PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

D2.2

Set of standard and improved procedures for detecting and quantifying H2 emissions – First release

Clean Hydrogen Partnership

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EXECUTIVE SUMMARY

The growing role of hydrogen as a sustainable energy carrier brings with it a demand for robust safety measures across the entire value chain. Due to its physical properties (particularly its low molecular weight, high diffusivity, low ignition energy, and wide flammability range) hydrogen presents unique challenges in terms of leakage and detection. In addition, the necessity of storing hydrogen under high pressure and using larger volumes compared to natural gas (to provide the same energy content) increases the risk of leaks and the associated safety implications. Ensuring effective leak detection and quantification is thus vital to maintaining operational safety, environmental compliance, and public trust in hydrogen infrastructure.

The work described in this report focuses on two issues. The first is the detection of hydrogen leaks at the component level occurring throughout the hydrogen value chain. In this respect, three leak detection methods were taken into account, using portable hydrogen detectors, acoustic cameras and a surfactant solution. For each of these methods, the possible scope of application, advantages and disadvantages resulting from the use of this method were indicated, and the equipment necessary to perform leak detection was identified.

The second issue taken into account in the report is the methods of measuring hydrogen emissions. In this area, the focus was on methods for measuring hydrogen fugitive emissions and on conducting measurements at the component level. In the scope of hydrogen emission measurement, one method was indicated as selected. This is the High Flow sampling method, which is successfully used to measure methane emissions in the Oil & Gas sector. Additionally, two other methods of measuring hydrogen emissions (acoustic method and bagging method) were presented, which in some conditions can be a complement to the HFS method and over time can gain sufficient technological readiness to become equivalent measurement methods. Similarly to the leak detection methods, the report also presents the hydrogen emission measurement methods: equipment requirements for carrying out measurements, the scope of application of individual methods and their advantages and disadvantages.

As part of the task, two procedures dedicated to leak detection and hydrogen emission measurement were developed, which are annexes to this report. These procedures will be validated as part of the activities planned in WP3. The results and conclusions resulting from the validation will be implemented in the improved procedures and included in the D2.3 report.

PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

1. Introduction

The transition toward a hydrogen-based energy economy brings new technical and safety challenges—as for example when hydrogen is introduced into existing gas networks originally designed for natural gas. Hydrogen, due to its fundamental physical properties, presents a unique set of risks. Its molecules are significantly smaller and lighter than those of methane, which makes them more prone to escaping through microscopic imperfections in seals, joints, and pipeline damaged materials. Moreover, hydrogen is characterized by a very low ignition energy and an exceptionally broad flammability range, increasing the severity of even small leaks.

Compounding this challenge is the volumetric energy density of hydrogen, which is approximately three times lower than that of natural gas. As a result, significantly larger volumes of hydrogen are needed to deliver equivalent energy, and this often requires compression and storage at very high pressures—ranging from 200 to 1000 bar. These pressure conditions elevate the mechanical stress on infrastructure and make leak prevention and detection even more critical.

In this context, detection and quantification of hydrogen leaks using validated and traceable methods is essential not only for operational safety, but also mitigating the impacts of hydrogen emissions on climate and ensuring efficient and secure energy systems. The effectiveness of emission monitoring methods (and their associated technologies and measurement protocols) will directly impact the ability to understand emission sources so that mitigation strategies can be successfully implemented, to find and repair leaks, report emissions and track reductions using inventories. This report identifies draft methods to be evaluated for hydrogen leak detection and quantification, tailored to the unique properties of hydrogen and the realities of industrial infrastructure. It provides a structured overview of available technologies —including portable detectors and advanced imaging systems, and examines their applicability in various parts of the hydrogen value chain.

Beyond the technical assessment, this document also aims to promote procedural standardization across inspection and maintenance practices. By addressing operational issues such as equipment calibration, field deployment protocols, and staff competency, this document contributes to improving safety culture and reducing the margin for error in industrial environments. Ultimately, the guidance provided here is intended to support informed decision-making and foster safe, efficient, and transparent management of hydrogen systems.

This report is the deliverable under the second activity (Task 2.2) which will develop a set of procedures for leak detection and quantification for bottom-up assessment on component level.

This report will:

- Describe methods, for H_2 gas leak detection and emission quantification, which have been selected by their high technology readiness level.
- Describe a set of developed procedures for leak detection and quantification using specialized equipment and apparatus.
- Define relevant data collection field survey using selected instruments.
- Create a base for method validation documentation.

Work package	Description	WP Leader	Timeline (months)
WP1	H2 releases inventory	UNIBO	1-36
WP2	Methodology development for H2 releases' quantification	INIG / NPL	3-27
WP3	Methodology validation and field tests assessment	NPL	7-34
WP4	H2 releases from supply chains	ENGIE	12-34
WP5	Hydrogen release scenarios	FBK	12-36
WP6	Dissemination, communication & exploitation	GERG	1-36
WP7	Coordination and Project Management	SNAM	1-36

2. Leak Detection methods

There are many methods for detecting leaks at the component level. However, due to their specificity, the scope of application of individual methods is diverse. The requirements for the equipment necessary for their implementation and the requirements for the competence of the personnel performing the measurement are also diverse. This chapter describes the leak detection methods available for hydrogen, indicating the advantages and disadvantages of each method and defining the scope of their application. For two of the methods described in this chapter (sniffers and passive sensors, acoustic camera) which were considered the most suitable for detecting leaks, a procedure describing how to conduct measurements was prepared (Appendix 1).

2.1 Sniffers and passive detectors (portable gas detectors)

2.1.1. Method description

Sniffers and passive detectors are typically battery operated and handheld portable systems that may be used to detect gas leaks. This method is of common concern to industrial sectors related to hydrogen production, transmission, distribution and end-use. This method applies to the manual detection of fugitive emissions of hydrogen from process equipment such as valves, joints, flanges, open-end lines, etc. The method can be applied to periodic inspections carried out at component scale; and can be used in Leak Detection and Repair (LDAR) schemes or in any other situation requiring the detection of hydrogen gas leaks. This method is also the first step in measuring hydrogen emissions using the High Flow sampling method which requires prior detection and localization of the gas leak. This method considers only above ground fugitive emissions (i.e. underground or underwater leaks are not considered). The principle of the leak detection method using portable gas detectors is to measure the hydrogen concentration in the air surrounding the potential source of the leak. For this purpose, the devices used in this method are equipped with sensors that enable the detection and measurement of hydrogen content in the air, such as catalytic combustion sensors, electrochemical sensors, metal-oxide-semiconductor (MOS) sensors, palladium-alloy sensors or thermal conductivity sensors (TCD) [1-5]. Most of the commercially available portable gas detectors are not hydrogen selective and can detect various types of flammable gases.

2.1.2. Required equipment and materials

To implement the method, a sniffer or passive detector with an appropriate measurement range is required. The appropriate measurement range is proposed to be the range in which the limit of detection is lower than the defined concentration threshold and the upper measurement limit is at least 10% LEL. The device used should be approved for use in explosion hazard zones, accordingly to the inspected site's rules. Due to the need to regularly check the correct operation of the instrument, carrying out measurements using sniffers or passive detectors requires the availability of calibration gases. Gases required to check the sensor are "Zero flammable or explosive gas" (dry air containing less than 10 ppm of H_2 or any other flammable gas detected by the instrument) and two certified reference gas mixtures being a mixture of hydrogen in air with a known/certified H_2 concentration. The hydrogen content in certified gas mixtures should be approximately 25 and 75% of the measuring range of the device used.

2.1.3. Advantages and disadvantages of the method

Main advantages of this method are relatively high accuracy of very few false positive cases of detecting hydrogen leaks in working conditions of industrial installations, relatively low impact of atmospheric and operating conditions on the detection in spite of these factor being of great impact while reading concentrations of hydrogen in air from a leaking element. An additional advantage of the method is the low operating cost and the availability of a wide range of instruments on the market to implement this method. The ease of the use of sniffers or passive gas detectors means that only basic training of personnel, mainly in the field of safety in explosion hazard zones, is necessary to detect leaks. Due to the above advantages, these kind of portable gas detectors are often chosen for leak detection of various types of industrial installations.

Main disadvantages of this method are: hard to reach components on the installation due to the physical range of hand-held devices, and the necessity of working in close proximity to leaking components which could means working directly in an explosive zone. An additional disadvantage of the method is the possibility of saturating or even poisoning some kinds of the sensors [6], both by exposing the device to a momentary high concentration of hydrogen, and by long-term exposure of the sensor to continuous contact with hydrogen. For this reason, correct measurement performance requires checking the sensor during each measurement survey. In addition, most sensors respond to flammable gases, so cross sensitivity and response factors must be considered for any detector not selective for hydrogen.

2.1.4. Recommendations for using the method

Sniffers and passive detectors are recommended as a primary method for leak detection in most of the hydrogen value chain. One exception is underground elements where excavation would be required to gain physical access to undertake measurements. In addition to underground elements, other elements of the hydrogen value chain for which the method using portable gas detectors cannot be used are those components where hydrogen is stored, transported or used by end users as chemical hydrogen carriers such as ammonia or LOHC, methanol. In cases where hydrogen is present in NG-H2 mixtures, leak detection may focus on hydrogen or methane as the main components of the mixture. It is then necessary to assess how the components of the mixture affect the detector response, especially in the case of detectors that are not selective for hydrogen [6, -8]. When detecting leaks in gas networks or installations transporting NG-H2 mixtures, the use of detectors equipped with methane sensors should be considered, as the main component of the mixture.

2.2 Acoustic cameras

2.2.1. Method description

Acoustic cameras are sophisticated devices used to detect gas leaks in various systems, including pipelines, tanks, and industrial equipment. They operate based on the principle of ultrasound wave detection and imaging. The primary function of an acoustic camera is to capture ultrasonic sound waves emitted by leaks. When a gas escapes from a pressurized system, it creates a distinctive sound, audible sounds and/or ultrasounds [9-11]. For this purpose, acoustic cameras are equipped with an array of microphones that can pick up sound from multiple directions. This array allows the device to triangulate the source of a sound by measuring the time it takes for the sound to reach each microphone. The processed sound data is then used to create visual representations of the sound sources. This is often displayed as a color-coded image, where the intensity of colors indicates the level of the sound. In some cases the brighter areas correspond to more significant leak sources. However, it is difficult to compare different leak sources in quantitative terms (even if they are almost identical components) since the produced sound depends on intimate details of each leak source (as the shape and size of the leak source).

2.2.2. Required equipment and materials

The sound frequency generated by the leakage source is mainly distributed from 10 kHz to 100 kHz, and the most obvious difference between leak signals and the environmental noise is at 20-40 kHz. Therefore, the 20-40 kHz is the preferred frequency for gas leak detection, and the ultrasound camera should be able to detect sounds in this frequency range [12]. The optimal solution is when the ultrasonic camera can detect ultrasound in a wider frequency range and the ability to select the optimal frequency of detected sounds. This is especially important when conducting measurements in conditions where ultrasonic noise is also generated by sources such as motors, fans, etc. In order to properly image the sound source, the ultrasound camera should be equipped with an appropriate number of microphones (typically 100-150). Due to the operating principle of the ultrasonic camera, no additional materials, such as certified reference gas mixtures, are required to detect leaks using this method. However, due to the possibility of generating false positive signals using this method, it is recommended that leaks detected with an ultrasonic camera be confirmed using another method (e.g. sniffers) if possible.

2.2.3. Advantages and disadvantages of the method

Fast response time and the ability to assess large or multiple components simultaneously are amongst the main advantages of this method. This allows for reduced inspection time, especially in the case of complex installations where many components are located in a small space. The second significant advantage of the leak detection method using acoustic cameras is the possibility of conducting inspections from considerable distances (up to 50 m depending on the sound level). This makes it possible to take measurements of components located in hard-to-reach/inaccessible places, e.g. at heights. Additionally, the ability to detect leaks from a distance increases safety by avoiding direct exposure to potentially explosive atmospheres. Another advantage of this method is the simplicity of documentation using the snapshot or video functions.

Unfortunately, this method has several disadvantages, mainly high interference due to atmospheric, rain or hail and operating conditions which leads to possible increased lower detection limit of a leakage [13]. Reliable reading interpretation requires a basic training. The possibility of generating false positive signals, e.g. as a result of sound reflection from flat surfaces or due to vibrating/rotating machinery is another disadvantage of this method, however reflections can be revealed since they move within the image when the leak source is focused from different angles, while real leak sources preserve their position. For that reason, whenever possible, leaks detected with acoustic cameras should be confirmed by another method, as portable gas detectors. The high cost of purchasing the device may also be a limitation in using this technique to detect hydrogen leaks.

2.2.4. Recommendations for using the method

This method was selected as a secondary (complementary) method for leak detection, mainly as supporting device for portable gas detectors, to rapidly recognize large leaks from a safe distance, for hard-to-reach places and possible hazardous zones. In those cases, the acoustic method is a good alternative to the sniffers and passive detectors increasing the area that can be inspected in a given time period. Places where ultrasonic noise occurs should be excluded from measurements, due to the acoustic camera high detection limit under such conditions. Also, those components in which the gas overpressure is lower than the minimum differential pressure specified by the device manufacturer cannot be measured using this method. Although direct sight is not required for leak detection, but the sound must propagate from the leak to the surface where the microphones are located. This method cannot be applied for underground components or components under thermal insulation, while we are not aware of any development for underwater leak detection. This method is also not applicable to detecting leaks for components where hydrogen is stored, transported or used by end users in liquid phase as LH2, LOHC, methanol. Potentially, this method can be used to detect leaks in storage and transportation systems for ammonia in gas phase, which is a hydrogen carrier. However, the use of the acoustic method in this area would require special safety rules due to the high toxicity of ammonia.

2.3 Bubble screening

2.3.1. Method description

The bubble leak detection method requires a minimum gas pressure difference on both sides of the component to be tested (internal and external). A testing liquid is placed in contact with the lower pressure side of the pressure boundary. This method involves squirting a soap-like solution on small and accessible components such as flanges, valves, fittings, threaded connections, etc. If there is a leak, soap-like bubbles will develop from the solution [14]. Gas leakage through the pressure boundary can then be detected by observation of bubbles formed in the detection liquid or liquid film at the exit points of leakage through the pressure boundary. This method provides immediate indications of the existence and location of leaks in the range from 10^{-4} to 10^{-2} mbar·L/s. Longer inspection times may be needed for the detection of smaller leaks

(10^{-5} to 10^{-4} mbar·L/s) [15]. Bubble tests are often classified according to the test liquid and means of application. In the liquid immersion ("dunking") technique, the pressurized test system is submerged in the test medium. In the liquid film application method, a thin layer of the test medium (soap solution or foam) is flowed over the low-pressure surface of the object. Because water-based detection solutions are used, they cannot be used on devices with temperatures above the boiling point of water (100 °C) or below the freezing point of water (0 °C).

2.3.2. Required equipment and materials

To implement the method, specially prepared solutions that form bubbles or foams are necessary. If a non-spray water solution is used, tools (e.g. a brush) may be required to properly apply the solution to the component being tested. To implement the method, materials are also necessary to remove dirt from the tested surfaces. Since dirt (grease, dust) can affect the properties of the solution and the effectiveness of bubble formation, it is recommended to clean the tested surface before applying the solution [16].

2.3.3. Advantages and disadvantages of the method

The advantages of bubble leak testing relate to its simplicity, rapidity and low cost. It is a fairly sensitive leak detection technique and enables the inspector to precisely locate the exit points of leaks. Another advantage is that it readily detects very large leaks yet provides reasonably rapid responses for small leaks [15]. The method does not generate false positive signals, hence there is no need to confirm leaks detected by this method, as is the case with acoustic methods. Rate of bubble formation, size of bubbles formed, and rate of growth in size of individual bubbles provide the means for estimating or comparing the size of the leak.

The main disadvantage of the method is that it can only be used in easily accessible places. The necessity of direct contact of the personnel carrying out the method with the tested elements means that the employees may be directly exposed to the occurrence of an explosive atmosphere. In addition, dirt on the tested surface may interfere with the formation of bubbles, and the additional need to clean the surface before performing the test increases the time consumption of the method. For this reason, leak detection efficiency is highly dependent on the precision and experience of the personnel.

2.3.4. Recommendations for using the method

Due to the same limitations of this method as the methods using sniffers and passive detectors, the use of the bubble screening method should be limited to situations when there are no portable gas detector devices available on the installation. The exception will be situations where, due to the occurrence of many leaks in a small space, precise localization of each of them is difficult to perform using sniffers. In this case, the bubble screening method can be a good complement to tests conducted using portable gas detectors.

Similarly to the previously described methods, the soap screening method applies only to above-ground components. This method involves squirting a soap solution on small and accessible components such as flanges, valves, fittings, threaded connections, etc. It is not effective on large openings such as open-ended pipes or vents. To apply this method it should be also excluded components with temperatures above 100 °C or below 0 °C [17]. The method cannot be used in those elements of the value chain where hydrogen is stored, transported or used in the form of liquid (LH2) or liquid chemical hydrogen carriers (methanol, LOHC, ammonia). For safety reasons, this method should not be used when the hydrogen carrier is ammonia gas.

3. Selected methods for leak quantification

Measurements of hydrogen fugitive emissions at the component level show some analogy with measurements of methane emissions. However, due to differences in the physicochemical properties of both gases, some of the methods used so far to measure natural gas emissions cannot be applied to hydrogen (e.g. methods based on IR absorption) [18]. Additionally, due to the dynamic development of measurement techniques dedicated to hydrogen, which has been taking place in recent years, in many cases there is a lack of commercially available devices on the market that would allow for the implementation of this type of measurements. Below, three methods for measuring hydrogen emissions are described, of which only the High Flow Sampler (HFS) method can currently be considered suitable for quantifying leakage. A detailed description of the implementation of this method is presented in Annex 2. The remaining two methods described in this chapter require additional tests to confirm or exclude the possibility of using them in measuring hydrogen emissions.

3.1 High Flow Sampling method

3.1.1. Method description

High Flow Sampling (HFS) method is based on the fact that the forced air flow at the site of the leak directs the escaping gas into a measuring system, where the gas flow rate and the diluted hydrogen concentration in the flowing gas are measured simultaneously. In addition, when relevant, a measurement of hydrogen concentration in the atmospheric air that forms the background of these measurements is carried out [19]. In the measurement of hydrogen emissions by the High Flow method, the greatest difficulty is to select the measurement accessories and air flow rate in such a way that all the hydrogen escaping from the leaking component is directed into the measurement system. In addition, in the case of small leaks it is important that the air flow rate is not too high, as this will cause a significant reduction in the concentration of hydrogen in the resulting mixture and make it difficult to perform measurements with an acceptable uncertainty, which at the same time affects the LOQ. In the case of measurements of methane emissions, the HFS method has become commercially available, which makes it possible to carry out HFS measurements with a single device. However, in the case of hydrogen emissions, its measurement by the HFS method currently requires the use of two independent devices: High Flow sampler and hydrogen detector.

3.1.2. Required equipment and materials

Implementation of the method requires integration of two devices. The first is the High Flow Sampler, whose task is to take an air sample containing escaped hydrogen and measure the flow rate of the collected sample. The HFS device should allow samples to be taken at an appropriate adjustable rate and allow direct reading of the sampling flow rate during measurements. The device should be equipped with a sufficiently long sampling hose with a set of attachments suitable for measuring leaks on components of different shapes. The second device necessary to carry out measurements by this method is a hydrogen gas detector having an internal sampling pump, whose task is to measure the concentration of hydrogen in the stream of gas sampled by the HFS. The detectors used in this case are devices with the same characteristics as given in section 2.1.2. Due to the need to control the readings of the detector used to measure the hydrogen content of the sampled air, the correct implementation of the method requires the availability of calibration gases, as given in 2.1.2.

