASES INDUSTRY (2020) [34]. This document explains the approach to be taken to estimate the separation distances for gas industrial installations.

Separation distances aim to enhance safety in two directions: between multiple hazards existing within the installation; by protecting external receptors from hazards arising from the installation; by protecting the installation from external hazard sources.

BCGA recommend minimum separation distances which are based on generic historically-proven custom and practice. If the BCGA recommendations are not followed, users shall conduct a specific risk assessment that is suitable and sufficient, to determine bespoke separation distances.

The document addresses the following gas-specific hazards:

- pressure, refer to Section 4.1 (projectiles due to catastrophic failure will not be fully catered for by separation distances);
- asphyxiation, refer to Section 4.2 (not applied to hydrogen, the flammability will be predominant);
- flammability, refer to Section 4.3;
- oxygen enrichment, refer to Section 4.4 (not directly applied to hydrogen);
- intoxication, refer to Section 4.5 (not applied to hydrogen);
- extreme cold, refer to Section 4.6;

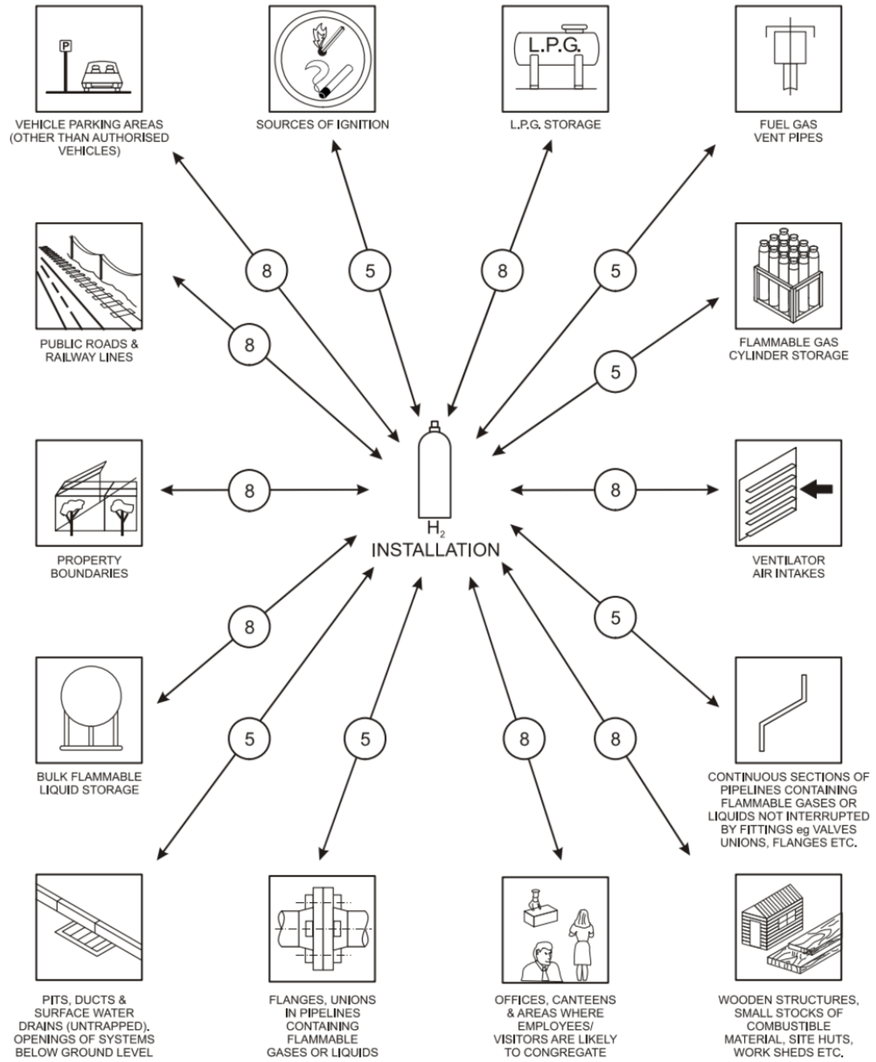
- toxicity, refer to Section 4.7 (not applied to hydrogen);
- corrosivity, refer to Section 4.8 (not applied to hydrogen);
- external hazards relevant to the installation, refer to Section 5 (fire risk, impact damage, local and site-specific hazards).

