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Pipelines for hydrogen transport: A review of integrity and safety challenges

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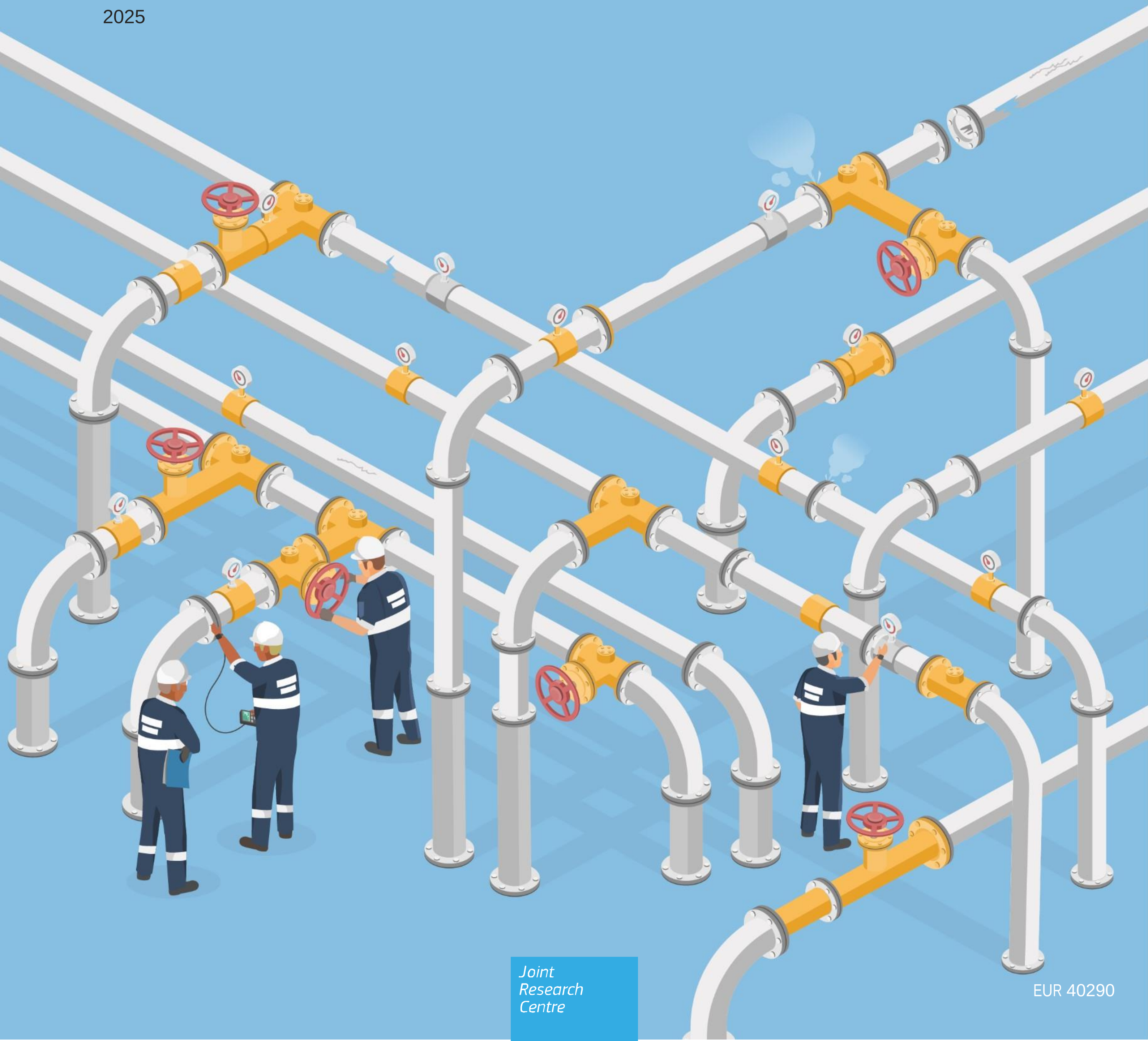

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Abstract

The European Commission highlights hydrogen as an important energy carrier and chemical feedstock that could help decarbonise sectors otherwise deemed hard-to-abate. Europe's existing natural gas grid is seen as a promising asset to repurpose for the transportation of hydrogen. This technical report provides a literature review of hydrogen's impact on pipeline materials, particularly steel and polymers. Hydrogen is known to reduce the ductility, fracture toughness, and the fatigue crack growth resistance of steel materials commonly found in transmission pipelines. It is also known to permeate through polymeric materials that are often used in the distribution grid. The possible implications for pipeline integrity and safety are reviewed. This report emphasises the need for further experimental research and practical experience combining material science and safety engineering disciplines. Key areas lacking knowledge include the full- or large-scale validation on pipeline sections of small-scale laboratory results, the behaviour of typical pipeline defects, and the long-term performance of polymeric pipeline materials, all under the influence of gaseous hydrogen. The report highlights the essential role of testing facilities such as the High-Pressure Gas Testing Facility (GasTeF) of the European Commission's Joint Research Centre in addressing these gaps.

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1 Introduction

The European Union has set an objective within its energy policy framework to transition to a cleaner and more sustainable energy future. This is aligned with the broader international commitments to mitigate climate change, as outlined in the Paris Agreement (European Union, 2016), and with the European Green Deal (European Commission, 2019) that established a roadmap for cutting greenhouse gas emissions, while also boosting a modern and resource-efficient economy. Hydrogen produced from low-carbon energy sources can play an important role in this transition due to its potential to decarbonise sectors that are hard to electrify, such as heavy industry and transport. It can also act as a storage medium to balance energy supply volatility from energy sources such as wind and solar. With this in mind, the European Commission has adopted strategies and plans, including the Hydrogen Strategy for a Climate-Neutral Europe (European Commission, 2020), the REPowerEU Plan (European Commission, 2022) and the EU Hydrogen and Gas Decarbonisation package (European Commission, 2024 [Directive (EU) 2024/1788 and Regulation (EU) 2024/1789]), which set ambitious targets to scale up hydrogen production and develop the necessary infrastructure.

The existing natural gas infrastructure, with its extensive network of pipelines and storage systems, presents an opportunity for the swift development of hydrogen transport pathways. By repurposing some of these assets for hydrogen, the European Union could potentially lower the costs and accelerate the deployment of a hydrogen transmission and distribution network. Such a strategy would also capitalise on the existing technical and regulatory experience from the natural gas sector.

This technical report aims to provide an overview of the current understanding of the interaction between hydrogen and pipeline material (mainly steel and polymers) properties, and to assess the implications for the integrity and safety of hydrogen pipelines in general, including repurposed natural gas pipelines. The objective is to deliver an examination of the challenges and risks from a technical perspective associated with transporting hydrogen through new and existing pipeline systems, and to suggest measures to address the identified gaps in knowledge and practice.

By integrating findings from experimental research, modelling, and industry experience, the report seeks to facilitate the convergence of material science and safety engineering disciplines in the context of hydrogen pipelines. It highlights the need for a multidisciplinary approach that combines research and development (R&D), standardisation, risk management, and policy development to ensure a successful and secure transition from natural gas to hydrogen infrastructure.

The report identifies several areas where knowledge is lacking, such as the full- or large-scale validation on pipeline sections of small-scale laboratory results, the behaviour of typical pipeline defects, and the long-term performance of polymeric pipeline materials, all under the influence of gaseous hydrogen. Addressing these gaps is essential for formulating reliable guidelines and standards. Furthermore, the report emphasises the role of testing facilities such as the High-Pressure Gas Testing Facility (GasTeF) of the European Commission's Joint Research Centre (JRC) in advancing experimental evaluations of the safety and performance of materials and components in hydrogen environments.

The report is structured in seven sections followed by a discussion.

Section 2 describes the natural gas and hydrogen infrastructure in the European Union.

Section 3 focuses on material science and the understanding of the interaction between hydrogen and pipeline materials, covering steel and polymeric materials.

Section 4 turns to safety engineering and the assessment of the implications for the integrity and safety of hydrogen pipelines.

Section 5 provides an overview of the requirements, codes, guidelines and standards for hydrogen pipelines.

Section 6 presents a review of testing facilities capable of performing experimental research of the behaviour of hydrogen pipelines.

Finally, Section 7 shows the capabilities of the High-Pressure Gas Testing Facility (GasTef) of the JRC and its role for filling knowledge gaps regarding the safety and performance of both new and repurposed natural gas pipelines transporting hydrogen.

2 Natural gas and hydrogen infrastructure in the European Union

2.1 Natural gas infrastructure

The natural gas infrastructure in the European Union (EU) is a vast and complex network that plays a crucial role in ensuring energy security and meeting energy demands of the EU countries. This infrastructure includes thousands of kilometres of pipelines, numerous storage facilities, liquefied natural gas (LNG) terminals, and various interconnectors that link different countries' gas systems. The EU has been focusing on diversifying its supply routes and sources, as well as enhancing the integration of its internal energy market.

The total length of the natural gas pipeline system within the EU is extensive. According to the European Network of Transmission System Operators for Gas (ENTSOG) (ENTSOG, 2022), the EU's and UK’s combined transmission network consists of approximately 200,000 km of high-pressure gas transmission pipelines as of 2022. This network enables the transportation of natural gas from production sites and import terminals to distribution networks, which in turn deliver the gas to consumers. The distribution network is even more extensive, with over two million km of pipelines in the EU (ACER, 2023).

The EU's natural gas infrastructure has been developed over many decades, with a significant expansion in recent years to integrate new EU countries and to secure alternative supply routes. For instance, the EU has focused on reducing its dependency on Russian gas by developing the Southern Gas Corridor, which includes the Trans Adriatic Pipeline (TAP) and the Trans Anatolian Pipeline (TANAP), delivering gas from North Africa and from the Caspian region to Europe.

LNG terminals are also important components of the EU's natural gas infrastructure. These facilities enable the importation of natural gas in its liquefied form from global markets, which is then evaporated and fed into the pipeline system. The largest LNG terminals in the EU are located in Spain, the Netherlands, France, and Italy, reflecting the strategic importance of these locations for accessing global LNG supplies (Gas Infrastructure Europe, 2022).

Storage facilities are used for managing seasonal demand fluctuations and ensuring the security of supply. The EU has significant storage capacity, with over one thousand TWh available across the EU countries (Gas Infrastructure Europe, 2021). These facilities enable the EU to stockpile natural gas during periods of low demand (like summer) and release it during peak demand in the winter months.

Although the EU's natural gas infrastructure is well-developed, there are still ongoing projects and plans to further enhance the network. Since the introduction of Regulation (EU) No 347/2013 on guidelines for trans-European energy infrastructure, several natural gas infrastructure projects have been recognised as Projects of Common Interest (PCI) by the European Commission. PCIs include key infrastructure projects that are intended to better interconnect the energy systems of the EU countries, thus improving security of supply and increasing competitiveness.

The EU's natural gas infrastructure is essential for the energy supply and economic stability of the EU countries. With ongoing investments in infrastructure and the progressive integration of renewable gases, the EU's natural gas network is set to play an important role in the energy transition of the EU countries’.

The European Green Deal (European Commission, 2019), and the EU's commitment to the Paris Agreement (European Union, 2016), also have significant implications for the future of the natural gas infrastructure. The EU aims to become carbon-neutral by 2050 (European Commission, 2019), which will require a shift from fossil fuels, including natural gas, to renewable energy sources. In the transition, natural gas is often seen as a 'bridging fuel', but the current infrastructure will need to adapt to accommodate renewable gases such as biogas and hydrogen.