3.1.3. Advantages and disadvantages of the method

The primary advantage of the HFS method is the precise measurement of hydrogen emissions over a wide range of flow rates compared to acoustic imaging methods. The need to obtain consistent results for two different sampling rates provides a certain kind of control over the correctness of the sampling while performing the measurement. In addition, if the full capture of the leaked hydrogen is achieved, the method is resistant to changes in the atmospheric and operational conditions in which the measurements are conducted. Interferences in this method will come mainly from other flammable gases in the air stream, unless the sensor used is selective to hydrogen. The main disadvantage of the method is that it requires direct access to the leak location, making it difficult or sometimes impossible to conduct measurements for hard-to-reach components. In the case of emission measurements on components located in hazardous areas (such as explosive zones) at least some of the measurement activities (sample collection) must take place in those areas. A certain difficulty in the implementation of the method is the necessity of selecting the appropriate attachments and sampling rate for the correct implementation of the measurement. It is necessary to capture the whole target leaking gas (hydrogen in this case) while doing the measurement, otherwise the measured leak rate will be an underestimation of the actual value. For these reasons, proper training of personnel is required to carry out the measurements.

3.1.4. Recommendations for using the method

The HFS method is the primary method recommended for measuring hydrogen emission rates at various components in the hydrogen value chain. However, measurement of hydrogen emissions with this method is limited to aboveground components located in accessible areas. It is possible to use the HFS method to measure emissions from underground components, after they have been previously excavated. In addition, the HFS method is applicable to components that store, transport or end-use hydrogen gas. At sites where liquid hydrogen carriers in the form of LH2, methanol, LOHC, or ammonia are used, the method in its current form cannot be applied.

4. Other emission quantification methods

4.1 Bagging method

4.1.1. Method description

Bagging is defined as a means to quantify volumetric gas emission rates from equipment leaks in Section 4 of the EPA Protocol for Equipment Leak Emission Estimates [20, 21]. The Protocol defines two bagging approaches: the vacuum method and the blow-through method. In both methods the emission rate of a component is measured by bagging the component with an impermeable foil constructed of inert antistatic material and evacuating the undiluted leak from the bag at a constant measured flow rate. In the EPA-described method two samples of leaking gases are taken, using a sampling train for laboratory analysis. Currently, instead of taking samples for analysis, portable gas detectors can be used. The methods differ in the ways in which the carrier gas is conveyed through the bag: in the vacuum method, a vacuum pump is used to pull air through the bag. In the blow-through method, a carrier gas is blown into the bag. Due to the fact that the blow-through method has several advantages over the vacuum method, the remainder of this chapter focuses solely on the blow-through method. The advantages of the blow-through method are mainly based on the smaller amount of equipment needed, ensuring better mixing of the sample and limiting the impact of air (background) contaminants on the quality of the results.

4.1.2. Required equipment and materials

To implement the bagging method, the necessary elements are a foil/bag made of appropriate antistatic material, along with a system of tapes or elastic bands for proper attachment of the bag to the tested component. This equipment is used to isolate the leaking element during measurements. In the blow-through method, the carrier gas is gas from the cylinder. For this reason, the use of this method requires the use of a cylinder with carrier gas and a calibrated rotameter which will control the gas supply to the bag. EPA documents recommend using an inert gas such as nitrogen as the carrier gas. However, in the case of hydrogen emission measurements, some sensors require the presence of oxygen for correct measurement, therefore the proper carrier gas for hydrogen emission measurements is dry synthetic air. The measurement of hydrogen concentration in the mixture formed inside the bag should be performed using gas detectors described in chapter 2.1.2. To implement the method, minor equipment is also needed that allows the integration of the entire measurement system, in the form of connectors, Teflon tubes, pressure regulators, and valves.

4.1.3. Advantages and disadvantages of the method

The blow-through method, in which the gas is blown into the hydrogen concentration measuring system, can be thought as the reverse of the HFS method, in which the gas is sucked into the measuring system. For this reason, the advantages and disadvantages of both methods are similar. The advantage of the HFS method over the bagging method is a less complicated measurement procedure, much shorter measurement time and the possibility of carrying out the measurement outside the explosion hazard zone (in the case of leaking elements located inside such a zone only one extreme of the hose needs to be close to the leak source). As far as we know, there is still a lack of available validation testing data to confirm the actual scope, range of application and limitations of this method for hydrogen leak rate quantification.

4.1.4. Recommendations for using the method

Theoretically, the scope of application of the HFS and bagging methods is similar, therefore the bagging method is recommended to be used only in the absence of access to equipment enabling measurement using the HFS method. In terms of the hydrogen value chain, the bagging method can only be applied to above-ground components related to the transport, storage or end-use of hydrogen as a gas.

4.2 Acoustic cameras

4.2.1. Method description

Quantification of hydrogen emissions using ultrasonic cameras is based on the same principle as leak detection using them (see chapter 2.2.1).

4.2.2. Required equipment and materials

The equipment required for measuring hydrogen emissions using an acoustic camera is analogous to that presented in Chapter 2.2.2. It should be noted whether the camera used has the ability to define the important parameters during measurements, i.e. the type of gas (whether hydrogen is available), pressure and the shape and size of the leak source.

4.2.3. Advantages and disadvantages of the method

The advantages of estimating hydrogen emission rates using the acoustic camera method are similar to those presented in chapter 2.2.3. These advantages mainly focus on the possibility of conducting measurements from a considerable distance (<30m), enabling measurements of difficult-to-access elements and limiting the exposure of personnel related to explosion hazard zones. The disadvantages of the acoustic method are primarily the lack of precision and accuracy in emission measurements. This is mainly due to the fact that the level of sound emitted by a leak is influenced by many factors, some of which can be defined (pressure, type of gas) while others cannot be precisely or even approximately determined (leak source shape and size). It is worth nothing that there is still a lack of available validation testing data to confirm the actual scope, range of application and limitations of this method for hydrogen leak rate quantification.

4.2.4. Recommendations for using the method

Due to significant disadvantages of the method of estimating hydrogen emissions using an ultrasonic camera, the use of this method should be limited only to rough estimates of leak rates from hard-to-reach places where emission measurement using another method is not possible.

In the hydrogen value chain, the ultrasonic method can be applied to above-ground and uninsulated components. The application of the method requires that the transported, gassed or ultimately used medium is hydrogen in gaseous form and the tested installations are characterized by an appropriate overpressure. This method is evenly applicable to emission rates measurements from gas networks or installations containing NG-H2 mixtures, since the method is not selective and is capable to detect and measure (sound levels) of any gas leak producing enough ultrasound noise. However, the available commercial devices using models to estimate the leak rates in terms of the measured sound levels by the moment do not consider the definition of the medium as a gas mixture (excluding air). This last is an additional limitation for the application of this method for that type of installations.

5. Application of measurement methods in the hydrogen value chain

The hydrogen value chain is a complex chain, which includes various segments (production and conversion, transport, storage, final consumption) (Figure 1). In the individual segments, hydrogen can occur as a pure gas or cryogenic liquid or in a mixture with other gases (e.g. NG-H2 mixture, post-reaction mixtures in hydrogen production) or as chemical compounds that are hydrogen carriers (such as ammonia, methanol, LOHC, metal hydride).

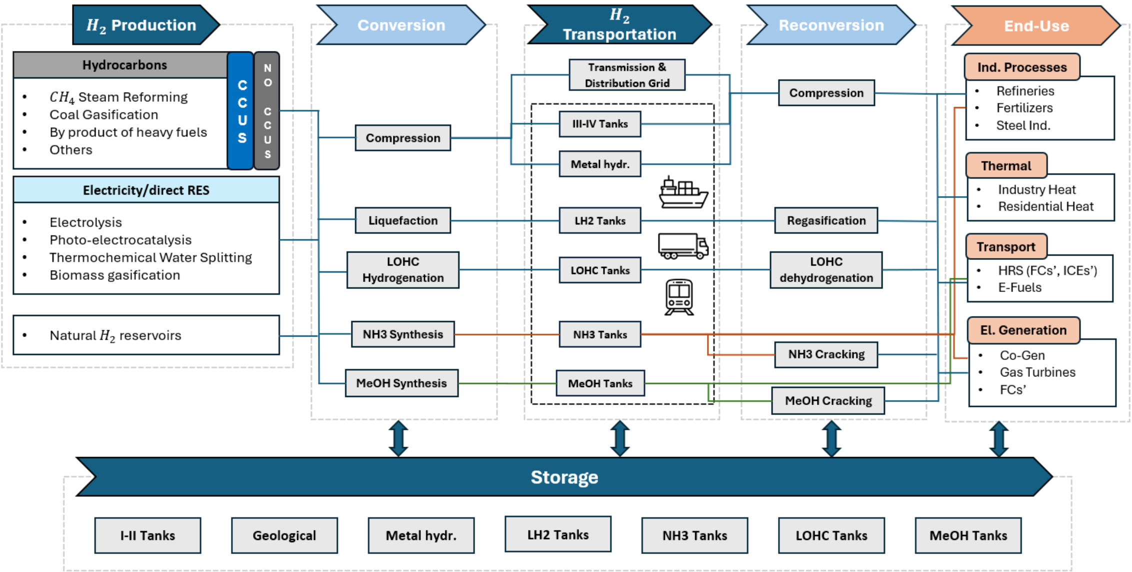


Figure 1. H_2 supply chains and evaluated technologies for NHyRA [22]

Each sector is subject to fugitive hydrogen emissions (resulting from gas permeation and escape through leaks at connections and components), emissions from process vents (the extent of which depends on the sector and the equipment used there) and emissions from incomplete combustion.

This report only describes methods for detecting fugitive hydrogen emissions, since the sources of emissions from process vents and incomplete combustion are known to the operator and do not require such methods. As well as in some cases other processes that are known and reasonable estimations of the emission rates can be achieved by engineering calculations, but this is not always the case. The emission measurement methods described in the report focus mainly on the measurement of hydrogen fugitive emissions related to leaks, since emissions related to permeation require other, long-term measurement methods due to the very low flow rate escaping gas. In some cases, the methods described in this report can be used to measure hydrogen emissions from vents, but this requires additional precautions when carrying out the measurements. Due to the characteristic of emissions from incomplete combustion, some of the challenging monitoring aspects are:

- low hydrogen content,
- presence of other substances such as moisture, nitrogen oxides,
- high exhaust gas temperature,

The methods described in this report are not suitable for measuring emissions from these types of sources. The methods of leak detection and hydrogen emission rate measurement proposed in this report focus on pure gaseous hydrogen, but in principle they could also be adapted and applied to liquefied hydrogen and its carrier in the form of ammonia. However, the application of the methods described in these areas requires special safety rules, testing and validation in relation to the above-mentioned media.

Each stage of the hydrogen value chain, from production to end use, comprises distinct technologies and operating environments, which require tailored measurement approaches. The most widely used practical tools for leak detection include portable gas detectors which actively draw samples through a pump (also called **sniffers**); portable gas detectors using **passive sensors**, which rely on gas diffusion into the sensor head; **acoustic imaging**, which detects high-frequency sound emissions from pressurized leaks; and, in selected cases, **bubble screening.** Leak rate quantification, in turn, is most accurately carried out using the **High Flow Sampler (HFS)** method, with the **bagging method** as an alternative method. **Acoustic imaging** may support rough estimations of the leak rates in hard-to-reach areas but is not considered yet a quantitative method.

Hydrogen production includes fossil-based routes such as steam methane reforming and coal gasification, as well as renewable-based methods like electrolysis, photo-electrocatalysis, thermochemical water splitting, and biomass gasification. In fossil-based environments, detecting hydrogen can be particularly challenging due to the presence of other gases such as methane, CO_2, CO and water vapor. In such settings, sensor selectivity is critical to avoid false readings or misinterpretation. However, when highly selective sensors are not available or suitable, the use of instruments with multiple detection capabilities may be considered, provided that the multiple sensors do not interfere with each other's readings, Sniffer sensors are preferred in open-air or ventilated areas, as they actively draw in samples and are less influenced by ambient air currents. Passive sensors, while simpler and easier to handle, require adequate conditions for reliable performance. High Flow Samplers offer the most efficient leak quantification, though physical access, availability of instrumentation and pressure conditions may sometimes necessitate the use of the bagging method instead.

In hydrogen production powered by direct renewable sources, such as electrolysis facilities, equipment density and layout often restrict accessibility. Sniffer sensors and passive sensors are again the primary methods, selected based on ambient conditions and proximity to suspected leaks. Acoustic imaging proves especially useful in compact installations where physical access is limited, providing quick, non-contact identification of leak sources. However, for accurate quantification, the High Flow Sampler currently remains the method of choice wherever feasible.

Hydrogen conversion involves preparing the gas for transportation and storage, through either compression or liquefaction. In high-pressure compression systems, potential leak points include seals, valves, and pipe fittings. Sniffer sensors perform well here due to their ability to work in windy or turbulent conditions. Passive sensors are appropriate for enclosed or protected spaces. Acoustic imaging supports the detection of leaks in complex piping networks or elevated areas where direct access is limited, although areas with high frequency ambient noise (such as compressing stations) must be taken into consideration which might increase lower detection limits. HFS continues to be currently preferred method due to many disadvantages of acoustic imaging method for measuring fugitive emission rates (or leak rates), with the bagging method employed as a fallback when space or geometry prevents effective use of the sampler.

In liquefaction systems, extremely low temperatures make contact-based detection methods such as bubble screening impractical. Acoustic imaging is therefore the most suitable detection methos, as it allows for rapid, non-intrusive identification of leaks in cryogenic equipment. However, it should be noted that this report focuses on gaseous hydrogen emissions, not liquid hydrogen or its carriers. While leaks of liquid hydrogen under industrial conditions are rare – given that operations typically do not occur at or just below hydrogen's boiling point (~20 K) - non-evaporated leaks may still pose a risk in pressurized systems. In such limited cases, the bagging method may be the only viable quantification solution, particularly where venting or accessible piping is available.

The transportation of hydrogen includes several modes: pipelines, tube trailers, liquid hydrogen tankers, chemical hydrogen carriers and metal hydride carriers. Pipelines present challenges in both accessibility and leak localization. While direct measurement is impossible for underground sections, detection can be carried out at surface-accessible installations such as pressure-reducing stations, joints, or valves. Sniffer detectors are again preferred in these settings, especially in open-air conditions, while passive detectors complement inspections for leak detection in calmer environments. Acoustic imaging is highly effective in scanning large or inaccessible areas. Quantification, when required, should be conducted using HFS. However, it is important to note that in underground pipeline segments, neither detection nor quantification is feasible using these conventional methods.

Tube trailers—used for high-pressure hydrogen transport—are typically inspected at refueling depots or during maintenance. Sniffer and passive detectors are the primary detection tools for fittings and valves, with acoustic imaging playing a valuable role in detecting large leaks and scanning around brackets and joints that may be difficult to inspect directly. HFS is preferred for quantifying emissions from valves or connections during maintenance. Similarly, LH_2 tankers, which carry hydrogen in liquid form, pose unique challenges due to their cryogenic temperatures. Acoustic imaging is the most appropriate leak detection method in these hard to reach systems, while HFS method may be used to quantify leaks at exposed, warmer interfaces.

Hydrogen storage exists in various physical forms, including pressurized composite tanks, cryogenic tanks, metal hydrides, and geological storage. HFS remains the most accurate tool for quantification. In contrast, underground storage—such as salt caverns or depleted gas reservoirs—cannot be directly monitored for hydrogen leakage using these tools. Integrity in such systems must be assessed indirectly, for example through pressure monitoring or chemical tracer analysis.

Reconversion involves re-pressurizing, re-gasifying, or chemically cracking hydrogen carriers back into usable hydrogen gas form. Compression risks and inspection strategies mirror those described earlier. In regasification systems, particularly those handling liquid hydrogen, acoustic imaging is the primary tool for leak detection. Passive and sniffer detectors are used selectively where environmental and access conditions permit it. In chemical reconversion systems, such as ammonia or LOHC dehydrogenation, hydrogen leaks might occur alongside other byproducts. In such environments, non-selective detectors may provide misleading readings; only detectors specifically selective for hydrogen should be used. Sniffer and passive detectors are again appropriate for leak detection, while HFS is recommended for measuring emission rates in controlled or maintenance scenarios.

End-use applications span industry, thermal systems, transport, and electricity generation. In industrial settings like refineries or steel plants, background gas concentrations may lead to sensor interference. Here, selective detection tools are essential. Sniffer detectors offer the greatest versatility, especially in variable airflow environments. Passive detectors are suitable for targeted checks in stable, low-disturbance conditions. Acoustic imaging can assist in general inspection. HFS remains the most reliable method for emission quantification.

In thermal systems and residential hydrogen applications, leak risks are lower but still critical to address. Sniffer and passive detectors remain the primary tools for leak detection, and HFS should be used for periodic inspection or incident response quantification. Similarly, in hydrogen mobility systems—such as refueling stations or onboard vehicle storage—detection requires a combination of pinpoint accuracy and quick assessment. Sniffer detectors and acoustic imaging are both well-suited to these environments. For quantification during refueling system validation or maintenance,

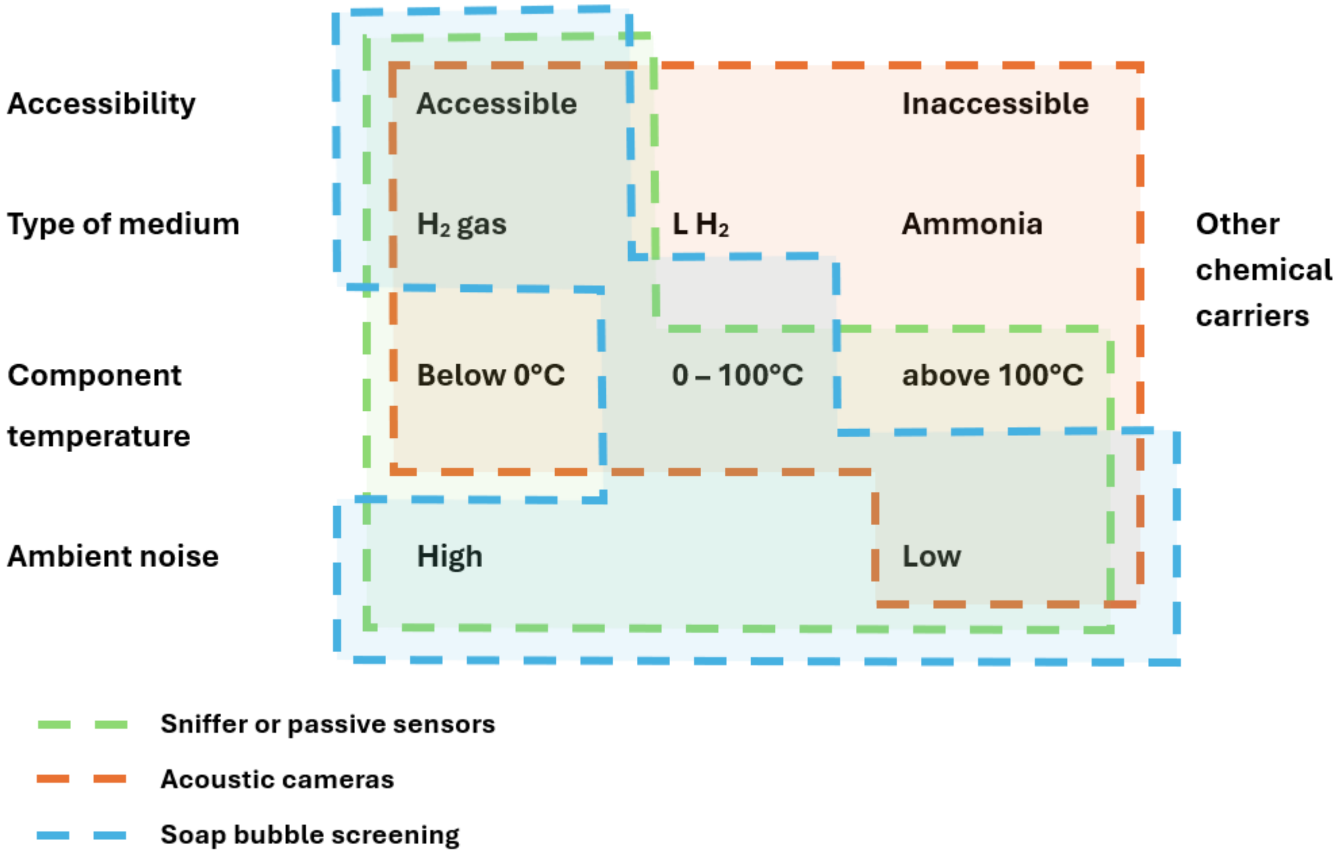
In power generation applications involving fuel cells or gas turbines, inspection routines follow a similar methodology. Sniffer and passive detectors support precise inspection, while acoustic imaging helps quickly locate leaks in larger or enclosed areas. Quantification can be carried out using HFS as needed during diagnostics.

