Instituut
Fysieke
Veiligheid

Safety aspects relating to the use of hydrogen in confined spaces

Institute for Safety
Knowledge development and education
P.O. Box 7010
6801 HA Arnhem
Kemperbergerweg 783, Arnhem
www.ifv.nl
info@ifv.nl
+31 26 355 24 00

Colophon

Institute for Safety (2020) *Safety aspects relating to the use of hydrogen in confined spaces*. Arnhem: IFV.

Title:	Safety aspects relating to the use of hydrogen in confined spaces
Date:	14 October 2020
Status:	Definitive
Version:	1.0
Authors:	Dr M.B. Spoelstra
With thanks to:	Ir. N. W. van den Berg and E.S. Korbee MSc (Rijkswaterstaat WVL), ing. J. van der Graaf and Ir. I. Trijssenaar (IFV), Ir. P. te Morsche (Alliander), ing. F.H.M. van Alphen (Stedin), ing. R. van Hooijdonk (Enexis), ing. M. van den Berg and ing. M. Meijer (VRR)
Review:	Dr Ir. N. Rosmuller
Responsible person:	Dr Ir. N. Rosmuller

Foreword

‘Is hydrogen the way forward, or will it be electricity after all?’ A frequently asked question with regard to mobility as well as to the supply of energy to households and industry. Nobody knows the answer for sure, and it is within the context of this report also less relevant. Whatever the future brings us (perhaps a mix of these two or even more options), it will be necessary to evaluate the safety risks in order to ensure that a solution is developed and implemented. That development falls largely under the responsibility of market participants, with the government’s role being to create the necessary frameworks. Some of these frameworks may, or perhaps must, be established by the Dutch Safety Regions. The Safety Regions are safety advisory bodies to the competent authorities, boasting knowledge in the field of building and environmental safety, incident development and incident management. The safety of hydrogen in confined spaces certainly falls under this remit. Confined spaces are spaces that are largely shielded from the environment, meaning that (a)typical distribution patterns may occur and any hydrogen released within them may accumulate.

This study reviews the specific safety aspects associated with the release of hydrogen in confined spaces. It provides information that advisors at the Safety Regions can use when they are consulted about projects and developments in relation to various applications of hydrogen in confined spaces. The information is structured according to the logical sequence (chronology) of a hydrogen incident scenario: release of hydrogen, its dispersion and the associated potential risks. For each of these ‘phases’ in the development of the incident scenario, measures are listed that the Safety Regions can refer to in their advisory reports.

Many organisations have a knowledge base available regarding some aspects of hydrogen safety. The beauty of this report is that it brings the various knowledge components together in one place. I thank the experts of the network operators and Safety Regions for their contribution to this document.

Our knowledge regarding the safety aspects of hydrogen is not static, but is continuously evolving based both on new studies and on practical experience and the evaluation thereof. This allows us to close the knowledge loop. For the IFV, this ‘closing of the knowledge loop’ is how we as a knowledge and training institute hope to achieve our ambition and fulfil our role in supporting the Safety Regions and other bodies. I would therefore like to call upon everyone to share with us any further knowledge of or experience with hydrogen safety in confined spaces that they are able to. It is this information that will ultimately allow us to live up to our ambition and role in this rapidly evolving field of the energy transition.

Nils Rosmuller
Lecturer for Energy and Transport Safety

Contents

Summary

The (partial) replacement of natural gas with hydrogen is one possibility for ensuring energy security in the Netherlands once the use of natural gas is reduced. Certain safety questions are raised when hydrogen is present and used in confined spaces such as homes. The Energy and Transport Safety Research Group of the IFV came up with the initiative to carry out a literature study regarding the safety aspects of using hydrogen in confined spaces. This study is relevant to the assessment of safety risks by advisors of the Safety Regions. The questions addressed by the study, which were drawn up in collaboration with participants in the Hydrogen Community of Practice, are as follows:

1. How can hydrogen be released in a confined space?
2. How does hydrogen disperse in a confined space?
3. How does this dispersion affects hydrogen concentrations?
4. What are the dangerous hydrogen concentrations in a confined space?
5. What is the likelihood of ignition at these concentrations?
6. What are the consequences when hydrogen ignites at various concentrations?
7. What measures can be taken to prevent hazardous concentrations from building up in confined spaces?

While the report was being written, it became clear that there was a lot of overlap between questions 4 and 6, so the two questions were combined. In order to respond to the questions put forward in this study, knowledge of the physical properties of hydrogen is required. These properties are discussed in Chapter 1. It is not always possible to deduce how hydrogen will behave in a certain situation based solely on its physical properties. Ambient conditions also affect the behaviour and dispersion of hydrogen.

When used in a home, pure hydrogen is fed to the boiler from the meter box via a system of pipes. Hydrogen may be released at various locations in the home as a result of leaky pipes or faulty systems. The amount of hydrogen released through pipe walls as a result of diffusion is negligible. The ways that hydrogen can be released are largely the same as for natural gas, except that embrittlement is an additional failure mechanism specific to hydrogen. However, embrittlement is unlikely to occur at the low pressures and temperatures found in hydrogen pipes in homes (and in the supply lines to those homes).

The dispersion of hydrogen in confined spaces can be divided into a release phase (in which the hydrogen concentration increases), a dispersion phase (in which the hydrogen disperses through diffusion) and a stationary end phase (in which the hydrogen concentration is uniformly distributed and static). In a confined space, hydrogen will accumulate below ceilings and roofs, where it can reach hazardous concentrations (depending on the circumstances). The structure of such hydrogen layers varies between two extremes: a uniformly distributed hydrogen layer where the hydrogen concentration is the same throughout, and a stratified hydrogen layer consisting of several sublayers with varying concentrations.

Small hydrogen leaks result in laminar flows with little turbulence, which cause a stratified hydrogen layer to form. Large hydrogen leaks result in turbulent flows, which cause a uniformly distributed hydrogen layer to form. Obstacles and ventilation cause changes in the distribution mechanism, resulting in better mixing of the hydrogen.

The total amount of hydrogen that is released determines the ultimate hydrogen concentration in a room. The higher the amount released, the greater the hydrogen concentration in the room and the longer it takes for the concentration to fall below the LFL. Low release rates result in stratification, and the hydrogen concentration in the highest sublayers is higher during the release and dispersion phases than during the end phase. Moreover, at low release rates the high hydrogen concentrations remain for longer than at high release rates, which cause uniform distribution of the hydrogen. Mixing a hydrogen-air mixture ensures distribution of the mixture and thus a reduction in hydrogen concentrations.

If hydrogen is released and the hydrogen plume meets an ignition source, hazardous situations like a jet flame or explosion may arise. The hydrogen concentration determines the direction and thus the distribution of hydrogen flames: these flames will go upwards at 4–6 vol.%, upwards and sideways at 6–9 vol.% and in all directions at 9 vol.% and over. The available amount of space necessary to develop the flame front, is determined by the hydrogen concentration and by the location of the ignition source. The more space the flame front has, the higher the overpressure can become if the hydrogen-air mixture ignites. The amount of overpressure in a space resulting from a hydrogen explosion depends on the hydrogen concentration, the size and geometry of the space, the presence and size of openings and the presence of obstacles. Hydrogen concentrations of up to 10 vol.% result in hardly any overpressure, unless the openings present are too small to release any pressure. Obstacles result in greater turbulence and better combustion of hydrogen, thereby increasing the amount of overpressure. A uniform hydrogen layer results in lower overpressure than multiple higher-concentration hydrogen layers.

In order to calculate the risks posed by systems containing hydrogen, the probability of ignition must be known. This is the sum of the probability of direct ignition and the probability of delayed ignition. The ignition probability for hydrogen is not known, but given the low ignition energy of hydrogen its ignition probability will be higher than that of other flammable gases. Much is contingent on ambient conditions. The lower the ignition energy, the greater the probability of ignition. The ignition energy of hydrogen is lowest at 30 vol.% and highest at the LFL and UFL. At low concentrations, the ignition energy of hydrogen is comparable to that of methane. If hydrogen does ignite inside a home, it is more likely to occur due to delayed ignition than direct ignition. Hydrogen mixtures with concentrations of 4–10 vol.% do not always ignite upon activation of a light switch. Spark discharges are the most common ignition source.

Measures have been identified to prevent or mitigate the risks associated with the release of hydrogen in confined spaces in accordance with the bow tie model. The preventative measures involve managing processes, intervening when faults are detected and ensuring emergency protection systems are in place. The mitigating measures involve limiting the release of hydrogen, preventing leaks from escalating, and personal protection and emergency response. When it comes to preventing the release of hydrogen indoors, the most important measures involve setting standards for the installation, management and maintenance of hydrogen-containing systems. The most important measures for managing a leak are overpressure relief valves and flow restrictors. Valves can limit leaks, whilst detection, ventilation, prevention or management of ignition sources and the implementation of safety distances are the key measures for preventing escalation of leaks. The primary measures for first responders combating hydrogen fires are cutting off supply and refraining from quenching the flames.

Introduction

Background

Consumption of natural gas in the Netherlands must be reduced, both in order to limit CO_2 emissions and in light of safety considerations (e.g. earthquakes in the Province of Groningen). Fully or partially replacing natural gas with hydrogen is one of the ways in which the Netherlands can ensure that it is supplied with sufficient energy. Compared to electricity, hydrogen is a more suitable medium for transporting and storing large quantities of energy (Topsector Energy, 2020a). Moreover, the fact that the Netherlands has an extensive gas network makes replacing natural gas with hydrogen a particularly promising option. The Dutch Climate Pact recognises this, stating that 'hydrogen must fulfil a number of crucial functions in the energy and raw materials system within the medium (2030) to long (2050) term, including in urban environments' (Dutch Ministry of Economic Affairs and Climate (EZK), 2019).

Almost all households in the Netherlands are connected to a natural gas line. Rules are in place regarding the supply and use of natural gas, ranging from work instructions to legislation and regulations. The Netherlands is only just setting out on the path towards greater hydrogen use: there is still minimal experience with transporting hydrogen through natural gas pipelines and using hydrogen in domestic boilers. That is why field trials are being carried out in homes in order to test and demonstrate the capabilities of hydrogen. Pilot studies are currently ongoing in Hoogeveen, Rozenburg, Lochem and Stad aan 't Haringvliet (Topsector Energie, 2020b).

The presence and use of pure hydrogen in confined spaces such as homes raises a number of safety questions. After all, like natural gas, hydrogen is a hazardous substance that must be handled with caution. The Energy and Transport Safety Research Group of IFV came up with the initiative to carry out a literature study regarding the safety aspects of using hydrogen in a confined space. This report describes the results of that study.

Objective

The objective of this study is to tap into existing knowledge regarding the safety aspects of using pure hydrogen in confined spaces based on a number of research questions (see the following page for details).

The knowledge compiled in this study is relevant to the evaluation of safety risks by advisors working on behalf of the Safety Regions. They are the primary target group of this document, as they advise competent authorities about safeguarding and promoting physical health and safety in the physical environment. This may take place both at provincial level (environment vision and regulation) and at municipal level (environment vision and plan, as well as advice on external safety aspects when granting licenses). Of course, this does not preclude other individuals from making use of the knowledge compiled in this report.

Research questions

The research questions were drawn up in collaboration with participants in the Hydrogen Community of Practice (CoP)[1], and essentially follow the timeline of a scenario where hydrogen is released into a confined space. As such, the research questions are presented in a chronological sequence and are:

1. How can hydrogen be released in a confined space?
2. How does hydrogen disperse in a confined space?
3. How does this dispersion affects hydrogen concentrations?
4. What are the dangerous hydrogen concentrations in a confined space?
5. What is the likelihood of ignition at these concentrations?
6. What are the consequences when hydrogen ignites at various concentrations?
7. What measures can be taken to prevent hazardous concentrations from building up in confined spaces?

While the report was being written, it became clear that there was a lot of overlap between questions 4 and 6. Therefore, research question 6 was combined with research question 4, and they are no longer shown as separate research questions in the contents table of this report.

Scope

In this report, a confined space means a space inside a home that is enclosed by walls, a floor and a ceiling or roof. The space may also be a garage, provided that it does not contain a hydrogen-fuelled car.

The subject matter of this study is ‘the safety of hydrogen in confined spaces’. This topic can be divided into four categories that all concern applications of hydrogen:

1. General aspects concerning hydrogen in confined spaces
2. Hydrogen used for central heating
3. Hydrogen-fuelled vehicles in tunnels
4. Parking of hydrogen-fuelled vehicles

This study focuses on the general aspects of the use of hydrogen in confined spaces (category 1) and the use of hydrogen in homes for the purpose of heating (category 2) but not for cooking. Categories 3 and 4 concern mobility, and thus fall under the Hydrogen Safety and Innovation Platform (*Waterstof Veiligheid en Innovatie Platform*, WVIP) (H2Platform, 2020).

Research method

In order to respond to the research questions and to corroborate those responses, a literature study was performed. This involved using various search terms to perform a targeted search of the ScienceDirect knowledge database. The search terms varied depending on the question, and consisted of combinations of two or more words that had to appear

---

[1] The Hydrogen CoP is an initiative of the IFV, and its objective is to collect and share knowledge and experience in the field of hydrogen usage. The CoP is formed of fire service specialists, researchers in Transport Safety and Firefighting at the IFV, specialists from business and public authorities.

in the title or abstract of a publication. Examples of search terms used include HYDROGEN, SAFETY, CONFINED, HOUSE, DOMESTIC, CONCENTRATION, BOILER, HEATING and variations of these words. After examining the titles and/or abstracts of the publications, one or several were selected per subject for closer examination. Most of the publications were from peer-reviewed journals, of which the *International Journal of Hydrogen Energy* is the most frequently cited.

Many of the publications identified in this way were often of limited relevance. As such, a search was performed for publications and documents using the ‘snowball method’. Finally, publications, articles and documents were acquired via contacts and by searching online using Google.

Application of the literature study

The knowledge compiled through the process of responding to the research questions will be used to develop and update course materials for fire services. The results of the literature study will also be used to draw up (supplementary) knowledge documents for the Safety Regions, for example an overview of structural, system-specific and organisational measures that is specifically applicable to the use of hydrogen for central heating in homes.

Guide

Since hydrogen is the primary focus of this research, Chapter 1 discusses a number of the (physical) properties of hydrogen. The following chapters each address one of the six research questions drawn up on the basis of the literature search. Each chapter ends with a summary of the key elements of that chapter.

1 Properties of hydrogen

1.1 Introduction

This report does not address the public perception of hydrogen, but describes the safety aspects that are relevant to the use of hydrogen based on information found in the literature. To this end, knowledge of the physical properties of hydrogen is required. These are discussed in this section.

1.2 Physical properties

Much has been written about the properties of hydrogen, for example in connection with UK and European projects such as HySafe, HyIndoor, HyResponse and Hy4Heat. The most important physical properties of hydrogen are set out below. Some properties are discussed in more detail elsewhere in this report.

- At standard temperature and pressure (20 °C and 1 atm.), hydrogen is gaseous, colourless[2], odourless, tasteless and non-toxic. This means that it is undetectable if released unexpectedly, unless specific measures are taken. Such measures may include adding an odorant, as is done with natural gas, or installing hydrogen detectors.
- Of all the gases, hydrogen has the lowest density relative to air: 0.083 kg/m^3 compared to 1.205 kg/m^3. This makes hydrogen fourteen times lighter than air, meaning it has a high buoyancy. Although this ensures rapid dilution, it can also result in hazardous situations. If hydrogen is released in a confined space, it can accumulate below the roof, where it can reach high concentrations.
- Given the speed at which hydrogen rises, diffusion plays a less significant role in the dispersion of hydrogen in air, even though the diffusion coefficient of hydrogen is greater than that of methane for example, which is the primary component of natural gas.
- Hydrogen has a broad flammable range. The LFL (lower flammability limit) is 4 vol.% and the UFL (upper flammability limit) is 75 vol.%.[3] The LFL is the more significant of these two limit values, as this is reached first when hydrogen is released. See also Section 5.3.1.
- The minimum ignition energy of hydrogen is 0.019 mJ, and this applies at a hydrogen concentration of around 30 vol.%. At the LFL and UFL, the ignition energy is higher. See also Section 6.2.
- A hydrogen flame does not radiate much heat due to the absence of carbon (which can result in the formation of heat-radiating soot particles) and the presence of heat-absorbing water vapour in the flame (HySafe, 2009). Hydrogen flames therefore retain their own heat, and are thus extremely hot in comparison to hydrocarbon flames.