2.2 Hydrogen infrastructure

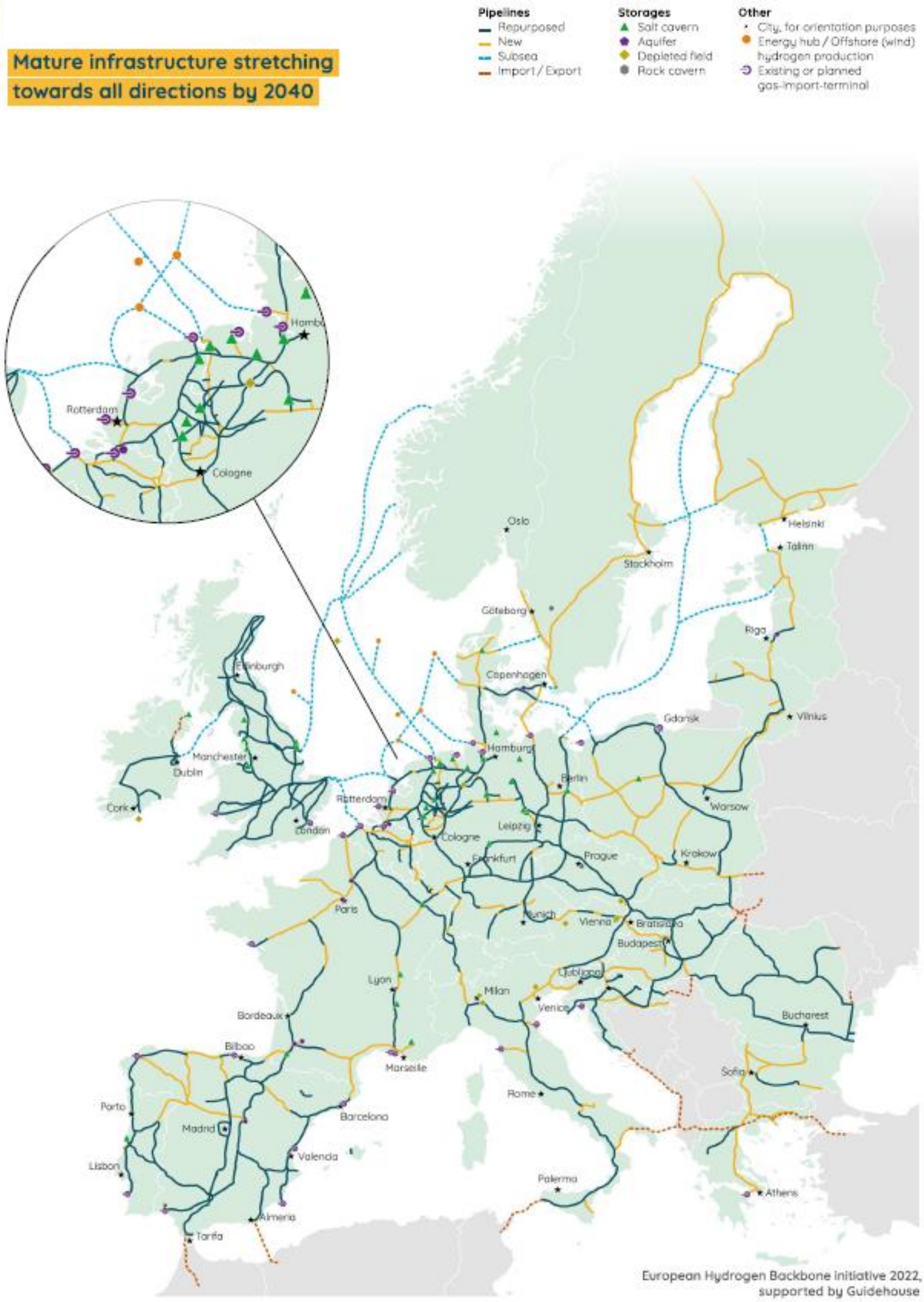
Today, there are approximately 5,000 km of hydrogen pipelines in operation worldwide (IEA, 2023). Around 2,000 km of those are located in Europe. Their use is primarily in hydrogen demanding industries such as petroleum refineries and chemical plants.

With the EU's aim to have a cleaner and more sustainable energy system, hydrogen has been gaining attention. The European Hydrogen Backbone (EHB) initiative, proposed by a group of 31 European gas infrastructure companies, envisions a hydrogen network spanning over 53,000 km by 2040 with 60% consisting of repurposed pipelines and the remaining being new construction (van Rossum et al., 2022). The vision is presented in Figure 1. An Important Project of Common European Interest (IPCEI) called Hy2Infra (European Commission, 2024a) is supporting this European development. IPCEI Hy2Infra will support the deployment of approximately 2700 km of new and repurposed hydrogen transmission and distribution pipelines between 2027 and 2029.

In addition, the 6th list of Projects of Common Interest adopted in November 2023 included for the first time hydrogen and electrolyser projects (European Commission, 2023). Out of the 65 project selected, 29 of them aim to develop cross-European hydrogen transmission pipelines.

Newly built hydrogen infrastructure projects and projects on the retrofitting/repurposing of existing infrastructure are also taking place at the national level in Europe. Those are complemented by national, regional and European R&D projects on pipelines for hydrogen transport. On the international stage, in addition to Europe, US has been the main player in setting up and implementing R&D projects of relevance for hydrogen transport by pipelines A non-exhaustive compilation of those projects is given in Annex 1.

Figure 1. The vision of the European Hydrogen Backbone by 2040.



Source: (van Rossum et al., 2022)

2.3 Characteristics of the natural gas grid

The natural gas infrastructure is divided into two parts: transmission and distribution. The function of the two systems is as the names imply to transmit large quantities of gas from one place to another, and to distribute the gas to customers. The two systems are connected, the distribution grid distributing gas from the transmission grid to the end customers. Generally, distribution grids operate at pressure below 16 barg while transmission grids operate above this threshold.

Pipes in the transmission grid in European countries are mainly made from steel material following the API 5L specification (API, 2018). These steels are characterised as plain carbon ferritic steels, with small amounts of alloying elements. Data from the European Gas Pipeline Incident Data Group (EGIG), which include data from 19 European gas transmission system operators, indicate that steel from Grade B to X70 are all common, with higher steel grades becoming popular in recent years (European Gas Pipeline Incident Data Group, 2024). More than 65% of the natural gas transmission pipelines operate at pressure in excess of 65 barg. Wall thicknesses between 5 and 10 mm represent around 40% of the total grid. The oldest parts of the transmission grid was constructed before 1954, and more than half of the operational grid in 2022 was constructed before 1984.

A pipeline is constructed from pipe segments, typically of 12 m each, welded together by girth welds in the field. Depending on the manufacturing method of the pipeline segments, they may also contain a longitudinal or spiral weld.

The gas distribution grid on the other hand is mainly made from polymeric material, with polyethylene (PE) and polyvinylchloride (PVC) being the most common polymers (Marcogaz, 2018). Steel, and to a lower extent cast iron, are also used. Cast iron is being phased out in favour of polymer pipes. The distribution grid operates at pressures below 16 barg, and more commonly below 5 barg (Marcogaz, 2018). Pressures can be even lower, 100-200 mbarg, depending on the end use.

2.4 Operating conditions for a future hydrogen gas grid

Operating conditions refer to the flows, pressures, gas quality, etc. and variations thereof that exist in the pipeline. The operating conditions influence the design of the pipeline. For example, a pipeline required to hold a higher pressure needs thicker walls, and a pipeline that should transmit larger amounts of energy needs a larger diameter. Hence, an understanding of the operating conditions is required to understand the behaviour of a pipeline transporting hydrogen.

The operating conditions are influenced by the supply and demand of hydrogen. The aim of this section is not to predict the balance between hydrogen supply and demand, but to provide a high-level discussion based on some case studies and the physical properties of hydrogen compared to those of natural gas.

The grid should preferably be able to transport roughly the same amount of energy (measured in watt-hours or joules) in hydrogen as in natural gas operation. Whereas hydrogen has roughly one third of the energy content per unit volume compared to natural gas, the energy content per unit mass is almost three times higher for hydrogen than for natural gas. Bainier and Kurz (Bainier & Kurz, 2019) have shown numerically that the energy transported at the same pressure ratios (pressure difference between start and end point) as in natural gas operation for 10%, 40%, and 100% hydrogen-methane blends leads to a reduction in energy transported of 4%, 14% and 15 to 20% respectively. When operating at the same pressure ratios, energy demands from compression increase by 7%, 30% and 210%, and maintaining the same energy flow requires an increase of compression power by 11%, 52% and 280% respectively (Bainier & Kurz, 2019).

Hydrogen's lower density and viscosity enable it to flow faster than natural gas at equal pressures (Hua et al., 2024). However, this increased velocity, potentially exceeding 60 m/s to match natural gas's energy transport due to hydrogen's lower volumetric energy density, can lead to pipeline safety concerns such as vibrations and erosion (González Díez et al., 2021; Hua et al., 2024; PWC, 2021). While natural gas pipeline velocities are typically limited to below 20 m/s, hydrogen's faster flow is less problematic regarding pulsations and vibrations according to studies in the HyDelta and HyWay27 projects (González Díez et al., 2021; PWC, 2021). Still, erosion - the removal of metal by solid particle impacts - poses a risk to pipeline integrity. The API RP 14E (API, 1991) formula for calculating erosion velocity, yielding an approximate value of 20 m/s for natural gas transmission pipelines, has been criticised for being overly conservative, especially since solids-induced erosion is less of a concern in gas pipelines compared to liquid ones (Hua et al., 2024; Topolski et al., 2022).

Natural gas transmission pipelines in Europe are typically between 508-1219 mm in diameter, and operated at a pressure between 50 and 80 barg (Wang et al., 2021). The primary stress on pipelines is hoop stress due to the internal pressure (Lipiäinen et al., 2023). This implies that the operating pressure of a repurposed natural gas pipeline cannot be significantly higher than the pressure it was designed for in natural gas use. The stress on a pipeline due to the internal pressure is calculated using Barlow's formula.

Equation 1. Barlow's formula.

$$\sigma = \frac{P \times OD}{2t}$$

P = pressure (MPa)

OD = outside diameter (mm)

T = wall thickness (mm)

σ = stress (MPa)

This formula is often combined with various design factors in order to define a maximum allowable operating pressure (MAOP). These design factors can include considerations such as the potential consequences of a rupture, the possibility of third-party damage, and materials' susceptibility to hydrogen embrittlement.

Another important operational condition is the fluctuations in pressure in the pipeline. These fluctuations can come from variations in supply and demand, but also from natural variations due to the flow conditions. Pressure cycling is a source of fatigue and should therefore be considered in managing the integrity of the pipeline. Typically, pipelines are maintained at a relatively constant pressure (Baek et al., 2017; Fekete et al., 2015; Kappes & Perez, 2023b; Monsma et al., 2023) where the ratio between lowest and highest pressures is above 0.8-0.9. The frequency of pressure fluctuations depends on the operating conditions.

3 Hydrogen's effect on pipeline materials

The materials used in pipelines range from steel, which is most common in transmission pipelines, to polymeric materials that are more frequently used in distribution pipelines. The effect of hydrogen on these two types of materials is vastly different. Hence, this section is split between steel and polymer materials.

3.1 Steel materials

Gas pipelines are typically constructed from plain carbon ferritic steels with low amount of alloying elements. The most common steel classification for gas pipelines is API 5L/ISO 3183. Steels from that classification are discussed in this section. Other kinds of steel, such as austenitic steels, or non-ferrous steels, are not covered in this report.

Hydrogen's specific properties allow it to dissociate into atoms and diffuse into solid materials, leading to hydrogen embrittlement. The interaction of hydrogen with materials is a multi-step process: hydrogen molecules adsorb onto the material surface, dissociate into atoms, and then these atoms are absorbed by the material and diffuse through it (Barrera et al., 2018).

There is some inconsistency over terminology in the field (Gallon et al., 2020). Hydrogen embrittlement is here used broadly, encompassing the effect of hydrogen on material properties such as strength, ductility, fatigue endurance, and fracture resistance when exposed to gaseous hydrogen at conditions expected in typical pipeline operation.

Hydrogen embrittlement is governed by three factors (San Marchi & Somerday, 2012):

— Environment (Partial pressure, impurities, temperature)

— Mechanics (Stress, defects, residual stresses)

— Materials (Strength, microstructure, homogeneity)

The diffusion process and hence hydrogen embrittlement is influenced by environmental factors. For instance, hydrogen absorption is less in a gaseous hydrogen environment than in a wet and sour H_2S environment (Sandana et al., 2021). The absorption scale depends on the hydrogen gas pressure, which is determined by the hydrogen proportion in a blend and the operating pressure of the pipeline. The equilibrium hydrogen concentration in steel can be calculated using Sieverts' and Fick's laws (Gallon et al., 2020).

In terms of material properties, hydrogen exposure generally decreases steel ductility and fracture toughness and increases fatigue crack growth rates (FCGR), with only a minor effect on steel strength (Gallon et al., 2020; Laureys et al., 2022; San Marchi & Somerday, 2012; Sandana et al., 2021). Moreover, hydrogen embrittlement is most severe at room temperature, particularly for carbon and low-alloy steels (Kappes & Perez, 2023b; Laureys et al., 2022).

To assess the impact of hydrogen on metal performance, small-scale laboratory tests are performed and include slow strain rate tensile tests, fatigue crack growth rate tests, and fracture toughness tests (Kappes & Perez, 2023b). However, there is a prevailing belief that small-scale laboratory tests may not accurately represent the behaviour of full-scale pipelines, leading to overly conservative predictions (Gallon et al., 2020). This has highlighted the need for full-scale component testing at specific infrastructures, such as at the High-Pressure Gas Testing Facility (GasTeF) of the European Commission's Joint Research Centre (JRC) (see section 7).