BCGA guidance [34] explains how to measure the separation distance and give the requirements for the periodic review of these distances.

The document also gives examples of separation distances for different installations, for instance the Figure 13 below represents the separation distances for gaseous hydrogen storage.

Source: BCGA CP 33 [17], *The bulk storage of gaseous hydrogen at Users' premises.*

TABLE 1 – MINIMUM RECOMMENDED HORIZONTAL DISTANCES

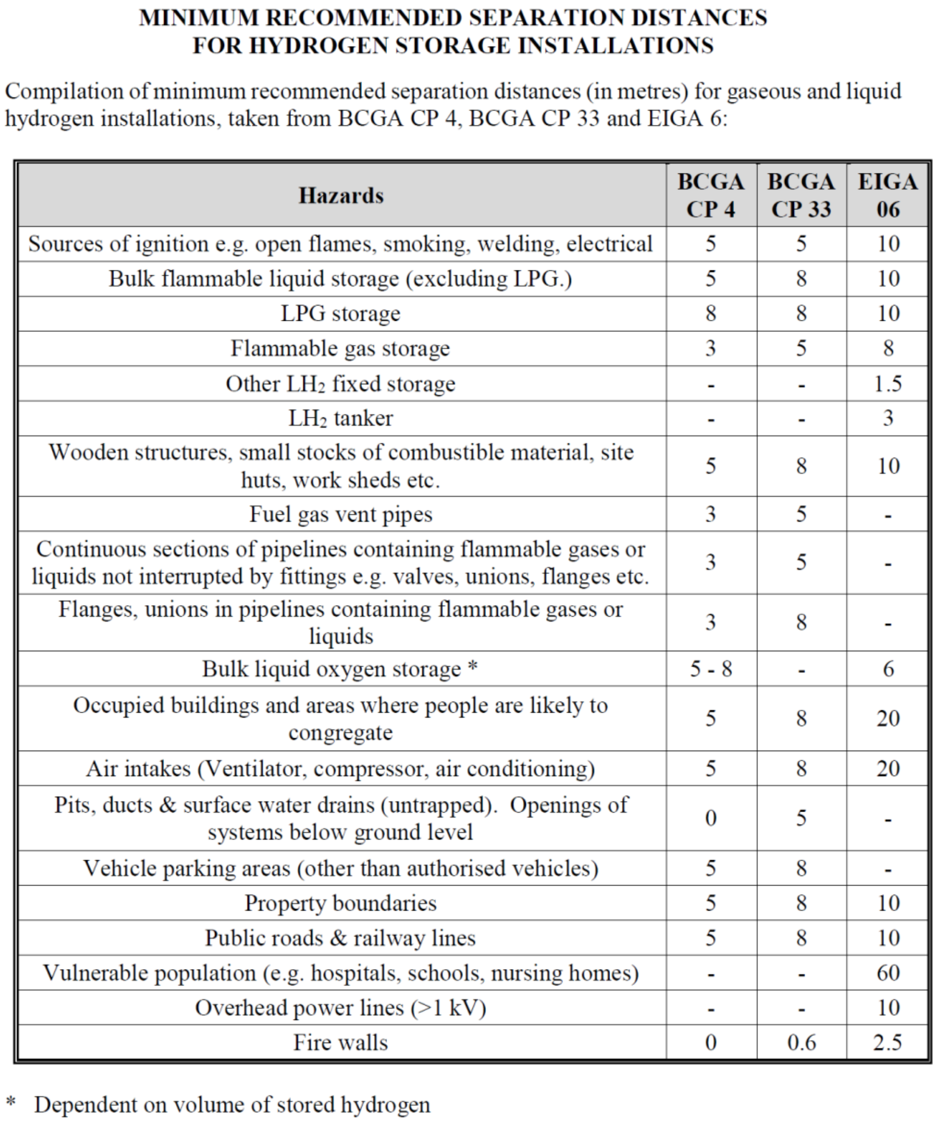


If a firewall is used, a minimum separation distance of 3 m should be maintained between the wall and any part of the trailer or fixed installation that could provide a likely ignition point. The distances shown above are horizontal distances. Where specified hazards exist vertically above the installation special considerations apply. A formal risk analysis will be needed to assess the requirements.