---

[2] If particles are carried along with it during combustion, for example as a result of mixing with air, these particles will also combust and make the hydrogen flames visible.

[3] The LFL and UFL are the lowest and highest concentrations respectively at which a flammable gas ignites and at which the flame produced can maintain itself.

- A hydrogen flame burns at a greater speed than a hydrocarbon flame: around 3 m/s for hydrogen compared to 0.4 m/s for methane. The greater the hydrogen concentration, the faster the burning rate and the greater the probability of a transition from deflagration to detonation (see Section 5.4).
- Hydrogen has a low viscosity. Viscosity is an indicator of how ‘thick’ a gas or liquid is. The lower the viscosity, the more easily the molecules are able to slide past each other. Combined with the particle size and diffusion capabilities of hydrogen, this can be expected to result in relatively quick formation of leaks at seals.

Hydrogen's physical properties are only partly responsible for the way it behaves in particular situations. The way in which it is released and the ambient conditions also influence the behaviour of hydrogen in the event of an unwanted leak.

In future, it is possible that hydrogen will replace natural gas in many applications. A comparison is therefore provided below of the physical properties of hydrogen and of methane, the primary component of natural gas.

Table 1.1 Physical properties of hydrogen and methane (sources: Molkov (2012), HyResponse (2016) and HySafe (2019))

Property	Hydrogen	Methane
Molecular weight (g/mol)	2.01	16.04
Density (kg/m^3)	0.08345	0.66
Stoichiometric concentration (vol.%)	29.6	9.5
Diffusion coefficient in air (m^2/s)	0.61×10^{-4}	0.21×10^{-4}
LFL for upward flame propagation (vol.%)	4.0	5.3
UFL for upward flame propagation (vol.%)	75.0	15
Explosive limits (vol.%)	11 – 70 (HySafe) 11 – 59 (HyResponse)	5.7–14
Minimum ignition energy (mJ)	0.019	0.28
Autoignition temperature (°C)	560–585	537
Flame temperature (°C)	2045	1960
Burning rate (m/s)	2.6–3.2	0.4

Summary

- The physical properties of hydrogen are discussed and compared with those of methane, the primary component of natural gas.
- It is not always possible to deduce how hydrogen will behave in a certain situation based solely on the physical properties of hydrogen. Ambient conditions also affect the behaviour and dispersion of hydrogen.

2 How can hydrogen be released in a confined space?

2.1 Introduction

The pressure of pure hydrogen used for domestic heating and cooking when it arrives at a home will be no more than 100 mbar, reduced to 30 mbar just before it enters the meter. The hydrogen is piped to the boiler via a system of pipelines. Hydrogen can be released at various locations in a home as a result of leaky pipes or faulty equipment.

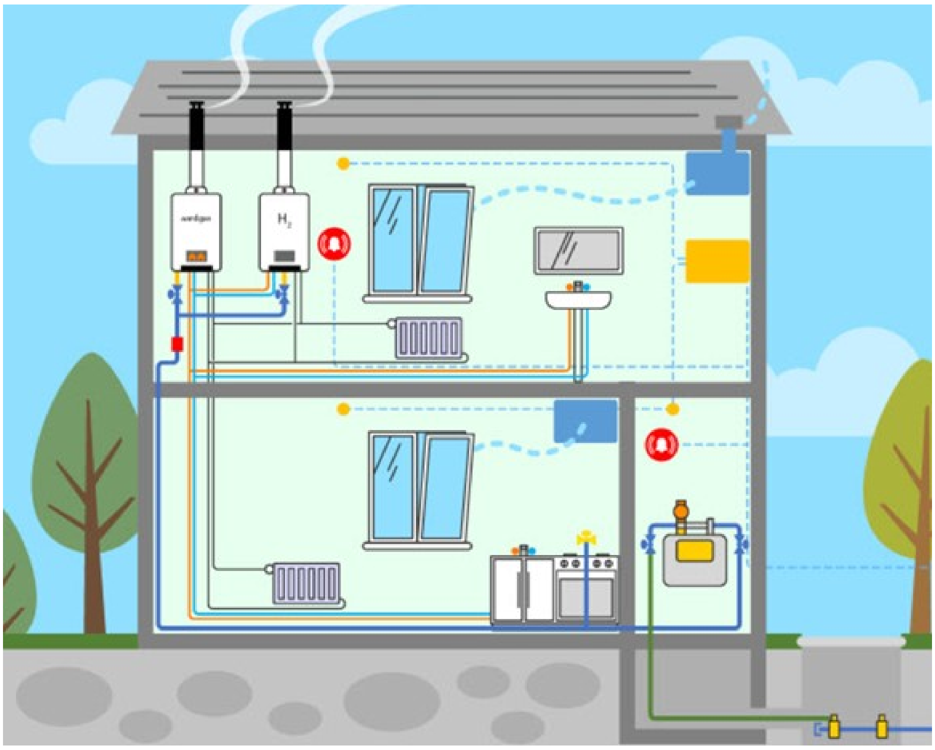


Figure 2.1 Schematic diagram of gas pipelines (source: Liander)

When systems fail, a distinction is often made between major and minor leaks. With a major leak, the contents of the system are released within a very short time frame, whereas with a minor leak the hydrogen is released over a longer period. This period can vary from a few seconds to hours or even days. A major leak is significantly less likely than a minor leak. In this report, the term ‘leak’ therefore primarily refers to a minor leak scenario.

2.2 Hydrogen leaks

2.2.1 Hydrogen versus natural gas

The calorific value of hydrogen is lower than that of natural gas: 10.8 MJ/m^3 vs. 36.4 MJ/m^3. This means that less heat is emitted in hydrogen combustion than in natural gas combustion. The number of cubic metres of hydrogen needed to heat a home is therefore around three times greater than in the case of natural gas. By volume, around three times more hydrogen than natural gas will be released in the event of a gas leak (at an equivalent pressure). This varies from a factor of 1.6 for minor leaks (from a 100-mbar pipeline) to a factor of 3 for major leaks (KIWA, 2019).

2.2.2 Convection, permeation

Scientifically speaking, convection and permeation are the primary means of release of hydrogen (Schefer et al., 2006). Convection involves the hydrogen molecules within the hydrogen-containing system[4] passing through openings (holes, cracks or defects) in the walls of the system due to the difference in pressure inside and outside the system. Hydrogen molecules are able to leave the system through these openings, as the diameter of these openings is many times the diameter of a hydrogen molecule.

Permeation involves a difference in concentration resulting in molecules passing through the walls of a hydrogen-containing system.[5] The degree of hydrogen permeation dependents on the material the wall is made of, the hydrogen concentration in the system and the temperature. With permeation there is no localised release of gas; instead, it is ‘leaked’ continuously over the entire surface of the hydrogen-containing system. From the collected examples in Table 2.1, it is apparent that the quantity of hydrogen released through permeation at room temperature is negligible when compared to the amount of hydrogen released through an opening (Mejia, 2020).

Table 2.1 Examples of release rates of hydrogen through a pipe wall (permeation) and through an opening (convection)

Example	Pressure (bar)	Type of release	Release	Source
Natural gas transport pipeline	80	Permeation	1.7 m^3/(km·year) ≡ 0.06 ml/(km·s)	(Krom, 2020)
Polymer distribution pipeline natural gas	0.1	Permeation	51 m^3/(km·year) ≡ 1.6 ml/(km·s)	(KIWA, 2018)
Polymer distribution pipeline hydrogen	0.1	Permeation	< 6 m^3/(km·year) ≡ < 0.2 ml/(km·s)	(KIWA, 2018)
Permitted leak rate natural gas	0.1	Convection	1.4 ml/s	(NEN, 2018)
Guillotine break hydrogen pipeline	0.1	Convection	170 ml/s	(Kiwa Gastec, 2015)

---

[4] The hydrogen-containing systems present in homes are pipelines. Hydrogen is used in boilers, cooking appliances and fuel cells, meaning that such systems are not used to store any hydrogen.

[5] This displacement is also referred to as diffusion, and both terms are often used interchangeably.

With permeation only 1.6 millilitres of hydrogen is released per second from a polymer pipeline with a hydrogen pressure of 100 mbar spread over a length of 1 kilometre, whereas with a leak a similar quantity or greater is released at a single location. Permeation does, however, present a risk in the case of plastic gas pipelines enclosed in jacket pipes, because hydrogen can accumulate in the space between the two casings if there is not sufficient ventilation (KIWA, 2018).

2.2.3 Failure modes

Hydrogen is released when an opening is present in the wall of the hydrogen-containing system. The size of the opening may be on the order of tenths of a millimetre to a millimetre or more. Gas may be released during installation, use and maintenance of hydrogen-containing systems.

The following failure modes were found in the literature for pipelines, regardless of the substance being transported (Mejia et al, 2020):

- components are not connected due to the incorrect use of materials.
- components are not properly connected due to incorrect installation.
- components are not properly connected due to poor maintenance.
- pipelines fail due to an external impact caused by human action.
- pipelines fail due to an external impact from falling objects, earthquakes or other circumstances not caused by human action.

Data from Netbeheer Nederland on natural gas pipelines and connections shows that failures are primarily caused by wear and/or ageing as well as internal defects. For pipelines outside of the house, excavation damage is the most significant failure mode (Netbeheer Nederland, 2019). Figure 2.2 illustrates the types of interruptions found in gas meter installations.

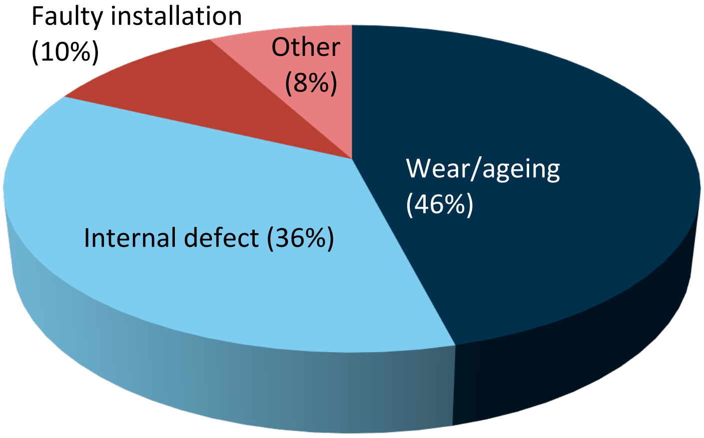


Figure 2.2 Distribution of interruptions (N = 33,456) for gas meter installations (source: Netbeheer Nederland)

It is expected that the distribution of interruptions for hydrogen will be comparable. The number of interruptions will not increase if hydrogen is used to a similar extent as natural gas, as both hydrogen and methane molecules are smaller than the size of an opening by at least a factor of 1000.[6] However, a greater quantity of hydrogen will be released compared to natural gas due to the volatility of hydrogen.

2.2.4 Material degradation

The materials in a burner can become damaged by flammable gases such as natural gas and hydrogen, for example as a result of blistering, cracking or melting. In homes, burners can be found in boilers (KIWA, 2016).[7] In addition, there are two other degradation mechanisms for hydrogen, namely hydrogen embrittlement under fatigue loading and under static loading. The degree of embrittlement depends, inter alia, on the manner of pressure-loading of the steel, the temperature and the presence of defects.

The extent of the pressure difference and the number of times the pressure in the pipeline changes both influence the fatigue behaviour of steel, and can lead to hydrogen embrittlement. Given the low pressure at which hydrogen is used in homes (< 100 mbar), hydrogen embrittlement as a result of fatigue loading is unlikely to pose a problem (Frazer-Nash, 2018).
With hydrogen embrittlement, diffusion of hydrogen atoms into the steel leads to static pressures in the steel and consequently the steel becomes more brittle. The conditions for use of hydrogen pipelines in homes are such (low pressure and temperature) that this type of embrittlement is not possible, but it does affect burners since the materials in the burner come into direct contact with hot hydrogen flames (Frazer-Nash, 2018). For this reason, new burners are being developed for burning hydrogen.

2.2.5 Leak locations

As hydrogen is not yet being used in homes in the Netherlands, no data is available on hydrogen leak locations. Such data is available, however, for natural gas: regional network operators record the location of interruptions[8] in the pipeline system to and in homes (Netbeheer Nederland, 2019). Most interruptins occur in the gas meter systems (61%), especially at connections, regulators, valves and taps.

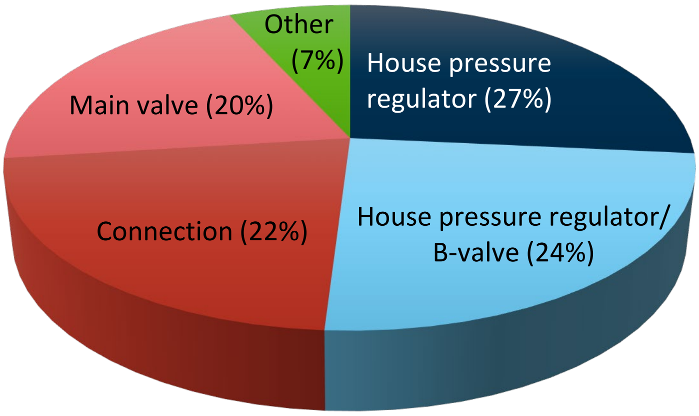


Figure 2.3 Distribution of interruptions (N = 33,456) per component for gas meter installations (source: Netbeheer Nederland)

---

[6] The size of methane and hydrogen molecules is on the order of 10^{-11} m.

[7] Burners may also be present in cooking appliances, but this scenario is not addressed in this report.

[8] An interruption does not by definition have to involve a gas leak. Many faults are also related to the rollout of smart meters.

Summary

- Gas leaks primarily occur at connections, regulators, taps and valves.
- Gas leaks are usually the result of ageing or internal defects.
- The quantity of hydrogen that passes through pipe walls as a result of diffusion is negligible compared to the quantity of hydrogen released from a leaky pipe.
- The ways that hydrogen can be released are largely the same as for natural gas, except that embrittlement is an additional failure mechanism specific to hydrogen. However, embrittlement is unlikely to occur at the low pressures and temperatures found in hydrogen pipes in homes (and in the supply lines to those homes).

3 How does hydrogen disperse in a confined space?

3.1 Introduction

When hydrogen is released into open air, it rapidly rises and becomes diluted. In terms of safety, the open air is a more favourable location than a building or other confined space, as in the latter cases hydrogen will accumulate below ceilings and roofs, where it can reach hazardous concentrations depending on the circumstances.

The dispersion of hydrogen in a confined space can be divided in three phases: a release phase, a dispersion phase and a stationary end phase. In the release phase, hydrogen is released and the hydrogen concentration increases for as long as hydrogen is being released from the opening. Once hydrogen stops being released, the hydrogen-air mixture slowly descends as a result of diffusion. This is the dispersion phase. After a long period (a period much longer than the duration of release), the hydrogen will become homogeneously mixed with the air in the confined space. The hydrogen concentration will no longer change, and a state of equilibrium is reached. This is the stationary end phase (De Stefano et al, 2019).

This chapter describes the way in which hydrogen is released and disperses, and the factors that affect this process in each phase.

3.2 Dispersion

3.2.1 General

Upon release, the hydrogen molecules go from a high-pressure environment to a low-pressure environment (ambient pressure). As a result of this pressure drop the molecules disperse; the jet expands and the hydrogen molecules lose speed. In addition, turbulence occurs at the edges of the jet and air is entrained leading to mixing of hydrogen with air.

The direction of a jet can be determined based on the buoyant force of hydrogen (1), the momentum with which hydrogen is released (2) or both (3). This is illustrated in Figure 3.1 for a horizontal release (Molkov, 2012).

The jet ultimately transforms into a plume. When hydrogen is released outdoors, the wind and the buoyant force of hydrogen cause the plume to disperse. When hydrogen is released in a confined space indoors, no wind is present and a hydrogen-rich layer forms below the ceiling of the room. This hydrogen-rich layer takes on a specific dimension and thickness, which can change over time. Such a layer may also form elsewhere in the building, for example under the roof.