No lower limit of hydrogen (partial pressure hydrogen or volume percentage hydrogen) has been identified under which there is no threat from hydrogen to material integrity (Kappes & Perez, 2023b, 2023a). Even in 10 MPa 1% hydrogen-methane blends, significant reductions in fracture toughness and resistance to fatigue crack growth were observed in X70 steel (Nguyen et al., 2021). Fatigue crack growth rate was in this study only measured at stress intensity factor ranges of around 21 MPa*$m^{1/2}$ and above, which may not be representative of conditions encountered in pipeline operation. FCGR increased roughly by a factor of 10. Fracture toughness decreased around 30% in 1% hydrogen and 50% in 100% hydrogen (Nguyen et al., 2021). The European Pipeline Research Group (EPRG) does not have a recommendation on the lower limit of hydrogen partial pressure or volume percentage of hydrogen that would not induce hydrogen embrittlement (EPRG, 2023). Instead, they refer to literature that suggests that no such limit exists.

It has been widely agreed that cracking of pipeline steel in a gaseous hydrogen environment takes place exclusively in the presence of pre-existing cracks or flaws (Sandana et al., 2021). For molecular hydrogen to have a negative effect on pipeline steels, it is hypothesised that there needs to be active plasticity and an exposed metal surface free from contaminants such as oxygen and carbon monoxide (Andrews et al., 2022).

The proposed mechanisms of hydrogen embrittlement typically fall into three types as presented in Table 1 (Chen et al., 2013; Lynch, 2011). However, degradation often needs to be explained by a combination of the different mechanisms (Djukic et al., 2019; Laureys et al., 2022). Depending on the source of hydrogen, the terms Internal Hydrogen Assisted Cracking (IHAC) (Chen et al., 2013) or Internal Hydrogen Embrittlement (IHE) (Lynch, 2011) can be used when the hydrogen was already present in the bulk material. The terms Hydrogen Environment Assisted Cracking (HEAC) (Chen et al., 2013) or Hydrogen Environment Embrittlement (HEE) (Lynch, 2011) is used when the source of hydrogen is external and hydrogen atoms form by dissociation at the crack tip.

The scope of this technical report is not to provide an exhaustive review of the fundamental physical and chemical mechanisms driving hydrogen embrittlement. Rather, it concentrates on the engineering consequences of this phenomenon. More precisely, the report investigates how hydrogen exposure alters material properties essential to pipeline integrity, safety and performance, with an emphasis on the resultant operational challenges and risks.

Table 1. Proposed mechanisms of hydrogen embrittlement.

Hydrogen Enhanced Decohesion (HEDE)	*"HEDE is based on the weakening of metal-metal bonds at or near crack tips by localized concentrations of hydrogen so that tensile separation of atoms (decohesion) occurs in preference to a slip system. [...] The weakening of bonds is caused by decreases in electron-charge density between metal-metal atoms due to the presence of interstitial hydrogen atoms."* (Chen et al., 2013)
Hydrogen Enhanced Localised Plasticity (HELP)	*"HELP is based on localized softening by solute hydrogen in the form of hydrogen atmospheres around both moving dislocations and obstacles to dislocations in a volume of material ahead of cracks. Since hydrogen diffusion is rapid in the temperature and strain-rate ranges where HE generally occurs, these atmospheres can adjust themselves readily in response to changing elastic stress fields, such that the total elastic energy is minimized when dislocations approach obstacles. Consequently, the resistance to dislocation motion due to obstacles is therefore decreased, and dislocation movements are enhanced. Since hydrogen concentrations are localized near crack tips due to hydrostatic stresses or entry of hydrogen at crack tips, deformation and plasticity are facilitated locally near crack tips and crack growth takes place by a more-localized process of microvoid-coalescence than that in an inert environment."* (Chen et al., 2013)
Adsorption Induced Dislocation Emission (AIDE)	*"For the AIDE model, the term 'dislocation-emission' encompasses both nucleation and subsequent movement of dislocations away from crack tip, and it is important to note that it is the nucleation stage that is critical and facilitated by adsorption. Once nucleated, dislocations can readily move away from the crack tip under the applied stress. The nucleation stage involves the simultaneous formation of a dislocation core and surface step by co-operative shearing of atoms (breaking and re-forming of interatomic bonds) over several atomic distances. Thus, weakening of interatomic bonds over several atomic distances by 'adsorbed' hydrogen can facilitate the process."* (Lynch, 2011)

Source: (JRC, 2024) based on (Chen et al., 2013; Lynch, 2011)

3.1.1 Tensile properties

Gaseous hydrogen is reported to have a relatively minor effect on yield and tensile strength (Gallon et al., 2020; Laureys et al., 2022; Nanninga et al., 2012; San Marchi & Somerday, 2012). The tensile strength is slightly decreased in notched specimens (San Marchi & Somerday, 2012) and the yield strength is insignificantly increased in welds (Gallon et al., 2020).

Ductility is a measure of a material's ability to deform under mechanical loading. A material with high ductility is described as ductile, and a material with low ductility as brittle. Steel specimens subjected to gaseous hydrogen show generally more brittle fractures than unaffected specimens, meaning that the steel becomes less ductile when exposed to hydrogen (Gallon et al., 2020).

Ductility can be measured either as elongation using Uniform Elongation (the elongation at maximum stress, i.e. ultimate tensile stress (UTS)) or Total Elongation (the maximum elongation before failure) or as Reduced Area (RA) in smooth or notched tensile tests.

Tests of RA in 6.9 MPa gaseous hydrogen reveal a relative reduction of 48-82% compared to in air, meaning that the hydrogen samples reduce less in area before breakage (Gallon et al., 2020). Reduction in ductility has been shown to be more pronounced in notched tensile specimens compared to smooth specimen (Gallon et al., 2020; San Marchi & Somerday, 2012). Using a novel technique of hollow specimen geometry in a slow strain rate tensile test, a decrease in RA was observed from 73% to 51% (relative reduction of 30%) when the hollow specimens were exposed in-situ to gaseous hydrogen at 60 barg (Konert et al., 2025). The hollow specimen geometry means that the steel surface is only exposed to hydrogen from one side, similar to what would be the case for a pipeline.

In summary, ductility (either measured as total elongation or reduction in area) shows a reduction of around 20-80% in hydrogen (Gallon et al., 2020; Sandana et al., 2021). Variation is found between samples and test methods.

3.1.2 Fracture toughness

In a situation where a material has a crack (or other defect), there is a possibility for stress concentration in the material. This stress concentration can give rise to brittle fractures of otherwise ductile materials. The amount of stress concentration depends on the type and size of defect, as well as the stress. Equation 2 displays the stress intensity factor (SIF) for crack mode I, opening crack propagation mode (Budynas & Nisbett, 2011).

Equation 2. Stress intensity factor for crack mode I, opening crack propagation mode.

$$K_I = Y\sigma\sqrt{\pi a}$$

K_I = Stress intensity factor for crack mode I

Y = Stress intensity modification factor

σ = Normal stress

a = Crack length

The value of the stress intensity modification factor (Y) depends on the crack type and shape. When the mode I stress intensity factor exceeds a critical value, denoted K_{IC}, the crack propagates in a sharp, rapid and unstable way. K_{IC} is termed the mode 1, plane strain fracture toughness. Fracture toughness is the ability of material with a pre-existing crack to absorb energy and resist crack growth (Perez, 2024). Therefore, a sufficient fracture toughness is needed to have a design that is resilient to the existence of cracks. Fracture toughness is typically measured using the crack tip opening displacement (CTOD), J-integral, or critical stress intensity factor (K_{IC}). Measurement in terms of J-integral from a fracture resistance curve is more suitable for pipeline materials that tend to exhibit stable crack growth (Kappes & Perez, 2023b), as opposed to unstable crack growth observed in brittle materials. Nevertheless, fracture toughness measured in terms of J-integral can also be expressed in terms of K_{IC} (denoted K_{JIC}).

Material strength and fracture toughness are interdependent depending on the manufacturing method. Vintage pipes were typically made stronger by increasing carbon content, but this also made them less tough (Gallon et al., 2023; Sandana et al., 2023). In contrast, modern pipeline steels are typically made stronger by thermomechanical processing, controlling grain sizes and microstructure. This also makes the material tougher. An example is given in (Gallon et al., 2023; Sandana et al., 2023) where Charpy V-Notch (CVN) values in air were compared between X42 and X70 steel grades. These had average CVN values of 18 J and 280 J respectively (Sandana et al., 2023). Even if the lower strength X42 steel grade would show an increase of 11% fracture toughness in hydrogen, and the stronger X70 steel grade a reduction of 85%, the residual fracture toughness of the latter would still be greater.

Mechanisms proposed to explain decrease in fracture toughness (see Table 1) assume that the driving factor is the concentration of hydrogen at the tip of a crack or defect. Since the diffusion coefficient of hydrogen in a steel lattice at ambient temperature is very low, this can suggest that a crack propagates quicker than the hydrogen diffuses (Gallon et al., 2020). This could also explain why hydrogen does not significantly affect Charpy impact energies which are characterised by high strain rates (Gallon et al., 2020; Laureys et al., 2022; Sandana et al., 2021).

There is no consensus on the influence of material strength on the relative reduction of fracture toughness in gaseous hydrogen environment (Gallon et al., 2020). There is also no clear consensus on the relative reduction overall, as sources range from reduction of 85%, to increases of 11%. Most sources report reductions in the range of 35-70% (Gallon et al., 2020; Sandana et al., 2021). Results from tests on welds are largely consistent with results on base metal (Ronevich et al., 2021). Some studies also report that as little as 1 Vol-% hydrogen in a hydrogen-methane blend can reduce fracture toughness as much as 50% (Nguyen et al., 2021; Sandana et al., 2021)

Although higher strength steels may show larger reduction in fracture toughness compared to lower strength steels when exposed to hydrogen, the residual fracture toughness for higher strength steels may still be higher due to a higher initial fracture toughness (Sandana et al., 2023). San Marchi et al. (2021) suggest that (residual) fracture resistance in hydrogen is negatively correlated with yield strength. It has been suggested that fracture toughness in hydrogen is similar for all pipeline steels irrespective of fracture toughness in air (Ronevich et al., 2022). Fracture toughness measurements of 58 different pipeline base metals and welds revealed that fracture toughness in hydrogen was in the range of around 80-160 MPa*m$^{1/2}$ for all tested samples (Steiner et al., 2023).

Fracture toughness is affected by hydrogen pressure (or more correctly, fugacity[1]) (San Marchi et al., 2021). Decrease in fracture toughness is proposed to scale with the square root of hydrogen fugacity resulting in a steep initial decline and a lesser effect at higher pressures (San Marchi et al., 2021).

It has been hypothesised that fracture toughness reported from small-scale laboratory tests are not necessarily representative of pipeline service (Gallon et al., 2020). This is because the hydrogen needs to concentrate at the crack tip first in order to have an effect. Hence, fracture toughness in hydrogen is time-dependent. Depending on the type of threat to the pipeline (e.g. internal pressure, third-party damage), the strain rate and therefore crack propagation speed will be different. This could result in small-scale laboratory scale results being either overconservative or underconservative.

Recently, a novel framework was proposed by Nyhus et al. (2025) to model the fracture toughness in the cross section of a pipeline wall, assuming one sided exposure to gaseous hydrogen. This model is proposed to reduce the conservatism in applying values of fracture toughness from testing in gaseous hydrogen on external and embedded defects. By using recognised hydrogen uptake and diffusion models, the hydrogen concentration gradient can be simulated and correlated to measured values of fracture toughness in hydrogen at different pressures. Numerically, it was shown that the fracture toughness for an external wall defect (with zero depth) was 228% higher compared to an internal defect for an X42 steel pipeline transporting hydrogen at 200 barg. For mid

[1] Fugacity quantifies the effective pressure exerted by a real gas such as hydrogen. It accounts for the deviations from ideal gas behaviour.

wall defects, the fracture toughness was approximately 36% higher compared to internal defects. However, it is also highlighted that external surface barriers, hindering hydrogen emission from the pipe wall, has a significant influence. The article uses the example of cathodic protection and concludes that it would reduce the fracture toughness at the outer wall by about 50%, which means that the increase in fracture toughness from the inner wall to the outer wall would be around 67%, much lower than the original 228% increase.

In summary, exposure to gaseous hydrogen significantly decreases the fracture toughness of pipeline steel. There are large variations in reported magnitudes of reduction, but 35%-70% is common (Gallon et al., 2020). Fracture toughness in hydrogen is negatively correlated with material strength and hydrogen fugacity, but the effect is still minor. Fracture toughness in air is not a good predictor of fracture toughness in hydrogen, but fracture toughness in hydrogen is typically greater than 55 MPa*m$^{1/2}$ for pipeline steels (Ronevich et al., 2022, 2023).