Figure 13 – minimum recommended horizontal distances from BCGA CP33 (Table 1)

The document also gives the separation distances for HRS, extracted from BCGA CP 41, The design, construction, maintenance and operation of filling stations dispensing gaseous fuels as reproduced in Table 13.

Table 13 – Minimum recommended separation distances for H_2 storage from BCGA CP 41



MINIMUM RECOMMENDED SEPARATION DISTANCES
FOR HYDROGEN STORAGE INSTALLATIONS

Compilation of minimum recommended separation distances (in metres) for gaseous and liquid hydrogen installations, taken from BCGA CP 4, BCGA CP 33 and EIGA 6:

Hazards	BCGA CP 4	BCGA CP 33	EIGA 06
Sources of ignition e.g. open flames, smoking, welding, electrical	5	5	10
Bulk flammable liquid storage (excluding LPG.)	5	8	10
LPG storage	8	8	10
Flammable gas storage	3	5	8
Other LH_2 fixed storage	-	-	1.5
LH_2 tanker	-	-	3
Wooden structures, small stocks of combustible material, site huts, work sheds etc.	5	8	10
Fuel gas vent pipes	3	5	-
Continuous sections of pipelines containing flammable gases or liquids not interrupted by fittings e.g. valves, unions, flanges etc.	3	5	-
Flanges, unions in pipelines containing flammable gases or liquids	3	8	-
Bulk liquid oxygen storage *	5 - 8	-	6
Occupied buildings and areas where people are likely to congregate	5	8	20
Air intakes (Ventilator, compressor, air conditioning)	5	8	20
Pits, ducts & surface water drains (untrapped). Openings of systems below ground level	0	5	-
Vehicle parking areas (other than authorised vehicles)	5	8	-
Property boundaries	5	8	10
Public roads & railway lines	5	8	10
Vulnerable population (e.g. hospitals, schools, nursing homes)	-	-	60
Overhead power lines (>1 kV)	-	-	10
Fire walls	0	0.6	2.5

* Dependent on volume of stored hydrogen

Code of Practice 41 [31] related to the design, construction, maintenance and operation of filling stations dispensing gaseous fuels gives more details on the approach used for the calculation of the corresponding separation distances. A reduced maximum internal pipe diameter of 8 mm is recommended for hydrogen systems above 200 bar. For greater pipe diameters, it may be appropriate to extend these distances. For potential leak points in the pipework and equipment involved in the dispensing of gaseous hydrogen, isolated from the storage vessels outside of a filling activity, separation distances taken from BCGA CP 4 [35] are recommended, again assuming a maximum internal pipe diameter of 8 mm.