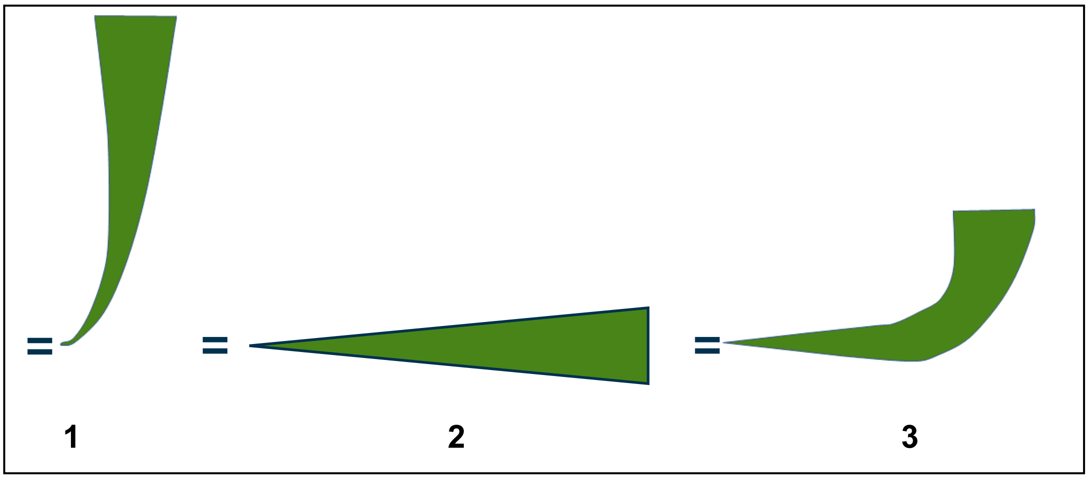


Figure 3.1 The three types of jet (according to Molkov (2012))

The structure of the layer can vary between two extremes (HySafe, 2009). At one end of the spectrum, multiple hydrogen-rich layers of varying concentrations may form and the concentrations in the upper layers can be quite high (> 10 vol.%). This stratification occurs whenever the buoyant force is dominant and there is too little energy for the hydrogen to mix with air. At the other end of the spectrum, a thoroughly mixed hydrogen layer may form with the same hydrogen concentration throughout. In that case, the buoyant force is not dominant and there is enough energy in the form of turbulence to achieve mixing (Cariteau et al., 2012).

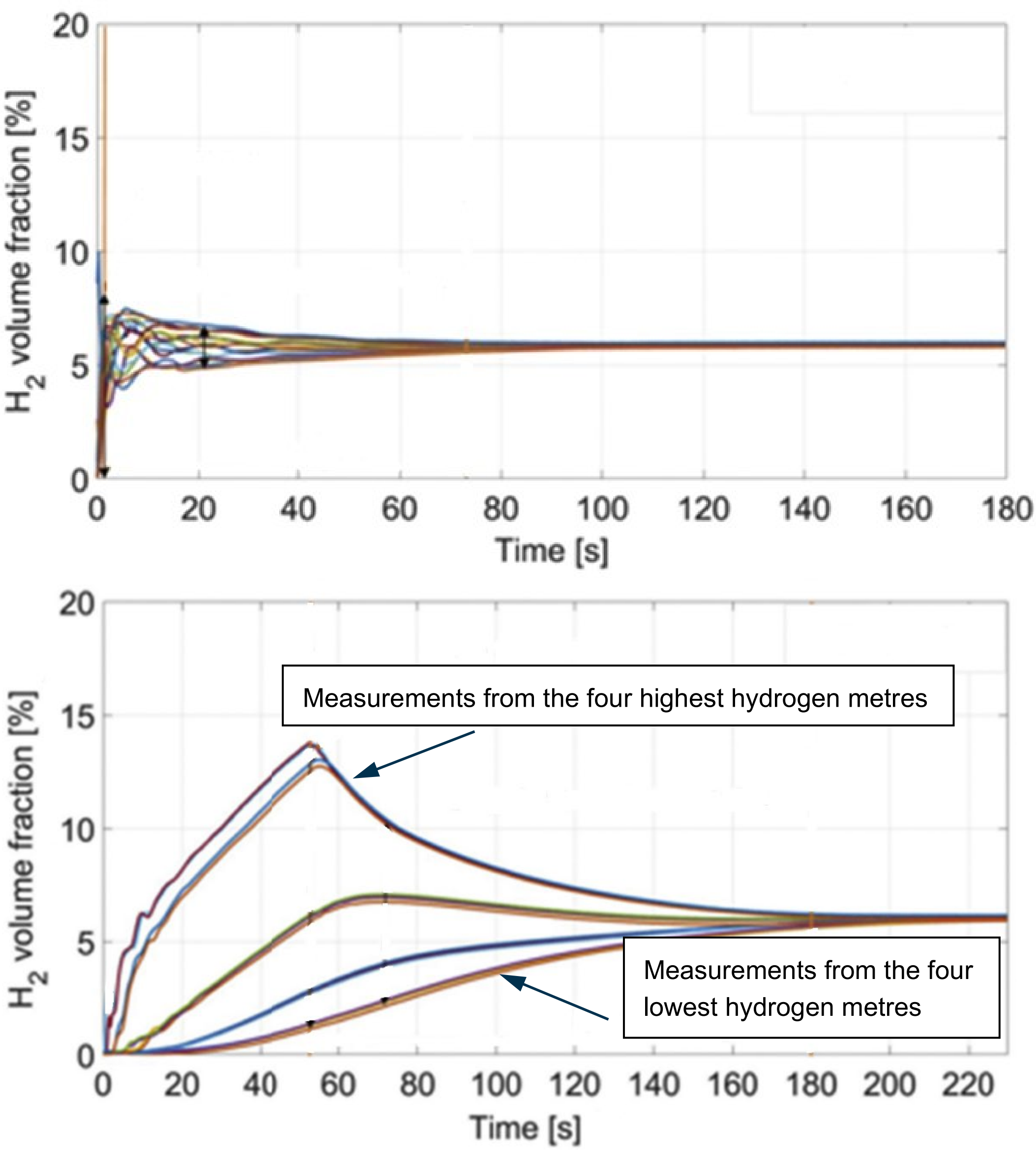
3.2.2 The influence of the release rate

The release rate (expressed in g/s or kg/s) has a decisive impact on the way in which hydrogen-rich layers form below the ceiling or roof of a space during the release phase. At high release rates, there is usually a lot of turbulence, in which case the hydrogen spreads along the ceiling and walls of the room and descends until the room is homogeneously filled. At low release rates, there is much less turbulence and the hydrogen rises to the ceiling where it forms layers of varying concentrations (stratification). The highest hydrogen concentrations can be found in the layers directly below the ceiling (Lacome, 2011) (De Stefano et al., 2019).

This behaviour is well illustrated in a set of experiments where the same amount of hydrogen was injected into a confined space at two different release rates, see Figure 3.2 (De Stefano et al., 2019). The room was equipped with 16 hydrogen meters (at four heights in four different locations) that measured hydrogen concentrations. Note that each hydrogen meter has its own colour in the graphs in Figure 3.2.

In the experiment where the room was filled at a high release rate (6 m^3 per hour), the release duration was 1 second. Few differences in concentration were measured in the beginning, but a homogeneous distribution was quickly achieved and the hydrogen concentrations became the same everywhere (Figure 3.2 above).
In the experiment where the room was filled at a low release rate (0.1 m^3 per hour), the release duration was 53 seconds and four different hydrogen concentrations were measured at the four measuring heights. This is an indication for stratification, and the higher the layer

the higher the hydrogen concentration in the layer. Once the release was stopped, the hydrogen concentration in the confined space became increasingly uniformly distributed through diffusion, until the same end concentration was achieved with respect to the release with a high release rate (Figure 3.2 below).



Measurements from the four highest hydrogen metres

Measurements from the four lowest hydrogen metres

Figure 3.2 Top: uniform distribution at Q = 6 m^3/hour. Bottom: stratification at Q = 0.1 m^3/hour. The 16 hydrogen meters are each assigned a different colour and are spread over four different heights (source: De Stefano, 2019; to improve readability all labels have been removed from the figures)

3.2.3 The influence of turbulence

Hydrogen leaks can either be turbulent or laminar in nature. A laminar flow is a steady flow going in one direction, whereas a turbulent flow is much more unpredictable and can go in multiple directions. The higher the pressure of the released gas, the more turbulent the release will be (Schefer et al., 2006). In the case of small fissures and at a release rate on the order of 1 litre per hour, the flow will be laminar. In the case of more major leaks, the flow will be turbulent (KIWA, 2018) (DNVGL, 2020a). Obstacles and ventilation influence the flow behaviour of hydrogen.

Obstacles

Obstacles do influence the dispersion behaviour of hydrogen, but to a lesser extent than the release rate. The effect of obstacles varies depending on whether the flow is laminar or turbulent. In the case of laminar flows, obstacles cause more turbulence, which results in better mixing of the hydrogen and a more uniform concentration throughout the hydrogen layer (Prasad et al., 2010). In the case of turbulent flows, obstacles actually disrupt the vortices, causing the hydrogen jet to lose energy and decelerate. This means hydrogen is less able to mix with the air in the room and becomes less uniformly distributed (De Stefano, 2019).

Ventilation

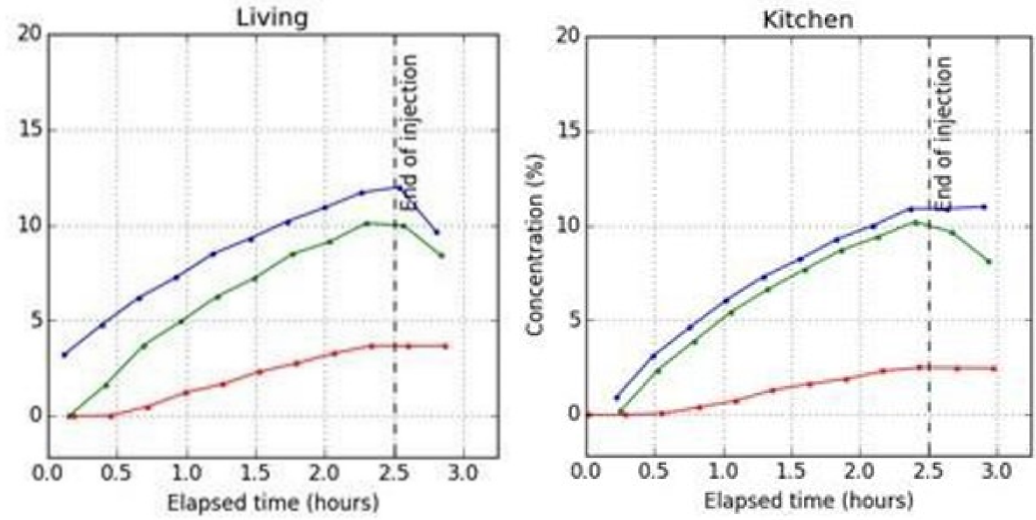
Ventilation in a building can be natural or mechanical. Natural ventilation is a passive form of ventilation where airflows are created in a room by opening doors and/or windows. Mechanical ventilation is an active form of ventilation where equipment is used to create airflows in a room. Ventilation creates airflows, especially when the ventilation openings are opposite to one another. These flows result in vortices and in better mixing of the hydrogen-air mixture (HySafe, 2009). Ventilation is discussed in Section 7.6.2.

3.2.4 Field tests in Scotland

In the HyHouse project, experiments were carried out in an old house in Scotland, where hydrogen leaks were simulated in several rooms on the ground floor (KIWA Gastec, 2015). The hydrogen concentration was monitored at three levels in rooms on the ground floor and the first floor. The doors between the rooms were all left open. The same patterns were always seen, regardless of the location of the release and the air-tightness of the house. On the ground floor, the hydrogen was always stratified. On the first floor, however, a uniform distribution was measured everywhere, with the three measuring points reporting more or less the same hydrogen concentrations. See Figure 3.3.

The explanation given for this is that a stack effect occurs, which causes a natural airflow inside the house. This effect is more apparent on the ground floor than on the first floor. In the view of the author of this report, a better explanation would be that the rate and speed of the hydrogen released on the ground floor are such that the buoyant force of hydrogen is always dominant, leading to a laminar flow on the ground floor and therefore stratification. The absence of stratification on the first floor could be explained by the fact that hydrogen is released into this area evenly through the regularly spaced gaps and holes in the wooden floor.

Ground floor:



First floor:

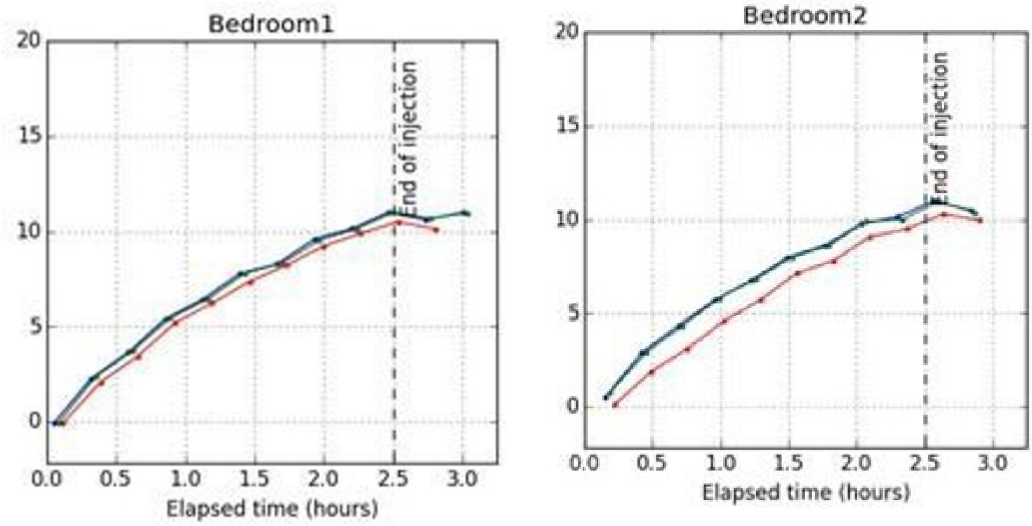


Figure 3.3 Hydrogen concentration as a function of time in four different rooms in the house. Over 2.5 hours, hydrogen was injected into the living room on the ground floor (labelled 'living') at a rate of 5.3 l/s. The measurement locations in the rooms were at either high (blue), medium (green) or low (red) heights (source: KIWA Gastec, 2015)

Summary

- The structure of the hydrogen layer that becomes 'trapped' below the ceiling varies between two extremes: a uniformly distributed hydrogen layer where the hydrogen concentration is the same throughout, and a hydrogen layer consisting of several strata with varying concentrations.
- Small hydrogen leaks result in laminar flows with little turbulence that cause a stratified hydrogen layer to form below the ceiling.
- Large hydrogen leaks result in turbulent flows that cause a uniformly distributed hydrogen layer to form below the ceiling.
- Obstacles change the nature of the dispersion mechanism.
- Ventilation produces turbulence, and therefore better mixing of the hydrogen in a room.

4 How does dispersion affects hydrogen concentrations?

4.1 Introduction

Chapter 2 stated that a hydrogen leakage in a house releases up to three times more cubic meters of hydrogen than a natural gas leakage at the same pressure and pipe diameter. In theory, the hydrogen concentration in the room would thus also be greater by a maximum factor of 3, but this was not found in experiments. In experiments a factor of 1.5–1.6 was found (Mejia, 2020; KIWA Gastec, 2015; KIWA, 2019a). The reason given for this is the low density and thus high buoyancy of hydrogen, which results in a faster dispersion of hydrogen through openings.
Whereas Chapter 3 addressed the way in which hydrogen disperses within a space, this chapter describes how (local) conditions impact the hydrogen concentration in a confined space.

4.2 Effect of the total quantity of hydrogen released

When hydrogen is released in a confined space, the process can be divided into a release phase, a dispersion phase and a stationary end phase. In the release and dispersion phases, local hydrogen concentrations may be much greater than in the end phase. In the end phase, an equilibrium has been reached, and the hydrogen concentration is the same everywhere in the room as a result of the diffusion process. The total quantity of hydrogen released determines the end concentration of hydrogen in the room (Gupta et al., 2009; De Stefano, 2019). The higher the quantity of hydrogen released, the more risky the situation is, as it takes much longer for the concentrations to fall below the LFL.

4.3 The effect of the release rate

The hydrogen release rate, i.e. the quantity of hydrogen released per second from an opening, affects the hydrogen concentration in a number of ways. This is illustrated by two examples.

The first example concerns model calculations used to determine the hydrogen concentration in the end phase as a function of the release rate (Prasad et al., 2010). In other words: the higher the release rate, the more hydrogen is released into a room. Figure 4.1 shows how the hydrogen concentration in the end phase increases as a result.