3.1.3 Fatigue

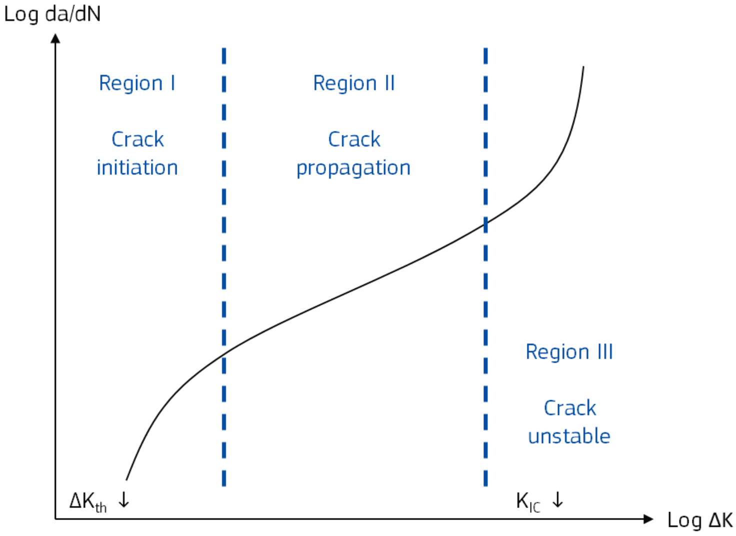
Fatigue refers to the deterioration of materials that happens due to cyclic or fluctuating stresses well below the ultimate strength of the material (Budynas & Nisbett, 2011). As such, fatigue results in sub-critical crack growth, i.e. the growth of a crack in a material under stress levels below the material's critical stress intensity factor, or fracture toughness. If the crack grows sufficiently large, or the stress is magnified, rapid crack propagation occurs when the stress intensity factor exceeds the material fracture toughness. A typical plot of crack growth rate with respect to stress intensity factor range is depicted in Figure 2.

Crack growth can be divided into different stages depending on the crack size (Lipiäinen et al., 2023):

- Initial crack size from manufacturing flaw or damage. The size of plausible initial cracks can be deduced from for example inspection tolerances.
- Inspectable crack size. The minimum crack size detectable can be determined with for example In-Line Inspection (ILI) tools.
- Safe crack growth. This is the size over which a crack can grow safely without jeopardising the integrity of the pipeline. In this region, sub-critical crack propagation occurs, resulting in stable crack growth. This is referred to as region II in Figure 2.
- Critical crack size. This is the size at which the crack leads to integrity failure. At this point, the stress intensity factor exceeds the fracture toughness of the material, causing unstable crack growth and subsequent failure of the material. This is referred to as region III in Figure 2.

As such, it is imperative to predict the duration between inspectable crack size and critical crack size. Pipelines typically operate under cyclic stresses due to variations in pressure in the pipeline. Hence, control of fatigue is important for safe pipeline operation.

Figure 2. Typical plot of crack growth rate with respect to stress intensity factor range.



Source: (JRC, 2024)

Fatigue crack growth under stable crack growth conditions (region II in Figure 2) is often described using the Paris law (Gdoutos, 2020; Paris & Erdogan, 1963).

Equation 3. Paris law.

$$\frac{da}{dN} = C(\Delta K)^m$$

a = crack length (mm)

N = load cycle

C, m = constants

ΔK = Stress intensity factor range ($MPa*m^{1/2}$)

The constants C and m are determined experimentally and therefore include all factors relevant to determine crack growth from stress intensity, assuming that sufficient and appropriate data are acquired and used for its determination. One example is the stress ratio (R)[2] which is not explicitly considered in the Paris law, but its effect on fatigue crack growth is contained in the C and m constants. Alternatively, additional contributing factors can be added by modifying the traditional Paris law equation.

Fatigue is commonly investigated using fatigue crack growth rate test methods such as those described in ASTM E647. These tests use compact tension (CT) specimens fabricated with a notch and pre-cracked to form a natural crack. The specimens are then subjected to cyclic loads and the crack growth is measured. Another way of studying fatigue is through S-N curves which compare number of cycles to fatigue life of the component. One difference between the two is that the former has a pre-formed crack and therefore does not include crack initiation. Steel pipelines

[2] The stress ratio (R) is the ratio between the lowest stress intensity factor (K_{min}) and the highest stress intensity factor (K_{max}) for a particular load cycle.

typically have some cracks or flaws from manufacturing or operation, which may lead to Fatigue Crack Growth Rate (FCGR) test methods being more suitable (Laureys et al., 2022).

Fatigue crack growth rates are substantially increased in hydrogen (Topolski et al., 2022). Results have shown at least one order of magnitude higher FCGR in hydrogen compared to air (San Marchi & Somerday, 2012).

FCGR at low ΔK is relatively minor, but it is also here that most fatigue life is spent, considering that most cracks start from a small size. High ΔK is only obtained in relatively major cracks. Hence, FCGR at low ΔK can be considered more important, and in particular the threshold where FCGR is accelerated further (as it can be seen in some graphs comparing FCGR in hydrogen and air) (Laureys et al., 2022). At the same time, FCGR at low ΔK is considered 'safe' crack growth, meaning that cracks of this size do not yet lead to any safety concerns.

When da/dN is lower than 10^{-7} mm/cycle, crack growth is considered non-present according to ASTM E647. The ΔK value at which this happens is called the 'thresholds stress intensity factor range' (ΔK_{th}). At low load ratios, the threshold stress intensity factor range is lower in dry hydrogen gas compared to moist air according to Suresh and Ritchie (1981). In many other studies, the threshold stress intensity factor range in hydrogen is reported to be 10-20% lower than in air (Laureys et al., 2022). The effect diminishes with increasing R, as the near-threshold FCGR in moist air converges to the one in hydrogen (Suresh & Ritchie, 1981). The culprit was reported to be moisture, as results in dry Helium are similar to dry Hydrogen, and results in moist hydrogen is similar to moist air (Suresh & Ritchie, 1981). A more recent study showed similar values of ΔK_{th} for hydrogen, helium and air under R ratio of 0.1, although no information was given on the moisture content in the air (Tazoe et al., 2017). The moisture is said to form an oxide layer on the crack, thereby protecting it from propagating (Kappes & Perez, 2023b). A study by Ronevich et al. (2020) revealed that FCGR was similar in both high-pressure hydrogen gas and air at load ratios of 0.5 and 0.7 for a X100 steel when stress intensity factor was kept below 5 $MPa{*}m^{1/2}$. Threshold stress intensity factor range was reported to be between 3 and 4 $MPa{*}m^{1/2}$ in both air and hydrogen gas.

There has been contradicting evidence about the effect of load ratio (R) on FCGR, especially at lower ratios (R<0.5) (Gallon et al., 2020). San Marchi and Somerday (2012) report that FCGR dependence on ΔK is independent of R at ratios between 0.1 and 0.4, and that it increases at higher ratios. More recent studies (Ronevich et al., 2022, 2023; San Marchi & Ronevich, 2022a) suggest that the load ratio is positively correlated with FCGR and that the effect is bigger for higher stress intensity factor ranges. Important to note is that the load ratio and stress intensity factor range (ΔK) are inherently correlated to each other when considering the operations of a pipeline, meaning that a decrease in load ratio results in a higher stress intensity factor range for the same maximum operating pressure (and therefore K_{max}). It is also shown that lower load ratios result in higher FCGR for the same K_{max} (San Marchi & Ronevich, 2022a).

It has been demonstrated and confirmed by numerous studies that FCGR increases with decreasing loading frequencies (Gallon et al., 2020; (Laureys et al., 2022; Steiner et al., 2023). In a study by Slifka et al., FCGR increased by almost 70% when comparing loading frequencies of 1 Hz and 0,01 Hz for a X70 steel (Slifka et al., 2018). At the same time, vintage X52 steel increased by around 15% for the same comparison (Slifka et al., 2018). Cheng & Chen (2017) reported that there may be a critical frequency at which hydrogen concentration saturates, and that this frequency is also dependent upon the magnitude of crack growth per cycle (San Marchi & Ronevich, 2022a). This is supported by the proposed mechanism in Table 1, which considers the concentration of hydrogen at the crack tip as the driving factor.

There appears to be no lower hydrogen pressure, partial pressure or blend ratio for which hydrogen accelerated FCG can be dismissed, although a higher hydrogen pressure (or fugacity) results in faster FCG for lower stress intensity factor ranges (Gallon et al., 2020; Ronevich et al., 2023, 2024; San Marchi & Ronevich, 2022a; Steiner et al., 2023). At higher ΔK, the fatigue crack growth is no longer dependent on hydrogen pressure (Ronevich et al., 2024). Exactly where this transition is depends on several factors such as stress ratio and fugacity, but it is often assumed to be around 10-30 $MPa*m^{1/2}$.

Comparing the influence of hydrogen gas pressure on FCGR between vintage X52 from 1964 and modern X52 pipeline steel revealed that the vintage steel saw a larger increase in FCGR when pressure was raised, compared to modern steel (Slifka et al., 2018). However, the FCGR in hydrogen was similar for both steels. This was confirmed in other studies that showed that both modern and vintage steels are bound by the same upper limit for FCGR (Ronevich et al., 2024).

It is clear that hydrogen enhances fatigue crack growth for a pre-existing crack that remains with positive crack opening displacement (COD) during the full load cycle. Another aspect is the initiation of cracks in a crack-free surface. A recent study by León-Cázares et al. (2024) investigated the crack initiation behaviour of Circumferentially Notched Tensile (CNT) specimens of a vintage X52 steel under gaseous hydrogen partial pressures of 1 bar and 207 bar. Crack initiation was found to be faster in air than in 1 bar partial pressure hydrogen, and slightly faster in high partial pressure hydrogen than in air, although comparable. More testing would be needed in order to draw any general conclusions.

There is no clear relationship between yield strength and FCGR (Gallon et al., 2020; Laureys et al., 2022; Ronevich et al., 2023, 2024; Slifka et al., 2018; Steiner et al., 2023). In a study comparing six different steels (3 steel materials of grade X52, 2 steel materials of grade X70, and 1 steel material of grade X100), no correlation between strength and FCGR could be seen (Slifka et al., 2018). The same result was reported in a study comparing steels with yield strengths differing by as much as a factor of two (Ronevich et al., 2024). FCGR is instead said to rely mainly on microstructure and chemistry (Laureys et al., 2022), but it has also been shown to be similar for many of the material grades used in gas pipelines (Ronevich et al., 2024; Slifka et al., 2018; Steiner et al., 2023). In fact, a recent study revealed that FCGR was consistent within a factor of 2-3 for a range of common microstructures found in pipeline steels (Ronevich et al., 2024). This behaviour allows for the construction of 'master-curves' of fatigue crack growth behaviour, such as the one introduced in ASME B31.12 (ASME, 2023) which was based on a number of tests of different steels (Amaro et al., 2018; Slifka et al., 2018).

There is some evidence from experiments in air and in near-neutral pH environment that the combination of shallow cycles (R=0.9) and deep cycles (R=0.5) leads to accelerated crack growth (Yu et al., 2015) not explained by the summation of the individual contributions. The fatigue crack growth rate was found to be three and five times larger for air and near-neutral pH environment respectively as compared to simply adding contributions of the different R ratios together. Similar evidence is not known to exist for gaseous hydrogen environments.

In summary, FCGR is significantly increased in hydrogen by a factor of 10-100 with larger increases for higher stress intensity factor ranges. The increase is relatively independent from material strength and microstructure. FCGR is higher for higher load ratios, and higher for increased hydrogen fugacity at lower stress intensity factor ranges.

3.1.4 Influence of hardness and steel microstructure

The influence of steel hardness on hydrogen embrittlement is an important topic in the context of hydrogen pipelines. Harder steels are often considered to be more susceptible to hydrogen embrittlement, and as such they should be avoided or used with caution in pipelines for hydrogen transport. High strength steels otherwise present a cost benefit in that less material can be used to achieve the same overall strength.

Ultimate tensile strength and hardness can be correlated using equations, such as those presented in ASTM A370. However, those correlations are not exact as they also depend on microstructure (Kappes & Perez, 2023b).

Steels have different microstructures depending on their chemical composition, manufacturing method, and heat treatment. For pipeline steel, polygonal and acicular ferrite, pearlite, bainite and martensite are most prominent. Bainitic/ferritic microstructures are reported to be more resistant to hydrogen compared to ferrite/pearlite microstructures (Gallon et al., 2020). As-quenched (non-tempered) martensitic microstructures are most prone to hydrogen embrittlement (Gallon et al., 2020). The relative susceptibility of different microstructures to hydrogen embrittlement is summarised in Table 2.

Table 2. Effect of hydrogen on material properties considering different microstructures.