Figure 14 below summarises the BCGA codes applicable to the HRS

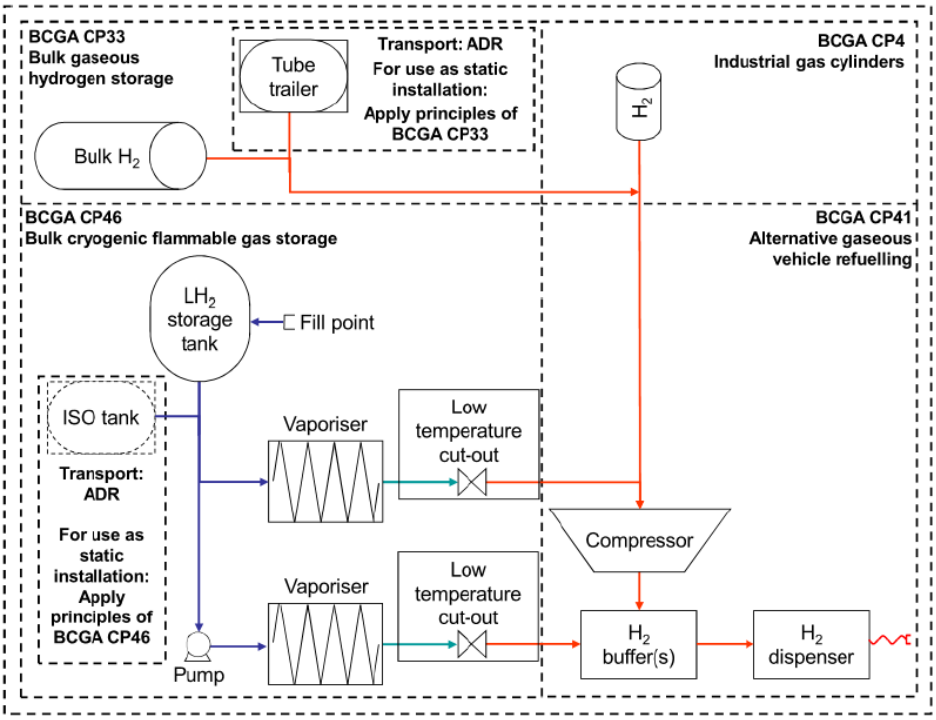


Figure 14 – BCGA codes applicable to the HRS

Under COMAH [36], where sub-threshold quantities of dangerous substances are stored, consideration should be given to the **total** quantity of products stored on a site according to the COMAH Aggregation Rule. For hydrogen this is 5 tonnes for Lower tier and 50 tonnes for Upper tier, and 2 tonnes for Planning (Hazardous Substances) Regulations.

The document also gives the requirements for multifuel stations. The Petroleum (Consolidation) Regulations [37] require that anyone operating a petrol filling and/or storage station shall have a storage certificate issued by their local Petroleum Enforcement Authority (PEA). The PEA will usually require the installation to meet the requirements of the Blue Book [11].
The requirement applies both to retail and non-retail filling stations i.e. those that dispense petrol to the general public and those, which only dispense petrol into their own vehicles. As part of the PEA assessment of a petrol filling station, prior to issuing a storage certificate, the PEA will ensure that the arrangements for any other fuels stored and dispensed on the site are also appropriate, and that the risks associated with the fuels are controlled so as not to impact upon each other.

3.5 IEA TCP task 43

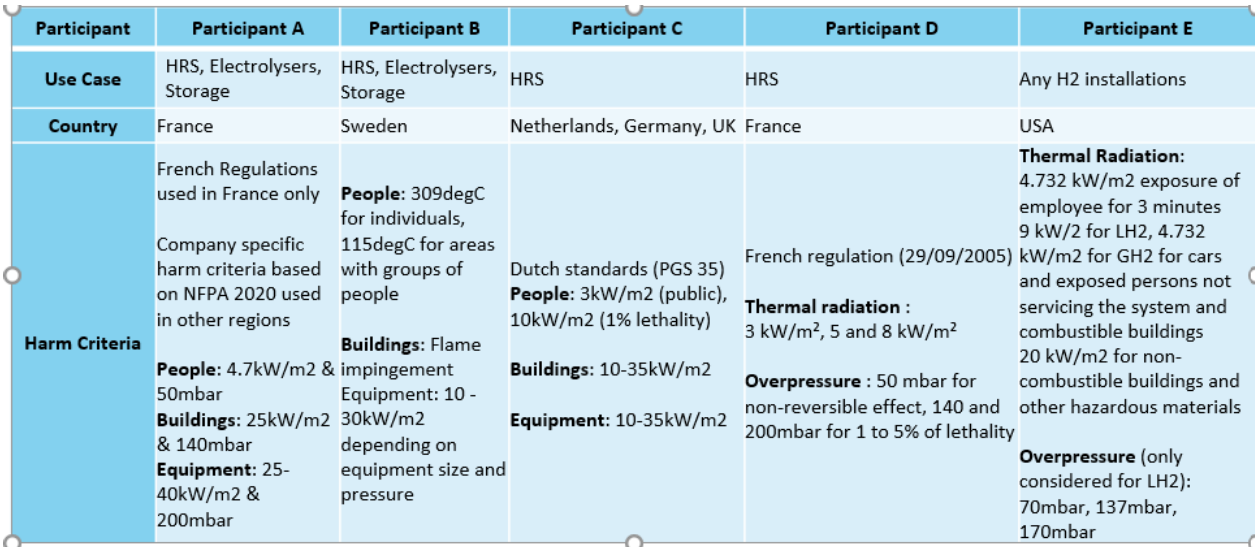
In 2022, Hydrogen Council completed a detailed analysis of safety and regulatory topics that are critical for significant market share penetration of hydrogen energy technologies. These critical topics included large scale compressed and liquid hydrogen systems, safety culture and management system, uniform methodologies for safety distances and hazardous areas classification, large scale electrolysis and confined environment.
All emerging large scale hydrogen applications must address common horizontal topics as follows:

- Social risk
- Safety culture and management system
- Safety distances

- Hazardous area
- Confined environment
- Hydrogen system safety
- Liquid and compressed hydrogen

A sub task related to safety distances in 2022 where an analysis of harm criteria was performed. Table 14 below summarise the outcomes.

Table 14 – Harm criteria comparison from IEA task 43 on H_2 safety



Participant	Participant A	Participant B	Participant C	Participant D	Participant E
Use Case	HRS, Electrolysers, Storage	HRS, Electrolysers, Storage	HRS	HRS	Any H2 installations
Country	France	Sweden	Netherlands, Germany, UK	France	USA
Harm Criteria	French Regulations used in France only Company specific harm criteria based on NFPA 2020 used in other regions **People**: 4.7kW/m2 & 50mbar **Buildings**: 25kW/m2 & 140mbar **Equipment**: 25-40kW/m2 & 200mbar	**People**: 309degC for individuals, 115degC for areas with groups of people **Buildings**: Flame impingement Equipment: 10 - 30kW/m2 depending on equipment size and pressure	Dutch standards (PGS 35) **People**: 3kW/m2 (public), 10kW/m2 (1% lethality) **Buildings**: 10-35kW/m2 **Equipment**: 10-35kW/m2	French regulation (29/09/2005) **Thermal radiation** : 3 kW/m^2, 5 and 8 kW/m^2 **Overpressure** : 50 mbar for non-reversible effect, 140 and 200mbar for 1 to 5% of lethality	**Thermal Radiation:** 4.732 kW/m2 exposure of employee for 3 minutes 9 kW/2 for LH2, 4.732 kW/m2 for GH2 for cars and exposed persons not servicing the system and combustible buildings 20 kW/m2 for non-combustible buildings and other hazardous materials **Overpressure** (only considered for LH2): 70mbar, 137mbar, 170mbar

4 APPENDIX C – Zone of Negligible Extent – Specific detailed risk assessment in a ventilated enclosure

4.1 Introduction

It has been anticipated that Negligible Extent (NE) classification might be able to be applied to equipment sections of the HRS, for instance a hydrogen electrolyser, as analyzed as part of configuration 2 in the project. The standard IEC 60079-10-1:2020 [12] 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 [12]. An example of a zone of negligible extent for natural gas is detailed in clause 4.4.2 of IEC 60079-10-1:2020 [12] and the extrapolation to hydrogen is detailed in 4.4. Depending of the pressure of the system, IEC 60079-10-1:2020 [12] 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 [12]. 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 [12] 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 [12].
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 4.2. The requirements of cloud volume, degree of dilution and background concentration for a classification of NE are analyzed in 4.4. A specific detailed risk assessment is performed in 4.5, by estimating the potential consequences of the ignition of the cloud volume for negligible extent and considering the available safeguards described in the example.