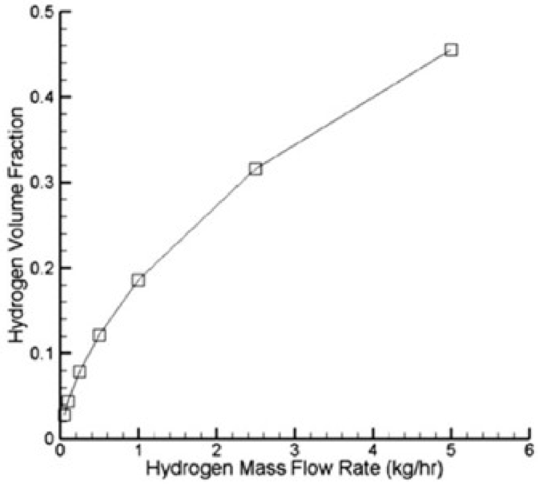


Figure 4.1 The effect of the release rate on the hydrogen concentration in the stationary phase (source: Prasad et al, 2010)

The second example concerns the results of the experiment already described in Chapter 3 (Figure 3.2). In that experiment, the total amount of hydrogen injected remained constant, but it was injected at two different rates (De Stefano, 2019). The hydrogen concentration in the end phase is the same in both experiments, namely 5.5 vol.%. More importantly however, is that stratification occurs at low release rates and that the hydrogen concentration in the highest stratum is higher than the hydrogen concentrations in the uniformly distributed hydrogen layer formed at high release rates. Therefore, the lowest release rate results in the highest peak concentrations. At low release rates, it also takes longer for the peak concentrations to diminish and for the end phase to be reached. Dangerously high concentrations therefore persist for longer.

4.4 The effect of turbulence

Obstacles and ventilation influence the flow behaviour of hydrogen (see Section 3.2.3) and affect the hydrogen concentrations in the manner described below.

Obstacles

With turbulent flows, obstacles disrupt the vortices and cause the hydrogen to lose energy, decelerate, and mix less thoroughly with the air in the room. Hydrogen therefore disperses less uniformly beneath the ceiling; there is more stratification, and this is associated with higher hydrogen concentrations. It also takes longer for hydrogen to become homogeneously distributed (De Stefano, 2019).

With laminar flows, obstacles have a different effect: they cause small vortices to arise where there previously were none. This promotes mixing of hydrogen, which therefore disperses more uniformly, resulting in lower concentrations below the ceiling.

Ventilation

Ventilation causes more turbulence, and therefore better mixing and dispersion of hydrogen: if there are several hydrogen layers of differing concentrations present in the release phase, ventilation causes these to be mixed to form one homogeneous layer (Hajji et al., 2014). In the dispersion phase, ventilation accelerates dispersion and results in lower hydrogen concentrations in the stationary end phase.

Natural ventilation is most effective when the ventilation openings are opposite one another and are large in size: the larger the surface area of the ventilation openings, the lower the hydrogen concentration. Multiple small openings result in better mixing than a single opening (Matsuura, 2009). It also holds that the greater the difference in height between the ventilation openings in a room, the lower the hydrogen concentrations (Prasad et al., 2010). This latter effect is less significant in absolute terms than the effect of the surface area of the ventilation openings.

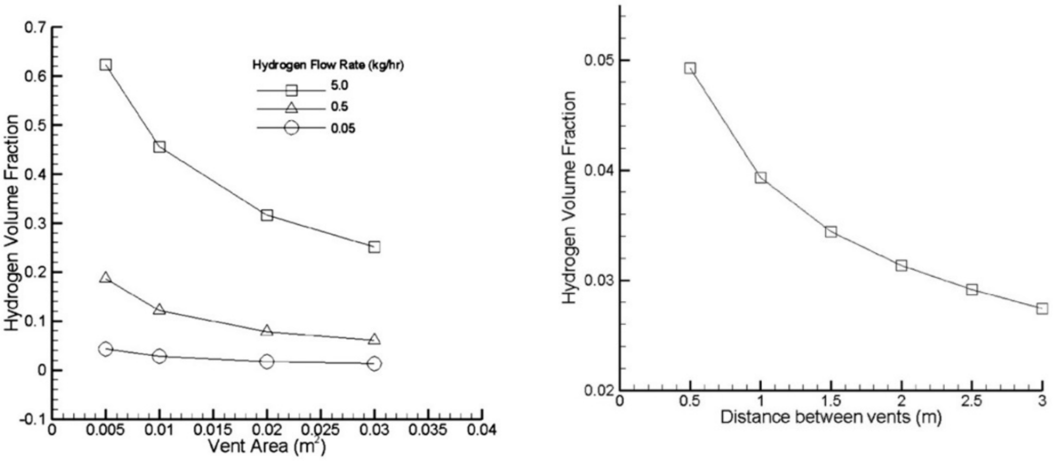


Figure 4.2 Left: Effect of size of ventilation openings on hydrogen concentration. Right: Effect of height difference between two ventilation openings on hydrogen concentration (source: Prasad et al, 2010)

In the HyHouse project, hydrogen was released into a house and hydrogen concentrations were measured at various locations inside the house throughout the release phase (Kiwa Gastec, 2015). The release rates varied from 0.16 l/s to 5.26 l/s (2 to 64 kW).[9] *The experiments were carried out at three different air permeabilities by gradually reducing natural ventilation. The maximum measured hydrogen concentrations are shown in Table 4.1. These were always measured in the room where the hydrogen was released, including inside the meter box.*

The main results of this study are shown below.

- *At release rates lower than 0.33 l/s (4 kW), no hydrogen was detected in the house.*
- *At release rates between 0.33 l/s and 0.66 l/s (8 kW), some hydrogen was detected but the LFL was not reached. Release rates of this order of magnitude are characteristic of minor leaks at pipe connections.*
- *At a release rate of 1.32 l/s (16 kW), the LFL was reached at the end of the release period (2.5 hours), but only in the room in which the leak was located. This suggests that if the release of hydrogen does not last too long, the LFL will not be reached.*
- *The highest maximum concentrations were measured in the meter box, and were a direct result of the limited capacity of that meter box.*

---

[9] According to NEN 8078+A1:2018 nl (*Supply for gas with an operating pressure up to and including 500 mbar - Performance requirements - Existing estate*), leakage losses from a gas supply system with a capacity of more than 50 litres are permitted to exceed 1 litre per hour (0.27 ml/s). For leaks of more than 5 litres per hour (1.4 ml/s), measures must be taken.

- *On the ground floor, the leaks resulted in the formation of a stratified hydrogen layer. This indicates that the leaks were most likely to have been laminar in nature.*
- *The highest maximum hydrogen concentration was always measured in the room in which the hydrogen was released, and always at the sensor located at the highest point. In the other rooms on the same floor, similar concentrations were detected.*
- *The more airtight the house was, the higher the maximum hydrogen concentration.*

Table 4.1 Maximum measured hydrogen concentrations in the HyHouse project

	Air permeability of house[10] ($m^3/h/m^2$) *($dm^3/s/m^2$)*	Maximum hydrogen concentration (vol.%)	
		House (excl. meter box)	Meter box
Phase 1	9.85 *(2.74)*	6.5 – 7.0	18.2
Phase 2	6.64 *(1.84)*	10.0 – 10.5	19.3
Phase 3	3.46 *(0.96)*	12.0 – 12.5	22.1

Summary

- The total quantity of hydrogen that is released determines the final hydrogen concentration in a room.
- The higher the quantity of hydrogen released, the more risky the situation is, as it takes much longer for the concentrations to fall below the LFL.
- Low release rates result in stratification, with the hydrogen concentration in those strata being higher during the release and dispersion phases than during the end phase.
- At low release rates, the high hydrogen concentrations last longer than at high release rates.
- High release rates result in uniform hydrogen distribution; the hydrogen concentration is therefore lower than at low release rates.
- Mixing of a hydrogen-air mixture, for example by ventilation, results in distribution of the mixture and thus a reduction in hydrogen concentrations.

---

[10] The Dutch Building Code (*Bouwbesluit*) specifies a number of classes for the construction of airtight buildings. In order to comply with the Building Code, the air permeability (Q_V10 value) for class 1 buildings must not exceed 1 $dm^3/s/m^2$. This class is no longer applicable in new buildings. Class 2 for energy-efficient buildings, is the standard for new buildings. Here, the air permeability value must be between 0.4 and 0.6 $dm^3/s/m^2$. The house used in the HyHouse project had quite a few draught gaps, as it was not until phase 3, after all of the gaps and holes were covered, that the air permeability value matched that of class 1 of the Building Code.

5 What are the dangerous hydrogen concentrations in a confined space?

5.1 Introduction

Working with hydrogen is associated with certain risks, given that if hydrogen is accidentally released and the hydrogen cloud meets an ignition source, hazardous phenomena such as jet flames or explosions can occur. This chapter addresses these risks, and describes the effects that can occur as well as the effects hydrogen concentration has on these effects.

5.2 Event tree

The effects that can occur after released hydrogen either ignites or does not ignite are shown below in the form of an event tree. Figure 5.1 shows a simple event tree for the continuous release of pressurised hydrogen (RIVM, 2020). At the point of release, a drop in pressure occurs and the hydrogen molecules adjust to ambient pressure.

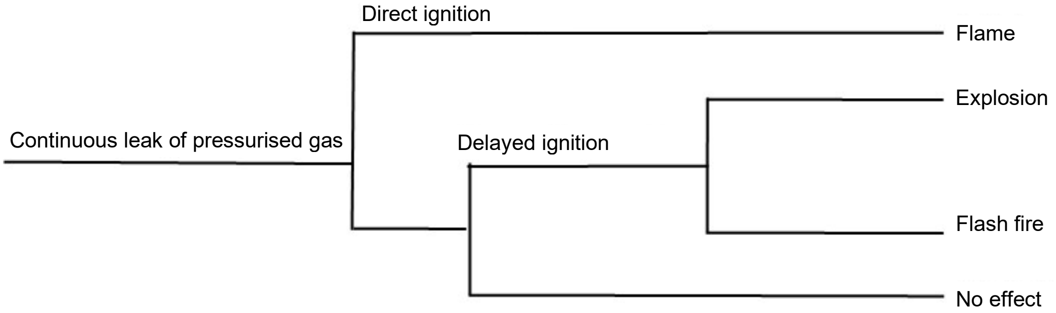


Figure 5.1 Event tree for continuous release of hydrogen (source: RIVM, 2020)

Ignition of hydrogen gas can take place immediately after release or some time later. This leads to various effects, which are described below.

- Direct ignition of hydrogen released from an opening will create an invisible jet flame that has a certain size and direction. Jet flames can injure people and damage nearby objects and buildings, possibly resulting in secondary effects.
  When hydrogen is released indoors, the jet flame will not be particularly large (in the centimetre range), because the pressure at which hydrogen is released is very low.
- With delayed ignition, some time passes between the hydrogen being released and ignition. During this time, hydrogen mixes with air to form a potentially flammable mixture. If the hydrogen cloud is out in the open and ignition takes place there, the cloud will burn (flash fire) and in principle no overpressure effects are to be expected, only heat effects. If the hydrogen cloud is ignited in a confined space such as a house, the cloud –

upon ignition and at a sufficiently high concentration - will explode with overpressure effects. These effects can cause major damage by throwing debris or by the collapse of the structure of the building or adjacent buildings. Overpressure effects of an explosion extend beyond the heat effects of the explosion, although fires and secondary fires cannot be ruled out.

5.3 Fire

5.3.1 LFL

As stated in Section 1.2, LFL stands for ‘lower flammability limit’, the lowest concentration at which a flammable gas ignites and at which the flame produced can maintain itself. Sometimes the term LEL (lowest explosion limit) is used instead of LFL, but this term is misleading as it suggests that ignition of a flammable gas at this concentration will lead to an explosion. However, this is not the case: at this concentration, hydrogen gas is only able to burn. The flammability limits of gases (LFL and UFL) are determined under specific conditions, for example in accordance with ASTM E681-09(2015): *Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases).*

At a hydrogen concentration of 4 vol.%, the propagation velocity of the flame is lower than the speed at which the hydrogen-air mixture rises. Under these conditions, the flame can only burn upwards, and not downwards or sideways. At hydrogen concentrations of 6 vol.% or more, the flames can burn sideways, and at concentrations of 9 vol.% or more they can also burn downwards (Kiwa Gastec, 2015).

Table 5.1 Flammability limits of hydrogen (source: Kiwa Gastec, 2015)

Flame direction	LFL (vol.%)	UFL (vol.%)
Upwards	4	75
Upwards and sideways	6	
All directions	9	

At the LFL of 4 vol.%, only a fraction of the hydrogen burns and, since the flames do not propagate sideways or downwards, the fire cannot spread, very little heat is produced and there is no build-up of pressure (Molkov, 2012). The higher the percentage of hydrogen in the hydrogen-air mixture, the higher the amount of hydrogen that burns. In a hydrogen-air mixture containing 5.6 vol.% hydrogen, half of the hydrogen present will burn; full combustion will only occur at hydrogen concentrations higher than 10 vol.% (Coward et al, 1952).

As mentioned before, a hydrogen flame can only burn downwards at hydrogen concentrations of 9 vol.% or more. However, this does not mean that hydrogen-air mixtures with lower concentrations are not dangerous. The danger largely depends on the location within the area where ignition takes place. If a 6 vol.% hydrogen-air mixture is ignited near the ceiling, the flames will only propagate upwards and horizontally until they reach the walls and the ceiling, at which point they will be extinguished. When the same mixture is ignited near the floor, the flames will propagate throughout the entire room, resulting in a significant increase in temperature and a large amount of overpressure. If the hydrogen concentration exceeds

9 vol.%, not only will the flames spread in all directions, but the propagation velocity will increase rapidly as well.

When hydrogen gas is released from an opening with a high speed, this speed will also affect the concentration at which a hydrogen-air mixture will ignite. In experiments attempts were made to ignite a horizontal hydrogen plume travelling at a speed of tens of metres per second by generating sparks at various locations throughout the plume. At concentrations above 4 vol.% it was often not possible to ignite the plume or ignition did not lead to the formation of a jet flame. The flames could not spread downwards because the flame speed was not high enough. The flames burned so slowly that they propagated away from the location of the leak and were extinguished due to a lack of hydrogen (Swain et al., 2007).
The red core in Figure 5.2 indicates where every ignition attempt resulted in full combustion of the cloud. The hydrogen concentration at the boundary of that core is around 10 vol.%. In the blue zone, not every attempt resulted in combustion. Ignition was possible, but this sometimes took hundreds of attempts. Outside of the blue zone, the cloud could not be ignited even though the hydrogen concentration was higher than 4 vol.%.

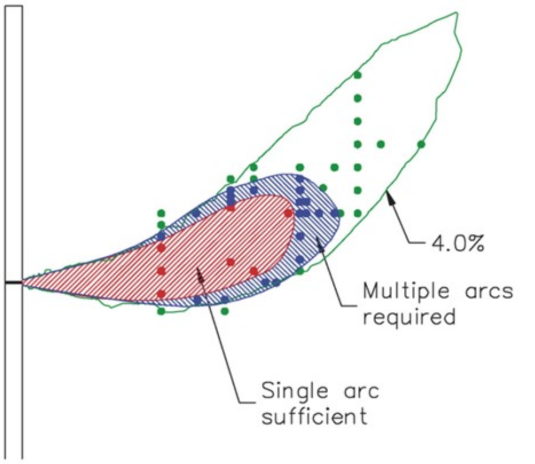


Figure 5.2 Hydrogen plume and ignition locations (green dots) (source: Swain, 2007)

5.4 Explosion

When a hydrogen-air mixture is ignited, a flame front is formed where combustion of hydrogen takes place. The flame front is actually also the reaction zone. The flame front travels quickly, causing a build-up of pressure ahead of it. The higher the speed of the flame front, the greater the increase in pressure. Obstacles and objects cause turbulence and increase the speed of the flame front, thereby also increasing overpressure (Lowesmith, 2011). This progression of the flame front is referred to as deflagration. Deflagration can turn into detonation[11] if the hydrogen burns so quickly that the speed of the flame front is greater than the speed of sound in the hydrogen-air mixture (BRHS, 2009).

5.4.1 Detonation

Detonation of a hydrogen-air mixture is a worst-case scenario, because the overpressure created by a detonation can be up to a factor of 20 greater than with a deflagration, causing much more damage (Alcock et al., 2001). Detonation can occur between 11–70 vol.%, but this range depends heavily on the size of the area in which the hydrogen-air mixture is located. The larger the area, the lower the threshold and the higher the upper threshold of the detonation range (Molkov, 2013). In practice, detonation is expected to occur at concentrations of 18–59 vol.% (Molkov, 2012) (HySafe, 2009).