Across all stages, the choice of method depends on accessibility, environmental conditions, gas composition, and operational constraints. While **High Flow Sampler** and **sniffer detectors** are generally preferred due to their precision and versatility, **passive detectors**, **acoustic imaging**, and **bagging** methods provide valuable alternatives in specific circumstances, especially when access is limited or operating conditions restrict the use of other tools. It is critical to match the detection and quantification method not only to the physical system but also to the technical limitations and safety context of each site.

In a similar scope (leak detection), but with certain limitations, the bubble screening method can be used, which, however, due to the subjective nature of the results, is not recommended.

Figure 2 illustrates the applicability of various hydrogen leak detection methods, emphasizing their suitability under different conditions of accessibility, environmental noise, and operational constraints.

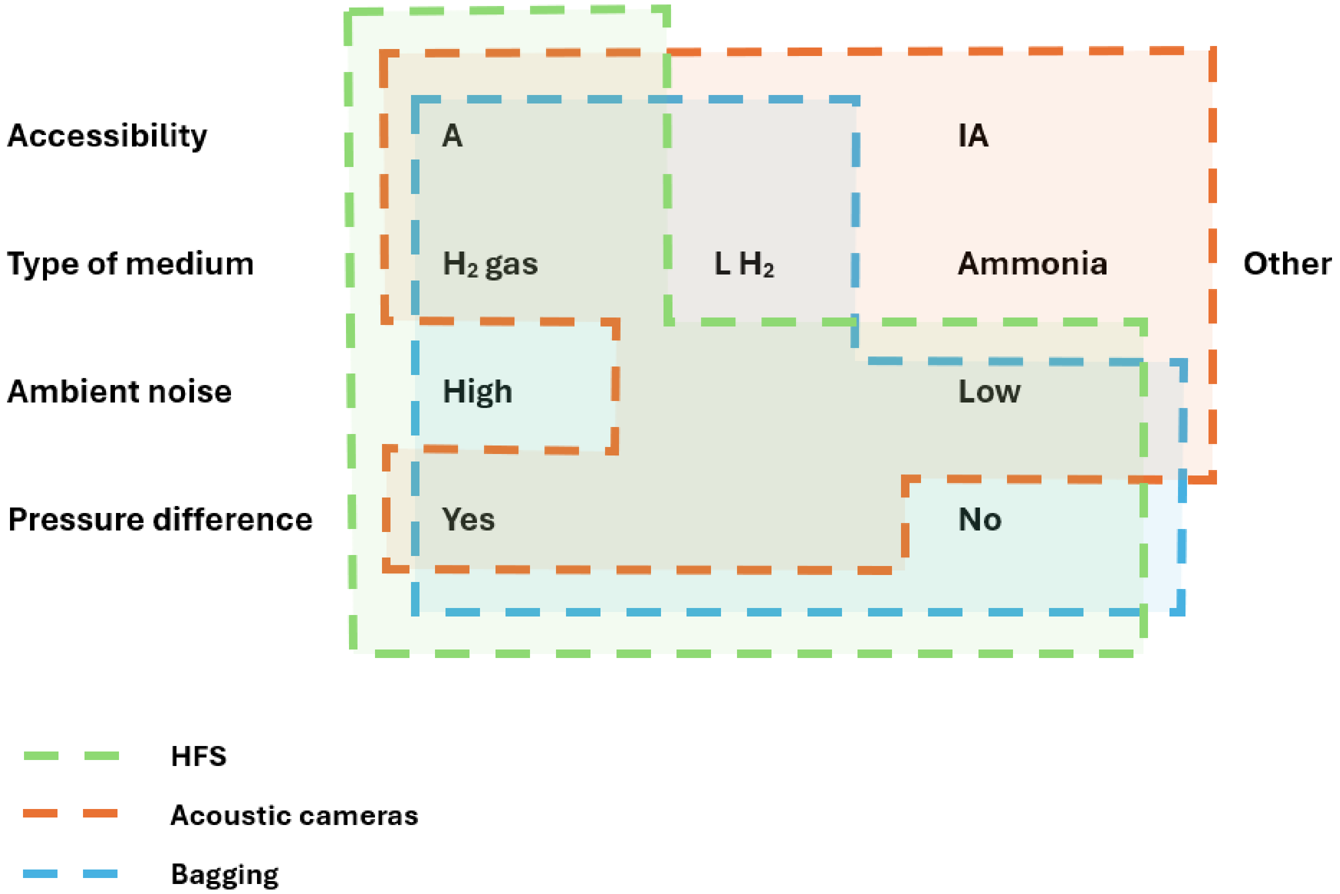
Figure 2. Application of hydrogen leak detection methods



In case of leak quantification, the best available technique is the HFS method. Bagging can also be used as a measuring technique but due to its longer response time and more complicated application on leaking element, it is recommended as a secondary method. Acoustic imaging is only recommended in inaccessible places due to its limitations and often increased lower detection limits.

Figure 3 highlights the recommended quantification techniques for hydrogen leaks, showing their comparative feasibility and effectiveness depending on site-specific challenges and leak characteristics.

Figure3. Application of quantification methods



In scope of measurement in whole value chain of hydrogen selected methods can be applied to most of the operational stages. But some of the methods are more feasible in relation to specific stages than others.

The summary table outlines the most appropriate detection and quantification methods across each stage of the hydrogen value chain, linking specific assets and subprocesses with the techniques best suited to their technical requirements.

Summary Table

Value Chain Stage	Subprocess / Asset	Detection Methods	Quantification Methods	Notes
Production	Fossil-based (SMR, coal gasification)	Portable gas detectors	High Flow Sampler (HFS)	Risk of gas interference; sensor selectivity important
	Electrolysis, photo-electrocatalysis, etc.	Portable gas detectors Acoustic Imaging	HFS (preferred), Bagging	Compact layout favors acoustic imaging
Conversion	Compression	Portable gas detectors Acoustic Imaging	HFS (preferred), Bagging	High pressure systems; precise localization important. High ambient noise disqualifies acoustic imaging
	Liquefaction	Portable gas detectors Acoustic Imaging	HFS, Bagging	Cryogenic temps limit detection options
Transportation	Pipelines (above-ground)	Portable gas detectors Acoustic Imaging	HFS (preferred), Bagging	Underground sections not directly measurable.
	Tube Trailers	portable gas detectors Acoustic Imaging	HFS	Detection during maintenance and depot checks
	LH_2 Tankers	Portable gas detector acoustic imaging	HFS	Cryogenic interfaces only
	Metal Hydride Systems	Not typically applied	Not typically applied	Low leakage potential; quantification rarely required.

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Storage	Above-ground tanks (I-II, LH_2, Metal hydr.)	Portable gas detectors Acoustic Imaging	HFS (preferred), Bagging	Acoustic imaging supports rapid inspection
	Geological storage	Not applicable	Not applicable	No direct detection/quantification possible
Reconversion	Compression	Portable gas detectors Acoustic Imaging	HFS	Similar risks as original compression
	Regasification (from LH_2)	Acoustic Imaging	HFS, Bagging	Low temp limits use of other methods
	LOHC, NH_3, MeOH Cracking	portable gas detectors (with selectivity)	HFS	Interference from other gases requires hydrogen-selective detection
End Use	Industrial Processes (refineries, etc.)	portable gas detectors Acoustic	HFS	High background gas – sensor selectivity crucial
	Thermal (residential & industrial heat)	portable gas detectors	HFS	Low leak risk, still requires inspection
	Transport (HRS, vehicles, e-fuels)	portable gas detector, Acoustic Imaging	HFS	Especially critical for refueling systems
	Electricity Generation (fuel cells, turbines)	portable gas detectors Acoustic Imaging	HFS	Full range of methods applicable based on setup

5. Safety Considerations for Hydrogen Leak Detection

The increasing integration of hydrogen in industrial processes driven by decarbonization goals and the shift towards alternative energy sources introduces a distinct set of safety challenges [23-25]. Hydrogen's physicochemical characteristics, such as its extremely low minimum ignition energy, wide flammability range, and high diffusivity, demand heightened caution during all phases of its handling, particularly during leak detection activities.

From a safety standpoint, hydrogen presents a distinct set of hazards when compared to more commonly handled gases such as methane. Although both are flammable, hydrogen's flammability range (4–77%) is significantly broader than that of methane (5–15%), and its minimum ignition energy is approximately an order of magnitude lower, making it far more prone to ignition from static electricity or mechanical sparks [26-27]. In the event of a leak, hydrogen's very low molecular weight and high diffusivity cause it to disperse much more rapidly and rise more aggressively than methane, which, while also lighter than air, tends to accumulate more locally before dispersing. As a result, hydrogen can reach ignition sources located at higher elevations in a shorter time frame, increasing the urgency of detection and ventilation. Furthermore, hydrogen can autoignite when escaping from pressurized containers as ultrasonic leak jets, due to the shock wave pressure gradient – even at low temperatures. This autoignition risk is especially pronounced in high-pressure systems. Additionally, hydrogen flames are nearly invisible in daylight, posing further detection and response challenges during an incident. These properties require stricter engineering controls, optimized gas detection strategies and the use of specialized PPE, emphasizing that hydrogen should not be treated merely as a drop-in replacement for methane or natural gas, but as a fuel with its own distinct and complex risk profile.

Personnel involved in hydrogen leak detection must undergo comprehensive training, tailored to the specific hazards associated with hydrogen and the environments in which it is used. This includes, at minimum, understanding the behavior of hydrogen in air, the relevance of flammability and explosive limits (LFL/UFL vs. LEL/UEL), and the significance of factors like autoignition temperature and gas density. Operators must be able to perform task-specific risk assessments that incorporate both hydrogen-specific properties and the broader hazard context of the site — including the presence of other flammable or toxic gases (e.g., ammonia, hydrogen sulfide, methane).

Compliance with regulatory frameworks is paramount. In the European context, adherence to the ATEX directives [2014/34/EU for equipment, 1999/92/EC for workplaces] is mandatory, while in other jurisdictions, national equivalents apply. All equipment used in hazardous zones—gas detectors, photographic tools, mobile devices, etc. — must be intrinsically safe and appropriately certified (ATEX, IECEx, UL), and explicitly permitted for use in the inspection area.

Appropriate selection and use of Personal Protective Equipment (PPE) form another pillar of hydrogen safety. PPE should be antistatic, flame-retardant, and compliant with relevant standards (e.g., EN 1149, EN ISO 11612 for clothing; EN ISO 20345 for footwear; EN 166/EN ISO 16321 for eye protection). Furthermore, operators should carry personal hydrogen gas monitors to ensure real-time exposure awareness. Given that many industrial sites where hydrogen is used are also multi-hazard environments, PPE selection should be informed by a thorough site-specific hazard identification and may require additional respiratory or chemical protection measures.

Operational protocols must include strict controls over the scope of work — no mechanical intervention (e.g., tightening flanges, adjusting connections) should occur without explicit authorization, proper training, and inclusion in an approved work plan and risk assessment. Leak detection work is typically subject to permit-to-work systems managed by site operational teams, and full compliance with permit conditions is mandatory.

Preparedness for emergency situations must be proactive and systematic. All personnel should be thoroughly familiar with site-specific emergency protocols, including the location of evacuation routes, the function and meaning of alarm signals, and the chain of communication during an incident. Regular drills and scenario-based training should be conducted to ensure rapid and coordinated response in high-risk environments where hydrogen-related incidents may escalate quickly.

To support detection reliability and decision-making, operators should be familiar with hydrogen detection and sensor technologies (e.g., catalytic, thermal conductivity, electrochemical, metal oxide), their operational principles, and known limitations, such as susceptibility to poisoning from certain toxic gases. Basic knowledge of gas network infrastructure — including common fittings, materials, and typical failure points — further enhances situational awareness and facilitates accurate source identification.

Finally, alternative detection methods (e.g., bubble screening method) may serve as valuable complements to portable handheld gas detectors, especially while performing leak monitoring in complex or high-interference environments.

In conclusion, safe hydrogen leak monitoring is not solely a matter of using the right tools, but of cultivating a deep understanding of the gas behavior, rigorously applying standards and procedures, and embedding safety into every step of the process — from training and planning to execution and emergency response. As hydrogen adoption grows, ensuring personnel are prepared for its unique risks will be essential for operational integrity and worker safety across industrial sectors.

5. Conclusions

For leak detection, no single optimal method can be identified. All mentioned methods are characterized by various advantages and disadvantages, which means that, depending on the measurement conditions, different methods may be optimal. However, using portable gas detectors is the more convenient option for hydrogen leak detection in most of the described scenarios.

Carrying out tests in laboratory leak simulated conditions is the next stage that will further confirm the scope of application of individual methods, their performance under defined conditions and their susceptibility to environmental and operational conditions (including humidity and temperature).

As for leak quantification methods, it can be said that among the methods selected for the project, the High Flow Sampling method is the preferred choice, as the acoustic imaging method has many limitations related to both atmospheric and process conditions at various installations, which make it difficult or even impossible to carry out a reliable measurement and obtain a relevant hydrogen leak quantification result. However, this complementary technology is really useful for detecting large leaks from a safe distance, including inaccessible places otherwise outside of the scope of the leak survey, and in some cases providing comparative estimations of the size of the leak rates (at least indicating the order of magnitude).

For both leak detection and quantification methods, it is necessary to conduct tests not only in laboratories but also through controlled releases and on industrial installations under real operating conditions to validate the methods and confirm the relevant metrological parameters.

Abbreviations

EPA	Environmental Protection Agency
HFS	Hi Flow Sampling
LDAR	Leak Detection and Repair
LEL	Lower Explosive Limit
LOHC	Liquid Organic Hydrogen Carriers
LOQ	Limit Of Quantification
LH_2	Liquid Hydrogen
MOS	Metal-Oxide-Semiconductor sensor
NG-H_2	Natural Gas and Hydrogen mixtures
TCD	Thermal Conductivity Detector
TRL	Technology Readiness Level

Glossary

Accuracy - Closeness of agreement between a measured quantity value and a true quantity value of a measurand [28].

Calibration – An operation that, under specific conditions, establishes a relationship between the quantity measured (with its uncertainty) and a traceable measurement standard (with uncertainties) [28].

Component – an entity that forms part of a process or system, e.g., flange, valve, connection.

Detector - device or substance that indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded [28].

Fugitive emission – emission to the atmosphere caused by loss of tightness of an item which is designed to be tight [EN 15446:2008].

LDAR – Leak Detection And Repair, typically referred to the schemes used in the industry.

Leak - the unintentional release of hydrogen from equipment used in value chain [OGMP2.0].

Limit of quantitation/ Lower Limit of Quantification (LOQ) - The smallest volumetric flow rate of hydrogen emissions that can be determined by a given method with a specified, acceptable uncertainty,

Lower Explosive Limit (LEL) – gas lowest concentration in air at NTP (normal temperature and pressure) that will burn or explode if ignited. Below this concentration the gas cannot explode because there isn't sufficient fuel.

Passive Detector - portable handheld hydrogen detector equipped with a hydrogen sensor operating by diffusion.

Sensor - An element that is directly affected by the phenomenon, body, or substance carrying the quantity to be measured [28].

Selectivity – the ability of the gas sensor or detector to differentiate a target from other gases, i.e. to produce signals or readings related only to the target gas even in the presence of other gases.

Sniffer - portable hand-held hydrogen detector equipped with a pump that sucks in gas, which is directed to the hydrogen sensor

Handheld portable gas detector – for the sake of this document both sniffers and passive detectors are categorized as such

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Annex

Annex 1 Leak detection method using portable gas detectors and acoustic cameras: Hydrogen leaks generated from equipment and pipes (component scale)

Annex 2 Fugitive emissions quantification using the High Flow method: Hydrogen leaks generated from equipment and pipework (component scale).

PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

Annex 1

Leak detection method using portable gas detectors and acoustic cameras: Hydrogen leaks generated from equipment and pipes (component scale)

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0.2		Preliminary reviews	NHyRA Consortium
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0.4	17/05/2025	Chapter on hydrogen leak detection using acoustic cameras was added	Haydn Barros / NPL

CONTENTS

1. Introduction

In this document a method to detect and localize fugitive hydrogen gas emissions at component scale is proposed. This document uses the terms leak and fugitive emission interchangeably (although they are defined separately). The method is based on current available technology.

The use of hydrogen in large scale industrial infrastructure introduces exigent tightness requirements due to two primary reasons: firstly, its smaller molecule size facilitates easier flow through defects or sealing materials, and secondly, its higher risk means that even small gas leaks pose increased hazards, due to its low ignition energy, broad flammability range and higher explosivity. On the other hand, it is needed near 3 times the volume of hydrogen as compared to natural gas to get the same amount of energy, then hydrogen is stored at high pressure (200-1000 bar) increasing then the risk of leaks.

The method described focuses on the effective use of portable (handheld) hydrogen leak detectors, particularly within hydrogen and hydrogen-enriched natural gas networks. It outlines the fundamental principles and practices for leak detection and location using this technology, emphasizing the importance of clear procedures and safety measures, by providing detailed instructions and insights into the detection process. The guide aims to standardize leak detection procedures, reducing human error and enhancing overall efficiency. It covers essential topics such as use of portable leak detectors, safety precautions, and specific procedures for hydrogen leak detection. It discusses various issues such as equipment maintenance and personnel training. Through comprehensive guidance, this document aims to ensure the safe and effective monitoring of gas leaks to inform management schemes in industrial settings.

A portable detector is used to detect potential hydrogen leaks from individual components. Any detector type is allowed, provided it meets the specifications and performance criteria contained in this method. This method is intended to identify and locate hydrogen leaks during manual monitoring using portable instruments and devices. There is a separate chapter in leak detection and localization using acoustic imaging (also called ultrasonic acoustic cameras), which is a relevant method that is complementary to the leak detection method using gas detectors. The method described in this document is for use in surveys performed solely to detect leaks and localize the leaks, or for Leak Detection And Repair (LDAR) campaigns.

This method does not include other instruments used for leak detection such as detectors used in stationary or mobile platforms, individual and/or sensor networks, although they can also be used for hydrogen leak monitoring.

The leak detection and the localization of the leak source is required to quantify the corresponding emission rates (or leak rates), that is why leak detection is considered as the first step in the hydrogen emissions monitoring strategy. However, this method alone is not intended to be used for emission quantification purposes. The fugitive emissions quantification (leak rate quantification) is covered in a separated document.