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 60079-13:2017 [38] [51] 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”.

4.2 Description of the enclosure

Hydrogen is generated within an enclosure using PEM electrolysis in three separated stacks (Figure 15). 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 area 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.

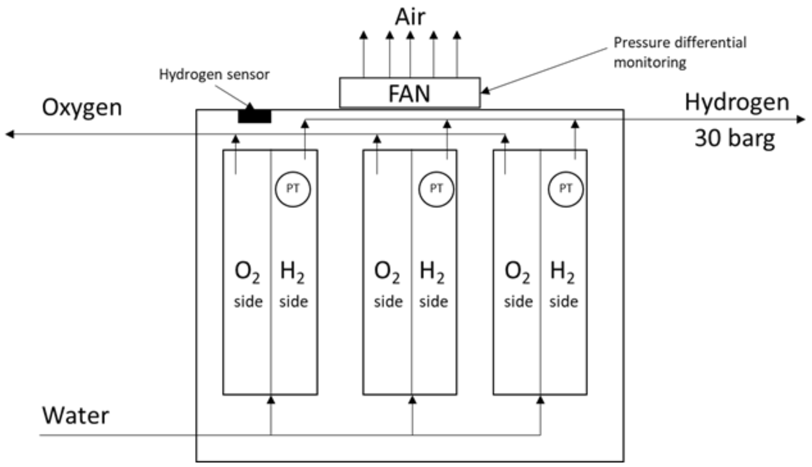


Figure 15 – Example of a hydrogen generator room

Table 15 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 [51].

Table 15 – 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)	

4.3 Methodology for 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 [12]. 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” [12]. 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 [12]. 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 4.2, 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 60079-10-1:2020 [12]. 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 [12]. 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.

4.4 Hazardous Area Assessment

The methodology used in this work follows an approach in the standard IEC 60079-10-1:2020 [12]. 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 (Qc) and the ventilation velocity (uw) 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 10) due to the working pressure, i.e. 3101 kPa.a above the critical pressure (Pc = 192 kPa.a) for hydrogen.

$$W_g = C_d S p \sqrt{\gamma \frac{M}{ZRT} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \quad \text{(Equation 10)}$$

where Wg (kg/s) is the mass flow rate, Cd 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 [12].

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 11, where ρg (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 [12] notes that a safety factor is not included in the formula and a safety factor should be determined by the designer of the application [12]. 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).

$$Q_C = \frac{W_g}{\rho_g \times 0.5 \times LFL} \quad \text{(Equation 11)}$$

The gas density is calculated using Equation 12, where pa (Pa) is the atmospheric pressure, Ta (K) is the ambient temperature.

$$\rho_g = \frac{p_a \times M}{R \times T_a} \quad \text{(Equation 12)}$$

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 Qc = 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 13:

$$u_w = \frac{1.5\ m^3/s}{3.4\ m^2} = 0.44\, m/s \quad \text{(Equation 13)}$$

The degree of dilution is estimated from Figure C.1 of IEC 60079-10-1:2020 [12] using the estimated volumetric release characteristic of the release and the estimated ventilation velocity, which is shown in Figure 16. IEC 60079-10-1:2020 [12] 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 Qc = 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 16. 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.