---

[11] This transition is referred to as DDT (deflagration to detonation transition).

5.5 Overpressure

Overpressure without explosion

When hydrogen is released into a confined space and there are no openings nor any ventilation, the pressure in the room will increase. This can be illustrated by way of a simple calculation[12]:

> *A room contains 40 m^3 of air. The pressure in the room is equal to ambient pressure: 1 bar. If 1 m^3 of gas is released into this room and cannot escape, the room will contain 41 m^3 air + gas. The pressure in the room then becomes (41/40) × 1 bar = 1.025 bar. This results in an overpressure of 25 mbar compared to ambient pressure.*

Overpressure in the event of explosion

The overpressure in a room as a result of a hydrogen gas explosion depends on numerous factors. The most important of these are the hydrogen concentration, the size and geometry of the room, the presence and size of openings, the presence of obstacles, the strength of the ignition source and the ignition location (Bauwens et al., 2012) (Kundu, 2016).

As part of the European HyIndoor project, research was carried out into the amount of overpressure created in a confined space of 1 m^3 where hydrogen-air mixtures were ignited under various conditions. The confined space was equipped with an opening in order to limit overpressure (‘vented explosion’, Kuznetsov et al., 2015). The overpressures measured during this experiment were low, since the capacity of the confined space was small. In larger spaces overpressure are higher because the flame front has more room to expand, resulting in more overpressure building up.

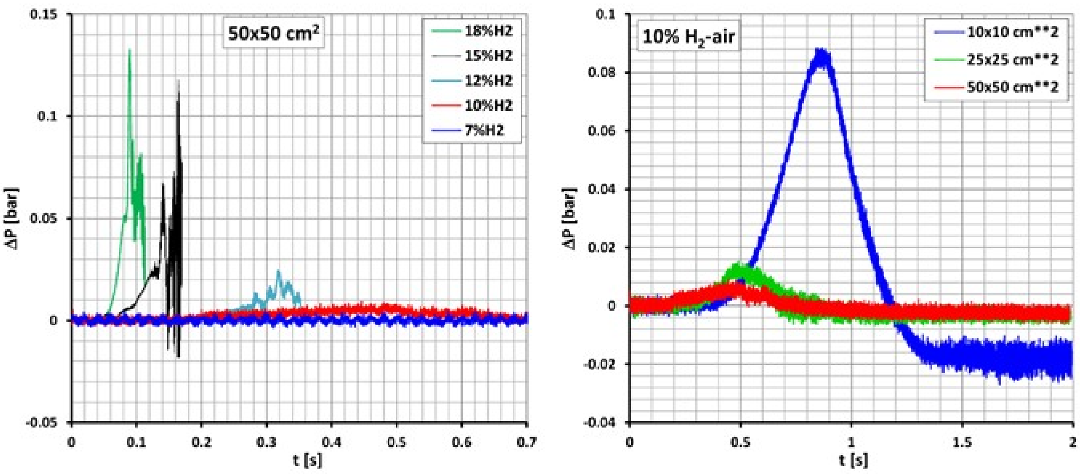


Figure 5.3 Left: Overpressures at different hydrogen concentrations with a hole area of 50x50 cm. Right: Overpressure at different hole areas at a hydrogen concentration of 10 vol.%. (Source: Kuznetsov et al., 2015)

The experiments demonstrated that at hydrogen concentrations of 12 vol.% or lower, little or no overpressure was generated, but higher hydrogen concentrations resulted in higher overpressures (Figure 5.3, left) (see also HyResponse, 2016c). At 10 vol.%, for example, the

---

[12] Based on Boyle’s law: p (pressure) × V (volume) = constant.

overpressure was less than 10 mbar, but it increased many times when the size of the opening was too small to provide pressure relief (Figure 5.3, right).

The experiments also looked at the effect of stratification on the amount of overpressure. A uniformly distributed hydrogen layer results in much lower overpressures than multiple hydrogen layers of varying concentrations (Figure 5.4, left). As such, a prolonged release of hydrogen from a small leak presents a real hazard, as this results in the formation of multiple hydrogen layers with higher concentrations, which lead to greater overpressures upon ignition.

Another parameter that was investigated is the presence of obstacles. Part of the room was filled with a wooden grid that varied in volume. The presence of this obstacle caused more turbulence, resulting in the acceleration of combustion and a considerable increase of the overpressure (Figure 5.4, right). The more space that was taken up by the obstacle, the higher the overpressure.

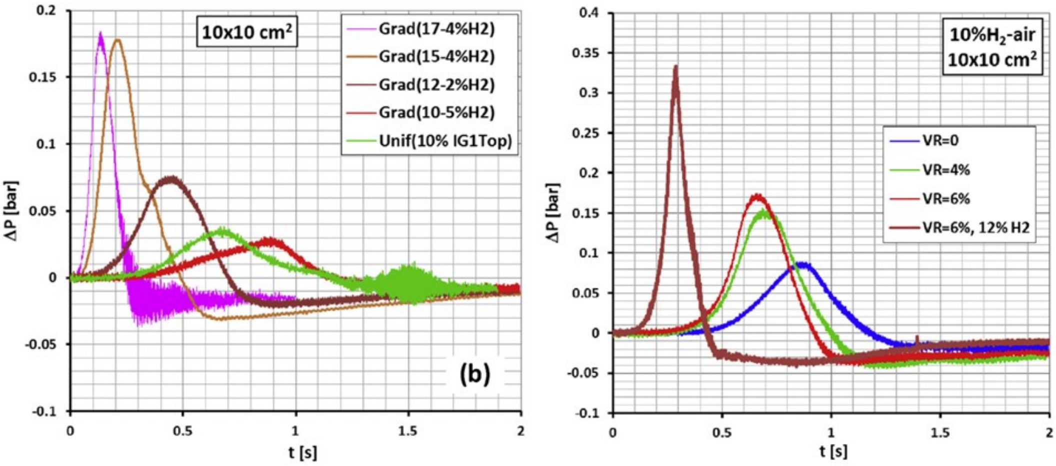


Figure 5.4 Left: Overpressure with uniform (‘Unif’) or stratified distribution (‘Grad’) of hydrogen. Right: Overpressure at different volume percentage with which the area is filled (Source: Kuznetsov et al., 2015)

5.6 Oxygen displacement

The average oxygen concentration in air is 21 vol.%. When hydrogen is released and is not ignited, it displaces the air and the oxygen it contains, causing the oxygen percentage to fall. People in a room with oxygen concentrations lower than 18 vol.% are less able to concentrate, and at concentrations lower than 10 vol.% they become apathetic and become unconscious (Linde, 2015). To obtain an oxygen concentration of 18% vol.%, a hydrogen concentration of 14.3% vol.% is required. For 10 vol.% oxygen this is 52.4% vol.% hydrogen (Buttner, 2014).

Summary

- The hydrogen concentration determines the direction, and thus the spread of hydrogen flames. Hydrogen flames will burn upwards at 4–6 vol.%, upwards and sideways at 6–9 vol.% and in all directions at 9 vol.% and over.
- The space the flame front has to develop is determined by the hydrogen concentration (see the previous point) and the location of the ignition source in the confined space.
- The speed of hydrogen molecules in the plume travel is important. If this speed is greater than the speed at which hydrogen burns, the flame will not return in the direction of the release point. See also the following point.
- Upon ignition of a hydrogen-air mixture at the LFL, only a fraction of the hydrogen present burns. As the flames are only able to spread to a limited extent (only upwards), no heat is produced and there is no build-up of pressure.
- In the HyHouse project, the LFL was not reached inside the house in the case of small pipe leaks.
- In the HyHouse project, the hydrogen concentration in the meter box was always higher than in the rest of the house when the leak was located in the meter box.
- The height of the overpressure of a hydrogen explosion in a confined space depends among other things on the hydrogen concentration, the size and geometry of the space, the presence and size of openings and the presence of obstacles.
- In general, the more space the flame front has, the higher the overpressure can become if the hydrogen-air mixture ignites.
- Hydrogen concentrations of up to 10 vol.% result in hardly any overpressure, unless the openings present are too small to release any pressure.
- Obstacles result in greater turbulence and better combustion of hydrogen, thereby increasing the amount of overpressure.
- A uniform hydrogen layer results in lower overpressure than multiple, high-concentration hydrogen layers.

6 What is the likelihood of ignition at hazardous hydrogen concentrations?

6.1 Introduction

In order to calculate the risks posed by systems containing hydrogen, the probability of ignition must be known. This is the sum of the probability of direct ignition and the probability of delayed ignition:

$$P_{total} = P_{direct} + P_{delayed}$$

It is very difficult to calculate ignition probabilities for hydrogen, both in terms of the total probability and the partial probabilities. There is often a lack of sufficient data, and the data that is available is often incomplete (Moosemiller, 2011). For example, in 2015 the Health and Safety Laboratory concluded that no direct ignition probabilities could be derived for hydrogen from the available literature on highly flammable substances (McGillivray, 2015).

This chapter provides a summary of the information found in the literature regarding the ignition of hydrogen, ignition probabilities, ignition sources and various parameters that may affect this.

6.2 Minimum ignition energy

In the absence of data on ignition probabilities, the literature was used to identify the minimum ignition energy and parameters affecting the minimum ignition energy. To this end, the minimum ignition energy of hydrogen is often compared with that of other gases to make a (qualitative) statement on ignition probabilities.

The ignition energy of a hydrogen mixture is lowest at the stoichiometric concentration (~ 30 vol.%), and is 0.019 mJ (Ono et al., 2007). The minimum ignition energy is higher the closer the hydrogen concentration comes to the LFL or the UFL, see Figure 6.1. At 4 vol.% hydrogen (LFL), the minimum ignition energy is a factor of 500 higher (10 mJ) than at the stoichiometric concentration. At 75 vol.% hydrogen (UFL), the minimum ignition energy is even greater (Swain, 2005). Many ignition sources deliver sufficient energy to ignite hydrogen, see Table 6.1.

For comparison, Figure 6.1 shows the curve for methane, the primary component of natural gas. It can be seen that at low concentrations (< 8 vol.%), the ignition energies for hydrogen and methane are similar.

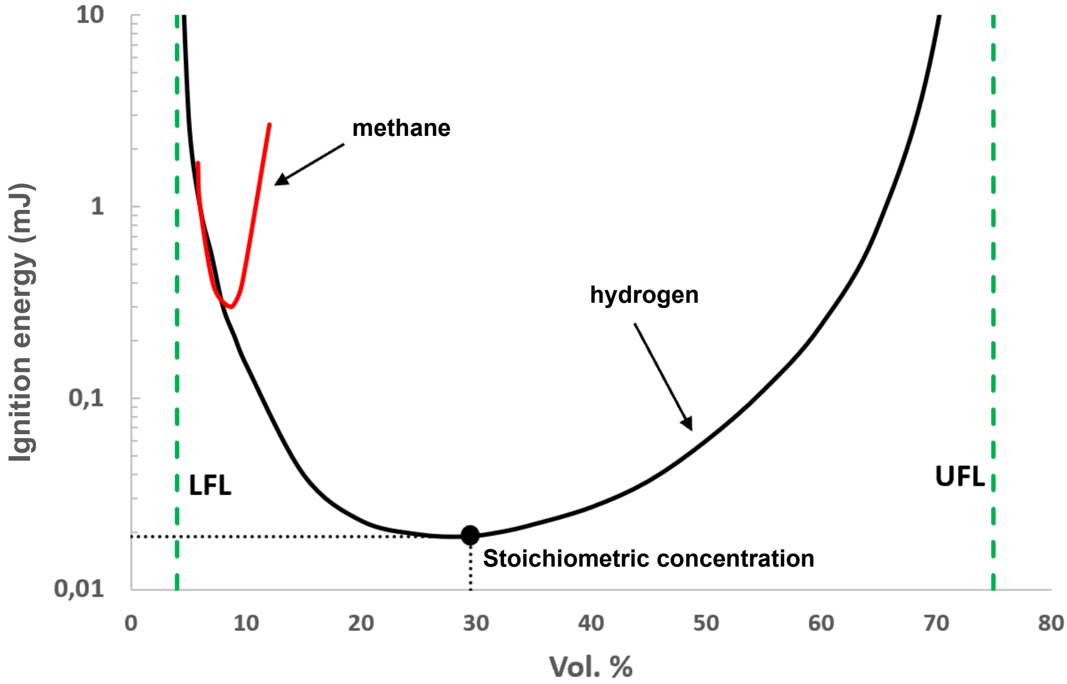


Figure 6.1 Ignition energy of hydrogen as function of concentration

6.3 Ignition

Flammable gases like hydrogen and methane can be ignited in a number of ways. The most common cause of ignition is electrostatic discharge. Other mechanisms are also possible, but only occur for example at high pressures or under special circumstances. These include the Joule-Thomson effect, diffusion discharges, hot surfaces and shock waves (Gummer et al., 2008). The following subsections address a few of the ignition modes.

It should be noted that when a flammable gas is ignited, it is often not possible to determine what the ignition source was and how exactly ignition took place; see also Section 6.5. This is sometimes also referred to as ‘spontaneous ignition’. There does not have to be a single ignition mechanism; a combination of ignition mechanisms is also deemed to be possible.

6.3.1 Electrostatic discharge

Spark discharges

Spark discharge occurs when a spark crosses the non-conducting medium between two conducting objects with a sufficiently large potential difference (Astbury, 2007). The energy of a spark is: $E = ½ \times C \times V^2$, where C is the capacitance of the object that may result in ignition and V is the voltage generated by charging. A voltage of 10 kV can easily be achieved through charging, which means that spark discharges are one of the most common causes of ignition of flammable gases. Some examples are provided in Table 6.1.

The energy generated by a spark is in principle high enough to ignite a mixture of hydrogen and air. At the LFL, the necessary ignition energy is around 10 mJ (see Section 6.2). The question is then whether there is sufficient energy available to ignite the hydrogen mixture. Experiments conducted by Swain have shown, for example, that hydrogen mixtures with concentrations of 4–10 vol.% cannot always be ignited by household equipment or switches, see Table 6.2 (Swain et al., 2005).

Table 6.1 Examples of spark energies (source: Sherwood, 2015)

Object	Capacitance (pF)	Energy of a spark (mJ) at different voltages		
		10 kV	20 kV	30 kV
Screw	1	0.05	0.2	0.45
Flange (∅ 10 cm)	10	0.5	2	4.5
Person	100–300	5–15	20–60	45–135

Table 6.2 Results of ignition tests carried out by Swain (source: Swain et al, 2005)

Ignition source	Description of ignition probability
Light switch	No ignition at concentrations of 4–10 vol.%
Wet and dry vacuum cleaner	Ignition at concentrations upwards of 6 vol.%
Pull cord for ceiling light	Ignition at concentrations upwards of 8 vol.%
Motor of garage door opening device	No ignition at concentrations of 4–10 vol.%

The probability of ignition of hydrogen by mechanical sparks (e.g. from falling tools or rotating discs) is low, and depens heavily on the fall height. The probability of ignition of hydrogen by mechanical sparks is on the order of 1–3 × 10^{-5} and is comparable to that for methane: < 0.7 × 10^{-5} (Shebeko et al., 2016).

Brush discharges

Compared to spark discharges, brush discharges are much less likely to cause an explosion (Wingerden, 2020). Brush discharges occur between a charged insulator (usually a plastic) and a conducting earthed point. They take the form of a brush, and have an energy of less than 4 mJ distributed over multiple discharge channels (Astbury, 2007).

Corona discharges

Corona discharges are formed when air around a conductor ionises, usually around the sharp points of a structure. The energy of a corona discharge is minimal (< 0.1 mJ). Corona discharges rarely cause explosions (Wingerden, 2020).

6.3.2 The reverse Joule-Thomson effect

Gases cool when the gas pressure decreases. Hydrogen, together with helium and neon, forms an exception to this rule: when expanding to atmospheric pressure, hydrogen heats up. However, this effect is only minimal: the Joule-Thomson coefficient for hydrogen at room temperature is less than 0.05 K/bar. At a pressure of 500 bar and a temperature of 9 °C, the temperature of hydrogen will increase by a maximum of 18°. This is not enough to reach the autoignition temperature of hydrogen (560–585 °) (Gummer, 2008).

6.3.3 Ignition by a hot surface

If a surface is hot enough, oxidation of hydrogen occurs. As a result, more heat is generated than lost to the environment, allowing the reaction to be perpetuated. Any hydrogen-air mixture in the range between the LFL and the UFL can in theory be ignited by a hot surface, but whether this actually happens or not depends on the size and geometry of the hot surface and of the confined space. The larger the hot surface and the larger the size of the hydrogen cloud, the higher the probability of ignition (Gummer, 2008).