2. Scope of application

This method is of common concern to industrial sectors related to hydrogen production, transmission, distribution and end-use. The aim is to develop methods suiting the needs of the industry and the regulatory bodies, while helping to reduce the risks and the environmental impact.

For practical reasons the two developed methods, one for hydrogen gas leak detection and other for hydrogen gas leak rate quantification, are published as two separate methods. This technical document covers only the leak detection of hydrogen (detection of fugitive emissions at component scale). The method is based on specific procedures using gas detectors having either passive detectors or having sampling pumps (sometimes called “sniffers”). The main scope is to identify and localise hydrogen gas from fugitive emission generated from equipment and piping leaks.

This method applies to the manual detection of fugitive emissions of hydrogen from process equipment, it specifically refers to individual equipment or parts of these, which is called leak detection at component scale. It specifically addresses gaseous hydrogen in its molecular form, H_2. The method can be applied to periodic inspections carried out at component scale; and can be used in Leak Detection and Repair (LDAR) schemes or in any other situation requiring the detection of hydrogen gas leaks. This method considers only above ground fugitive emissions (i.e. underground or underwater leaks are not considered in this procedure).

The leak sources considered here include, but are not limited to, valves, flanges and other connections, pressure relief devices, process drains, open-ended lines, pump and compressor seal systems, electrolysers, agitator seals, access door seals, welding seams, and pipes suspected under fatigue, excessive mechanical stress or even corroded. This method covers leak detection in all parts of the hydrogen value chain where pure hydrogen or a mixture containing hydrogen is present.

The main hydrogen gas leak detection method discussed here is based on screening, an action which relies on the measurement of the gas concentration resulting from the escaping gas blended with the atmospheric air near the leak source. The concentrations are measured with a portable instrument (passive or pumped). Detecting leaks in components requires direct access to the components being checked.

The scope of this method includes only the detection of hydrogen leaks at component scale. This method also includes the data processing and the generation of the corresponding leak detection report. This method is based on metrological principles to improve the reliability of results.

Screening is carried out around components that are potential leak sources, as it is done for natural gas [EN 15446:2008]. However, the present document does not define a screening value (a threshold concentration indicating that a leak is present), since it depends on the scope and the specific features of the site and equipment being monitored.

This method does not prescribe the number of potential emission points that should be screened nor the frequency at which these points should be screened. The sampling strategy shall indeed take into account the plant characteristics, the safety aspects, and the required level of control over fugitive emissions.

Acoustic imaging methods currently available can help to ease the detection of gas leaks in plants and the use of this technology in conjunction with the present method is advisable and therefore a section on this topic is described in the present document (Section 8). In any case, measurements have to be performed according to the requirements of this method.

In summary, this document aims to:

- Provide information about leak detection procedures with portable gas detectors of hydrogen (and additionally aided with acoustic ultrasonic cameras).
- Give an overview of the potential risks faced when performing H_2 gas leak detection.
- Standardize hydrogen gas leak monitoring methods to enable proper identification and location of fugitive emission sources, reducing the human factor.

3. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies. The present method is related only to parts of the content included within these reference documents.

BS EN 15446:2008. Fugitive and diffuse emissions of common concern to industry sectors -Measurement of fugitive emission of vapours generating from equipment and piping leaks.

ISO 5725-2, Accuracy (trueness and precision) of measurement methods and results - Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method (ISO 5725-2:1994 including Technical Corrigendum 1:2002).

4. Terms and definitions

For the purposes of this document, the following terms and definitions apply.

Accuracy – Closeness of agreement between a measured quantity value and a true quantity value of a measurand [6].

Autoignition temperature – minimum temperature required to ignite a gas or vapor in air without a spark or flame being present.

Calibration – An operation that, under specific conditions, establishes a relationship between the quantity measured (with its uncertainty) and a traceable measurement standard (with uncertainties) [6].

Calibration precision – degree of agreement between several measurements of calibration gas with the same known concentration. It is the ratio of the average absolute value of the difference between the meter readings and the known concentration to the known concentration, expressed in percent [EN 15446:2008].

Component – an entity that forms part of a process or system, e.g., flange, valve, connection.

Component scale – the level of detail related to the components; it refers to the component itself and is related to an approximate spatial scale of centimetres to metres [OGMP2.0].

Detector – device or substance that indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded [6].

Detection limit / Lower Limit Of Detection / Limit Of Detection (LOD) - The lowest measurand value (i.e. concentration or signal) that is used to infer the presence of a leak, (such as a signal produced by a detecting device) and which can be reliably detected with a sufficient degree of confidence [7].

Explosive concentration range – concentration which covers from LEL to UEL of the specified gas.

Flammable concentration range – concentration which covers from LFL to UFL of the specified gas.

Fugitive emission – emission to the atmosphere caused by loss of tightness of an item which is designed to be tight [EN 15446:2008].

Hydrogen calibration gas – a gas mixture whose hydrogen amount fraction have been validated [EN ISO 14532:2017].

LDAR – Leak Detection And Repair, typically referred to the schemes used in the industry.

Leak - the unintentional release of hydrogen from equipment used in value chain [OGMP2.0].

LOD - Limit Of Detection, Lower Limit Of Detection or Detection limit (defined above).

Lower Explosive Limit (LEL) – gas lowest concentration in air at NTP (normal temperature and pressure) that will burn or explode if ignited. Below this concentration the gas cannot explode because there isn’t sufficient fuel.

Lower Flammable Limit (LFL) – gas lowest concentration in air at NTP (normal temperature and pressure) that will produce a flash of fire when an ignition source (heat, arc or flame) is present. Below this concentration the gas cannot ignite because there isn’t sufficient fuel.

Measurand - The physical quantity subject to be measured [6].

Monitoring - A generic term used to describe the estimation, measurement, location and/or detection of gas emissions.

The Minimum Ignition Energy (MIE) – minimum electrical energy which, when discharged, is sufficient to ignite the most ignitable mixture of a fuel in air under specified test conditions. It is a measure of how sensitive an explosive is to electrical spark ignition. It gives guidance on whether ignition by electrostatic discharge from plant personnel or process conditions is likely to occur in practice.

Response factor – ratio between the actual concentration of the target gas (H_2 in this case) in the measured sample and the observed instrument reading. This is particularly important in the case of detectors devised for flammable gas (not specific for hydrogen). If used, the response factor should be determined accordingly with the indications provided in this method. The response factor shall be used to correct the direct meter readings to obtain the corresponding values for the target gas (hydrogen). This correction accounts for differences in response between hydrogen and the gas used for calibration.

Response time – time interval from a step change in gas concentration (using a reference gas) at the input of the sampling system to the time at which 90 % of the corresponding final value is reached as displayed on the instrument readout meter [EN 15446:2008].

Sampling Strategy - describes how the measurement is collected and represented, and the platform used [7].

Sensor – An element that is directly affected by the phenomenon, body, or substance carrying the quantity to be measured [6].

Screening – action of measuring the concentration in the target gas at the interface of a potential leak source.

Screening value – local gas concentration at the surface of a leak source that indicates a gas emission is present. It must be a value above the Limit of Detection (LOD) of the used instrument.

Selectivity – the ability of the gas sensor or detector to differentiate a target from other gases, i.e. to produce signals or readings related only to the target gas even in the presence of other gases.

Sensitivity - The ratio of the change in the measured value to the corresponding change in the value of the quantity being measured [6].

Source level – detection of emissions at the level of a process component or device that releases hydrogen into the atmosphere intentionally or unintentionally, periodically or continuously [OGMP2.0]. This is related only to the spatial scale.

Threshold concentration – pre-set performance target for the individual sources [EN 15446:2008]

Uncertainty - A non-negative parameter which characterises the dispersion of measurement results attributed to a measurand [6].

Upper Explosive Limit (UEL) – gas highest concentration of a gas in air at NTP (normal temperature and pressure) that will burn or explode if ignited. At this concentration the gas cannot explode because there isn't sufficient air (i.e. insufficient O_2).

Upper Flammable Limit (UFL) – gas highest concentration of a gas in air at NTP (normal temperature and pressure) capable of producing a flash of fire when an ignition source (heat, arc or flame) is present. At this concentration the gas cannot ignite because there isn't sufficient air (i.e. insufficient O_2).

Zero gas - Gas recommended by the manufacturer, which is free of the target gas and contaminating substances, the purpose of which us calibration / adjustment of the equipment zero reading [8]

5. Before starting leak detection

5.1 Safety precautions

- Staff performing the leak detection survey must have appropriate training about the hazards present on the environment they will be working in. This should include training on working in explosive atmospheres. Within the EU, this topic is covered by the ATEX (ATmosphères EXplosibles) directives on equipment [2014/34/EU] and workplaces [1999/92/EC].

- Additionally, staff performing the leak detection survey must have a basic knowledge on safe work with pressurised gas cylinders and transporting gas cylinders by road if needed.

- Operators should also be aware of applicable national regulations on explosive atmospheres for the country that they are working in (such as UK's the Dangerous Substances and Explosive Atmospheres Regulations, DSEAR).

- Operators must understand the concepts of Lower and Upper Flammable Limits (LFL & UFL) and flammable range, as well as the concepts of Lower and Upper Explosive Limits (LEL & UEL) and explosive range. It is worth noting that for hydrogen those values are different (see Table 1), and historically for natural gas and methane the flammable limits have been often called explosive limits.

- Any used detector, personal safety monitor, equipment, photographic camera, tablet or mobile phone must work within the conditions of the work permit, complying to the applicable standards, such as UL, ATEX, or IECEx certifications for equipment used in explosive atmospheres. They should be authorized for use in the inspected areas.

- Operators should also be familiar with other concepts such as gas density (and how it impacts on the gas buoyancy in air), autoignition temperature and minimum ignition energy, all these should be considered when risk assessing work with hydrogen and/or different fuel gases.

- The relevant characteristics are listed for methane and hydrogen in Table 1.

Table 1 – Some methane and hydrogen gas characteristics

Parameter	Methane	Hydrogen
Relative density (to air)	0.55	0.07
Molecular mass, g/mol	16.04	2.016
Kinetic diameter, pm	380	289
Diffusion coefficient (in air), cm^2/s	0.21	0.756
Absolute Viscosity, 10^{-5} Pa s	1.1	0.9
Flammable range (in air, 21% O_2), v/v	4.4 – 17 %	4 – 77 %
Explosive range (in air 21% O_2), v/v	No information	17 – 56 %
Stoichiometric fraction (in air), v/v	8 %	29 %
Minimum ignition energy, μJ	525	19
Autoignition temperature (in air, 21% O_2), ºC	600	560
Flame temperature (in air, 21% O_2), ºC	1937	2127
Flame velocity, cm/s	36	255

Note: Many of these values refers to 20 °C and 1 atmosphere pressure [EN ISO 80079-20:2019].

- Do not attempt to make any changes to suspected parts, such as tightening connections or fastening flanges unless you have (written) authorization, training and that task is among the duties, and included in the work plan and Risk Assessment.

- To mitigate the risks of ignition of flammable gases, and to protect the operator should ignition occur, it is critical to select the correct Personal Protective Equipment (PPE):

- Footwear – footwear should be antistatic/electrostatically dissipative, confirming to standards such as: EN ISO 20345
- Clothing – the outer layer should be antistatic and flame retardant, conforming to standards such as: EN 1149, EN ISO 11612
- Eyewear – to provide protection to eyes in the event of fire or explosion and ejected particles, conforming to standards such as: EN 166, EN ISO 16321
- Individual personal safety monitor specific for hydrogen gas

- Sites where fugitive emissions of flammable gases may occur are likely to be multi-hazard environments, where the presence of flammable gases is only one risk to the operator of emission monitoring equipment. The list of PPE above is not exhaustive, and operators should consider other appropriate items of PPE as part of developing a risk assessment for the task that identifies all significant hazards present on the site.

- Verify the possible presence of other flammable (e.g., natural gas) or toxic gases (e.g., ammonia, carbon monoxide) and consider them accordingly in your risk assessment. Also, remember that many detectors can also suffer from poisoning in the presence of toxic gases, causing degradation in detector response.

- Obtain the necessary permissions required to access all areas and follow all the safe and safety rules in place. If working on a controlled site, the work is managed by an operational team that authorises the emissions monitoring via a permit scheme; the conditions of the work permit and the associated risk assessment must always be followed.

- In the event of an incident or emergency occurring, follow the instructions provided to you in your site induction regarding reporting situations to the site controller, and the appropriate response to site alarms, such as the process for site evacuation.

- Familiarize yourself with emergency procedures in case of hazards, including evacuation routes and contacting appropriate authorities.

- Personal performing the leak survey should also have other training like the following:

- Familiarization with alternative methods of leak detection and tightness testing, as the snoop liquid leak detection, which can be used as a complementary method
- Basic knowledge on hydrogen sensor technologies, particularly those employed on the used detector
- Knowledge of gas distribution networks, including common equipment and fittings. Understanding of sealing techniques and common mechanical failures

5.2 Preparation before use of equipment

The following checklist provides additional items to check before using a hydrogen gas detector for leak detection. The listed items are essential for a correct operation of the gas detector (called also leak detector).

- Familiarize yourself with the manufacturer’s instructions for operating the detector
- Ensure batteries are fully charged, and spare ones are included for uninterrupted operation
- Ensure that certified or calibrated gas mixtures are available to test the detector at any time before, during or after monitoring
- If applicable, have a spare replaceable sensor and knowledge of how to replace it in case of need
- Develop a clear plan defining what to test and where to start to ensure efficient testing procedures

5.3 Detector maintenance

- Some leak detectors often have a filter at the probe end. Inspect this filter regularly and replace it if necessary. In the case of detectors equipped with sampling pumps the pumping efficiency could be compromised, and in the case of passive detectors clogged filters could prevent the gas reaching the internal sensor.

- In instances of sensitivity loss, replacing the sensor should be contemplated, for those detectors allowing users to replace it by themselves, following the manufacturer's guidelines. It is advisable to keep a spare sensor on hand for swift replacement when necessary. Some sensors degrade faster when exposed to a high concentration of hydrogen.

- For detailed instructions on maintenance and cleaning, refer to the manufacturer's manual.

- Verify the batteries charge and conditions before the survey (daily if possible).

- It is advisable to maintain a record of the usage of leak detectors to facilitate monitoring the lifespan of components, such as the batteries and the sensor itself, for timely assessment.

6. Detection equipment for hydrogen leak detection and location

6.1 Specification for hydrogen detectors

To perform the leak detection and location, hydrogen detectors with the following characteristics are required:

- The gas detector shall respond to the hydrogen gas. The sensor types used in the detector (instrument) include, but are not limited to, catalytic oxidation, semiconductor, electrochemical, metal oxide (MOX), and palladium alloy. Most of these detectors respond to flammable gases, so cross sensitivity and response factors must be considered for any detector no selective for hydrogen
- The gas detector response shall be linear with the hydrogen concentration in the range of interest. The lower detection limit declared by the manufacturer should be lower than the concentration threshold used during the survey (if any)
- Minimum measurement range should be up to 4000 µmol/mol or ppm (0,4% v/v), which is 10% of the Lower Flammable Limit for hydrogen

- Instrument shall conform with the conditions of the work permit and the applicable standards. They shall be authorised for use in the inspected areas, considering the corresponding zone classification (as zones 1, 2, etc.) and the specific gas group for the gas (or gases) potentially present.
- If a gas detector with a sampling pump is used, the device should be able to provide a nominal sampling flow rate between 0,2 L/min to 1,2 L/min
- If a passive detector is used, equipped with a sensor located at the end of the sampling probe
- In both cases, the instrument shall be equipped with a probe or probe extension with a maximum outside diameter of 6,4 mm, with a single end opening exposed to the gas being scrutinised

6.2 Performance criteria

Detectors used for leak detection should meet performance criteria related to response time and calibration precision.

Response time

The response time specified on the instrument configuration used for leak detection must be equal to or lower than 5 seconds. Determination of response time is required:

- before a new device is put into service for the first time
- if a modification to the sampling system has been made that would change the response time
- If any unusual delay or behaviour is noticed in the detector response

Determination of response time is performed as follows:

- **Step 1:** Introduce zero gas into the instrument's measuring probe
- **Step 2:** When the meter reading stabilizes, quickly switch to the specified calibration gas
- **Step 3:** Measure the time from switch to when 90% of the calibration gas value is reached
- **Step 4:** Perform the sequence of steps 1-3 three times
- **Step 5:** Calculate the average response time

Calibration precision

The calibration precision of the instrument used for leak detection must be lower or equal to 10 % of the calibration gas value. Calibration precision test shall be completed prior to placing the instrument into service, and it shall be performed with the frequency recommended by the manufacturer,.

Determination of calibration precision is performed as follows:

- **Step 1:** Measure hydrogen content of zero gas
- **Step 2:** Measure hydrogen content using the specified calibration gas and record the reading after the response time
- **Step 3:** Perform the sequence of steps 1 and 2, three times
- **Step 4:** Calculate the arithmetic mean difference between the meter readings and the known value from the calibration gas certificate
- **Step 5:** Divide this mean difference by the known calibration value and multiply by 100 to express the final calibration precision as a percentage

Calibration gases

Gases required for monitoring and instrument performance evaluation are:

- Zero flammable or explosive gas (dry air containing less than 10 ppm H_2)
- A certified reference gas mixture being a mixture of hydrogen in air with a known/certified H_2 concentration. Here concentration refers to the amount fraction

The diluent for the Hydrogen reference gas mixture must be dry air (synthetic air) because most detectors require oxygen for a proper functioning, and also to reproduce the conditions of a leak detection survey (done in air, with around 21 % O_2. Note that the molar fraction (% mol/mol) is the same as the volume fraction (% vol/vol) at usual atmospheric pressure and temperatures (ideal gas approximation).

It is recommended to use two certified reference mixtures with a hydrogen content of approximately 25% and 75% of the measuring range of interest.

The expanded uncertainty (k=2) of the calibration gas mixture should not be worse than +/- 2% (%mol/mol or vol/vol) with respect to the used reference value, and a shelf life should be certified for each used gas cylinder.

7. Procedures

7.1 Preparation

- **Step 1:** At the beginning of the instrument performance evaluation test, assemble and start up the instrument according to the manufacturer's instructions for the recommended warm-up period and preliminary adjustments.
- **Step 2:** Perform the instrument response time test and calibration precision test provided in Section 6.2 when required. This evaluation shall be performed at first use and after instrument maintenance.

7.2 Check and adjustment

- **Step 1:** Start the device according to the manufacturer's instructions, performing all required startup actions (e.g. warm-up period, internal zero calibration procedure, airtight control)
- **Step 2:** Introduce the calibration gas with the highest concentration into the gas detector sample probe and, if needed, calibrate the instrument according to the manufacturer instructions.
- **Step 3:** Check the instrument with the calibration gas with the lower concentration. If the reading is within 10 % of the calibration gas concentration, the check is accepted. Otherwise, the check procedure needs to be restarted, or corrective action is required.
- **Step 4:** If the corrective actions (change filters, replace batteries, restart the instrument, etc.) does not work, a malfunction of the analyser is indicated, and major corrective action (e.g. servicing the equipment) and check revaluation (Steps 1 to 3) should be successfully undertaken before use.

The detector check according to the points above should be carried out at least twice a day, first before starting the measurements and the secondary check should be carried out after the last measurement. If the checks are carried out during the day and it is found that the reading deviates from the calibration gas concentration by more than 10%, the instrument should be adjusted and the leakage should be rechecked, discarding the values obtained after the last correct check.