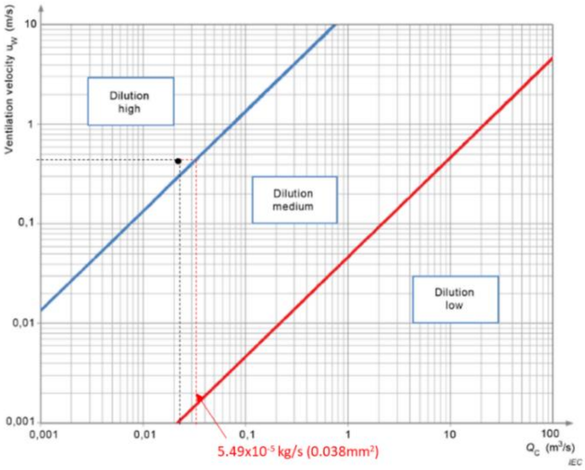


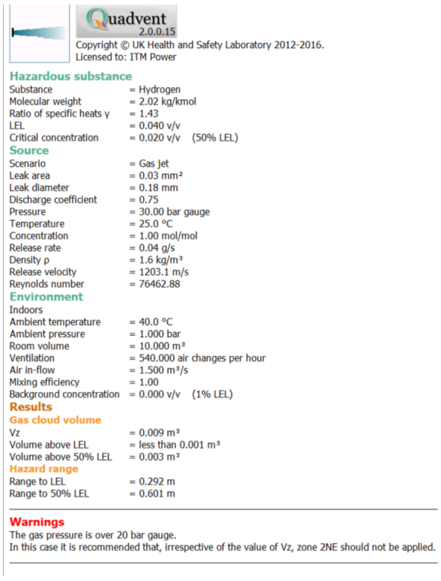
Figure 16 – Dilution level for the release in the example using Figure C.1 from IEC 60079-10-1:2020 [12]

The background concentration is estimated using Equation 14, where Qg (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. Qg (m^3/s) is defined as the ratio between the mass flow rate of the leak and the gas density ρg (kg/m^3).

$$X_b = \frac{f \times Q_g}{Q_2} \qquad \text{(Equation 14)}$$

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 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 17 shows that the results using Quadvent generally agree with the estimations obtained by following the approach used from IEC 60079-10-1:2020 [12].



```
Quadvent
2.0.0.15
Copyright © UK Health and Safety Laboratory 2012-2016.
Licensed to: ITM Power
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.
```

Figure 17 – 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 [12] is used as reference, as shown in Figure 18, for secondary grade releases and with a high degree of dilution. From Figure 18, 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.

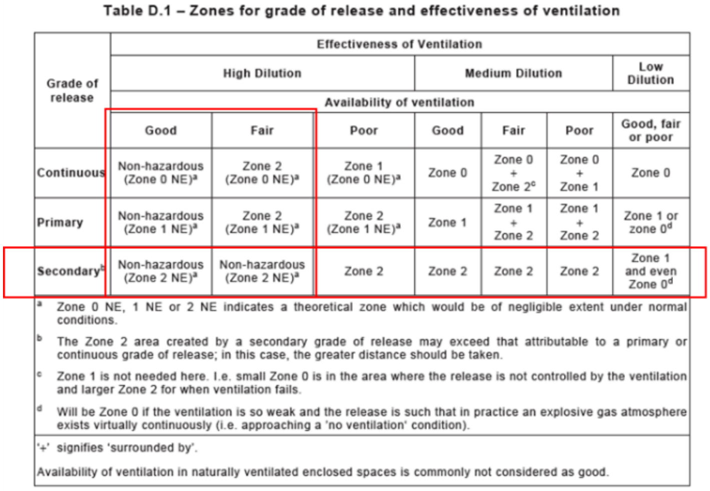


Table D.1 – Zones for grade of release and effectiveness of ventilation

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 18 – Hazardous zone classification depending on the grade of release and effectiveness of ventilation [12]

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 18 indicates that a Zone 2 NE extent might be able to be applied. However, section 4.4.2 of

IEC 60079-10-1:2020 [12] also defines other requirements to be considered for a flammable cloud and specific requirements depending on pressure. IEC 60079-10-1:2020 [12] 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 [12]. Following this basis, Table 16 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 0.01 m^3 or 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 0.01m^3, therefore this volume of cloud is used to validate the classification of Negligible Extent. Figure 17 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 16 – Hydrogen and methane properties

Material Property	Hydrogen H_2	Methane CH_4	Ratio CH_4/H_2
Heat of Combustion (MJ/kg) [52]	141.8	55.5	0.39
Max. Explosion Pressure (bar g) [53]	8.3	8.4	1.01
Max. Rate of Pressure Rise (bar m/s) [52]	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.