6.4 Ignition probability

There are formulae in the literature that can be used to calculate the total probability of direct ignition (P_{direct}) and delayed ignition ($P_{delayed}$) (Moosemiller, 2011). The products of these formulae are an approximation and should only be regarded as indicative.

6.4.1 Probability of direct ignition

The probability of direct ignition is the sum of the probability of autoignition and the probability of static discharge.

- It is assumed that the probability of autoignition is 0 when the temperature is much lower than the autoignition temperature of hydrogen (585 °C). This will usually be the case in practice.
- The probability of static discharge is related to the energy generated, which in turn is related to parameters such as process pressure and rate of release. The more energy is generated, the greater the probability direct ignition. The probability of static discharge is calculated using formula 1:

$$P_{static\ discharge} = 0{,}0024 \times \frac{(P)^{1/3}}{(MIE)^{2/3}} \qquad [1]$$

Where:

P = pressure in psi (1 psi = 0.069 bar)

MIE = minimum ignition energy in mJ

The formula is presented in graph form in Figure 6.2, whereby the process pressure has been converted from psi to bar and a minimum ignition energy of 0.019 mJ is applied.

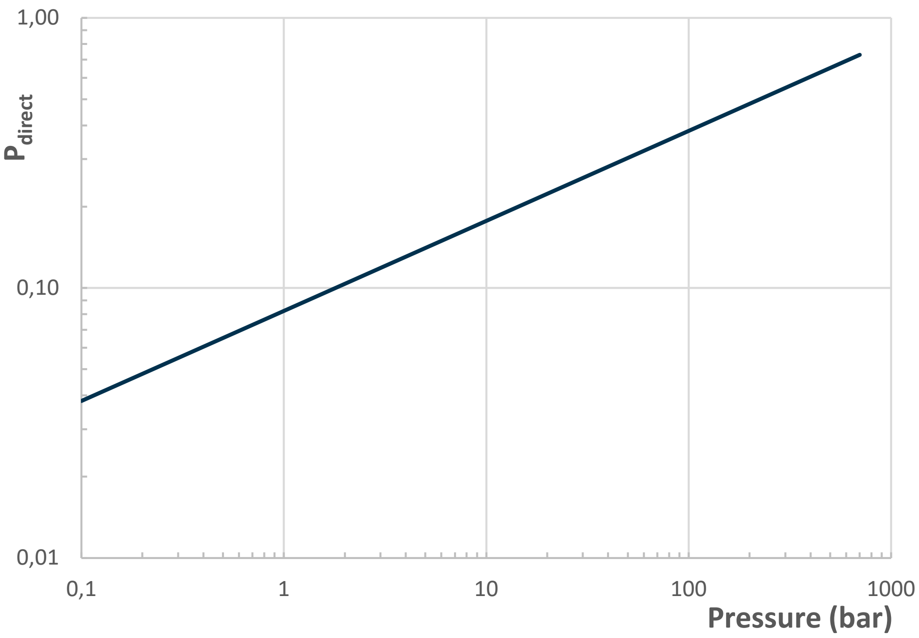


Figure 6.2 Probability of direct ignition as a function of process pressure

At a process pressure of 100 mbar (1.45 psi), P_{direct} is equal to 0.04. In a house, the process pressure will be lower, as will the probability of direct ignition. If hydrogen does ignite inside a home, it is more likely to occur due to delayed ignition than direct ignition.

6.4.2 Probability of delayed ignition

With delayed ignition, some time passes between the release of a flammable gas and its ignition. Ignition is then caused by an external ignition source. The probability of delayed ignition is determined by (external) factors such as the minimum ignition energy, the volume and duration of the leak, and the location of the leak (inside or outside). As the immediate surroundings of the leak affect the probability of delayed ignition, no values are available in the literature for the probability of delayed ignition. However, formulae have been developed with which the approximate probability of delayed ignition can be determined (Moosemiller, 2011). The formulae and an elaborated example can be found in Annex 1.

6.5 Ignition probabilities in major incidents

The MHIDAS (Major Hazard Incident Database Service) database compiles information on incidents that have occurred in the process industry. The pressure at which hydrogen is used in the process industry cannot be compared with that for hydrogen in homes. As such, the probability of direct ignition in the process industry according to Figure 6.2 will be greater than for hydrogen in homes.[13] Nonetheless, these incidents do provide an indication of ignition causes and probabilities. Astbury used the MHIDAS database to investigate hydrogen gas leaks and ignition causes and to compare these to leaks of other flammable gases, see Table 6.3 (Astbury, 2007). It is stated that:

- all but one of the incidents involved hydrogen under high pressure

---

[13] In the Netherlands, a (conservative) ignition probability of 1 is used in risk calculations for process installations and pipelines involving hydrogen, with a direct ignition probability of 1. This means that whenever there is a hydrogen leak, it will always ignite immediately (RIVM, 2020a and 2020b).

- the ignition source is not known for the majority of the incidents investigated
- 4 of the 81 incidents involved delayed ignition, but the ignition source was unknown
- the fact that there are no hydrogen incidents without ignition in the database does not mean that such incidents did not occur. As no effects were perceived, such incidents may not have been recorded in the database.

Table 6.3 Distribution of ignition sources of hydrogen and other flammable gases according to the MHIDAS database

Ignition source	Hydrogen		Other flammable gases	
	Number	**%**	**Number**	**%**
Arson	0		37	2.6
Impact	2	2.5	121	8.4
Flame	3	3.7	113	7.9
Hot surface	2	2.5	56	3.9
Electrical equipment	2	2.5	114	7.9
Spark produced by friction	2	2.5	33	2.3
Not identified	70	86.3	942	65.5
No ignition	0	0	21	1.5
Total	**81**	**100**	**1437**	**100**

Summary

- The ignition probability for hydrogen is not known, but given the low ignition energy of hydrogen its ignition probability will be higher than that of many other flammable gases. Much depend on the local conditions.

- The lower the ignition energy, the higher the probability of ignition. The ignition energy of hydrogen is lowest at 30 vol.% (stoichiometric concentration) and highest at the LFL and the UFL (500 times higher than at 30 vol.%).

- At low concentrations, the ignition energy of hydrogen is comparable to that of methane.

- If hydrogen ignites inside a home, it is more likely to occur due to delayed ignition than direct ignition.

- Hydrogen mixtures with concentrations of 4–10 vol.% do not ignite upon activation of a light switch.

- Spark discharges are the most common ignition source.

7 What measures can be taken?

7.1 Introduction

Hydrogen leaks are an unwanted event. Using the bow tie model, it is possible to systematically map out both the causes of hydrogen leaks (fault tree) and the effects of such leaks (event tree). This provides a structural basis for coming up with probability-reducing and effect-reducing measures. These measures are referred to as LoD (Lines of Defence).

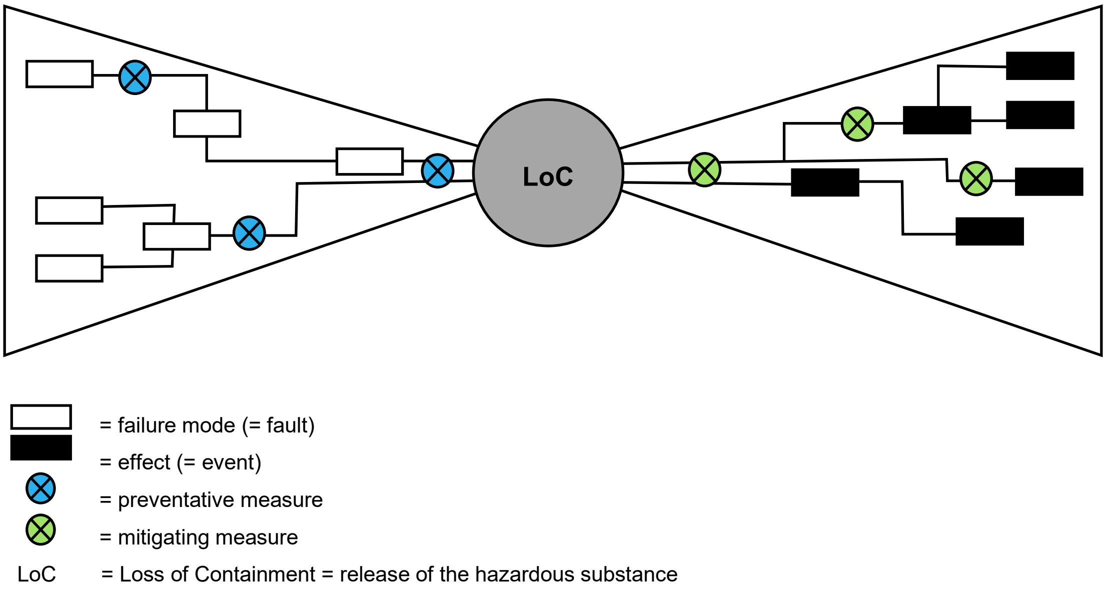


Figure 7.1 Bow tie model for the release of a hazardous substance. Fault tree (left) and event tree (right)

There are three types of preventative and three types of mitigating lines of defence (RIVM, 2019).[14] Each line of defence may consist of one or several measures:

1. Preventative:
   - Process management
   - Correcting deviations
   - Emergency protection

2. Mitigating:
   - Limiting the outflow
   - Preventing escalation
   - Personal protection and emergency response

---

[14] The model was created for the chemical industry, but the principles still apply to the use of a hazardous substance like hydrogen in homes.

The following sections discuss measures that can be taken when hydrogen is used indoors.

7.2 Process management

The first line of defence concerns process management. This entails, among other things, guaranteeing the integrity of the hydrogen installation, managing process parameters and addressing environmental factors that may damage the installation (RIVM, 2019).

In order to manage risks and limit the negative effects on humans and the environment, standards, regulations, protocols and similar documents are drawn up for the installation, management and maintenance of installations. In the Netherlands, there are currently no standards for the indoor use of hydrogen[15], but the following documents may be useful:

> Since early 2020, the UK has a standard for the development and construction of hydrogen-fired gas appliances that are either purpose-built to use hydrogen or are designed to be converted to use hydrogen: PAS 4444-2020 - *Hydrogen-fired gas appliances – Guide* (BSI, 2020).[16] The standard acts as a supplement to existing standards.

> The National Fire Protection Association (NFPA) has regulations on the use of gases in industry and hospitals: NFPA 55 - *Compressed Gases and Cryogenic Fluids Code* (NFPA, 2020). Section 10 discusses hydrogen, and as the regulations apply to pressures upwards of 35 mbar (15 psi), they can also be applied to hydrogen in homes.

> For natural gas, NEN 8078:2018 (*Supply for gas with an operating pressure up to and including 500 mbar*) and NPR 3378 (*Code of practice gas installations*) are the applicable standards in the Netherlands, and provide examples and explanations.

There are requirements for approval available for the Netherlands, which were drawn up by the certification body Kiwa. These requirements apply to distribution systems for gasses up to a pressure of 16 bar with the addition of up to 100% hydrogen gas, i.e. up to the meter (KIWA, 2019b). The requirements for approval concern, inter alia, the leak-tightness of valves and controllers.

> Not using hydrogen is a possibility to ‘control’ a process with hydrogen. This is a form of inherently safe design, similarly to mitigating and avoiding risks. The idea behind inherently safe design is that if a hazardous substance is not present, it cannot be released (Vaughen et al., 2012).

> Avoiding risks is another option, and is described in the document ‘Five safety principles for hydrogen used as an energy source in homes’ (IFV, 2020).

> Finally, it is also possible to reduce risks by keeping the required pressure and diameter of the hydrogen-containing system as low as possible (Fuster et al., 2016).

---

[15] The webinar held by the Dutch Standardisation Platform for Hydrogen in the Industrial and Urban Environment (NP H2IGO) showed that work is being done on standardisation, but there are not yet any published standards (NEN, 2020).

[16] Under the Hy4Heat programme, standards and certification requirements are being developed. See https://www.hy4heat.info/.

7.3 Correcting deviations

The second line of defence concerns measures aimed at the timely identification and correction of deviations outside of operational limits. The following could apply to the use of hydrogen in homes:

- Malfunctions with respect to pressure, temperature and flow rate are relevant in hydrogen-containing systems and these parameters can be monitored by pressure, temperature and flow meters.
- When malfunctioning occurs in a hydrogen-containing system, it is investigated what the problem is and, where necessary, (semi-)automatic or manual action must be taken to rectify the malfunction and prevent escalation.

7.4 Emergency protection

The third line of defence concerns measures to prevent a major leak if malfunctions do arise and are not rectified. Examples from the process industry include secondary containments, emergency blow-off systems, emergency shutdown systems and rupture discs (RIVM, 2019). The following could apply to the use of hydrogen in homes:

- the supply line outside the home should be equipped with an overpressure protection system which causes a pressure relief valve to open automatically if a pre-defined pressure threshold is exceeded.
- the supply line should be equipped with flow limiters (Fuster et al., 2016).

7.5 Limiting the outflow

The fourth line of defence involves limiting the impact of the incident. Related measures include closing the containment vessels and limiting the supply of the hazardous substance (RIVM, 2019). The following could apply to the use of hydrogen in homes:

- Hydrogen systems in homes should be equipped with an automatic flow limiter to close the supply of hydrogen if the pipe laks (KIWA Gastec, 2015).
- A manual valve should be present in a safe location.

7.6 Preventing escalation

The fifth line of defence involves measures to prevent the incident from getting worse (escalating). An example from the process industry is the presence of a bund to contain spillages and leaks of liquids. For hydrogen systems, key measures include preventing ignition and maintaining sufficient distance between hydrogen storage and any objects requiring protection.

7.6.1 Detection

One of the most important ways to detect hydrogen is by odour. This is only possible if an odorant is added to the hydrogen gas (odorisation). The best option for this appears to be THT (tetrahydrothiophene), as this odour is easily recognisable and is associated with natural gas (DNVGL, 2020b). THT contains sulphur; one disadvantage of sulphur-based odorants is that they reduce the service life of catalysts in fuel cells. A sulphur-free odorant would be a possible alternative, but then recognisability and association with danger are not guaranteed (KIWA, 2018).

The presence of hydrogen can also be ascertained using detectors. A detector contains a sensor that is linked to an alarm system. There are various types of sensors which vary not only in terms of their mode of operation, but also in terms of sensitivity (detection time) and service life. When selecting a sensor, attention must therefore be paid to the requirements it will have to meet in the room it is intended to protect, for example detection time. A single sensor will not usually be able to meet all requirements, meaning that it is necessary to use several types of sensor at once. As the performance of sensors diminishes over time, they must be monitored and maintained.

The presence of hydrogen can be detected directly with hydrogen sensors. The applicable standards are set out in ISO 26142:2010 *(Hydrogen detection apparatus — Stationary applications)*.[17] When deciding where to place sensors, it is important to consider aspects such as release direction, dilution and airflows. The alarm levels identified in the literature are 25% of the LFL (= 1 vol.%) for triggering an alarm and 60% of the LFL (= 2.4 vol.%) for shutting down hydrogen-containing systems and activating ventilation (Hysafe, 2009). Network operators are considering applying 10% of the LFL as the alarm level for a safe working environment, similarly to natural gas (Morsche, 2020).

The presence of hydrogen can also be detected indirectly with carbon monoxide or oxygen sensors. The advantage of carbon monoxide sensors is that they can detect hydrogen at an early stage, as their measurement range is in the ppm region (1 vol.% ≡ 10,000 ppm). The disadvantage of oxygen sensors is that minor fluctuations can lead to a false alarm for hydrogen. It only takes a decrease of 0.084 vol.% oxygen to trigger an alarm level of 0.4 vol.% hydrogen (10% LEL). Oxygen sensors are therefore more suitable for detecting major rather than smaller changes in hydrogen concentrations (Buttner et al., 2014).

An interesting option for detecting a hydrogen leak is the use of coatings or tape that change colour when they come into contact with hydrogen. This enables a visual inspection of pipelines and equipment (Hoagland, 2012).

7.6.2 Ventilation

Ventilation is one of the most important mitigating measures mentioned in the literature. Ventilation ensures that:

- flammable gas is prevented from accumulating as it is blown out of the room
- the volume of the explosive atmosphere is reduced (through dilution)
- the duration for which an explosive atmosphere is present is limited (HySafe, 2009).