Microstructure phase	Effect on material properties
Ferrite (polygonal)	Significantly degraded
Pearlite	Relatively immune
Ferrite (acicular)	Significantly degraded
Bainite	Good resistance
Untempered martensite	Severely degraded
Tempered martensite	Good resistance

Source: (JRC, 2024) based on (Gallon et al., 2023; Sandana et al., 2023)

Hard spots are typically formed by local warming and subsequent rapid cooling (quenching) of the material (Tran et al., 2023). This results in a local change in microstructure, leading to increased hardness. Untempered martensite is one of the microstructures that can be formed. The hardness of as-quenched martensite is typically in excess of 300 HV (UTS=960 MPa) and is almost solely dependent on the carbon content of the steel, where an increase in carbon yields higher hardness (Grange et al., 1977). Vintage steel materials typically contain higher amounts of carbon (Kappes & Perez, 2023b), since carbon was used as a way of producing harder steels. Experience from transportation of non-hydrogen fluids have focused mainly on the potential threat from external hard spots as nucleation sites for hydrogen embrittlement (Tran et al., 2023). Internal hard spots may also be a concern in the presence of hydrogen.

Based on inspections in the U.S. by the company ROSEN over a three-year period, 41% of validated hard spots anomalies had hardness in excess of 237 HB (Tran et al., 2023). Most of these hard spots were found in pipes fabricated between 1950 and 1960 (Tran et al., 2023).

Studies on hydrogen-charged notched tensile specimens from fastener grade steels have shown that higher hardness leads to lower notch failure stress (Nanninga et al., 2010). The difference between in air and hydrogen-charged notch failure stress was minimal for the lower strength steels measured (350 HV, UTS=1120 MPa) while it was significant (more than 80% reduction) for the higher strength steel grades (550 HV, UTS=1830 MPa) (Nanninga et al., 2010). The strengths of the steels used in this study were however significantly higher than what is expected in pipeline steels (API 5L PSL 2 X80 grade steel allows a maximum UTS of 825 MPa, corresponding to 261 HV).

Brauer et al. (2020) tested two X52 grade steels manufactured using two different methods. One was normalised in hot rolling (N) and the other one was thermomechanical rolled (M). The latter showed a much finer and homogenous grain size. The latter also showed much less reduction in ductility (measured as reduction in area): 5% versus almost 50%. The former also had a higher carbon content (0.169% vs 0.048%) which may have influenced the observed behaviour.

A study by Nanninga et al. (2012) compared the tensile properties of X52, X65 and X100 pipeline steels in high-pressure hydrogen. Results showed a correlation between pipe grade and reductions in ductility measured as total elongation at failure and reduction in area (RA). The elongations at failure in high-pressure hydrogen for the X52, X65 and X100 steels were respectively 78%, 72% and 50% of those measured in air.

In a study investigating the fracture toughness and FCGR of pressure vessel steels, San Marchi et al. (2019) found that steels with tensile strength less than 915 MPa exhibit fracture toughness in excess of 40 MPa*m$^{1/2}$, whereas higher strength steels have fracture toughness in air as low as 12 MPa*m$^{1/2}$. These strength levels are higher than what is to be expected in pipeline steel, but it could be possible in local hard spots. In the same study, it is hypothesised that the rapid acceleration of FCGR observed in some tests are due to the fact that K_{max} gets closer to K_{IH}, transitioning fatigue crack growth from stage II (intermediate) to stage III (high propagation rate) (San Marchi et al., 2019).

As part of the DVGW project SyWest H2: '*Investigation of Steel Materials for Gas Pipelines and Plants for Assessment of their Suitability with Hydrogen*', a specimen of L485 steel was tested for both fracture toughness and fatigue crack growth (Steiner et al., 2023). Tests were performed on girth weld areas tempered to 296 HV, and on hardened samples with 360 HV. The tempered samples had fracture toughness in excess of 100 MPa*m$^{1/2}$ under 100 bar hydrogen, and fatigue crack growth was in line with the ASME B31.12 master curve. The hardened sample had fracture toughness in excess of 65 MPa*m$^{1/2}$, but fatigue crack growth became unstable already at a stress intensity factor range of approximately 15 MPa*m$^{1/2}$ (Steiner et al., 2023). The test was conducted at R=0.5 indicating that K_{max} would have been around 30 MPa*m$^{1/2}$. These results indicate that there may be an increased risk of sub-critical crack growth in exceptionally high hardness pipeline steels. However, the exact threshold hardness value is not known, if it exists.

In summary, high strength or hardness is not correlated to FCGR. It is only slightly related to fracture resistance. Reduction in ductility is more strongly connected to material strength. These statements are true for steel strength and hardness typically found in pipelines. Hard spots, for which hardness is significantly higher compared to the base metal, can be observed, especially in vintage steels. The threat from these hard spots needs to be further assessed.

3.1.5 The effect of gas impurities

Recent research suggests that introducing small amounts of gases such as oxygen or carbon monoxide in the hydrogen gas can obstruct hydrogen adsorption onto the steel surface, thereby reducing hydrogen embrittlement (Gallon et al., 2020). This is due to the competitive adsorption of these impurities with hydrogen for the steel surface sites. Notably, oxygen has been identified as an effective fatigue crack growth inhibitor, with laboratory tests indicating its ability to significantly delay fracture initiation, even at concentrations as low as 100 ppm (Gallon et al., 2020).

A study by Wheeler et al. (2023) investigating the influence of oxygen impurities in hydrogen gas on the fracture resistance of pipeline steels found that oxygen markedly delayed crack initiation in Wedge Opened Loaded (WOL) specimen. Fracture toughness values remained however consistent regardless of oxygen presence. This observation suggests that oxygen may not prevent hydrogen-induced degradation in fracture toughness but merely postpone it. The implications of these findings for FCGR are not yet clear. The long-term effects of inhibitors such as oxygen or carbon monoxide are not well understood neither, and their impact on fracture toughness and FCGR under operational conditions remains to be clarified (Laureys et al., 2022).

The European Pipeline Research Group (EPRG, 2023) advises caution in relying on such gases due to the challenges associated with achieving consistent concentration distribution along pipelines. The consumption of oxygen due to adsorption onto pipeline surfaces may lead to an effectiveness that varies along the pipeline length, a factor not yet investigated over extended distances or for large scales (Giannini et al., 2024; Kappes & Perez, 2023b).

Thus, further research on the potential use of gas impurities to mitigate hydrogen embrittlement is necessary to better understand their practical application and long-term effectiveness in pipeline systems.

3.2 Polymers

Polymeric materials, such as polyethylene (PE) and polyvinylchloride (PVC), are typically used in modern distribution pipelines. Distribution pipelines, of small diameters and used at low pressures, are generally made of PVC; those, of higher diameters and used at higher pressures, generally consist of PE. Since the properties of those polymers differ from each other, they may exhibit different behaviours under the influence of hydrogen.

Polymers are not subject to hydrogen embrittlement in the same way as metals. In metals, hydrogen dissociates into hydrogen atoms at the metal surface, whereas polymers can absorb diatomic hydrogen (Gallon et al., 2020). Failure and degradation mechanisms relevant for polymers in gaseous high-pressure hydrogen include blistering due to rapid decompression, ageing and microstructural degradation (Gallon et al., 2020).

Short-term mechanical testing on PE pipelines has shown that hydrogen at low pressures does not significantly alter mechanical properties, whereas, at higher pressures, a minor reduction in tensile strength and failure strain is observed (Alvine et al., 2014; Castagnet et al., 2010; Klopffer et al., 2010; Menon et al., 2016). The specific cause, whether due to hydrogen itself or pressure effects, remains unclear.

A study on medium density polyethylene (MDPE) showed no significant reductions in fatigue life or fracture resistance when exposed to gaseous hydrogen up to pressures of 21 MPa (Meeks et al., 2022).

The current data primarily focus on pipeline bodies. The effect of hydrogen on heat fusion joints and the influence of different resin formulations on hydrogen compatibility are still to be thoroughly investigated (Topolski et al., 2022). Additionally, more testing is required on long-term exposure of polymeric materials to hydrogen (Simmons et al., 2022).

Leakage of hydrogen from polymeric distribution pipelines is a concern (Topolski et al., 2022). Although permeation through the pipe wall is small per square meter, in a full-scale pipeline, there are many square meters over which permeation can occur. The rate of permeation through a PE pipeline wall is four to five times higher for hydrogen than for natural gas (Haeseldonckx & D'haeseleer, 2007; Melaina et al., 2013). However, the losses are still estimated to be between 0.0005% and 0.001%, which is considered economically insignificant (Haeseldonckx & D'haeseleer, 2007). Another study estimated that losses due to permeation through pipeline walls (excluding joints and valves) could amount up to 0.06% per year for the most severe service conditions considered (Simmons et al., 2022). Ultimately, the total amount of leakage for the pipeline is determined by the polymeric material used for making the pipeline, its dimensions, and its operating pressure. Although leakages may be economically insignificant, leakage in confined and unventilated spaces may pose a safety hazard. Given the vast variation in pipeline and weld characteristics, and the potential implications for a hydrogen economy, more permeation tests are recommended for both new and vintage pipes (Simmons et al., 2022).

Although the literature on the subject is limited, there seems to be consensus that the most important concern for polymeric pipelines is the increased permeability and therefore continuous leaks, rather than instantaneous leaks from lost integrity (Gallon et al., 2020).

Elastomeric materials used in transmission and distribution grids include o-rings, diaphragms, gaskets, boots, flange, and quad seals (Topolski et al., 2022). The existence of these materials in the infrastructure is limited, meaning that their replacement is considered relatively easy. The permeation coefficient of hydrogen is greater in elastomers than in polymeric materials (Melaina et al., 2013). Still, the leakage through pipeline walls is estimated to account for the majority of gas loss in the system based on the much larger exposed surface area (Melaina et al., 2013). Permeation of hydrogen into elastomers also reduces their tensile strength which may lead to even more leakage (Melaina et al., 2013).

4 Integrity and safety challenges for hydrogen pipelines

Integrity and safety are two important aspects of pipeline operation that are closely connected. Integrity management involves a comprehensive approach to prevent and monitor for material degradation, leaks, and other factors that could compromise the system's performance or lifespan. Safety on the other hand encompasses the safety of people and external objects during the operation of the pipeline. As most safety concerns related to pipelines are connected to loss of integrity of the pipeline, these two aspects are closely intertwined. This report discusses the integrity and safety of the hydrogen pipelines; the integrity and safety of auxiliary components such as valves, compressors, etc. are not part of the scope.

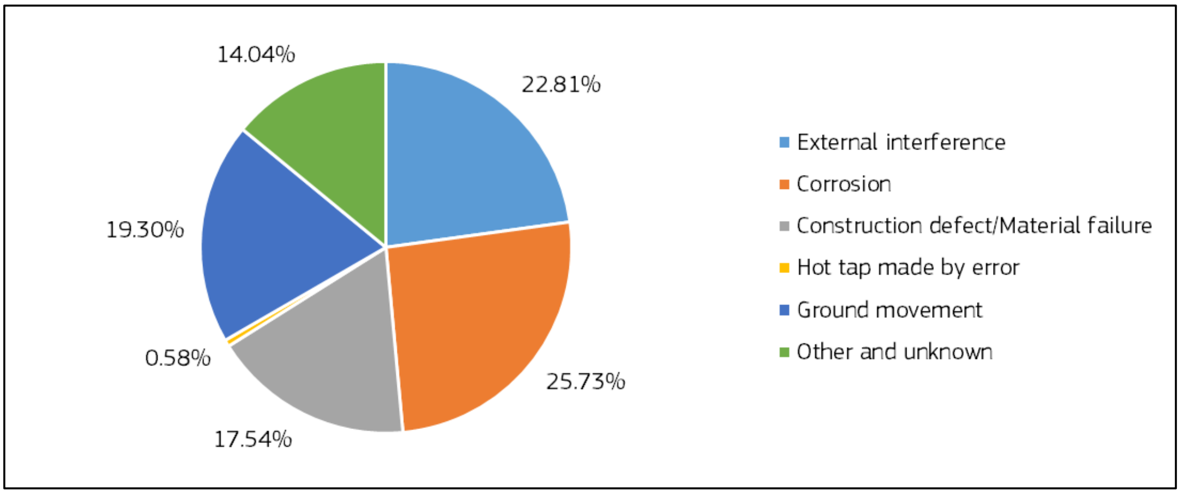
Significant amounts of research have been conducted in the field of material compatibility with hydrogen (see section 3). However this knowledge needs also to be interpreted in terms of integrity and safety. In that frame, Giannini et al. (2024) reported the lack of connection between knowledge in material science and safety engineering and the lack of literature concerning pipeline safety.

4.1 Integrity challenges

Hydrogen pipelines, like natural gas pipelines, are subject to various threats to their integrity. Integrity is here meant as the pipeline ability to maintain the transported gas within. For the purpose of this report, no distinction is made between functional and structural integrity. As the component under investigation is the line pipe, the difference between functional and structural integrity is minimal. It is fair to assume that the integrity threats to hydrogen pipelines will be mainly the same as for natural gas pipelines, if by integrity threats it is meant the type of possible failure causes. This is also evidenced in comparing the failure modes to be considered in ASME B31.12 and ASME B31.8S which show many similarities. However, the frequency and magnitude of integrity threats will most likely be affected by the presence of hydrogen.