7.3 Manual survey of individual components for leak detection: Scope of survey.

- This method considers only above ground fugitive emissions (i.e. underground or underwater leaks are not considered).

- Hydrogen leak detection involves identifying the presence of a leak. In this method it is done by detecting the target gas (hydrogen) in the vicinity of the leak source. In practice, the detection is based on a threshold concentration that is above the detection limit. This document is focused on the measurement of a concentration, although no concentration threshold for general use is given.
- All the components which can be regarded as potential leak sources shall be screened. This refers to equipment or components in process service, it means they have internal positive (> 1 atmosphere) pressure of hydrogen gas or other gas mix containing hydrogen.
- General practice is also to exclude: components not accessible, components for which monitoring would require some dismantling, e.g., of insulation, and components for which monitoring could entail safety issues. If this is the case, if possible, it is advised to report the type and number of equipment not included in the survey.
- Items under vacuum are also excluded (emissions from items under vacuum are non-existent).
- Avoid performing leak detection surveys under extreme ambient conditions. At very low temperatures, material contraction may occur, potentially suppressing or altering the leakage, thus complicating its assessment. Moreover, the presence of rain, snow, or high moisture concentration can hinder the accurate detection of exposed leaks, compromising their evaluation. Work always within the range of working conditions specified by the detector manufacturer.

7.4 Screening procedure for hydrogen leak detection

- **Step 1:** Check that there is no explosive atmosphere at the measurement site.
- **Step 2:** Check that the weather conditions allow the use of the detector for measurement, it must not rain so as not to flood the detector, and the air temperature and relative humidity should be consistent with the operating range of the device used. In the case of detectors having an internal pump, usually it can be turned off (without turning of the instrument) when not needed to extend the use of battery.
- **Step 3:** Determine the background concentration of hydrogen placing the probe inlet in a point which is far (as possible) and upwind of any equipment potentially producing gas leaks. Repeat this at least in three different places within the area to be inspected.

The background is more relevant in closed spaces and areas with limited ventilation. The background reading must be above the LOD to be considered as a significative value. Record the background levels (if any).

- **Step 4:** Determine whether the detector reading is affected by ambient humidity (moisture). If the reading is less than 5% of the values obtained for hydrogen leaks, then do not apply any correction. Otherwise, if possible, evaluate if the response to humidity is systematic, and take this into account to correct back the instrument readings.

For some instruments it could be enough to subtract the reading produced by the humidity, for other detectors it may be better the use of specific response factors.

- **Step 5:** When screening a potentially leaking component, place the probe inlet at the surface of the point of component where leakage could occur.
- **Step 6:** Move the probe slowly along the component periphery while observing the instrument readout.

All the surface points potentially leaking must be inspected. This scanning process should be slow enough to allow the dragging of the sampled gas inside the detector. WARNING: If the screening speed is too fast, then the amount of leaked gas introduced in the detector system will be low, and there is a higher risk of not detecting and existing leak.

- **Step 7:** If an increased meter reading is observed, slowly sample the component where leakage is indicated until the maximum meter reading is obtained.

Due to the low molecular weight of hydrogen and its ease of diffusion, the maximum hydrogen content in atmospheric air should be expected above the leaking element. However, the local wind is largely impacting the transport of the leaked hydrogen, making difficult to predict the gas distribution even near the leak source.

- **Step 8:** Leave the probe inlet at this maximum reading location for at least twice the instrument response time, record the result (maximum values) as the concentration assigned to the detected leak. Record the values using the units shown in the equipment display (if needed, units' conversion should be worked out later).

Measured maximum values are more reliable than averages values since wind and diffusion could dilute further the leaked gas plume, but it is not possible to concentrate the gas, so overestimations of the measured concentrations can't happen.

Care should be taken to minimize the effect of the wind, particularly when the wind speed exceeds 0,5 m/s, and when working in elevation. In these cases, wind barriers may be employed to limit its impact on the areas being scanned. If the value is rapidly changing (variable results could be observed due to local wind and other factors), then take the maximum value and include a note reporting this behaviour (i.e. fluctuating value).

In some cases, the probe tip could be coincidentally located on top of the leak source producing high concentration readings, even if the leak rate is not necessarily large. For some detector types, care should be taken to not exceed the upper measuring range of the detector, as this may lead to its poisoning. If the measured hydrogen concentration at the leak location increases rapidly to a value close to the upper measurement range, the measurement should be terminated. In such a case, the measurement result is assumed to be higher than the upper limit, the measured concentration value should be reported as > the upper limit for the equipment.

After detecting a leak, take some measurements far from the equipment being assessed and be sure that the instrument readings have returned to zero (or to background levels) before attempting to search for more leaks. Take the necessary time until the measured value returns to the commented low level (certain detector types require more time than others, especially if they were exposed to high hydrogen gas concentrations).

7.5 Typical leak components and locations to be screened

Amongst the components/locations where this leak detection procedure can be used, the most typical are:

- Valve stem:
  Leaks can occur at the interface between the seal and the stem or the seal and the stuffing box. Place the probe at the interface where the stem exits the packing and sample the stem circumference. Repeat for packing gland nose.
- Flange and other connection:
  Place the probe at the outer edge of the flange-gasket interface and sample the circumference of the flange or connection. Try to maintain the probe tip facing the centre of the circumference (facing to the flange or pipe axis) while it is being moved around the flange.
- Pump, compressor or agitator's seal:
  Place the probe at the interface of the seal with the shaft and sample the circumference, maintaining the probe tip within 1 cm of the shaft-seal interface. A spacer can be used to avoid direct contact of the probe tip with rotating parts.
- Pressure relief device:
  This kind of device discharges to the atmosphere when the internal pressure is higher than an operationally set value. Place the probe inlet at approximately the centre of the exhaust area to the atmosphere, to measures potential leakage through the discharge path when the device is closed (not when discharging gas). WARNING: the idea is to detect if there is a leak, not to measure the concentration during a discharge event. It means that the screening of this specific kind of equipment

shall be performed only when the internal pressure is lower than the threshold pressure activating the release valve. Support from the site's personal shall be required to ensure that the working pressure during the leak detection is below the release pressure, otherwise do not attempt to screen the device, and just report that this was not included in the survey.

- Process drains:
  For open drains, place the probe inlet as near as possible to the centre of the area open to the atmosphere.
  For covered drains, locate probe at the surface of the cover and move around the periphery.
- Open-ended lines or valves:
  Place the probe inlet approximately at the centre of the opening to the atmosphere. In the case of valves, also scan the areas where the valve is connected to the pipes or other devices (tank, manifold)
- Access door seals:
  Place the probe inlet at the surface of the door seal interface and move around the periphery.
- Other components
  Joints, connections, welding seams, pipes suspected under fatigue, excessive mechanical stress or even corroded are also susceptible to leak hydrogen gas. Once identified one of these components, scan it maintaining the probe tip facing the surface which could be the potential leak interface or leak source (perpendicular to the surface).
- Other leak indications
  If any local (installed on site) or personal safety hydrogen monitor is activated in a given area or place, consider the equipment/components nearby, the wind direction and other relevant aspects (venting systems flow, shape of walls or other barriers to the gas movement, etc.) and try to determine the potential leak origin. If this brief research point to any equipment/component, then, if possible, also screen it.

7.6 End of the survey

Bear in mind that after the leak detection survey is concluded, the detector calibration shall be verified.

Then, after the last measurement the used detector needs to be purged with ambient air to zero the readings before turning the detector off, and battery put on charge.

8. Hydrogen gas leak detection using acoustic cameras

8.1 Acoustic cameras applied to detect gas leaks

When a pressurized gas leaks through an opening, it flows from the higher-pressure side to the lower-pressure side. The escaping gas jet collides with the surrounding atmosphere disturbing their molecules and generating turbulence and results in the emission of a broadband sound containing both audible sounds and ultrasounds. These sound waves propagate through the air, first through the gas plume (the leaked gas and then a zone in which the leaked gas is blended with air) and then through the surrounding air. These waves can be captured with adequate sensors (microphones). By analysing the corresponding signals detection of the leak presence and leak location (triangulation of the ultrasonic source) can be obtained. Acoustic imaging devices use an array of microphones to detect the presence of ultrasounds cause by escaping gas, creating an acoustic image which is overlaid in real time onto a standard digital image (the instrument is built on a digital camera). The location of the detected gas leak is shown as a map with a gradient of colours related with the sound intensity.

Acoustic imaging cameras are useful tools for screening gas leaks. They can be used to detect gas leaks without the need to be in contact with the gas plume. This aspect make it different from most other hydrogen detection techniques. There are several commercially available ultrasound cameras for gas leak detection.

After a leak detection using acoustic cameras it shall always be confirmed using a gas detector (or a solution for leak detection), unless approaching the leak source is not safe or possible. Here is described the application of this technology for hydrogen leak detection and location.

8.2 Preparation before use of acoustic cameras

The following checklist provides items to check before using an acoustic imaging camera for hydrogen gas leak detection. The listed items are essential for a correct operation while performing a leak survey.

- Get the appropriate training for using the acoustic camera for gas leak detection
- Familiarize yourself with the manufacturer's instructions for operating the detector
- Ensure batteries are fully charged, and spare ones are included
- Verify the optical camera lens is clean
- Ensure that acoustic camera register and record standard pictures and videos before starting the monitoring
- Ensure that acoustic camera register and record acoustic images overlaid on the picture/video. This can be done directing the camera to a sound source (machines, clapping hands or whistling sounds), a coloured spot should be seen over the sound source. This action ensures that the microphone array is working properly.
- If necessary, any maintenance or reparation should be undertaken by the manufacturer

8.3 Specifications for gas leaks acoustic cameras

To perform the leak detection and location, acoustic cameras with the following characteristics are required:

- The acoustic camera shall respond to the ultrasound produced by the gas leak. The microphones and their setup should respond to usual sound frequencies and sound levels produced by the gas leaks.
- The sound frequency generated by a gas leakage source is mainly distributed from 10 kHz to 100 kHz, and the most obvious energy difference between leak signals and the environmental noise is at 30-40 kHz.
- Cross sensitivity due to the response to the sound produced by industrial machinery (motors, rotating machines, etc.) should be minimised considering ultrasonic most appropriate frequencies.
- Background noise (sound level in the frequential region of interest) in absence of leaks (while not pointing the camera to a leak) should be considered during the detection to avoid false positive cases
- Acoustic focusing function. An acoustic imager would operate reliably with only the most basic settings. However, in noisy environments or where there are multiple sound sources, a focusing function is invaluable, allowing the user to target specific sound sources and exclude local background noise.
- Instrument shall be intrinsically safe for operation in explosive atmospheres following the regulations in place
- Acoustic cameras should be portable/handheld walk over type instruments that are battery operated or they can be engineered into mobile platforms
- Number of microphones. The larger the number of microphones in the array, the more detailed the produced acoustic images. However, beyond a certain number of microphones, the potential benefits are outweighed by increased cost/complexity. Around 100-150 microphones is generally found to be the optimum number
- The instrument may include additional features which could enhance leak detection such as frequency controls or meter/display response selection, or both
- Response time: both, standard optical digital images (pictures and videos) and acoustic images (typically a map of colours) are generally mastered with a good enough time response. Few frames by second is sufficient for gas leak detection.

- The limits of detection of such cameras depends on the differential pressure between the gas inside the leaking equipment and the atmosphere (amongst other parameters as the shape and size of the leak source). Leaks from components with pressures above 0.05 bar (5 kPa) are usually detected, while there is not available information yet about the limit of detection for H2 leaks.
- Some indications on the limit of detection for methane leaks in ideal conditions are given in the figure below.
- When leaks are spread over a long line (large aspect ratio), lower air turbulences is created, and the limit of detection can be as high as 1 L/min even at short measuring distances.

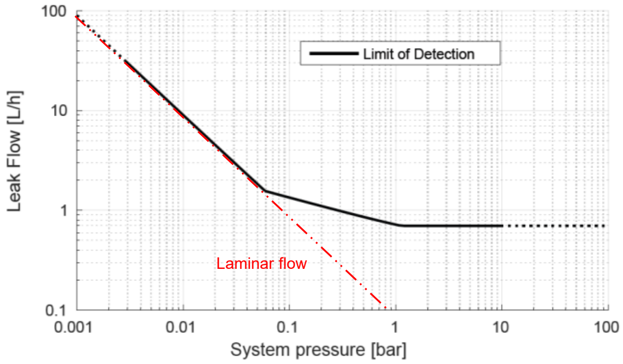

Figure 1. Ultra Pro camera lower limit of detection for CH_4 leaks at 1m and at 30kHz for leaks created by small, rounded holes. Modified from Distran.

8.4 Comparison between gas detectors and acoustic cameras for leak detection and location.

The two detection technologies explained here (portable gas concentration detectors and acoustic cameras) are complementary when used to detect gas leaks. Acoustic cameras cannot substitute gas detectors, but they provide a large list of advantages that makes this technology a valuable tool facilitating and expanding the scope of the gas leak survey. Each of these technologies has advantages and limitations, some of them can be seen in the following table.

Table 1. Some features of the leak detection using gas detectors and acoustic cameras.

Parameter	Gas detectors	Acoustic camera
Detection distance	Need to be near the leak source (few cm), the operator (or mobile platform) could potentially be exposed to explosive atmospheres. Possible loss of important leaks if survey is not thoroughly or if any place is missed to be inspected (e.g. difficult access places).	Leaks can be detected from a safe distance (units to tens of metres) avoiding exposure to potentially explosive atmospheres. Possible discovery of unexpected or inaccessible leaks (located at difficult places e.g. heights, confined spaces, risky/restricted areas, etc.).
Coverage / range	Usually detect gas from a given leak from one component, unless two or more leaks are close (some cm).	Large areas, possible simultaneous detection of multiple leaks, identification of the largest leaks within the field of view.
Survey time	Detectors response is fast (typically < 1 sec once the gas has reach the sensor). However, the manual process of scanning large areas to find gas leaks is a time-consuming work.	Acoustic images/videos are produced almost in real time. This allows the fast detection and location of gas leaks, potentially identifying the major sources quickly.
Limit of detection	Detect gas concentrations typically from tens of parts per million (v/v), allowing the detection of leaks with low leak rates (even below 1 L/min if the detector probe is located close enough the leak source).	Detect only the ultrasound produced by the leaking gas, so it is more probably to detect larger leaks. Possible loss of small leaks or leaks not producing enough ultrasound (diffusional ones).
Sensitivity	Responds to the presence of the gas. Depending on the sensing technology it could require oxygen gas to work properly.	Respond to ultrasound produced by the turbulent flow caused by a gas leak, which

		requires a minimum differential pressure & a relatively small size leak source/hole.
Selectivity	Usually detect flammable gases (e.g. catalytic, MOS, etc.) without discrimination. Some of them detects only VOCs (e.g. IR) or H_2 gases (Pd-alloy, electrochemical).	Only detect ultrasound produced by a gas leak without any capability to discriminate the gas type or composition (any gas leak producing sound patterns will be imaged).
Interferences	Flammable gases can mask the H_2 signal (depending on the sensing technology). Poison gases (e.g. SO_2) could damage the sensor inside the detector. Also, gas detection can be affected by wind, ventilation systems or heat convection, which can disturb the local gas distribution (plume).	Ultrasound produced by industrial machinery (motors, rotating machines, compressors, etc.). Sound reflections off nearby surfaces (which generally can be solved by observing the leak source from different angles): Acoustic images remain practically unaffected by local wind or vent. Doppler effect at usual wind (< 50 km/h) and ventilation speeds is negligible. Heat convection is also not affecting the images.

An extensive work on methane leaks monitoring (67 oil/gas production sites) has shown that the gas sniffer leak detection method can detect a larger number of leaks; while using Optical Gas Imaging (OGI) it were found fewer leaks but greater total emissions than using gas sniffers, which pinpointed a higher number of small leaks but missed some of the biggest leaks found with OGI. This was partially attributed to the capabilities of OGI to discover gas leaks in unexpected locations not included in the sniffer surveys [Pacsi et al. 2019]. On the other hand, it is well known that the leak size distribution is such that the largest 5% of leaks typically contribute over 50% of the total leakage volume in natural gas systems [Brandt et al. 2016]. Therefore, a technique that quickly pinpoints the largest gas leaks would be an advantage, screening also potential sources that would otherwise be out of reach because they are not easily accessible. A similar situation might be expected in the case of hydrogen leaks when investigated using acoustic cameras.

8.5 Hydrogen leak detection method using acoustic cameras

All components that can be accessed safely shall be screened. For health and safety reasons measurements are not recommended within pits, at height, enclosed places or in inaccessible areas, unless it is safe to do so, and specific training, emergency measures and corresponding permissions are considered. If possible, these inaccessible areas can be scanned remotely using the acoustic camera from a safe distance.

The site should be divided into areas, each area shall be screened, and every potential leak found shall be verified to be a real hydrogen leak using a hydrogen gas detector. Then, once it is verified, the leak source is temporarily tagged. Components to be screened include, but not limited to: valves, flanges, compression fittings, door seals and drains. Prior to screening, all pipework that is pressured with hydrogen could be identified within the areas to be screened so as to define the scope of the survey.

Acoustic techniques may be able to provide greater coverage of the spatial (component to site scale) and temporal scales (periodic to continuous). Further work is required to establish the required performance of these methods to meet the data reporting requirements and emission scenarios. Its application to quantify leaks is not considered here due to the complexity and limitations of the used models (which requires a large set of additional information as leaking equipment internal pressure, gas composition, shape and size of the hole/leak-source, among others), and the need to validate these models. Some commercial acoustic detection devices include some functionalities to estimate the magnitude of an emission. Although in certain cases these could be used as a preliminary guidance, further work is needed to assess the performance of these devices for this application.

8.6 Screening individual components for hydrogen leaks using Acoustic Imaging

In order for an acoustic imaging device to successfully detect an emission source, the following criteria must be met:

- The source must create ultrasounds
- Those ultrasounds to propagate to the device
- The targeted ultrasound must be louder (higher acoustic intensity) than others in the area (other leak sources or noise made by machinery within the selected frequency band and acoustic field view)

Note that leaks originated from a low pressure differential may not create sufficient ultrasound to be detected.

Detecting Leaks

1) Point the device at the area to be screened. A direct path should be maintained between the potential leak sources being surveyed and the device such that ultrasounds can travel to the device. Larger fields of view may detect the loudest one or two sounds. Reducing the field of view by moving closer can help to better localise leaks and detect smaller leaks. A minimum distance to the leak source shall be maintained (around half a metre).
2) When a potential leak is identified it should be approached changing the view field so as to confirm the presence of a leak and to more accurately define the source location.
3) It is important to assess potential leaks from multiple angles scanning the area around any detected leak source. Ultrasounds can be detected by reflection off walls or other flat surfaces and may appear as leaks. Assessing from different angles can help determine if the detection is just a reflection. If the detection moves location when assessed from different angles it is likely a reflection. Actual leaks sources do not move within the image when observed from different angles.
4) Once a leak is identified and its source is located using an acoustic camera, then it must be further confirmed the presence of the gas being leaked using a gas detector. It is particularly important in the case of flammable gases as hydrogen.
5) Sound distribution is usually emitted with higher intensity in a preferential direction. If possible try to find this preferential direction, by changing the position (angle) between the camera and the leak source. Once the camera is pointing to the leak from the position maximising the sound level (e.g. dB), then approach to the leak source in straight line to better pinpoint the leak source position (remember to not approach more than about half a metre to avoid worsening the acoustic focusing).