Ventilation is an efficient and frequently used safety measure, and can be either natural or mechanical. In the Netherlands distinction is made between four basic techniques, referred to as A, B, C and D (RvO, 2014).

- **Natural ventilation (type A)**
  Pressure differences between indoor and outdoor spaces produce a natural ventilation flow in buildings (RIVM, 2009). The pressure differences occur as a result of the wind

---

[17] The generally applicable standards for flammable gas sensors are NEN-EN-IEC 60079-29-2:2015 (selection, installation, use and maintenance) and NEN-EN-IEC 60079-29-1:2017 (performance requirements).

blowing against the building and the thermal draw caused by the difference in temperature between indoors and outdoors. The inclusion of ventilation openings can promote natural ventilation. When installing such openings, it is important to bear in mind their size and the difference in height between them (Prasad et al., 2010). Wind directions, wind speeds and temperature differences are constantly changing, which makes it difficult to regulate natural airflows.

- **Mechanical ventilation**
  Air blowers (type B) and extraction fans (type C) or a combination thereof (type D) allow for a controlled supply of fresh air to a room or building. A fan has rotating blades that push air in a certain direction, whereas a blower supplies fresh air. Fans and blowers can be combined. The functioning of ventilation systems must be guaranteed and monitored. In this regard, it should be noted that switching on mechanical ventilation could generate a spark and thus ignite a hydrogen-air mixture.

The most pertinent application for hydrogen at present is in old houses that are difficult to insulate and can only be kept warm using gas. Many of these houses do not have mechanical ventilation, meaning that natural ventilation is the only way to ensure a supply of fresh air in the house. Natural ventilation occurs via windows, doors, vents, cracks and seams. The way in which a house or building is ventilated will in any case affect the way in which hydrogen can dispers, should there be a leak.

The following recommendations have been formulated for natural ventilation (HyIndoor, 2015) (Fuster et al., 2016):

- Horizontal ventilation channels should be avoided in order to prevent the transition to detonation.
- It is preferable to have ventilation openings in walls rather than in the roof, as roof openings are less efficient.
- When there is only one ventilation opening, it should be located as high as possible in the room and should be as close to the ceiling as possible.
- When there are multiple ventilation openings, there must be as much of a difference in height between the openings as possible in order to generate maximum air displacement.
- The orientation of a ventilation opening should preferably be portrait rather than landscape.
- Multiple ventilation openings in walls located opposite one another at various heights are preferable to a single ventilation opening with the same total surface area. In the case of natural ventilation, multiple small openings allow for better mixing (Matsuura, 2009).
- The wind speed and direction can either promote or counteract ventilation. Ventilation is hindered when the wind blows against the uppermost ventilation opening, which makes it harder for gas to flow out (Prasad et al., 2010).
- Ventilation openings should be free of obstructions on both sides of the wall.

The following recommendations have been formulated for mechanical ventilation:

- A ventilation system must have sufficient capacity to prevent a hazardous atmosphere from developing. When designing such systems, it is necessary to take account of the speed of release, the quantity of hydrogen that may be released and the speed at which the hydrogen can be detected. Appendix 2 contains a nomogram, a graphical device for calculating the required dimensions of a ventilation opening in order to keep the hydrogen concentration below a certain limit at a certain hydrogen flow rate (Molkov, 2014).

- Ventilation systems may be switched on permanently in order to supply a room with fresh air, or may only be activated when hydrogen is detected in a room. In the latter case, the supply of hydrogen should also be cut off, if possible. The hydrogen supply should also be cut off if the ventilation system ceases working. It should be noted that a hazardous concentration of hydrogen will always be present in the direct vicinity of a hydrogen leak, and that this cannot be remedied by way of ventilation.
- In the literature, it is stated that ventilation rates of 20x/hour or more are required for hydrogen, and that the concentration must remain below 0.4 vol.% hydrogen if people are likely to be present in the room (HySafe, 2009).

7.6.3 Precluding or managing ignition sources

A home is not a processing facility and the measures in place to prevent the formation of explosive atmospheres in processing facilities (i.e. ATEX zoning) are not applicable to homes (European Parliament, 1999). Nonetheless, the same principles and measures can still be applied in homes.

- There are many ignition sources that are able to ignite a hydrogen cloud (see also Section 6.3). These potential ignition sources must be identified, and the number of such sources should be kept to a minimum.
- Hydrogen itself is a poor conductor, but if the release rate is high enough this can be sufficient to generate static electricity. As such, hydrogen-containing systems should always be earthed, especially if the pressure in the system is high (Molkov, 2012).
- Any hydrogen that is released will move upwards due to its buoyant force. Ignition can be prevented in many cases simply by placing ignition sources lower than potential leak locations (Pritchard et al., 2009). It is also possible to use partitions or pressure differences to keep any hydrogen clouds away from ignition sources.

7.6.4 Safety distances

Safety distances are intended to protect buildings, facilities, people outside and the environment in the event of a potential incident. There are various safety distances that can be observed, such as the distance between the release point and ignition sources, or between the release point and buildings.

The separation established by safety distances must be sufficient to ensure that:

1. the flammable hydrogen cloud does not encounter any ignition source, and
2. if the released hydrogen is ignited, the heat radiation and/or overpressure cannot reach or damage the person or object being protected.

Examples of safety distances for hydrogen facilities in the process industry are provided in NFPA 55 (NFPA, 2020). When defining the various safety distances, it is necessary to take into account the contents and operating pressure of the hydrogen-containing system as well as the layout of the site as much as possible. The application of safety distances is reflected in the question whether hydrogen-containing systems should be located inside or outside a building. After all, when a hydrogen leak occurs outside, th chance of high hydrogen concentrations is a lot smaller.

Safety distances such as the ones referred to above are intended to be applied outdoors. The programmes used to calculate the dispersion and effects of a hydrogen leak (e.g. Phast and Effects) are not intended, nor are they suitable, for determining safety distances indoors, as hydrogen can accumulate in rooms and below ceilings in indoor spaces. CFD software[18] such as FLACS, on the other hand, is suitable for this purpose.

---

[18] Computational Fluid Dynamics.

In order to give an impression of the size of safety distances indoors, a search was made for examples, but these were not found.. However, it was possible to identify some preliminary calculations for the vertical release of hydrogen from a 100-mbar pipeline in the ground in an open space (AVIV, 2019). The LFL of the plume released was 1 m or less. It is to be expected that for a 30-mbar indoor hydrogen pipeline this distance will be of the same order. There are a number of reasons for this: the distance to the LFL would be a lot smaller for a 30-mbar pipeline than for a 100-mbar pipeline; moreover, hydrogen disperses indoors less quickly and less far than outdoors. However, this effect is negated if the leak flows horizontally, as the distance to the LFL increases in this case. Since these three effects can offset one another, it may thus be assumed that the distance indoors is in a similar range.

7.6.5 Limit on the maximum quantity of hydrogen

In the HyIndoor project, it is recommended that a maximum of 0.26 g/m^3 hydrogen may be released in a confined space in order to prevent overpressures of more than 0.1 bar (HyIndoor, 2015). This is equivalent to 0.3 vol.% hydrogen, which is lower than the LFL by more than a factor of 10. Although windows would break at this level of overpressure, the load-bearing structure of the building would remain intact.

7.7 Personal protection and emergency response

The sixth and final line of defence concerns ensuring that people inside or outside of the house can either get themselves to safety, or can be brought to safety by bystanders and professionals. As a minimum, inhabitants should be able to exit the house quickly, first responders should be able to work safely enough and there should be no risk of collapse (Fuster et al., 2016).

> No attempts should be made to quench hydrogen fires until the supply has been cut off due to the possibility of reignition and subsequent explosion. Nearby objects should be cooled.
> Hydrogen flames are difficult to extinguish. Quenching hydrogen flames can exacerbate the situation, because this promotes turbulence and thus combustion, and because hydrogen is able to burn around water droplets (HyResponse, 2016b).
> The hydrogen-containing systems must be clearly identifiable (Fuster et al., 2016).

Summary

> Based on the bow tie model, three types of preventative measures and three types of mitigating measures can be distinguished.

> Preventative measures involve managing processes, intervening when deviations are detected and ensuring emergency protection systems are in place.

> Mitigating measures involve limiting the outflow of hydrogen, preventing leaks from escalating and ensuring personal protection and emergency response.

> The most important measures for the prevention of unwanted hydrogen leaks indoors, are standards for the installation, management and maintenance of hydrogen-containing systems.

> Important measures for managing an unwanted leak are pressure relief valves and flow restrictors.

> The most important measure for limiting a hydrogen gas leak is the presence of automatic and/or manually operated valves.

> The most important measures for preventing the escalation of a hydrogen leak are detection, ventilation, avoiding or controlling ignition sources and safety distances.

> The most important measures for first responders who fight hydrogen fires are to stop the supply of hydrogen and not extinguish hydrogen fires. .

Literature

Alcock, J.L. et al. (2001) *Compilation of existing safety data on hydrogen and comparative fuels*, Deliverable report of European FP5 project EIHP2.

Astbury, G.R. et al. (2007) Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms. *International Journal of Hydrogen Energy*, 32, 2178–2185.

AVIV (2009) The QRA was obtained privately, therefore the title and origin cannot be disclosed.

Bauwens, C.R. et al. (2012) Effect of hydrogen concentration on vented explosion overpressures from lean hydrogen-air deflagrations. *International Journal of Hydrogen Energy*, 37, 17599–17605.

Brain, P. (2019). *Hy4Heat* presentation at the KIWA Hydrogen Knowledge trip November 2019.

British Standards Institution (BSI) (BSI, 2020). *Hydrogen-fired gas appliances – Guide. PAS 4444-2020*. Available at https://shop.bsigroup.com/ProductDetail?pid=000000000030389165 (consulted 9 July 2020).

Buttner, W.J. et al. (2014) An assessment on the quantification of hydrogen releases through oxygen displacement using oxygen sensors. *International Journal of Hydrogen Energy*, 39, 20484–20490.

Cariteau, B. et al. (2012) Experimental study of the concentration build-up regimes in an enclosure without ventilation. *International Journal of Hydrogen Energy*, 37, 17400–17408.

Coward, H.F. & Jones, G.W. (1952) *Limits of flammability of gases and vapors*, Bulletin 503, Bureau of Mines. Washington: United States Government Printing Office.

De Stefano, M. et al. (2019) Hydrogen dispersion in a closed environment. *International Journal of Hydrogen Energy*, 44, 9031–9040.

Det Norske Veritas – Germanischer Lloyd (DNVGL, 2020a) *Gedrag van waterstof bij lekkages in het gasdistributienet. [‘Behaviour of hydrogen in the event of leaks in the gas distribution network.’]*

Det Norske Veritas – Germanischer Lloyd (DNV-GL, 2020b) *Ruikbaarheid van een aantal odoranten in aardgas-/waterstofmengsels. [‘Olfactory properties of a number of odorants in natural gas or hydrogen mixtures.’]*

European Parliament (1999) Directive 1999/92/EC on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31999L0092 (consulted 18 August 2020).

Frazer-Nash Consultancy. (2018) *Appraisal of Domestic Hydrogen Appliances*. Report Number FNC 55089/46433R.

Fuster, B., et al. (2016) Guidelines and recommendations for indoor use of fuel cells and hydrogen systems. *International Journal of Hydrogen Energy*, 42, 7600–7607.

Gummer, J. et al. (2008) *Spontaneous ignition of hydrogen – Literature review*. Report RR615, Health and Safety Executive.

Gupta, S. et al. (2009) Hydrogen-related risk within a private garage: concentration measurements in a realistic full scale experimental facility. *International Journal of Hydrogen Energy*, 34, 5902–5911.

H2Platform (2020) *Ons werk rond veiligheid (WVIP)* [‘Our work with respect to safety (Hydrogen Safety Innovation Programme, WVIP)’] [online]. Available at https://opwegmetwaterstof.nl/ons-werk-rond-veiligheid-wvip/ (consulted 2 September 2020).

Hajji, Y. et al. (2014) Dispersion and behavior of hydrogen during a leak in a prismatic cavity. *International Journal of Hydrogen Energy*, 39, 6111–6119.

Hoagland, B. (2004). *Hydrogen leak detection – low cost distributed gas sensors* [online]. Available at https://www.energy.gov/sites/prod/files/2014/03/f10/webinarslides_element_one_040312.pdf (consulted 17 August).

Hydrogen Incidents and Accidents Database (HIAD, no date) [online]. Available at https://odin.jrc.ec.europa.eu/giada/ (consulted 7 July 2020).

HyIndoor (2015) *Pre-normative research on safe indoor use of fuel cells and hydrogen systems - D6.1 Report on recommendations for RCS*.

HyResponse (2016a) *D6.3 European Emergency Response Guide.*

HyResponse (2016b) *Basics of hydrogen safety for first responders – Lecture: Hydrogen properties relevant to safety*.

HyResponse (2016c) *Strategies and Intervention tactics - FC stationary installations*.

HySafe (2009) *Deliverable D113 - Initial Guidance for Using Hydrogen in Confined Spaces - Results from InsHyde*.

Instituut Fysieke Veiligheid (2020) *Vijf veiligheidsprincipes voor waterstof als energiebron voor woningen* [‘Five safety principles for hydrogen used as an energy source in homes’]. Arnhem: IFV.

Lacome, J.M. et al. (2011) Large-scale hydrogen release in an isothermal confined area. *International Journal of Hydrogen Energy*, 36, 2302–2312.

KIWA Gastec (2015) *Energy storage component research & feasibility study scheme – HyHouse - Safety issues surrounding hydrogen as an energy storage vector*. Cheltenham: Kiwa Ltd.

KIWA Gastec (2016) *DECC Desk study on the development of a hydrogen-fired appliance supply chain*. Cheltenham: Kiwa Ltd.

KIWA (2018) *Toekomstbestendige gasdistributienetten* [‘Future-proof gas distribution networks’], report no. GT-170272. Apeldoorn: Kiwa Technology B.V.

KIWA (2019a) *Eerste inventarisatie naar waterstofuitstromen bij kleine toelaatbare aardgaslekken [‘Initial observations regarding hydrogen leaks based on minor acceptable natural gas leaks’].* Apeldoorn: Kiwa Technology B.V.

KIWA (2019b) *Keuringseis 214 - Geschiktheid voor bijmenging tot en met 100% waterstofgas* [‘Approval requirement 214 – Suitability for mixing up to 100% hydrogen gas’]. Apeldoorn: Kiwa Technology B.V.

Kobayashi, K. et al. (2005) *Application of Passive Autocatalytic Recombiner (PAR) for BWR Plants in Japan* [online]. Available at https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/003/33003503.pdf?r=1&r=1 (consulted 26 May 2020).

Krom, A.H.M. (2020) *Hydrogen concentration/equivalent hydrogen pressure in steel from different sources of hydrogen*. ID number VA 20.0203. Memo received via email on 8 July 2020.

Kundu, S. et al. (2016) A review on understanding explosions from methane-air mixture. *Journal of Loss Prevention in the Process Industries*, 40, 507–523.

Kuznetsov, M. et al. (2015) Medium-scale experiments on vented hydrogen deflagration. *Journal of Loss Prevention in the Process Industries*, 36. 416–428.

Lacome, J.M. et al. (2011) Large-scale hydrogen release in an isothermal confined area. *International Journal of Hydrogen Energy*, 36, 2302–2312.

Linde (2015) *Folder Zuurstofgebrek* [‘Leaflet on oxygen deficiency’]. Schiedam: Linde Gas Benelux B.V.

Liu, X. et al. (2014) Influence of initial pressure and temperature on flammability limits of hydrogen-air. *International Journal of Hydrogen Energy*, 39, 6774–6782.

Lowesmith, B.J. et al. (2011) *Vented confined explosions involving methane/hydrogen mixtures. International Journal of Hydrogen Energy*, 36, 2337–2343.

Matsuura, K. (2009) Effects of the geometrical configuration of a ventilation system on leaking hydrogen dispersion and accumulation. *International Journal of Hydrogen Energy*, 34, 9869–9878.

McGillivray, A. (2015) *Review of the event tree structure and ignition probabilities used in HSE's pipeline risk assessment code MISHAP*, Research Report RR1034.

Mejia, A.H. et al. (2020) Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure. *International Journal of Hydrogen Energy*, 45, 8810–8826.

Dutch Ministry of Economic Affairs and Climate (2019) *Klimaatakkoord* ['Climate Pact'].

Molkov, V. (2012) *Fundamentals of Hydrogen Safety Engineering I*. London: Bookboon.com Ltd.