Incident causes of natural gas transmission pipelines in Europe are shown in Figure 3 (European Gas Pipeline Incident Data Group, 2024). Incidents from the gas distribution grid are collected by the association Marcogaz but are less detailed (Marcogaz, 2024). Data from Marcogaz indicate that third-party damage is a major cause of incidents also in the gas distribution grid. (Marcogaz, 2024).

Figure 3. Distribution of incident causes for natural gas transmission pipelines in Europe for the years 2013-2022.



Source: (JRC, 2024) based on data from (European Gas Pipeline Incident Data Group, 2024).

Given the limited number of hydrogen pipelines in operation today, no equivalent statistics exists for hydrogen pipelines. An important database for hydrogen related incidents and accidents is the Hydrogen Incidents and Accidents Database (HIAD) (JRC, 2025), a database maintained by the European Commission's Joint Research Centre (JRC). Only a handful of incidents related to hydrogen pipelines can be found in this database. It is anticipated that at least during the early deployment of hydrogen pipelines, failure frequencies will instead have to rely on comparisons with similar operations such as natural gas pipelines. A key activity in this comparison is the careful examination of the interaction between hydrogen and observed failure modes.

Assessment of defects in pipelines is typically done through 'Fitness-for-service' evaluations. In API 579-1, this is described as '*quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage, or that may be operating under a specific condition that might cause a failure*'. Two of the most important standards related to defect assessment of pipelines are API 579-1 and BS 7910 (Freire de Franca, 2023).

Stress-Corrosion Cracking (SCC) is an important integrity issue for pipelines in general (Fang et al., 2003). The mechanism is different depending on the acidity of the environment, with high-pH SCC and near-neutral (or low-pH) SCC being two distinct forms. SSC is dependent on the type of external coating applied. Coatings which are prone to disbondment and that have high electrical-resistivity properties are more prone to SSC (Sandana et al., 2021). Hydrogen plays a major role in near-neutral pH SCC which is an important failure mechanism for natural gas pipelines (Freire de Franca et al., 2024; Lynch, 2011). However, it is uncertain if hydrogen transported in the pipeline can diffuse through the metal and escalate the external SCC (Sandana et al., 2021).

Pipeline steels transporting natural gas, oil, etc. are also known to exhibit embrittlement when pipeline steel is overprotected with cathodic protection (Sandana et al., 2021). In such cases, atomic hydrogen from the outside environment is adsorbed onto the steel surface. This can in turn lead to hydrogen atom absorption into the microstructure and subsequent failure through either Hydrogen-Induced-Cracking (HIC) or Hydrogen-Induced-Stress-Corrosion-Cracking (HISC) (Sandana et al., 2021). It is not clear whether transporting gaseous hydrogen within the pipeline would have any effect on this. Design codes and guidelines such as ASME B31.12 and EIGA IGC Doc 121/14 mention the use of cathodic protection against corrosion. A study by National Gas Grid Transmission mentions that the current procedure needs to be validated also for hydrogen pipelines (Bannister & Brown, 2019).

4.1.1 Defects

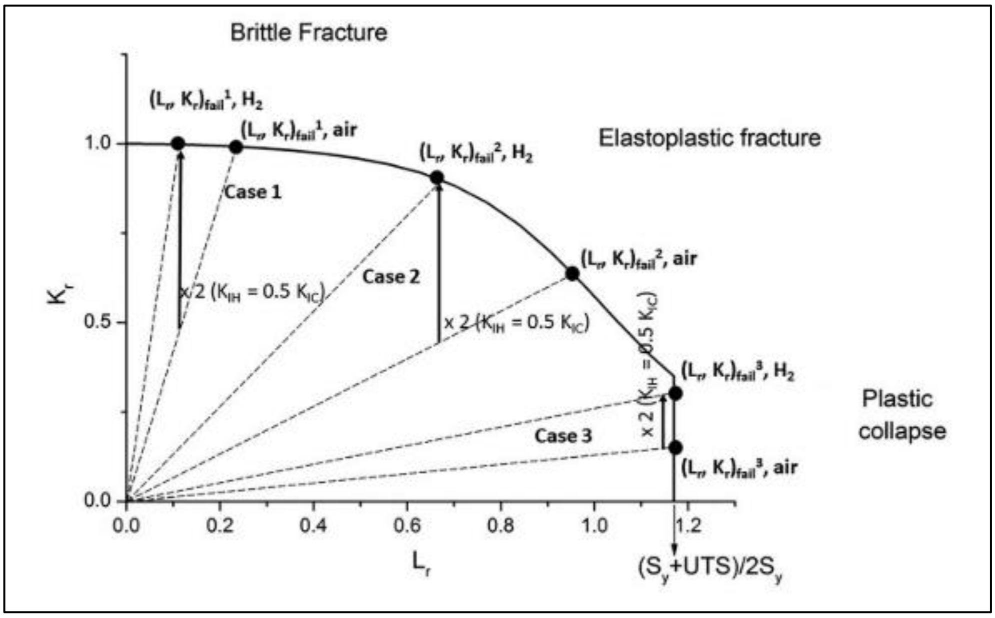
This section gives an overview of some typical defects that are relevant for hydrogen pipelines. It also refers to studies that have investigated numerically or experimentally the effect of gaseous hydrogen on such defects.

4.1.1.1 Crack-like defects

A key challenge for hydrogen pipelines is crack-like defects. The severity of a crack depends on the size and orientation. An axial crack is often more severe, since the principal load in a pipeline is circumferential hoop stress. Cracks are a challenge for hydrogen pipelines due to the observed reduction in fracture toughness and increase in fatigue crack growth in gaseous hydrogen, see section 3.1. Given the increased fatigue crack growth rate in hydrogen, it is assumed that many existing cracks that do not affect the integrity of the pipeline in natural gas operation will start to grow when hydrogen is introduced (Sandana et al., 2021). Crack-like defects are commonly assessed using failure-assessment-diagrams (FAD) as presented in for example API 579-1 and BS 7910. The FAD distinguishes failure modes as either brittle fracture, plastic collapse, or a combination thereof. Materials with a higher fracture toughness and less severe crack-like defects typically exhibit plastic collapse behaviour, whereas more brittle materials with more severe defects exhibit brittle fracture.

Figure 4 shows an example of a Failure Assessment Diagram (FAD) as presented in API 579-1 (Kappes & Perez, 2023b).

Figure 4. An example of a Failure-Assessment-Diagram (FAD).



Source: (Kappes & Perez, 2023b)

In Figure 4, it can be seen that for some situations (cases 1 and 2) hydrogen induced reduction of fracture toughness (y-axis) will lead to a lower failure pressure (x-axis). As K_r represents the ratio between observed K and K_{IC}/K_{IH}, cases 1 and 2 represent situations where the fracture toughness is relatively low, or where cracks are particularly large. Vintage pipelines typically have lower fracture toughness than modern pipelines due to differences in production methods and materials. As such, failure mode of modern pipelines, and pipelines with only minor flaws, are represented by case 3 in the figure (Kappes & Perez, 2023b). In conclusion, for a pipeline with large flaws, or with lower fracture toughness, introduction of hydrogen should also be followed by an introduction in pressure of the same magnitude as the decrease in fracture toughness, typically 30-80% (Kappes & Perez, 2023b). Some studies suggest that the residual fracture toughness in hydrogen (K_{IH}) is similar for all pipeline steels and independent of K_{IC} (Ronevich et al., 2022), questioning the validity of the above argumentation. If so, the probability of a pipeline exhibiting brittle fracture from a given crack would be independent on the fracture toughness or exhibited fracture mode in air. More research is necessary on that topic.

Kappes and Perez (Kappes & Perez, 2023a) conducted a numerical study based on the Failure Assessment Diagram according to API 579-1. The study was on a hypothetical pipeline made of X52 steel with a wall thickness of 6.35 mm and a diameter of 558.8 mm. K_{IC} and K_{IH} were 300 and 140 MPa*m$^{1/2}$ respectively (representing a reduction of 53%). For a small crack close to the detection limit (crack height=a=2 mm, crack length=2c=40 mm), the failure pressure of the pipeline was not affected by hydrogen as the predicted failure mode was plastic collapse. A flaw that would not survive a hydrostatic test at 100% of the pipeline yield strength (a=4.13 mm, 2c=82.6 mm) exhibited a 17% reduction in failure pressure in hydrogen due to the failure being predicted as elastoplastic. The study considered external crack like flaws, and it is uncertain if external cracks exhibit the same reduction in fracture toughness observed in small-scale laboratory tests (Gallon et al., 2020). In the same study, it was found that there is a specific value of fracture toughness - known as the threshold fracture toughness - related to hydrogen's effect on a pipeline failure prediction. This threshold is specific to certain conditions, such as the type of pipeline, operating conditions, and crack characteristics. When the fracture toughness is below this threshold value, hydrogen affects the failure prediction by changing the nature of the predicted failure. Specifically, the predicted failure mode shifts away from plastic collapse.

Performing fracture mechanics based failure assessments of crack-like defects according to BS 7910 Option 1, it was shown numerically that high toughness steel was less negatively affected by hydrogen compared to a low toughness steel (Andrews et al., 2022). The reason for this is that for low toughness steel, failure was predicted as brittle, implying that a reduction in fracture toughness gives a more severe reduction in performance. A high strength steel, exhibiting plastic failure, is less affected by (a proportionally equal) reduction in fracture toughness.

Cosham et al. (2024) conducted full-scale burst tests on test vessels manufactured from an X52 pipeline originally manufactured in 1969. Five defects were introduced in the test samples; an internal and external, sharp, part-through-wall defect (the internal defect was only tested in hydrogen); an external, blunt part-through-wall defect; a plain dent; and a dent and gouge (a notch). External defects showed similar burst pressures for both tests with hydrogen and with water, suggesting that hydrogen has no significant effect on fracture toughness for external defects. The internal defect, although only tested with hydrogen, resulted in a burst pressure significantly lower than expected. The external and internal sharp, part-through-wall defects had similar predicted failure pressures (not accounting for the effect of hydrogen), but the external failed at 117.5 barg and the internal at 47.1 barg. This equates to a reduction of 60%, which aligns well with reported reductions of fracture toughness of 35-70% (Gallon et al., 2020).

Fatigue is observed in pipelines through the sub-critical crack growth observed during cyclic loading. Fatigue leads to the growth of existing cracks in pipelines, which lead to integrity failure once the crack is large enough. It is well known that hydrogen enhances fatigue crack growth (see section 3.1.3). However, most of these studies are performed at low R ratios (Gallon et al., 2020; San Marchi & Somerday, 2012), which are not necessarily representative of real-life operating conditions. Furthermore, studies are most often performed at constant amplitude, also not fully representative of real-life conditions (Kethamukkala et al., 2024). Including hourly pressure fluctuations as compared to daily min/max aggregates has been numerically shown to reduce the calculated fatigue life by roughly 50% (Kethamukkala et al., 2024). This study concluded that it is necessary to identify the sampling frequency needed to accurately describe the fatigue behaviour. Most other calculations of fatigue life consider a constant amplitude load with one or two cycles per day, which might produce non-conservative results.

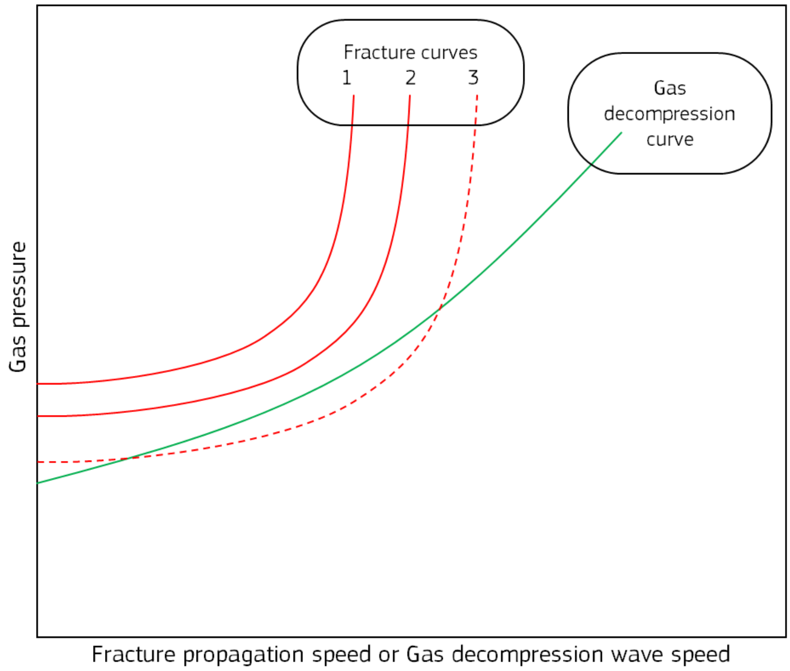
Dadfarnia et al. (2019) performed a numerical study to investigate fatigue life in hydrogen pipelines ranging in diameter from 152.4 mm to 304.8 mm. Fatigue crack growth rate was modelled based on small-scale laboratory results for X42 steel from (Cialone & Holbrook, 1985) and a combination of results for Grade B, X52, X56, X60 and X65 steels respectively. Pressure cycle data were extracted from data observed by a pipeline operator (SoCalGas). The conclusion drawn in the study is that, for pipelines made of X42 steel, any initial cracks that are less than 40% of the pipeline's wall thickness are not expected to grow to a critical size - defined as 75% of the wall thickness - within a time span of 100 years. In comparison, for the other group of steel grades (different from X42), the threshold for initial crack size is slightly higher. In this other dataset, initial cracks can be up to 50% of the wall thickness and still are not expected to reach the critical size of 75% of the wall thickness within the same 100-year period. Numerical simulations considering natural gas instead of hydrogen concluded to maximum initial crack depths of 55% and 67% respectively.