The limit of detection at any given time will be affected by presence of background or interfering sources of ultrasound. Additionally large leaks, or those creating the largest ultrasound, will mask the detection of smaller leaks in the vicinity (or leaks producing less ultrasound). Potential mitigations for interfering sources include:

- Adjustment of the measured ultrasound frequencies which could exclude those from the background and decrease the detection limit if the device allows.
- Large sources could be blocked from view of the device to facilitate the screening of nearby components for leaks which would otherwise be masked.

These steps are a general guide to using acoustic imaging devices for leak detection. It is recommended that specific training on the particular instrument to be used be undertaken prior to conducting a leak detection survey.

8.7 Final remarks on hydrogen gas leak detection using acoustic imaging

It is recommended that operators keep abreast of emerging technology and new products which may lead to adaptations to this methodology, or it being superseded in future.

The methodologies should be applied in conjunction with the specific instrument manufacturers operation manuals and training in these instruments should be sought independently.

Any reference to safety considerations are included as a guide and to prompt discussion. The specific safety requirements of individual sites must be followed, and work conducted in accordance with work permits.

9. Reporting

The leak detection report shall include the following information:

Site and survey information:
Date and place; scope of the survey (site, area, group of components, specific components); facility type and identification of the site; contact details of the site contact person and the personnel performing the leak detection survey (company or organization, email, phone, certification documents if applicable); type and size of equipment screened (e.g. pipes 2 inches diameter 50 linear metres, or 2 electrolyser units); streams (e.g. H_2, CH_4, natural gas, etc.); purpose (e.g. LDAR, commission, regulatory); screening conditions (atmospheric pressure, temperature, wind conditions, indoor or outdoor areas, etc.); reporting period.

Detector information:
Characteristics of instrument used: type; model; brand; serial number; calibration verification (obtained values with their corresponding units); response time; LOD, precision (indicated by the manufacturer or determined as in 6.2), sampling pump rate (if it is dragging the gas sample with an internal pump), target gas (e.g. flammable gases or specific for a given gas), and whether it is selective for H_2 (or not). Include the description of any used accessory (probe tip, extensions, etc.).

Calibration gas information:
Used calibration gas or certified gas cylinders (if applicable) and their concentrations.

Background values information:
Measured background values (at least in three different places) or LOD if it is the case.

Reporting leaks:
For each one of the detected leaks: leaking component; site label identification if any; location of the detected leak; measured H_2 gas concentration; actions taken (if the case, only for authorised works); component's internal hydrogen concentration (e.g. pure H_2, or 20% v/v H_2, etc.); internal gas pressures (if known); whether the screened components are under continuous or intermittent work; type of area as indoor or outdoor; pictures can be included to ease the location of leaks (only use authorised cameras / mobile phones). Consider whether is worth labelling the located leak sources to easier their location in subsequent repair operations or when quantification methods are going to be applied. Any case in which the detector reading is due to ambient humidity, describe any correction applied to the data (include both, raw and processed data). If possible, mark the leaking items in the site plan or map.

An example of a leak detection survey report is presented in Annex A.

10. Bibliography

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Annex A.

Form 1. General information (site, survey, equipment)

Site general information					
Site		Site contact person		Email / phone	
Date		Reporting period		Installation/ equipment type	
Atm. pressure		Range of atm. Temperature		Wind conditions	
Hydrogen leak detection survey general information					
Leak survey company		Leak survey contact person		Email / phone	
Survey scope		Survey purpose		Gas(es) type(s)	
Internal gas concentration (split by areas if needed)			Internal gas pressure (split by areas if needed)		
Hydrogen gas detector general information					
Detector type		Model / Brand		Serial number	
Response time		LOD (conc.)		Sampling rate (if applicable)	
Target gases		H_2 selective	YES NO	Accessories	
Initial cal. precision (%)		Final cal. Precision (%)		Calibration H_2 Concentration(s)	

Form 2. Hydrogen leak detection survey report

Data obtained in the leak detection survey. In this example the form was written grouping the components in classes (e.g. flanges, valves, etc.). Some examples in the comments sections have also been included.

Item #	Element ID	Leaking component and location	H_2 Conc. ppm	Photo ID (file)	Notes / Comments -
NA	Bkg 01	Background			
	Bkg 02	Background			
	…				
1		Valve ¾ inch			
2		Valve ¾ inch			Fluctuating value
…		…			…
20		Valve ½ inch			Internal P = 20 bar
21		Valve ½ inch			
…		…			
30		Flange 3 inch			Well above LEL, priority LDAR
…		…			
35		T connection ¼			Permitted action taken: adjusted, leak eliminated
…		…			
50		P relief valve			Outdoor, windy
…		…			
55		Compressor seal			
56		Welded joint			

Form 3. Hydrogen leak detection summary report

This reorganises the leak detection survey data to gain insights on the overall site leaks during the assessed survey.

Class #	Component classes	Total screened	Leaking this survey Date:	Leaking previous survey Date:	Never reported / measured	Total in use	Notes
1	Valves ¾ inch	50	12	22	0	50	
2	Valves ½ inch	40	10	16	0	40	
3	Flanges 3 inch	12	5	8	0	12	
4	T connections ¼	35	0	0	4	39	1 leak repaired (not counted)
5	Pressure relief valves	6	2	6	4	12	
6	Compressor seals	4	0	0	0	4	
7	Soldered joints	22	1	0	≈10	≈32	(≈) Estimated
…	…						

PRE-NORMATIVE RESEARCH ON HYDROGEN RELEASES ASSESSMENT

Annex 2

Fugitive emissions quantification using the High Flow method: Hydrogen leaks generated from equipment and pipework (component scale).

AUTHORS

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VERSIONS

Revision Version	Date	Changes	Changes made by Partner
0.1	08/04/2025	Draft	Haydn Barros / NPL
0.2	17/06/2025	First review	INIG / NPL

CONTENTS

1. Introduction

In this document a method to quantify fugitive hydrogen gas emissions (previously detected and locate) at component scale is proposed. This document uses the terms leak and fugitive emission interchangeably (although they are defined separately). The method is based on currently available technology.

The use of hydrogen in large scale industrial infrastructure introduces exigent tightness requirements due to two primary reasons: firstly, its smaller molecular size facilitates easier flow through defects or sealing materials, and secondly, its higher risk means that even small gas leaks pose increased hazards, due to its low ignition energy, broad flammability range (4% to 77% v/v) and higher explosivity. On the other hand, it is needed near 3 times the volume of hydrogen as compared to natural gas to get the same amount of energy, then hydrogen is stored at high pressure (200-1000 bar) increasing then the risk of leaks.

The method described focuses on the effective use of portable High Flow samplers, which are vacuum cleaner type instruments capable of drawing in a considerable amount of ambient air and capturing the escaped gas with it. This technology is currently available for natural gas or methane, while in these cases the sampling system incorporates the gas sensors internally. The present method is based on the NPL experiences on both areas: natural gas leak rate quantification using a commercial High Flow system, and hydrogen leak rate quantification integrating a handheld hydrogen gas detector to an existing High Flow sampler.

The present document outlines the fundamental principles and practices for leak quantification using the High Flow method using commercial-off-the-shelf technology, emphasizing the importance of clear procedures and safety measures, by providing detailed instructions and insights into the quantification process. The guide aims to standardize leak quantification procedures, reducing human error and enhancing overall efficiency. It covers essential topics such as use of High Flow sampler systems, portable leak detectors, safety precautions, and specific procedures for hydrogen leak quantification. It discusses various issues such as equipment maintenance and personnel training. Through comprehensive guidance, this document aims to contribute to the safe and effective monitoring of H_2 gas leaks to inform management schemes in industrial settings.

This method does not include other instruments used for leak quantification or estimation such as measurements employing differential pressure methods or sensor networks, although in principle they can also be used for hydrogen leak monitoring.

The quantification of a leak requires its previous detection and the localization of the corresponding leak source (first step). The physical quantity to be quantified is the item or component emission rate, or leak rate. The leak rate quantification is considered as the second step in the monitoring strategy. The fugitive emissions leak detection and localization is covered in a separated document (Leak detection method using passive or pumped gas detectors and acoustic cameras: Hydrogen leaks generated from equipment and pipes (component scale)).

2. Scope of application

This method applies to the manual quantification of fugitive emissions (leaks) of hydrogen from process equipment, it specifically refers to individual equipment or parts of these, which is called leak detection at component level. We specifically refer to gaseous hydrogen in its molecular form, H_2. The leak sources include, but are not limited to, valves, flanges and other connections, pressure relief devices, process drains, open-ended valves, pump and compressor seal systems, agitator seals, access door seals, welding seams, and pipes suspected under fatigue, excessive mechanical stress or even corroded.

Care shall be taken at any attempt to include complex parts such as: pumps, compressors, agitator seals, access door seals, storage tanks, which will possibly introduce factors that are not considered here, and additional risks (e.g. rotating parts potentially colliding with the probe tip, or release valves that suddenly discharge high-pressure gas). However, the guidelines presented here could be extended to hydrogen leak monitoring of such systems to produce specific good practice guides as needed. This leak rate quantification method applies to all gases which contains hydrogen (H_2) as a significant part of its composition, as is the case of natural gas blends mixed with hydrogen.

The method consists of two parts. The first part is based on the sampling of the leaked hydrogen gas (using a High Flow sampler) and the precise quantification of the sampling flow rate, which is considerably higher than the assessed leak rate (sampling rates are typically several hundreds of litres per minute). The second part consists of measuring the hydrogen concentration in the sampled gas inside the High Flow sampling system, which is made of the escaping hydrogen gas diluted with ambient air. This concentration is measured with a portable instrument, sometimes called leak detector. The scope of this method includes only the quantification of hydrogen leaks at component level, leaving the leak detection and location for a separate method. This method also includes the data processing and the generation of the corresponding leak detection report.

This method does not prescribe the number of potential emission points that should be screened and or quantified each year nor the frequency at which these points should be screened. The sampling strategy shall indeed take into account the plant characteristics and the required level of control over fugitive emissions.

During the leak detection step, it is a common use to define a concentration threshold to then decide whether or not to quantify a given gas leak, and some rules and/or examples have been given for natural gas or methane [EN 15446:2008]. However, this document does not define a screening value neither a guidance threshold concentration indicating that a leak shall be quantified. In our opinion this depends on the scope of the survey and on the specific features of the site being monitored.

This document aims to:

- Provide information about leak quantification procedures using the High Flow method, using a High Flow samplers and a portable hydrogen gas detector, since there are no high flow samplers available yet that incorporate hydrogen detectors internally
- Give an overview of the potential risks faced when performing H_2 leak quantification.
- Standardize leak monitoring methods to enable proper quantification of fugitive emission sources, reducing the human factor in LDAR or emission surveys campaigns.

3. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies. The present method is related only to parts of the content included within these reference documents.

BS EN 15446:2008. Fugitive and diffuse emissions of common concern to industry sectors -Measurement of fugitive emission of vapours generating from equipment and piping leaks.

ISO 5725-2, Accuracy (trueness and precision) of measurement methods and results - Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method (ISO 5725-2:1994 including Technical Corrigendum 1:2002).

4. Terms and definitions

For the purposes of this document, the following terms and definitions apply.

Accuracy - Closeness of agreement between a measured quantity value and a true quantity value of a measurand [6].

Autoignition temperature – minimum temperature required to ignite a gas or vapor in air without a spark or flame being present.

Calibration – An operation that, under specific conditions, establishes a relationship between the quantity measured (with its uncertainty) and a traceable measurement standard (with uncertainties) [6].

Calibration precision – degree of agreement between several measurements of calibration gas with the same known concentration. It is the ratio of the mean absolute value of the difference between the meter readings and the known concentration to the known concentration, expressed in percent [EN 15446:2008].

Component – an entity that forms part of a process or system, e.g., flange, valve, connection.

Component level – the level of detail related to the components, it refers to the component itself and is related to an approximate spatial scale of centimetres to metres.

Detector - device or substance that indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded [6].

Detection limit / Lower Limit Of Detection/ Limit Of Detection (LOD) - The lowest measurand value (i.e. concentration or signal) that is used to infer the presence of a measurand (such as a signal produced by a detecting device) and which can be reliably detected with a sufficient degree of confidence [7].

Explosive concentration range – concentration which covers from LEL to UEL of the specified gas.

Flammable concentration range – concentration which covers from LFL to UFL of the specified gas.

Fugitive emission – emission to the atmosphere caused by loss of tightness of an item which is designed to be tight [EN 15446:2008].

Hydrogen calibration gas – a gas mixture whose hydrogen amount fraction have been validated [EN ISO 14532:2017].

LDAR – Leak Detection And Repair, typically referred to the schemes used in the industry.

Leak - the unintentional release of hydrogen from equipment used in value chain [OGMP2.0].

Limit of quantitation/ Lower Limit of Quantification (LOQ) - The smallest volumetric flow rate of hydrogen emissions that can be determined by a given method with a specified, acceptable uncertainty,

Lower Explosive Limit (LEL) – gas lowest concentration in air at NTP (normal temperature and pressure) that will burn or explode if ignited. Below this concentration the gas cannot explode because there isn't sufficient fuel.

Lower Flammable Limit (LFL) – gas lowest concentration in air at NTP (normal temperature and pressure) that will produce a flash of fire when an ignition source (heat, arc or flame) is present. Below this concentration the gas cannot ignite because there isn't sufficient fuel.

Measurand - The physical quantity subject to be measured [6].

Monitoring - A generic term used to describe the estimation, measurement, location and/or detection of gas emissions [9].

The Minimum Ignition Energy (MIE) – minimum electrical energy which, when discharged, is sufficient to ignite the most ignitable mixture of a fuel in air under specified test conditions. It is a measure of how sensitive an explosive is to electrical spark ignition. It gives guidance on whether ignition by electrostatic discharge from plant personnel or process conditions is likely to occur in practice.

Response factor – ratio between the actual concentration of the target gas (H_2 in this case) in the measured sample and the observed instrument reading. This is particularly important in the case of detectors devised for flammable gas (not specific for hydrogen). If used, the response factor should be determined accordingly with the indications provided in this method. The response factor shall be used to correct the direct meter readings to obtain the corresponding values for the target gas (hydrogen). This correction accounts for differences in response between hydrogen and the gas used for calibration.

Response time – time interval from a step change in gas concentration (using a reference gas) at the input of the sampling system to the time at which 90 % of the corresponding final value is reached as displayed on the instrument readout meter [EN 15446:2008].

Sampling Strategy - describes how the measurement is collected and represented, and the platform used [7].

Sensor - An element that is directly affected by the phenomenon, body, or substance carrying the quantity to be measured [6].

Screening – action of measuring the concentration in the target gas at the interface of a potential leak source.

Screening value – local gas concentration at the surface of a leak source that indicates a gas emission is present. It must be a value above the Limit of Detection (LOD) of the used instrument.

Selectivity – the ability of the gas sensor or detector to differentiate a target from other gases, i.e. to produce signals or readings related only to the target gas even in the presence of other gases.

Sensitivity - The ratio of the change in the measured value to the corresponding change in the value of the quantity being measured [6].

Source level – detection of emissions at the level of a process component or device that releases hydrogen into the atmosphere intentionally or unintentionally, periodically or continuously [OGMP2.0]. This is related only to the spatial scale.

Concentration Threshold– pre-set performance target for the individual sources [EN 15446:2008]

Uncertainty - A non-negative parameter which characterises the dispersion of measurement results attributed to a measurand [6].

Upper Explosive Limit (UEL) – gas highest concentration of a gas in air at NTP (normal temperature and pressure, 293,15 K and 101,325 kPa) that will burn or explode if ignited. At this concentration the gas cannot explode because there isn't sufficient air (i.e. insufficient O_2).

Upper Flammable Limit (UFL) – gas highest concentration of a gas in air at NTP (normal temperature and pressure, 293,15 K and 101,325 kPa) capable of producing a flash of fire when an ignition source (heat, arc or flame) is present. At this concentration the gas cannot ignite because there isn't sufficient air (i.e. insufficient O_2).

Zero gas - Gas recommended by the manufacturer, which is free of the target gas (hydrogen in this case) and contaminating substances, the purpose of which is calibration / adjustment of the equipment zero reading [8]

5. Before starting leak quantification

5.1 Safety precautions

- Staff performing the leak detection survey must have appropriate training about the hazards present on the environment they will be working in. This should include training on working in explosive atmospheres. Within the EU, this topic is covered by the ATEX (ATmosphères EXplosibles) directives on equipment [2014/34/EU] and workplaces [1999/92/EC].

- Additionally, staff performing the leak detection survey must have a basic knowledge on safe working with pressurised gas cylinders and transporting gas cylinders by road if needed.

- Operators should also be aware of applicable national regulations on explosive atmospheres for the country that they are working in (such as the UK's the Dangerous Substances and Explosive Atmospheres Regulations, (DSEAR) 2002).

- Operators must understand the concepts of Lower and Upper Flammable Limits (LFL & UFL) and flammable range, as well as the concepts of Lower and Upper Explosive Limits (LEL & UEL) and explosive range. It is worth noting that for hydrogen those values are different (see Table 1), and historically for natural gas and methane the flammable limits have been often called explosive limits.

- Any used detector, High Flow gas sampler, personal safety monitor, equipment, photographic camera, tablet or mobile phone must work within the conditions of the work permit, complying to the applicable standards, such as UL, ATEX, or IECEx certifications for equipment used in explosive atmospheres. They should be authorized for use in the inspected areas.

- Operators should also be familiar with other concepts such as gas density (and how it impacts on the gas buoyancy in air), autoignition temperature and minimum ignition energy, all of these properties should be considered when risk assessing work with hydrogen and/or different fuel gases.

The relevant characteristics are listed for methane and hydrogen in Table 1.

Table 1 – Some methane and hydrogen gas characteristics

Parameter	Methane	Hydrogen
Relative density (to air)	0.55	0.07
Molecular mass, g/mol	16.04	2.016
Kinetic diameter, pm	380	289
Diffusion coefficient (in air), cm^2/s	0.21	0.756
Absolute Viscosity, 10^{-5} Pa s	1.1	0.9
Flammable range (in air, 21% O_2), v/v	4.4 – 17 %	4 – 77 %
Explosive range (in air 21% O_2), v/v	No information	17 – 56 %
Stoichiometric fraction (in air), v/v	8 %	29 %
Minimum ignition energy, µJ	525	19
Autoignition temperature (in air, 21% O_2), ºC	600	560
Flame temperature (in air, 21% O_2), ºC	1937	2127
Flame velocity, cm/s	36	255

Note: Many of these values refers to 20 °C and 1 atmosphere pressure [EN ISO 80079-20:2019].

- Do not attempt to make any changes to components that are suspected to be leaking, such as tightening connections or fastening flanges unless you have (written) authorization, training and that task is among the duties, and included in the work plan and Risk Assessment.

- To mitigate the risks of ignition of flammable gases, and to protect the operator should ignition occur, it is critical to select the correct Personal Protective Equipment (PPE):

- Footwear – footwear should be antistatic/electrostatically dissipative, confirming to standards such as: EN ISO 20345
- Clothing – the outer layer should be antistatic and flame retardant, conforming to standards such as: EN 1149, EN ISO 11612
- Eyewear – to provide protection to eyes in the event of fire or explosion and ejected particles, conforming to standards such as: EN 166, EN ISO 16321
- Individual personal safety monitor specific for hydrogen gas

- Sites where fugitive emissions of flammable gases may occur are likely to be multi-hazard environments, where the presence of flammable gases is only one risk to the operator of emission monitoring equipment. The list of PPE above is not exhaustive, and operators should consider other appropriate items of PPE as part of developing a risk assessment for the task that identifies all significant hazards present on the site.

- Verify the possible presence of other flammable (e.g., natural gas) or toxic gases (e.g., ammonia, carbon monoxide) and consider them accordingly in your risk assessment. Also, remember that many detectors can also suffer from poisoning in the presence of toxic gases, causing degradation in detector response.