Molkov, V. (2013) *Chapter P: Hydrogen fundamental properties* [online]. Available at http://www.h2euro.org/hyfacts/wp-content/uploads/sites/2/2014/06/1-Chapter-P-teaching-materials-Hydrogen-fundamental-properties-VM-130228-altered-UU.docx (consulted 15 August 2020).

Molkov, V. (2014) *Passive ventilation of enclosures with one vent, the uniformity criterion, and validation of pressure peaking phenomenon (unignited releases)*. Presentation given during the HySafe Research Priorities Workshop in Washington DC, November 2014. Available at https://www.hysafe.info/wp-content/uploads/2016/07/156_RPW2014_Presentations-Research-Priorities-2014-distribution-updated-2016-05-20.pdf (consulted 10 July 2020).

Moosemiller, M. (2011) Development of algorithms for predicting ignition probabilities and explosion frequencies. *Journal of Loss Prevention in the Process Industries*, 24, 259–265.

Morsche, P. te. (2020) Personal communication during the review of this report.

National Fire Protection Association (NFPA, 2020) *Compressed Gases and Cryogenic Fluids Code* [online]. Available at https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=55 (consulted 16 August 2020).[19]

Dutch Standardisation Institute (NEN, 2018). *Supply for gas with an operating pressure up to and including 500 mbar - Performance requirements - New estate*, NEN 1078:2018 nl.

Dutch Standardisation Institute (NEN, 2020) *Webinar NP-H2IGO* [online]. Available at https://www.nen.nl/Evenementen/Presentaties/20200724-NPH2IGO.htm?utm_medium=email (attended 24 July 2020).

Netbeheer Nederland (2019) *Betrouwbaarheid van gasdistributienetten in Nederland - Resultaten 2018* ['Reliability of gas distribution networks in the Netherlands – 2018 results']. Version: 098, ID no.: GT-190045.

Ono, R. et al. (2007) Minimum ignition energy of hydrogen-air mixture: Effects of humidity and spark duration. *Journal of Electrostatics*, 65, 87–93.

---

[19] NPFA 55 can be consulted free of charge. This works in the Google Chrome browser but not in Microsoft Edge.

Prasad, K. et al. (2010) Effect of wind and buoyancy on hydrogen release and dispersion in a compartment with vents at multiple levels. *International Journal of Hydrogen Energy*, 35, 9218–9231.

Pritchard, D.K. et al. (2009) *Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version.* Buxton: Health and Safety Laboratory.

Reinecke, E.-A. (2013) Simulation of the efficiency of hydrogen recombiners as safety devices. *International Journal of Hydrogen Energy*, 38, 8117–8124.

Netherlands Enterprise Agency (RvO, 2014) *Infoblad Ventilatiesystemen in energiezuinige nieuwbouwwoningen* [‘Info sheet on ventilation systems in energy-efficient new-build properties’].

Dutch National Institute for Public Health and the Environment (RIVM, 2009) *GGD-richtlijn medische milieukunde - Beoordeling van ventilatie en ventilatievoorzieningen van woningen* [‘Guidelines of the Municipal Health Department on Medical Environmental Science – Evaluation of ventilation and ventilation equipment in homes’]. RIVM report no. 609330011/2009.

Dutch National Institute for Public Health and the Environment (RIVM, 2019) *Vijftien jaar incidentanalyse - Oorzaken, gevolgen en andere kenmerken van incidenten met gevaarlijke stoffen bij majeure risicobedrijven in de periode 2004-2018* [‘Fifteen years of incident analysis – Causes, consequences and other characteristics of incidents involving hazardous substances at high-risk companies in the period 2004–2018’]. RIVM report no. 2019-0042.

Dutch National Institute for Public Health and the Environment (RIVM, 2020a) *Handleiding Risicoberekeningen Bevi,* [‘Bevi Risk Assessment Manual’], version 4.2, April 2020.

Dutch National Institute for Public Health and the Environment (RIVM, 2020b) *Handleiding Risicoberekeningen Bevi,* [‘Bevi Risk Assessment Manual’], version 3.1, April 2020.

Schefer, R.W. et al. (2006) Characterization of leaks from compressed hydrogen dispensing systems and related components. *International Journal of Hydrogen Energy*, 31, 1247–1260.

Shebeko, A.Y. (2016) An investigation of an ignition of flammable gaseous mixtures with mechanical sparks. *Fire Safety Journal*, 78, 122–129.

Sherwood, J. (2015). *The new standard on avoidance of electrostatic hazards*. Hazards 25, Symposium Series No 160, paper 6007-32-1.

Swain, R.M. et al. (2005) Ignition of lean hydrogen-air mixtures. *International Journal of Hydrogen Energy*, 30, 1447–1455.

Swain, R.M. et al. (2007) An experimental investigation into the ignition of leaking hydrogen. *International Journal of Hydrogen Energy*, 32, 287–295.

Topsector Energie (2020a) *Waterstof voor de energietransitie - Een programmatische aanpak voor innovaties op het thema waterstof in Nederland voor de periode 2020 – 2030. [‘Hydrogen for the energy transition – A programme-based approach to innovations in the field of hydrogen in the Netherlands for the period 2020–2030’].*

Topsector Energie (2020b) *Overview of hydrogen projects in the Netherlands* [online]. Available at https://www.topsectorenergie.nl/nieuws/tki-nieuw-gas-zet-nederlandse-waterstofprojecten-de-etalage (consulted 19 July 2020).

TNO (1992) *Onderzoek naar de effecten van een explosie in verdiept gelegen wegen met (niet) constructieve afdekking* [‘Investigation into the effects of an explosion in sunken walkways with (non-)structural coverings’]. TNO report PML 1992-C33. Rijswijk: TNO

Vaughen, B.K. et al. (2012) What you don’t manage will leak: A tribute to Trevor Kletz. *Process Safety and Environmental Protection*, 90, 411–418.

Wingerden, K. (2020) *Webinar: Electrostatics hazards when handling flammable materials* [online]. Available at https://www.youtube.com/watch?v=znm1jp3X7Bk&feature=youtu.be&utm_source=Email&utm_medium=Email&utm_campaign=Epost-22062020-Webinar-Replay&utm_content=Visit-to-YouTube-Page (consulted 22 June 2020).

Appendix 1

Calculating the probability of delayed ignition

In the article by Moosemiller from 2011, formulae are provided which can be used to calculate the probability of delayed ignition through approximation. It should be noted, however, that the formulae were developed in the absence of much of the hard data required. The formulae are the result of combining the limited practical data available with the experience and opinions of experts. In spite of these significant limitations, the predictions are nonetheless very robust.

Various factors determine the probability of delayed ignition (P_{delayed}). It is possible to calculate the contribution of each of these factors (F) to the probability of delayed ignition. The following factors are considered:

Minimum ignition energy:	F_{MIE}
Flow rate:	$F_{\text{flow rate}}$
Leak duration:	F_{duration}
Location of the leak:	F_{location}.

F_{location} consists of the sub-factors $F_{\text{room volume}}$, $F_{\text{ventilation}}$, F_{strategy} and $F_{\text{electr. classification}}$.

If the product of these factors is *greater* than 1, then the following formula is used to calculate P_{delayed}:

$$P_{\text{delayed}} = 1 - [\, 0.7 / (F_{\text{MIE}} \times F_{\text{flow rate}} \times F_{\text{duration}} \times F_{\text{location}})\,] \qquad [2]$$

If the product of these factors is *less* than 1, then the following formula is used to calculate P_{delayed}:

$$P_{\text{delayed}} = 0.3 \times F_{\text{MIE}} \times F_{\text{flow rate}} \times F_{\text{duration}} \times F_{\text{location}} \qquad [3]$$

Table B 1.1 on the following page provides a description of the (sub)factors and a worked example is provided for the following scenario.

In a house with a volume of 300 m^3, a hydrogen leak occurs causing 1 litre of hydrogen per second to be released for a duration of 1 hour. One person is present in the house, and the ventilation rate in the house is 4x per hour. All of the doors in the house are open. There is no specific strategy for ventilation or ignition sources.

Table B 1.1 Formulae for calculating the probability of delayed ignition (source: Moosemiller, 2011)

Factor	Formula	Parameters	Result
F_{MIE}	= 0.6 - 0.85 (log MIE) [4] Provided that: $0.1 \le F_{MIE} \le 3$ (MIE in mJ)	MIE = 0.019 mJ	$F_{MIE} = 2.06$
$F_{flow\ rate}$	$= 7 \times e^{[0.642 \times \ln(\text{flow rate}) - 4.67]}$ [5] Provided that: $F_{value} \le 2$ (Flow rate in lbs/s. 1 lbs/s = 0.4535 kg/s)	Flow rate = 0.183 lbs/s (≡ 1 l/s ≡ 0.083 kg/s)	$F_{flow\ rate} = 0.022$
$F_{duration}$	$= [1-(1-S^2) \times [e^{-(0.015 \times S)t}] / 0.3$ [6] $S = 1–0.99^N$, N = number of people in the house (t in seconds)	S = 0.01 t = 3600 s	$F_{duration} = 1.39$
$F_{indoors\text{-}outdoors}$	$= F_{volume} \times F_{ventilation} \times F_{strategy} \times F_{electr.\ class.}$		$F_{indoors\text{-}outdoors} = 2.42 \times 1 \times 1 \times 2 = 4.84$
F_{volume}	$= (4250 / \text{volume}_{room\text{-}building})^{-0.3333}$ [7] Provided that: $0.5 \le F_{volume} \le 3$ (Volume of room/building in m^3)	Volume of home = 300 m^3	$F_{volume} = 2.42$
$F_{ventilation}$	$= (4 / \text{ventilation rate})^{-0.5}$ [8] Provided that: $0.3 \le F_{ventilation} \le 3$ (Ventilation rate in number of times per hour)	Ventilation rate = 4x/hour	$F_{ventilation} = 1$
$F_{strategy}$	= 0.5 if the gas cloud is displaced away from the ignition source by ventilation = 1 if there is no specific ventilation strategy = 2 if the gas cloud can come into contact with the ignition source due to ventilation	There is no strategy	$F_{strategy} = 1$
$F_{electr.\ class.}$	= 0.5 for Class I, Div. 1 (ATEX) = 1 for Class I, Div. 2 (ATEX) = 1.5 for Class I, Div. 2 (ATEX) = 2 for non-classified area	Area is not ATEX-classified	$F_{electr.\ class} = 2$

The product of the four factors $= F_{MIE} \times F_{flow\ rate} \times F_{duration} \times F_{indoors\text{-}outdoors}$

$$= 2.06 \times 0.022 \times 1.39 \times 4.84$$

$$= 3.05$$

This is greater than 1, which means that the probability of delayed ignition is approximated as:

$$\begin{aligned} P_{delayed} &= 1 – [\ 0.7 / (F_{MIE} \times F_{flow\ rate} \times F_{duration} \times F_{indoors\text{-}outdoors})\ ] \\ &= 1 – (0.7/3.05) \\ &= \mathbf{0.77} \end{aligned}$$

Appendix 2

Nomogram for performing graphic calculation of the hydrogen concentration in a room in the presence of one ventilation opening

The nomogram can be used to determine the maximum steady state hydrogen concentration based on the known height and width of a ventilation opening and based on flow rate. The nomogram applies to both uniform and non-uniform hydrogen-air mixtures in a confined space with one ventilation opening.

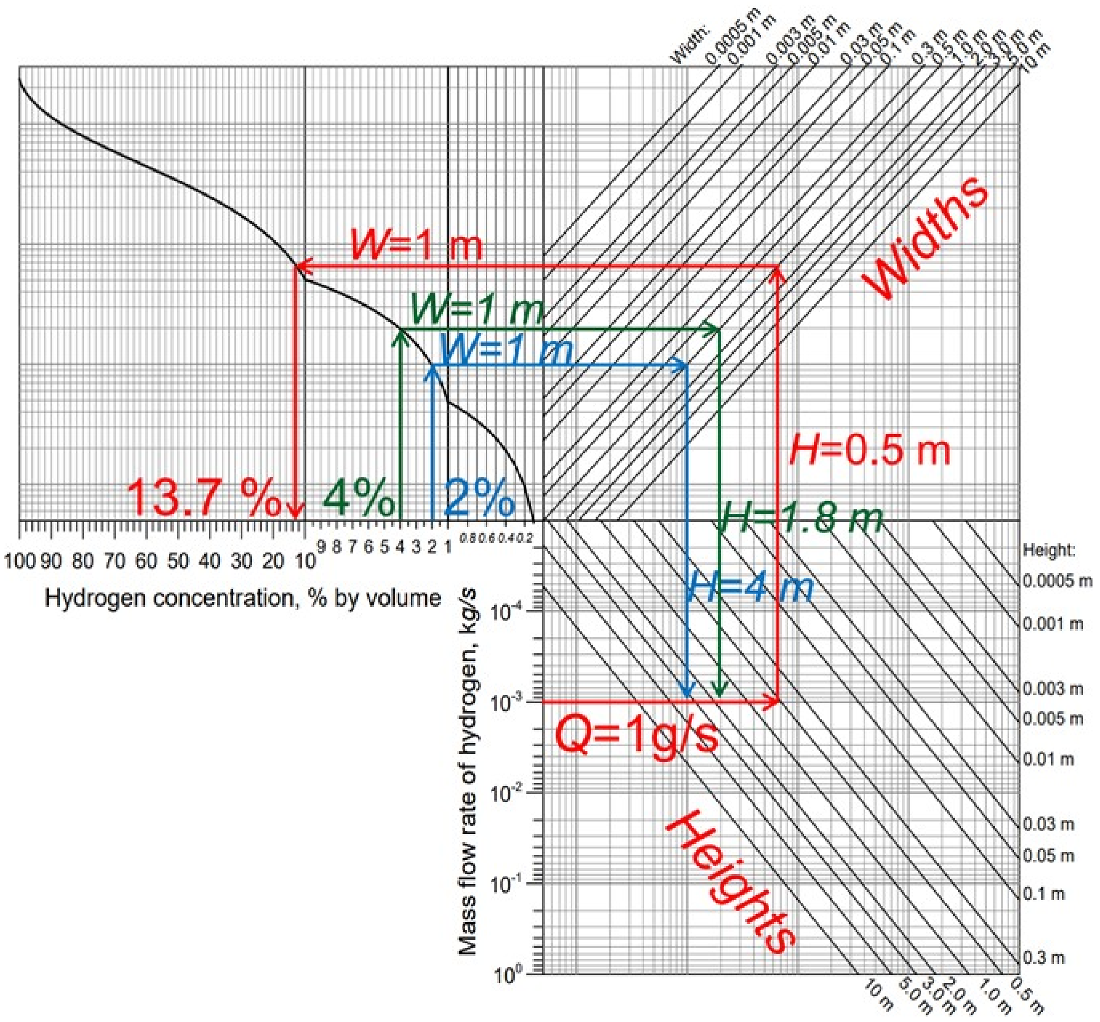


Figure B2.1 Nomogram for determining the hydrogen concentration in a room with a single ventilation opening

The procedure for calculating the hydrogen concentration can be illustrated by way of an example (follow the red line on the nomogram). In a room with a ventilation opening measuring 1 m wide and 0.5 m high, hydrogen is released at a rate of 1 g/s. It is assumed that the hydrogen-air mixture is uniformly distributed throughout the entire room. The procedure is as follows:

- Select the flow rate of the hydrogen leak on the vertical axis of the lowest block of the nomogram and draw a horizontal line until it intersects one of the diagonal lines. These lines represent the possible heights of the ventilation opening. There are 15 of these lines on the nomogram, covering heights from 0.5 mm to 10 m.
- From the first intersection point, draw a vertical line upwards until it intersects one of the diagonal lines in the top right-hand block of the nomogram. These diagonal lines represent the possible widths of the ventilation opening. There are 15 of these lines on the nomogram, covering widths from 0.5 mm to 10 m.
- From the second intersection point, draw a horizontal line left until it intersects the curve in the left-hand block of the nomogram.
- Draw a vertical line from the third intersection point to the horizontal axis of the left-hand block. The value on the horizontal axis is the hydrogen concentration (vol.%).

The result is 13.7 vol.%. This means that at a continuous release rate of 1 g/s and in the presence of a ventilation opening measuring 1 x 0.5 m (W × H) a concentration of 13.7 vol.% will be reached in the room.

The nomogram can also be used in reverse, i.e. to determine the size of ventilation opening required in order to prevent a certain hydrogen concentration from being exceeded at a certain flow rate.