4.5 Specific detailed risk assessment

Clause 4.4.2 of IEC 60079-10-1:2020 [12] 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.

4.5.1 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 m3 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 m3 cloud (Vz) 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 (VESV), the volume of the flammable cloud (Vfuel) is multiplied by the ratio between the concentration of the cloud (C) and the stoichiometric concentration of the mixture (φ = 29.5% v./v. H2 in air), as shown in Equation 15.

$$V_{ESV} = V_{Fuel}\left(\frac{C}{\phi}\right) = 0.01m^3 \times \left(\frac{4\%}{29.5\%}\right) = 0.0014\, m^3 \quad \text{(Equation 15)}$$

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 16.

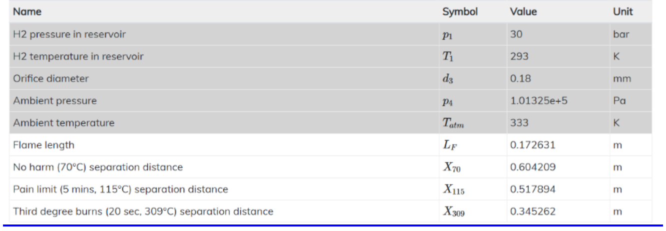
$$P = P_{max}\left(\frac{V_{ESV}}{V}\right) = 8.3\, barg \times \left(\frac{0.0014\, m^3}{10\, m^3}\right) = 1.13\, mbarg \quad \text{(Equation 16)}$$

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 [54] 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 [54] 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.

4.5.2 Jet fire scenarios

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 [12]. 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 [55], based on Molkov and Saffers model [56], 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 [54]. Figure 19 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 20, 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 [33])



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 19 – Flame length correlation and hazardous distances using e-laboratory platform [55]

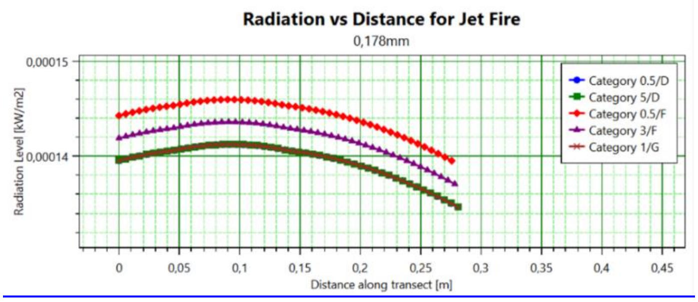


Figure 20 – Results of radiative heat from a jet fire using DNV Phast 8.6.1 [57]

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.

4.5.3 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 [58] [59] [60].

Table 17 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 4.5.1, 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 17 – 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: ISO 22734:2019 [61] - Type and routine tests	No Ignition: No Consequence	-Automatic pressure drop test (details in Table 15) - Forced ventilation (section 4.4) with pressure differential on the fan to initiate shutdown in case of loss of ventilation - H_2 detection initiating shutdown (details in Table 15) Calibration and inspection to follow the manufacturers operating procedures. Exiting protection barriers to avoid ignition: - Equipment required to act in	Asphyxiation is 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 with locked access)	b) locked container and restricted access to the process area authorized persons b) interlock in the doors to initiate shutdown in case of opening during generation.	Delayed ignition: Confined explosion (ignition of localized cloud)		With the incorporation of the barriers (active pressure drop detection, forced ventilation, *etc.*), the explosion severity is estimated to be below the required pressure to generate failure of the weakest part of the system (see section 4.5.1)

	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 [62] [63])	Immediate ignition: Jet fire	case of leak is rated for hazardous areas for a scenario without artificial ventilation. - Prohibition of smoking, mobile phones	Estimations of jet fire suggest limited radiative heat and temperatures (see section 4.5.2) 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).

4.6 Conclusion of case study

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 60079-10-1:2020 [12] when considering the application of Zone NE concepts.

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MultHyFuel

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