- Obtain the necessary permissions required to access all areas and follow all the safety rules in place. If working on a controlled site, the work is managed by an operational team that authorises the emissions monitoring via a permit scheme; the conditions of the work permit and the associated risk assessment must always be followed.

- In the event of an incident or emergency occurring, follow the instructions provided to you in your site induction regarding reporting situations to the site controller, and the appropriate response to site alarms, such as the process for site evacuation.

- Familiarize yourself with emergency procedures in case of hazards, including evacuation routes and contacting appropriate authorities.

- Personal performing the emission quantification procedure should also have other training like the following:
    - Familiarization with different methods of leak detection and tightness testing, as leak detection fluids (bubblers), sniffers (having internal sampling pumps) or passive gas detectors or acoustic imaging
    - Basic knowledge on hydrogen sensor technologies, particularly those used in the detector employed in conjunction with the Hi Flow sampler
    - Knowledge of gas networks or installations on which measurements are being taken, including common equipment and fittings. Understanding of sealing techniques and common mechanical failures

5.2 Preparation before use of equipment

The following checklist provides additional items to check before using High Flow method for leak quantification . The listed items are essential for a correct operation of the gas detector (called also leak detector) and High Flow sampler equipment.

- Familiarize yourself with the manufacturer's instructions for operating the High Flow sampler and the hydrogen gas detector
- Ensure batteries or each equipment are fully charged, and spare ones are included for uninterrupted operation. Note: change batteries or charge the devices only in safe / authorised areas
- Ensure that certified or calibrated gas mixtures are available to test the gas detector at any time before, during or after monitoring
- If applicable, have a spare replaceable sensor and knowledge of how to replace it in case of need
- Develop a clear plan defining what to test and where to start to ensure efficient testing procedures

5.3 High Flow system and detector maintenance

- Different High Flow samplers have different type of mechanisms, commercially available instruments can be found with sampling flow rates capacities up to 220 L/min, and some models even up to 700 L/min. The sampling flow rate shall be stable within the range prescribed by the manufacturer. The commercially available instruments incorporate methane / VOCs detectors. For that reasons, here we propose the use of commercially available hydrogen detectors to be used in tandem with the High Flow samplers.

- In case of High Flow samplers having integrated detectors (for VOCs) which could be recalibrated for hydrogen, the sampling flow rate and the concentration gas calibrations must be verified separately.

- In case of High Flow samplers devised for gases different to hydrogen, the coupling between the sampler and the gas detector shall be consistent with sampling the diluted gas suctioned by the sampler. In some models the outlet of the sampler can be used to feed the gas detector. Any coupling between a gas sampler and a gas concentration detector shall be tested and validated beforehand using simulated leaks (known gas leak rates).

- Some gas leak detectors often have a filter at the probe end. Inspect this filter regularly and replace it if necessary. In the case of detectors equipped with sampling pumps, the pumping efficiency could be compromised, and in the case of passive detectors clogged filters could prevent the gas reaching the internal sensor.

- In instances of detector's sensitivity loss, replacing the sensor should be contemplated, for those detectors allowing users to replace it by themselves, following the manufacturer's guidelines. It is advisable to keep a spare sensor on hand for swift replacement when necessary. Some sensors degrade faster when exposed to a high concentration of hydrogen.

- For detailed instructions on maintenance and cleaning of any of the used instruments refer to the manufacturer's manual.

- Verify the batteries charge and conditions before the survey (daily if possible).

- It is advisable to maintain a record of the usage of leak detectors to facilitate monitoring the lifespan of components, such as the batteries and the sensor itself, for timely assessment.

6. Equipment for hydrogen leak rate quantification

6.1 Specifications for High Flow hydrogen leak samplers

To perform the leak rate quantification, High Flow gas samplers with the following characteristics are required:

- The sampler shall have a large capacity for sucking the sample gas, at least in the range of hundreds of litres per minute.
- The volumetric sampling flow rate (commonly known as sampling rate) should be adjustable, allowing to perform the sampling at different rates.
- The flow rate shall be accessible to the user, by means of direct readings on a display.
- Flow rate data should be also able to be registered electronically, producing data in a format able to be processed offline after the survey.
- The sampler shall be a portable device, as a backpack which can be taken comfortably along the site when performing the survey.
- The sampling hose or line should be long enough to allow leaks located at different positions and heights. The lines shall have at least several meters.
- The equipment could be used by locating the sampler near but outside the exclusion zones and then using a long sampling hose to capture the diluted leak inside the High Flow sampler. If this procedure is performed, additional safety measures should be in place to avoid feeding the High Flow with hydrogen gas above the LEL (4% v/v). This is necessary only in the case of high leak rates, and the sampling can be undertaken by approaching slowly and progressively the probe tip to the leak while observing the concentration readings to prevent trespassing the mentioned threshold.
- The user must be familiar with the High Flow user manual instructions, so that its power source can promptly and safely isolated in case of need. Or at least the sampling pump shall have this feature.

- High Flow samplers shall conform with the conditions of the work permit and the applicable standards. They shall be authorized for use in the inspected areas, considering the corresponding zone classification (as zones 1, 2, etc.) and the specific gas group for the gas (or gases) potentially present.

6.2 Specification for hydrogen detectors

To perform leak rate quantifications using the High Flow method, hydrogen detectors with the following characteristics are required:

- The gas detector shall respond to the hydrogen gas. The sensor types used in the detector (instrument) include, but are not limited to, catalytic oxidation, semiconductor (e.g. metal oxide semiconductor), electrochemical, and palladium alloy. Most of these detectors respond to flammable gases, so cross sensitivity and response factors must be considered for any detector no selective for hydrogen
- The gas detector (instrument) response shall be linear within the hydrogen concentration in the range of interest.
- It is common that industrial sites define threshold values to take actions (LDAR schemes, safety measures, stop processes, etc.). If a given leak rate threshold value is provided at the site being monitored (or at any specific area within the site), then the used equipment should be suitable to certainly quantify leak rates below the intended threshold. In this case, the combined devices (High Flow sampler + H_2 detector) should be able to measure leak rates below the threshold at least when sampling at the lowest flow rate. The following sketch depict the possible outcomes of the measurements as compared with a given threshold.

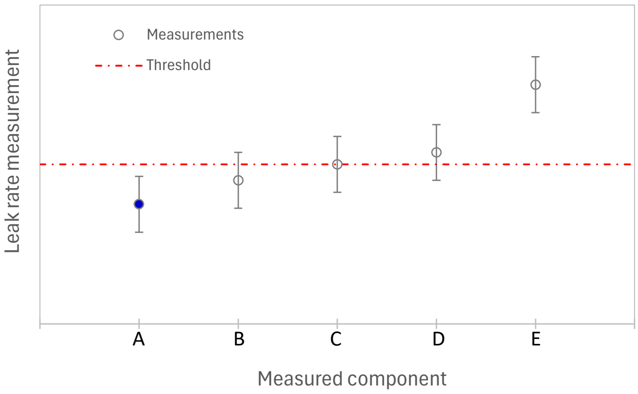


Figure 1. Requested measurement performance for a threshold value to be considered.

Case E correspond to measurements that are certainly above the given threshold, cases B, C and D correspond to cases where there is a probability P for that measure to be above the threshold, and a probability 1-P of the actual value being below. Finally, the case A (highlighted in blue colour) correspond to a measurement that is undoubtedly below the threshold (considering also the measurement uncertainty), being this case an example of the required measurement capability for a given threshold to be considered.

- Nowadays, the minimum range of standard portable detectors for measuring hydrogen concentrations is about tens of µmol/mol or ppm. The minimum concentration value required for hydrogen gas detectors to be used in combination with High Flow samplers is not defined in general. However, a guidance can be seen considering the minimum High Flow sampling rate (e.g. 160 L/min for some commercial devices) and the LOQ for the used H_2 detector (e.g. 100 ppm for some commercial detectors). With these information it can be computed the minimum measurable leak rate (in the case of our example 0.016 L/min), which in turns could be used to inform whether the concentration measuring device has a suitable LOQ.
- Minimum resolution of the combined instruments should be up to 5% of the threshold value (if any).

- Instrument shall conform with the conditions of the work permit and the applicable standards. They shall be authorized for use in the inspected areas, considering the corresponding zone classification (i.e. zone 0, 1, 2) and the specific gas group for the gas (or gases) potentially present.
- If a gas detector with a sampling pump is used, the device should be able to provide a nominal sampling flow rate between 0,2 L/min to 1,2 L/min
- If a passive detector is used, located the sensor tip at the High Flow sampler exhaust. Although this practice could lead to a reasonable estimation of the leak rate, we advise validating this before use. We have successfully tested only the use of hydrogen sniffers (detectors with an internal pump) in combination with the High Flow method to quantify hydrogen leak rates.

6.3 Performance criteria

High Flow samplers and gas detectors used for leak quantification using this method should meet the following performance criteria.

High Flow Sampling Flow Rate features

- The uncertainty of the sampling flow rate is determined by comparing the readback of the internal flow rate measurement system with a reference. This should be calibrated by the manufacturer or other entity with proven metrological capacities in this area. The calibration of the sampling flow rate must be documented and available, specifying the validity and expiration date.
- The sampling flow rate shall be stable (constant flow / steady state) and any deviation of this should be corrected (if above the determined uncertainty). Check the battery charge and any indication given by the manufacturer. The stability of the flow rate shall be within the range prescribed by the manufacturer. Typically, it is stable with a precision better than few percentual units.

Determination of the sampling flow rate stability:

- **Step 1:** Switch on the instrument and the sampling mechanism following the instructions given by the manufacturer.
- **Step 2:** Use any of the hose attachments and do not interpose any obstacle to the air being sucked inside the instrument. Wait until the system is working in a steady state.
- **Step 3:** Record (either manually or automatically) the sampling flow rate at least for 15 minutes, taking measurement at least every 30 seconds.
- **Step 4:** Perform the mean and the standard deviation and express it as a percentage of the mean flow rate.
- **Step 5:** Verify that the standard deviation is equal or lower than the deviation assumed by the manufacturer. If not, verify that it is at least less than 10%. Include the sampling rate standard deviation in your report.
- **Step 6:** If the standard deviation of the sampling rate is higher than 10% corrective actions must be taken (replace batteries, verify the other functionalities of the equipment, take corrective actions indicated by the manufacturer). After corrective actions have been taken, repeat steps 1 to 6 until the 10% is achieved or suspend the use of the equipment.

Hydrogen detector calibration precision

The calibration precision of the instrument used for hydrogen concentration measurement must be lower or equal to 10 % of the calibration gas value. Calibration precision test shall be completed prior to placing the instrument into service, and it shall be performed with the frequency recommended by the manufacturer, at the next use or at least at subsequent 3 months intervals.

Determination of the detector calibration precision is performed as follows:

- **Step 1:** Measure hydrogen content of zero gas
- **Step 2:** Measure hydrogen content using the specified calibration gas and record the reading after the response time

- **Step 3:** Perform the sequence of steps 1 and 2, three times
- **Step 4:** Calculate the arithmetic mean difference between the meter mean reading (at least n=3) and the known value from the calibration gas certificate
- **Step 5:** Divide this difference by the known calibration value and multiply by 100 to express the final calibration precision as a percentage

Calibration gases

Gases required for monitoring and instrument performance evaluation are:

- Zero flammable or explosive gas (dry air containing less than 10 ppm H_2, i.e. 10 µmol/mol)
- A certified reference gas mixture being a mixture of hydrogen in air with a known/certified H_2 concentration (typically below H_2 LEL). Here concentration refers to the amount fraction.

The diluent for the hydrogen reference gas mixture must be dry air (synthetic air) because most detectors require oxygen to function correctly, and also to reproduce the conditions of a leak detection survey (done in air, with around 21 %v/v O_2. Note that the molar fraction (%mol/mol) is the same as the volume fraction (%vol/vol) at usual atmospheric pressure and temperatures (ideal gas approximation).

If possible, it is recommended to use two certified reference mixtures with a hydrogen content of approximately 25% and 75% of the measuring range of interest.

The expanded uncertainty (k=2) of the calibration gas mixture should not be greater than +/- 2% with respect to the certified reference value, and a shelf life should be certified for each used gas mixture.

System consisting of High Flow sampler and hydrogen detector

Response time

The hydrogen gas leak detector response time specified on the instrument configuration must be equal to or lower than 5 seconds. In the case of detectors integrated to the High Flow system, the sampling time shall be considered, due to the length of the sampling hose and system. For example, when sampling at 200 L/min using a hose with a diameter of 5 cm, the gas speed inside the line will be 170 cm/sec. In this case a 2 metres length hose (with the additional 40 cm of internal pipework) will require 1.4 seconds to bring the sampled gas inside the instrument.

Determination of response time is required:

- before a new system is put into service for the first time
- if a modification to the sampling system has been made that would change the response time
- If any unusual delay or behaviour is noticed in the response

Determination of the response time can be done in two ways, using a calibration gas or a simulated leak of known flow rate.

Determination of response time of the leak rate measuring system:

- **Step 1:** Introduce zero gas into the High Flow instrument's sampling hose (synthetic air or ambient air in a location where no hydrogen leaks are suspected)***
- **Step 2:** When the hydrogen meter reading stabilizes, verify that this corresponds to the zero H_2 concentration reading.
- **Step 3:** Then quickly switch to a constant flow rate of hydrogen gas (from a calibration gas cylinder below H_2 LEL and balance in air, or from a simulated H_2 leak). Feed the High Flow sampler ensuring

that the whole hydrogen gas flow is being sampled (full capture condition). Then, measure the time from switch to when 90% of the measured steady state concentration is reached. The steady state concentration value corresponds to the dilution of the incoming hydrogen gas, which multiplied by the (constant) sampling flow rate will give the hydrogen flow rate feeding the system.

- **Step 4:** Perform the sequence of steps 1-3 three times
- **Step 5:** Calculate the mean response time.
- When this procedure is applied to High Flow systems, the previous value indicates the total response time (detector plus sampling process) at a given sampling rate. It means that the value already consider the time due to the length of the sampling hose and system. If the hose is exchanged for another one having a different length or internal diameter, then the response time should be measured again, or it should be corrected by calculating the time difference in terms of the new hose length/diameter and the used sampling flow. Also, if a different sampling rate is used, a different response time will be obtained.

7. Procedures

7.1 Manual survey of individual components for leak quantification: Scope of survey.

- This method considers only above ground fugitive emissions (i.e. underground or underwater leaks are not considered). Items under vacuum are also excluded (fugitive emissions from items under vacuum are non-existent).
- Hydrogen leak quantification involves only previously identified leak where the leak source was also located. In this method the quantification is done by sampling the leaked target gas (hydrogen) in the vicinity of the leak source at a relatively high sampling flow rate. In practice, this will be producing a mixture between the leaked gas and the ambient air, producing a diluted gas concentration inside the sampler. Then an aliquot of this diluted gas is taken by the gas detector to determine the target gas concentration within the mixture. The dilution factor will depend on the sampling flow rate and shall not be large enough to end with an excessively diluted gas which won't be sensitively detected (surpassing the detector limit of quantification). On the other hand, the suction capacity of the sampler need to be enough to guarantee that the whole leaked gas is sampled inside the system during the measurement period, otherwise the leak rate will be underestimated. Then, there is a trade or compromising both factors, the need of a high sampling rate and the need of a not too big dilution factor.
- This document is focused on both, the measurement of the sampling flow rate and the measurement of a diluted hydrogen concentration inside the High Flow sampler.
- In order to estimate the site emissions, all the components which can be regarded as leak sources (previously identified leaks) shall be quantified, unless there are specific site rules which prevent to undertake the quantification for technical or safety reasons, in this case they shall be included in the report anyway. This refers to equipment or components in process service, it means they have internal positive (> 1 atm) pressure of hydrogen gas or other gas mix containing hydrogen.
- General practice is also to exclude the followings: components not accessible, components for which monitoring would require some dismantling, e.g., of insulation, and components for which monitoring could entail safety issues. If this is the case, it is necessary to report the type and number of leaking equipment not included in the quantification.
- Avoid performing leak quantification surveys under extreme ambient conditions. At very low temperatures, material contraction may occur, potentially suppressing or altering the leakage, thus complicating its assessment. Moreover, the presence of rain, snow, or high moisture concentration can hinder the accurate detection of exposed leaks, compromising their evaluation. Work always within the range of working conditions specified by the detector manufacturer.

7.2 Preparation

- **Step 1:** At the beginning of the instrument performance evaluation test, assemble and start up the instrument according to the manufacturer's instructions for the recommended warm-up period and preliminary adjustments.
- **Step 2:** Perform the instrument response time test and calibration precision test provided in Section 6.3 when required. This evaluation shall be performed at first use and after instrument maintenance.

7.3 Check and adjustment

- **Step 1:** Start the devices according to the manufacturer's instructions, performing all required startup actions (e.g. warm-up period, pump checks, sensor checks, sampling flow stabilization, internal zero calibration procedure, airtight control)
- **Step 2:** Introduce the calibration gas with the highest concentration into the gas detector sample probe and, if needed, calibrate the instrument according to the manufacturer instructions.
- **Step 3:** Check the gas detector with the calibration gas with the lower concentration. If the reading is within 10% of the calibration gas concentration, the check is accepted. Otherwise the check procedure needs to be restarted, or corrective action is required.
- **Step 4:** If the corrective actions (change filters, replace batteries, restart the instrument, etc.) does not work, a malfunction of the gas detector is indicated, and major corrective action (e.g. servicing the equipment) and check revaluation (Steps 1 to 3) should be successfully undertaken before use.
- **Step 5:** Set the High Flow sampler with a fixed sampling flow rate and observe the sampling flow readings until it stabilises. If the measured flow rate (mean read back) is within 10 % of the nominal sampling rate (or set up point) the check is accepted. Otherwise the check procedure needs to be restarted, or corrective action is required.
- **Step 6:** If the corrective actions (change filters, replace batteries, restart the instrument, etc.) does not work, a malfunction of the High Flow sampler is indicated, and major corrective action (e.g. servicing the equipment) and check revaluation (Step 5) should be successfully undertaken before use.

The High Flow sampler and the detector checks according to the points above should be carried out at least twice a day, first before starting the measurements and secondly after the last measurement. If the checks are carried out during the day and it is found that the readings deviates from the corresponding values by more than 10%, the instruments should be adjusted and the leakage should be rechecked, discarding the leak rate values obtained after the last correct check.

7.4 Sampling and measurement procedure for hydrogen leak quantification

- **Step 1:** Check that there is no explosive atmosphere at the measurement site.
- **Step 2:** Check that the weather conditions allow the use of the equipment (sampler and detector) for measurement, it must not rain so as not to flood the detector, and the air temperature and relative humidity should be consistent with the operating range of the device used. High Flow sampler internal pump should be turned off (without turning off the instrument) when not needed to extend the use of battery.

Care should be taken to minimize the effect of the wind when the wind speed exceeds 0,5 m/sec, particularly when working in elevation.

- **Step 3:** Determine the background concentration of hydrogen placing the probe inlet in a point which is far (as possible) and upwind of any equipment potentially producing gas leaks. Repeat this at least in three different places within the area to be inspected.

The background is more relevant in closed spaces and areas with limited ventilation. The background reading must be above the LOD to be considered as a significative value. Record the background levels (if any). For the background records just register the ambient target gas concentrations (no leak rate is associated to this).

- **Step 4:** Determine whether the detector reading is affected by ambient humidity (moisture). If the reading is less than 5% of the values obtained for hydrogen leaks, then do not apply any correction. Otherwise, if possible, evaluate if the response to humidity is systematic, and take this into account to correct back the instrument readings.