A similar study was conducted by Kethamukkala et al. (2024). Fatigue crack growth was modelled based on experimental small-scale laboratory results and fatigue life was simulated using observed pressure cycle data. The authors did not disclose the source of those data. Pipelines with outer diameter of 762 mm and wall thickness of 16 mm were considered. Initial cracks assumed to have a depth of 25% of the wall thickness and an aspect ratio (a/2c) of 1/3 resulted in calculated fatigue life of between around 30 to 170 years. Critical crack depth was considered either 60 or 90% of wall thickness. Interestingly, using the same pressure cycle dataset but increasing resolution from daily minimum and maximum to hourly data resulted in roughly half the estimated fatigue life (Kethamukkala et al., 2024).

Large variations exist in published estimates of fatigue life for hydrogen pipelines. One key aspect seems to be the definition of the pressure cycles used in the modelling effort. Pressure cycle behaviour is local, which makes it difficult to make any general recommendations. However, the definition and use of pressure cycle data in fatigue life estimations are considered a knowledge gap.

A running ductile fracture is a phenomenon sometimes observed for gas pipelines. It involves the initiation of a fracture from a small crack that then propagates, potentially over a long distance. The most common model for ductile fracture arrest is the Battelle Two-Curve Model (BTCM), which is a semi-empirical model. The principles behind the BTCM is shown in Figure 5 (Liu et al., 2019). The three curves represent the fracture propagation speed of three different materials with different toughness values. The decompression speed curve is a characteristic of the fluid. When the decompression speed curve and the fracture propagation speed curve intersect, the crack is propagated at the same speed as the decompression wave front, meaning that the crack continues to propagate and is not arrested (Liu et al., 2019). Preferably, materials should be chosen so that this does not happen (e.g. curve 1 in Figure 5).

Figure 5. Fracture propagation speed and gas decompression speed as a function of gas pressure.



Source: (JRC, 2024) based on (Liu et al., 2019)

The applicability of the BTCM to hydrogen service is unknown (Gallon et al., 2020). It is observed that the decompression speed of hydrogen is the same or faster than in natural gas, meaning that this will be less of an issue. In fact, a numerical study showed that cracks were arrested faster in hydrogen than in natural gas (Aihara et al., 2010). In the same study, experimental results also revealed that cracks were arrested in short distances. The European Pipeline Research Group hypothesises that the speed of running brittle fracture is probably too fast to be affected by gaseous hydrogen, but it has not been experimentally proven (EPRG, 2023).

4.1.1.2 Dents & gouges

Another integrity threat to pipelines are dents and gouges. Those can be the result from for example excavation equipment making contact with the pipeline (Naib et al., 2024), or the pipeline lying on a hard object such as a rock. A dent is a geometric abnormality in the pipe cross section. A gouge is a type of metal loss defect caused by scraping towards a hard object (Freire de Franca, 2023). Both dents and gouges can affect fitness-for-service as described in API 579-1 (Kappes & Perez, 2023b).

Cracks can sometimes be found in the vicinity of dents and gouges. In the context of gouges, the cracks can be hidden by the plastic 'smearing' of metal. Cyclic loading may also induce cracks where dents or gouges have been formed, due to the concentration of stresses around the defect (Freire de Franca, 2023). As such, dents can cause either immediate or delayed failure.

Damage due to external interference is in fact one of the primary causes of natural gas transmission pipeline incidents according to the statistics collected by EGIG (European Gas Pipeline Incident Data Group, 2024). This is anticipated to remain an important integrity threat also for hydrogen pipelines.

How critical a dent is for the integrity of the pipeline depends on factors such as the geometry of the dent and the strains (Naib et al., 2024). A combination of defects such as a dent and a gouge, a dent and a crack, poses even higher challenges for the pipeline integrity. Dents in close connection to welds are seen as more critical, as the probability of crack formation is increased (Naib et al., 2024; Pluvinage et al., 2019). Dents can be more severe in hydrogen service due to the reduced ductility (elongation at failure) observed for pipeline steels in hydrogen gas. A numerical study (Pluvinage et al., 2019) showed that a dent was more severe in hydrogen than in air under static loading condition. Presumably, this relates to a dent being formed while under a hydrogen environment, and not to a pre-existing dent.

Zhang and Adey (2009) investigated the theoretical effect of hydrogen on failure frequency from third-party excavation damage. They explained that data from EGIG on natural gas transmission pipelines reveal that nine out of ten third-party damages result in immediate failure, the rest in delayed failure. Zhang and Adey hypothesise that hydrogen will not have an effect on the frequency of immediate failure mode, but that it could significantly increase the failure frequency for delayed failure which is dominated by crack-like defects formed during the denting (L. Zhang & Adey, 2009).

As ductility is reduced by approximately 50% in hydrogen service (see section 3.1.1), the maximum allowable strain in dents in hydrogen pipelines should be half that of the allowable strain in natural gas pipelines (Andrews et al., 2022). ASME B31.8 restricts strain to 6% (if no other material data are known), compared to only 2% in ASME B31.12 (GR-5.6) (Andrews et al., 2022).

According to a database owned by the company ROSEN on dents in natural gas pipelines containing approximately 1500 data points, 6.3% of the dents are unacceptable for natural gas (over 6% strain) while 58.4% of the dents are unacceptable for hydrogen (over 2% strain) (Andrews et al., 2022). It is not clear if dents existing before repurposing a pipeline should be evaluated by the same criteria (2% strain) or if this should only apply to dents formed during hydrogen operation (Andrews et al., 2022). This is due to the presence of an oxide film, which hinders hydrogen from adsorbing on the steel surface.

Dents and gouges formed by for example accidental contact with an excavation equipment represent cold worked areas which increase the hardness. Hardness in gouges on X52 steel (normally 180 HV) has been reported to be as high as 350 HV (1120 MPa UTS) (Kappes & Perez, 2023b). As such, threats from hard spots need to be considered when dents and gouges are present.

4.1.1.3 Corrosion

Corrosion is the biggest source of natural gas transmission pipeline incidents considering the years 2013-2022 according to EGIG (European Gas Pipeline Incident Data Group, 2024). This covers both internal and external corrosion, although internal corrosion is not considered a big threat to pipelines transporting dry gases (EIGA, 2021). Corrosion is a form of metal-loss damage that may in the absence of cracks lead to either sudden rupture failure or leakage failure (Freire de Franca, 2023). Data from EGIG reveal that corrosion almost exclusively leads to 'pinhole' leaks (European Gas Pipeline Incident Data Group, 2024). Metal loss due to corrosion reduces the amount of material remaining to withhold the stresses. The quantity of metal loss that is acceptable is determined by the stresses and the material yield strength.

As yield and tensile strength are not significantly affected by hydrogen (see section 3.1), failure from volumetric (metal loss) corrosion should not be affected. This is because most corrosion-related failure models assume plastic failure. Hydrogen reduces however ductility significantly, which may affect the real situation (Andrews et al., 2022). In a numerical study of corrosion failure (Pluvinage et al., 2019) based on the assessment method in ASME B31G, it was shown that the introduction of hydrogen had no significant effect on the failure assessment for a pipeline with thickness 13 mm and operating pressure 6.82 MPa. This is due to the assessment method in ASME B31G that includes only the material strength, which is not significantly influenced by hydrogen.

4.1.1.4 Ground movement

Ground movement is another source of natural gas pipeline failure according to EGIG. It is also the second largest source for full pipeline ruptures (European Gas Pipeline Incident Data Group, 2024). When a pipeline fails due to ground movement, it usually entails the local displacement of the pipeline, resulting in stress in excess of the steel ultimate tensile strength. Hence, failures due to ground movement tend to be more severe than crack-related defects, as the former typically results in pipe ruptures, and the latter in smaller leaks (European Gas Pipeline Incident Data Group, 2024). It is suggested that the reduction in ductility from hydrogen exposure may increase the risk of failure (Joundi et al., 2023), but research is still limited.

4.1.1.5 Summary

There have been numerous studies using small-scale laboratory experiments that investigated the effects of hydrogen on specimen with defects. However, there is a lack of research investigating the effect of gaseous hydrogen on full- or large-scale pipeline sections with realistic defects (Andrews et al., 2022). There is currently ongoing research by PRCI Emerging Fuels Institute with C-FER technologies (see section 6.8) that investigates defects in vintage pipes[3]. Similar efforts are conducted as part of the SAFEH2PIPE project[4]. Several numerical studies have been performed extrapolating small-scale laboratory results to fitness-for-service evaluations. As referenced in the previous sections, some of these evaluations differ substantially, indicating a need for further investigations.

Assuming that active plasticity at an exposed metal surface is needed for hydrogen damage to be possible, damage inflicted before the repurposing of a pipeline may not be as severe as predicted by extrapolating laboratory results. This is due to the assumed presence of an oxide film, which hinders hydrogen from adsorbing on the steel surface. Hydrogen damage is then only possible following the breakage of this oxide film, if it does (Andrews et al., 2022). In fact, one study performing several mechanical tests on specimens exposed to gaseous hydrogen reported significant effects of hydrogen embrittlement in the dynamic tests, but no effects in the static tests (Briottet et al., 2012). This was hypothesised to be attributed to the formation of an inhibiting oxide layer in the static tests, effectively hindering the adsorption of hydrogen.

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[3] https://albertainnovates.ca/projects/full-scale-testing-of-legacy-pipeline-materials-for-the-purpose-of-retrofitting-existing-natural-gas-pipeline-networks-for-hydrogen-service/

[4] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43252449/101112650/RFCS2027?order=DESC&pageNumber=1&pageSize=50&sortBy=title&keywords=%20Hydrogen%20Pipeline&isExactMatch=false

4.1.2 Inspection of pipelines

Inspection and monitoring of pipeline assets are crucial to detect possible (time-dependent) flaws before they become critical. As most pipelines are buried underground, their inspection is less accessible than for above-ground assets. Determining the current state of a natural gas pipeline is however fundamental for the evaluation of its repurposing potential (Topolski et al., 2022). Internal inspections of existing pipelines will likely be required in most cases.

Pipeline integrity assessment methods can be divided into four categories (EIGA, 2021):

- Visual inspection
- In-line inspection (ILI)
- Pressure testing
- Direct assessment (DA)

The applicability of visual inspection is limited for gas pipelines given that most of the assets are buried underground.

Pigs are devices used for several different purposes (Camerini et al., 2023). They are devices that move inside the pipeline and perform various tasks related to cleaning and inspection. Pigs are a convenient and non-intrusive way of inspecting pipelines. However, not all pipelines are 'piggable'. Presence of sharp bends, diameter reduction, etc, are factors that can limit the use of pigs in a pipeline. For the inspection of gas pipelines, the following pigs are most relevant: geometric pig, metal loss pig, crack detection pig. The inspection of pipelines via pigs is referred to as in-line-inspection (ILI).

A geometric pig is used, as the name suggests, to detect geometric anomalies in the pipeline. This could include dents, bends, and asymmetry. This is a comparably simple technology with a long track record.

Metal loss pigs are used for detecting and localising corrosion in a pipeline. Corrosion is one of the more important integrity threats to current natural gas transmission pipelines (European Gas Pipeline Incident Data Group, 2024) and therefore needs to be managed carefully. Metal loss pigs can rely on various methods, most notably magnetic flux leakage (MFL) and ultrasound (Camerini et al., 2023). The former relies on observing a magnetic field induced by the device's strong magnets. Where metal is lost, a distortion occurs in the magnetic field. This distortion can be quantified to estimate the amount of metal loss. In connection with another 'discriminating' sensor, it is possible to determine if the metal loss is on the outside or on the inside of the pipeline. Ultrasonic metal loss detectors on the other hand rely on liquid media in the pipeline to transport the sound waves, and are as such not frequently used in gas pipelines (Camerini et al., 2023).