For some instruments it could be enough to subtract the reading produced by the humidity, for other detectors it may be better the use of specific response factors.

- **Step 5:** When measuring a confirmed leaking component, select the probe tip attachment most convenient for this specific situation. The aspects to be considered here are (this point is fully covered in Section 7.6):
    - Size and type of the leaking component
    - Whether the leak source location has been found with precision and whether it is vaguely located
    - Geometry and accessibility of the leak source, i.e., whether there are pipes or other equipment preventing the easy approach of the tip probe or any bigger attachment
    - Whether it is an individual, a dual, or a multiple leak
    - Whether the measured gas concentration in the leak detection stage is small, medium or high
- **Step 6:** Attach the selected accessory (if any) to the hose/probe
- **Step 7:** Place the probe inlet/attachment at the surface of the point of component where leakage is occurring
- **Step 8:** Wait at least twice the response time while observing the instrument readout

The sampling and measurement processes should be slow enough to allow the dragging of the sampled gas inside the sampling system and the detector.

WARNING: If the measurement time is too short, then the amount of leaked gas introduced in the sampling system could be low, and there is a higher risk of underestimating the assessed leak.

- **Step 9:** If a variable gas concentration reading is observed, wait until the maximum meter reading is obtained and record this value. Keep observing and register the number replicas you planned (at least 3) taking only the maximum values during each observation time (no less than 1 minute each).
- **Step 10:** Record the results (maximum concentration values and corresponding sampling rates) as the data assigned to the quantified leak. Record the values using the units shown in the equipment display (if needed, units' conversion should be worked out later). In the case of equipment registering data automatically, verify that you waited long enough to allow the capture of the required maximum concentration values during each one of the observation times. These individual observations are called tests, and different tests shall be recorded for each leak under assessment (as Test 1, Test 2, etc., at least three of them).

After placing the sampling hose as close as possible of the leak source, it is suggested to wait until a stable steady state is achieved (typically one minute is enough). In that condition, measured maximum values are more reliable than mean values, since wind and diffusion could cause that the whole leaked gas plume is not captured by the sampling system (leading to underestimations). However, the usual procedures are not likely to concentrate the gas (in the steady state), so overestimations of the measured concentrations are not expected.

Care should be taken to minimize the effect of the wind, particularly when the wind speed exceeds 0,5 m/s. In these cases, wind barriers may be employed to limit its impact on the areas being sampled.

In the unusual case of extremely large leaks (several tens to hundreds of litres per minute) the leak will be producing high concentration readings, care should be taken to not exceed the upper measuring range of the detector, as this may lead to its poisoning. Even more importantly, if the measured hydrogen concentration or leak rate is higher than any upper limit previously agreed as for safety reasons, the measurement should be terminated. In such cases, the measurement result is assumed to be higher than the upper limit, and both the measured concentration value and the leak rate value should be reported as > corresponding preset upper limit.

After any leak quantification measurement, take some measurements far from the equipment being assessed and be sure that the instrument readings have returned to zero (or to background levels) before attempting to quantify more leaks. Take the necessary time until the measured values return to the commented low level (certain detector types require more time than others, especially if they were exposed to high hydrogen gas concentrations).

7.5 Uncertainty calculations

This chapter will be created after the method is validated.

7.6 Typical leak components and locations to be quantified

Typical components/locations where this leak quantification procedure can be used:

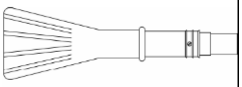
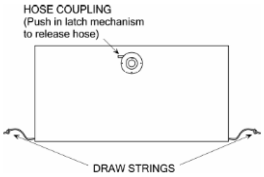
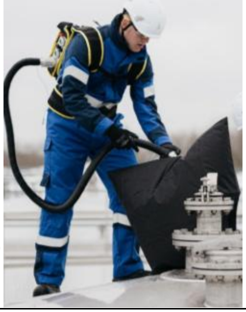
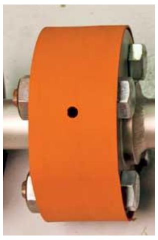
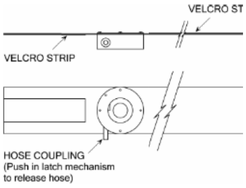
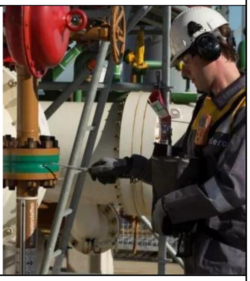
- Valves and valve stems
- Flange and other connections
- Pump, compressor or agitator's seal
- Process drains
- Open-ended lines or valves
- Access door seals
- Other components
- Joints, connections, welding seams, pipes suspected under fatigue, excessive mechanical stress or even corroded are also susceptible to leak hydrogen gas.
- Pressure relief device
  WARNING: the idea is to quantify the leak, not the discharge event. It means that the measurement of pressure relief devices shall be performed only when the internal pressure is lower than the threshold pressure activating the release valve. Support from the site's personal shall be required to ensure that the working pressure during the leak detection is below the release pressure, otherwise do not attempt to measure the device, and just report that this was not included in the quantification survey.
- Other leak quantifications. If any local system (installed on site) is quantifying hydrogen leaks in the same component or group of components (as systems based of differential pressure loss), consider the possibility of comparing the High Flow method results with these results (if the data is available).

7.7 Selecting the attachment for leak sampling and measurement

The sampling volumetric flow rate is the main parameter to be selected when sampling a previously detected leak in order to quantify it. During the sampling, the leak jet is being dragged by the sampler suction force. The complexity of the leak and the speed of the escaping gas jet challenge the mentioned suction force, making difficult to achieve complete gas capture in some cases. Sometimes it is convenient to increase the suction force by reducing the size of the probe inlet. For a given volumetric flow rate, the smaller the probe tip diameter the faster the sampling flow speed. On the other hand, there are cases in which the inspected equipment (or specific part of an equipment) is bigger than the hose diameter, or cases where the leak source is not a simple point. In these cases, a wider probe tip is required to cover the area of interest. For that reason, there is a trade of between the size of the probe tip and the area being covered. The commercially available High Flow samplers are provided with set of attachments or accessories covering a range of situations and conditions to be sampled. The most commonly used are described below in Table 2.

Table 2. Types of attachments and accessories used to sample the leaking gas.

High Flow probe tip attachment

Sampling gas hose (sampling line) The sampling hose can be found with different lengths, typical 2-3 m length, or up to 10 m length. They can even be assembled in tandem, allowing longer distances. However, take into account that this could potentially reduce the sampling flow rate, which require to be monitored.	
Claw Tool For leak sources spread out over a narrow area, such as a crack in a pipe, square flanges, and cylinder heads.	
Bevelled Nozzle For simple pin-hole type leaks, position this attachment directly over the leak source. Used to get the best possible approach to the known leak source.	
Hose (use of the naked hose tip) For simple pin-hole type leaks or for small leaking items, position this attachment directly over the leak source. Used when no obstacles to approach a leak source are present (no space restrictions preventing the hose access for a direct contact with the point of interest).	
Cone Also known as plunger or bellows tool. It is useful in capturing leaks in valve stems and small fittings. Better if the leaking item fits (at least partially) inside the cone.	
Capture bags The are several types of bags that can be used. Bags are used to constrain the escaping gas. Surround or wrap the leaking item with the bag. The bag is connected to the sampling hose. Some bags have special connection ports to couple the hose hermetically.  	
Straps around flanges There are several strap types: plastic disposables, reusable adjusted with Velcro, rubber, etc. Some of them have airtight hose couplings. Wrap the strap around the flange and do sample the gas from the orifice or coupling. If the strap was installed previously, verify its integrity.  	
WARNING any probe attachment must be made of antistatic materials to prevent electric sparks. **WARNING** do not close the bags or straps tightly, they need an ambient air entrance, typically opposite to the hose coupling.	

7.7 High Flow method for leak rate quantification

This method is based on the large pumping capacity of a sampling system, which effectively capture nearly all of the gas around the area where a gas leak has been previously detected and located. The gas inside the detector chamber is made up by the leaked gas blended with the surrounding air. Subsequently, this diluted mixture of gases is analysed internally by a sensor or subsampled and measured externally by a detector, providing a quantification of the concentration of the target gas in the blend. The sampling flow rate pumped inside the detector is also accurately measured in real time. The method consists in using both measurements, the diluted gas concentration (assumed to be homogeneous inside the detector chamber) and the sampling flow rate, to calculate the target gas leak rate as follows:

$$Q_{leak} = S\,(c_{H2} - c_{Bk}) \quad \text{Eq. 1}$$

Where Q_{leak} is the target volumetric leak rate (in L/min), S is the sampling rate (also in L/min) and c_{H2} is the hydrogen concentration inside the detector chamber (expressed as a volume fraction, for instance if a concentration of 1% is measured, then c_{H2} is 0.01), while c_{Bk} is the background concentration (if any) also should be expressed as a volume fraction. The background concentration is measured in the same area but outside the zone being influenced by the leaks.

The used leak rate equation (Eq. 1) is based on the assumption that the whole leaked gas has been captured during the measurement period, this condition is known as leak full capture or complete capture. In the cases in which the sampling process is not able to drag the whole leak, the multiplication of the sampling flow rate and the gas concentration value will be an underestimation of the actual leak rate. That is why it is of paramount importance to use the best possible strategy and accessories (Table 2) to achieve the full capture condition.

The calculated volumetric hydrogen leak rate is given at the conditions at which the measurements were done. If needed, the corresponding volumetric leak rates can be calculated for any given condition, for example for 20 ºC (293.15 K) and standard atmospheric pressure (101.325 kPa). In the section 7.10 it is discussed how to express the leak rates in terms of mass leak rates, which does not depend on the temperature or pressure at which the measurements were performed.

Typically, the high flow sampling device allows for the total sample flow to be adjusted. A measurement should be made at both at the maximum flow and at a lower flow ~70-80% of the maximum. In this way, any potential subsampling can be identified. If both measurements are in agreement within 10%, it means that the leak rate measurement can be regarded as a valid one. On the contrary, if the first measurement produces leak rate values higher than the second one (with differences > 10%) it means that at least the second (lower flow) measurement is underestimating the actual leak rate, and possibly even the first (highest flow) measurement too. In that case, if possible, the sampling flow rate should be increased, and the process should be repeated until the mentioned agreement is reached. In the case that the sampler is operating at its maximum sampling flow capacity and there are still discrepancies, the leak rate shall be registered as higher than the obtained value (Leak rate > Q_{leak} given by Eq. 1), and a note on the lack of ability of using a higher sampling rate should be registered.

Some manufacturers have developed instruments designed for methane leak quantification using this method, such as the SEMTECH HI-FLOW 2 ($S_{max} \approx 1000$ L/min) or the BACHARACH HI-FLOW sampler ($S_{max} \approx 280$ L/min), which have been successfully used for many years in methane and natural gas leak monitoring. However, to the best of our knowledge, there are no commercial equipment of this kind specifically developed for hydrogen leak monitoring yet (although the available ones can be used with an external hydrogen detector for H_2 leak rate quantification).

This method can be used to monitor hydrogen leaks, if the used detector (or sensor) can measure large H_2 concentrations (e.g., thermal conductivity detectors can measure up to 100% in volume) and if a proper ATEX certification (or equivalent) is provided. In the best case the maximum leak rate to be measured by the High Flow method is constrained by the maximum sampling rate of the equipment ($Q_{leak} \leq S$). This represents hundreds of litres per minute with the above mentioned commercially available equipment.

While these instruments are portable, they offer a highly convenient method for quantifying relatively large leak rates (potentially up to hundreds of litres per minute).

7.8 End of measurements

Bear in mind that after the leak quantification stage conclude, the detector calibration shall be verified.

Then, after the last measurement the High Flow sampling system and the used detector need to be purged with ambient air to zero the readings before turning the detector off.

7.9 Correction for the leak rate measured values

It is important to note that the equations described before assumes that the target gas concentration inside the leaking element is 100%, and that the lower concentration measured by the instrument is caused only by the dilution of the gas with atmospheric air. It means that the equations above can be used only for leaking elements containing pure gases, as pure hydrogen in our case. In case of having diluted or blended gases inside the leaking element, equations 1 and 2 must be corrected as follows:

$$Q_{blended\_leak} = \frac{Q_{pure\_gas}}{c_0} \tag*{Eq. 2}$$

where Q_{pure_gas} is the result given by Equation 1, or in this case:

$$Q_{blended\_leak} = \frac{S\,(c_{H2} - c_{Bk})}{c_0} \tag*{Eq. 3}$$

c_0□ represents the concentration of the target gas inside the leaking equipment (tank, pipeline, etc.). For instance, in the case of hydrogen diluted in nitrogen, if a 20% H_2 + 80% N_2 c_0□ = 0.2 for H_2. Another example, hydrogen enriched methane, if a 20% hydrogen + 80% methane blend is being transported in a pipe, then □ c_0 2 and □= 0.8 for CH_4 respectively. The last example shows a case that requires the use of selective detector for hydrogen and methane.

Leak rates should also be corrected for different temperatures, since this is affecting the flow rate measurements. This is particularly important when the temperature of calibration differs from the temperature when using, as when comparing winter to summer times. Some system's flow meter is calibrated for a given temperature, then the detector measures continuously the temperature in the internal chamber, in order to provide the actual volumetric flow rate in the measuring conditions by correcting the flow reading using the following relation:

$$S = S' \frac{T}{T_0} \tag*{Eq. 4}$$

where S' is the direct measurement of the internal flowmeter, calibrated for a given temperature T_0 (typically 20 ^{o}C), and S is the actual sampling flow rate under the measuring conditions at temperature T. Note that in Eq. 4 all the temperatures are absolute (measured in Kelvin). Most instruments can perform the correction internally, directly providing the actual sample flow rate to be used for the leak rate quantification. The application of this correction should be verified by the user.

The method uses two different sampling flow rates, one at the highest pump capacity (S_{max}) and the other around 75-80% of this value. Both measurements should be approximately the same (a typical acceptance criterium is having a difference ≤ 10%), since the larger sampling rate causing a larger dilution compensates with the lower measured concentration inside the detector. This way it is ensured that the leak measurement is a good estimate and is not affected by saturation (which could occur in the case of large leaks).

For instance, at the usual sampling rates (S ≈ 220 L/min), if the internal detector is registering a gas concentration of 4.5% in volume (slightly above the hydrogen LEL), it means that the assessed leak rate is approximately 10 L/min. Measurements of larger leak rates will imply measuring hydrogen concentrations higher than 100% LEL in the detector internal chamber.

7.10 Relation between mass and volumetric leak rates

It is often useful to represent the leak rate in terms of mass flow rate instead volumetric flow rate, it means they can be converted to mass of leaked gas per unit time (instead leaked gas volume per unit time), this is important for emissions inventories and other cases where total emissions or balances are relevant.

In this case, the previously discussed leak flow rate (Q_{leak}), which is indeed a volumetric flow rate (Q_V), can be used to calculate the corresponding leak mass rate (Q_M), using the ideal gas state equation leading to Equation 5.

$$Q_M = Q_V \frac{M\,P}{R\,T} \qquad \text{Eq. 5}$$

Where M is the molar mass of the target gas (M = 2 g/mol in the case of H_2), P is the absolute pressure of the atmosphere where the experiment is done (usually standard atmospheric pressure P = 101.325 kPa), R is the ideal gas constant ($R \approx$ 8,314 L Pa/mol K) and T is the absolute temperature of this atmosphere (in Kelvin). Then, if Q_V is the leak rate value in L/min, using the suggested units, the Equation 5 will produce leak mass rates (Q_M) in grams per minute (g/min).

8. Reporting

The leak quantification report shall include the following information:

Site and survey information:

Date and place; scope of the survey (site, area, group of components, specific components); facility type and identification of the site; contact details of the site contact person and the personnel performing the leak detection survey (company or organization, email, phone, certification documents if applicable); type and size of equipment screened (e.g. pipework 2 inches diameter 50 linear metres, or 2 electrolyser units); streams (e.g. H_2, CH_4, NG, etc.); purpose (e.g. LDAR, commission, regulatory); screening conditions (atmospheric pressure, temperature, wind conditions, indoor or outdoor areas, etc.); reporting period.

Note: all this information is required for the Leak Detection report (which in principle should be conducted before the leak quantification). Therefore, it may be not necessary to input this information again if the mentioned report was provided.

High Flow sampling system information:
Characteristics of instrument used: type; model; brand; serial number; sampling rate calibration (provided by manufacturer or other, due date, corresponding units); Include the description of any used accessory (probe tip, extensions, etc.).

Detector information:
Characteristics of instrument used: type; model; brand; serial number; calibration verification (obtained values with their corresponding units); response time; LOD, precision (indicated by the manufacturer or determined as in 6.3), sampling pump rate (if it is a sniffer), target gas (e.g. flammable gases or specific for a given gas), and whether it is selective for H_2 (or not). Include the description of any used accessory (probe tip, extensions, etc.).

Calibration gas information:
Used calibration gas or certified gas cylinders (if applicable) and their concentrations.

Background values information:
Measured background values (if possible in three different places) or LOD if it is the case. This is needed mainly in enclosed spaces where H_2 background concentrations could be built up along the time.

Reporting leaks:

For each one of the quantified leaks: leaking component; site label identification if any; location of the detected leak; measured H_2 leak rate; actions taken (if the case, only for authorised works); component's internal hydrogen concentration (e.g. pure H_2, or 20% H_2, etc.); internal gas pressures (if known); whether the screened components are under continuous or intermittent work; type of area as indoor or outdoor; photos can be included to ease the identification of leak location (only use authorised ATEX cameras / mobile phones). Consider whether is worth labelling the quantified leak sources to help identify their location in subsequent repair operations. Any case in which the detector reading is due to ambient humidity, describe any correction applied to the data (include both, raw and processed data). If possible, mark the leaking items in the site plan or map.

An example of a leak quantification survey report is presented in Annex A

9. Bibliography

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ANNEX A

Form 1. General information (site, survey, equipment)

Site general information					
Site		Site contact person		Email / phone	
Date		Reporting period		Installation/ equipment type	
Atm. pressure		Range of atm. Temperature		Wind conditions	
Hydrogen leak detection survey general information					
Leak survey company		Leak survey contact person		Email / phone	
Survey scope		Survey purpose		Gas(es) type(s)	
Internal gas concentration (split by areas if needed)			Internal gas pressure (split by areas if needed)		
Hydrogen gas detector general information					
Detector type		Model / Brand		Serial number	
Response time		LOD (conc.)		Sampling rate (if applicable)	
Target gases		H_2 selective	YES NO	Accessories	
Initial cal. precision (%)		Final cal. Precision (%)		Calibration H_2 Concentration(s)	

Form 2. Hydrogen leak quantification report

Data obtained in the leak quantification survey. In this example the form was written grouping the components in classes (e.g. flanges, valves, etc.). Some examples in the comments sections have also been included.

Hydrogen leak detection survey report

Item #	Element ID	Leaking component	Hydrogen Leak rate L/min	Photo ID (file)	Location / Notes / Comments -
NA	Bkg 01	Background			Zone 2
	Bkg 02	Background			
	…				
1		Valve ¾ inch			
2		Valve ¾ inch			Fluctuating value
…		…			…
20		Valve ½ inch			Internal P = 20 bar
21		Valve ½ inch			
…		…			
30		Flange 3 inch			Well above LEL, priority LDAR
…		…			
35		T connection ¼			Permitted action taken: adjusted, leak eliminated
…		…			
50		P relief valve			Outdoor, windy
…		…			
55		Compressor seal			
56		Welded joint			