From manufacturers, the most common ILI technique for finding and sizing metal losses inside and outside pipelines is Magnetic Flux Leakage (Barker, 2020). Successful inspections using hydrogen as propellant have been performed (Barker, 2020; Gallon et al., 2022). Magnetic flux leakage can also be used to identify hard spots in pipeline steels, using two levels of magnetisation to differentiate between metal loss and hardness change (Tran et al., 2023). Hard spots can also be found via Eddy Current (EC) array technology. This technology is often used to verify MFL ILI (Tran et al., 2023). EC array testing is performed on the exterior of the pipe.

Compared to metal loss pigs, crack detection pigs are more advanced (Camerini et al., 2023). They rely on mainly two technologies: ultrasound and electromagnetic acoustic transducer (EMAT) (Sandana et al., 2023). Ultrasonic crack detection relies on a coupling agent which can be the liquid fluid being transported. If the fluid is gas (e.g. compressed hydrogen), a separate coupling agent is needed.

The depth and size of cracks that pipeline inspection gauges (pigs) can reliably find dictate the initial value for the crack length for engineering assessments. The maximum allowable crack depth is then dictated by the fracture toughness of the material and some safety margin based on the frequency of inspection. The introduction of hydrogen may require more frequent inspections based on the enhanced fatigue in hydrogen (Topolski et al., 2022).

Recently, inspection technology based on high-resolution eddy current measurement has been developed (Eiken & Thale, 2016). The signal response can be translated into values for Yield Strength (YS) and Ultimate Tensile Strength (UTS) via algorithms (Sandana et al., 2023). This technology is useful when material certificates have been lost.

Hydrogen has a damaging effect also on the ILI tools used for pipeline inspection (Gallon et al., 2024). This includes the polymer seals and the magnets used in MFL and EMAT technologies. Magnets need to be applied with protective coating to not disintegrate.

Pressure testing, or hydrostatic testing, is a relatively simple inspection method (Kishawy & Gabbar, 2010). Advisable is to use a non-compressible and non-toxic medium (such as water) for the pressure testing. A drawback of this method is the destructive nature of it (if critical flaws exist), and that it gives no indication of flaws that are close to critical but not yet critical. Also, the need to fill the pipeline with water is a practical burden, especially if the section to be inspected is long. However, the method can be helpful in situations where the pipeline is difficult to inspect with other means, or if the pipeline is thought to have flaws undetectable by other methods (Kishawy & Gabbar, 2010). Another aspect to consider is the reduced fracture toughness observed in gaseous hydrogen (see section 3.1.2) which might be missed in an evaluation using hydrostatic testing where the in-situ charging with gaseous hydrogen is missing.

Direct assessment is a method most often used when ILI is not possible (Camerini et al., 2023). In short, it relies on an accurate prediction of integrity threats, the accurate determination of where these threats are most probable to have occurred, and an excavation and subsequent inspection of the pipeline. The methods used for direct assessment would need to be altered to be suitable for a hydrogen pipeline, since the integrity threats are similar to but not identical to natural gas pipelines.

4.1.3 Pipeline integrity management systems

The management of pipeline integrity is formalised in a Pipeline Integrity Management System (PIMS). The structure of such a system is described by EIGA (EIGA, 2021), and in ASME B31.8S and IGEM/TD/1. PIMS are loosely based on the well-known Plan-Do-Check-Act cycle. Inspection, prevention, detection and mitigation are all important parts of the PIMS (EIGA, 2021). From the discussions in the previous sections, it is clear that this system will need to be adapted if a pipeline is to be repurposed or designed for hydrogen instead of natural gas. For example, more frequent inspections may be mandated given the increase in fatigue crack growth (section 3.1.3). Defect assessment procedures (section 4.1.1) and risk assessment procedures (section 4.3) may have to be updated as well.

4.2 Safety challenges

Hydrogen and natural gas are different gases, meaning that they have different characteristics in terms of safety and operational aspects. In Table 3, some characteristics of hydrogen and natural gas are presented, as well as the possible implications for safe handling and use.

Table 3. Safety related characteristics of hydrogen compared to methane.

Characteristic	Hydrogen	Methane	Comment
Relative density (air=1)	0.07 (Chemsafe, 2024)	0.56 (Chemsafe, 2024)	Hydrogen is more buoyant, meaning that it rises quicker from the point of release.
Diffusion coefficient	0.61 cm^2/s (Verfondern, 2022)	0.22 cm^2/s (Chemsafe, 2024)	Hydrogen has higher diffusivity, meaning that it mixes easier with air and dilutes quicker.
Auto-ignition temperature	585°C (Alcock, 2001)	540°C (Alcock, 2001)	The auto-ignition temperature is closely linked to the surface temperature that would ignite the mixture. This temperature is in the same range for hydrogen and methane, and high compared to other flammable gases.
Energy density (LHV) (volumetric)	11 MJ/m^3 (Verfondern, 2022)	35 MJ/m^3 (Hurley et al., 2015)	Hydrogen has a lower volumetric energy density.
Energy density (LHV) (gravimetric)	120 MJ/kg (Verfondern, 2022)	50 MJ/kg (Hurley et al., 2015)	Hydrogen has a higher gravimetric energy density.
Fuel to air ratio at stoichiometry	29.53 Vol-% (Verfondern, 2022)	9.5 Vol-% (Chemsafe, 2024)	Methane has a lower stoichiometric fuel to air ratio, meaning that it is most reactive at a lower concentration.
Flame temperature	2318 K (Verfondern, 2022)	2158 K (Alcock, 2001)	Hydrogen has a slightly higher flame temperature.
Flame visibility	Low	High	Hydrogen burns with an almost invisible flame, especially in daylight and in air free from particulates.
Maximum laminar burning velocity in air	3.46 m/s (Alcock, 2001)	0.43 m/s (Alcock, 2001)	Hydrogen has a significantly higher maximum laminar burning velocity. This means that a hydrogen flame propagates faster.
Minimum ignition energy (MIE)	0.02 mJ (Verfondern, 2022)	0.29 mJ (Alcock, 2001)	Hydrogen has a lower MIE. However, there are only few ignition sources below the MIE of methane.
Maximum experimental safe gap (MESG) at Normal Temperature and Pressure (NTP)	0.29 mm (Chemsafe, 2024)	1.14 mm (Chemsafe, 2024)	The value is significantly lower for hydrogen, influencing the design of ATEX equipment.

Lower flammability limit (LFL) in air	4.0 Vol-% (Verfondern, 2022)	5.3 Vol-% (Alcock, 2001)	The LFL is slightly lower for hydrogen compared to methane.
Upper flammability limit (UFL) in air	75.0 Vol-% (Verfondern, 2022)	15.0 Vol-% (Alcock, 2001)	The UFL is much higher. This influences for example the probability of finding an ignition source within the flammable regions of the gas cloud.
Fraction of chemical combustion energy emitted as flame radiation	0.05-0.1 (Alcock, 2001)	0.1-0.33 (Alcock, 2001)	Hydrogen has a much lower radiative fraction, meaning that it emits less energy as flame radiation.
Maximum detonation velocity in air	1980 m/s (Groethe et al., 2007)	1863 m/s (Zipf et al., 2013)	The detonation velocities of the two gases are in the same range of magnitude.
Detonation cell size at stoichiometry	15 mm (Verfondern, 2022)	220 mm (Malik et al., 2019)	Detonation cell size is a measure of the reactivity of a fuel-air mixture. The smaller the cell size is, the more reactive the gas is. Detonation cell size increases the further from stoichiometry you get.

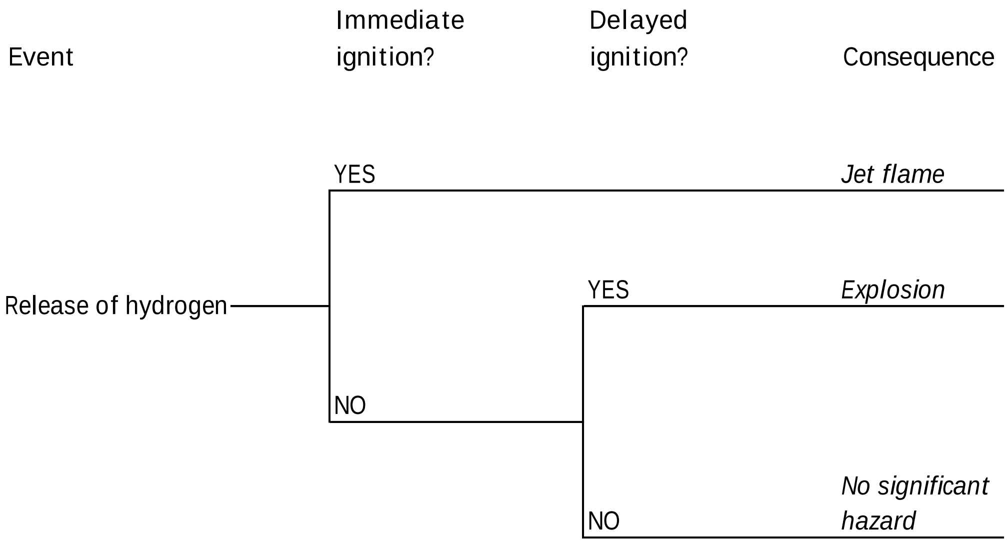
Source: (JRC, 2024)

Hydrogen and natural gas are gases lighter than air. This means that they both exhibit the same type of behaviour upon leakage; they (in due time) rise due to buoyant forces. This characteristic makes them safer, compared to for example dense gases such as propane, which tend to dwell around the place of leakage for a longer time.

Important to note is that several of the characteristics included in Table 3 depend on the mixture fraction between fuel and air. The most severe effects are usually found at or near stoichiometric mixture. As the fuel-air ratio at stoichiometry is much higher for hydrogen compared to methane, several of the characteristics indicated as more severe for hydrogen in the table above, are actually less severe for hydrogen at certain fuel-air mixture ratios. This is true for example for detonation cell size (Ehrhart et al., 2023) and laminar burning velocity.

Most safety concerns related to hydrogen (or natural gas) pipelines are related to the possibility of accidental release of flammable gas from the pipeline. Figure 6 depicts the possible events following an accidental release of flammable gas from the pipeline. This depiction is called an ‘event tree’.

Figure 6. Event tree relating to the accidental release of hydrogen from a pipeline.



Source: (JRC, 2024)

Hydrogen release and dispersion behaviours are well understood in open-air conditions (Kotchourko, 2022). Hydrogen pipelines are however located to a great extent underground, which influences the behaviour of released gas. Small releases underground may diffuse up through the soil. Such releases have been numerically modelled by Zhang and Zhao (2024) investigating the effects of leakage hole, soil type, pipeline pressure and pipeline diameter. Zhang et al. (2024) studied numerically the behaviour of pinhole leaks in low-pressure (0.1-0.4 MPa) buried hydrogen pipelines and estimated the hazard at ground level. Larger releases create craters uplifting the soil (Bonnaud et al., 2018; Houssin-Agbomson et al., 2018). The different flow properties of hydrogen and natural gas influence how and when craters are formed during accidental releases, meaning that existing models for natural gas need to be adapted and revalidated for hydrogen. However, many hydrogen pipeline incidents are anticipated to be caused by external interferences, for example by excavation equipment. In such a situation, the hydrogen can be released more freely.

Hydrogen flames emit radiation like all other flames. However, hydrogen emits less in the visible spectrum compared to carbon-based fuels like methane (Schefer et al., 2009). Hydrogen emits ultraviolet light from the hydroxide radicals, and infrared light from the vibrating water molecules. High doses of thermal radiation cause harm to humans and structures. Most experimental studies on thermal radiation from hydrogen jet flames are for smaller fires and situations different from those expected for a pipeline. Pipelines are generally buried underground, and it is possible that a jet flame from such a pipeline would involve not only the hydrogen gas but also particles from the surrounding soil, which might affect thermal radiation behaviour.

There are many experimental data on hydrogen jet flames (Ewan et al., 2022), but those are very limited for large scale fires such as expected in case of a pipeline rupture. In the European NATURALHY project, jet flame experiments were conducted involving a rupture of a 150 mm pipeline holding a gas pressure of 70 bar (Lowesmith & Hankinson, 2013). Two experiments were conducted, one with pure methane and one with a mixture of 78% methane and 22% hydrogen. Only minor differences in radiated heat were found, while the gas mixture yielded a slightly reduced heat release rate and depressurised faster compared to pure methane. The fraction of heat emitted as flame radiation was found to be roughly 0.3 in both cases. Overall, a slightly lower thermal radiation dose was observed for the methane-hydrogen mixture due to the shorter duration and faster de-escalation.

Some full-scale experiments of pure hydrogen pipeline leakage have been performed, but the amount of data collected is usually limited. In the FutureGrid project in the UK, a rupture test of a 6 inch carbon steel pipeline was conducted at 60 barg (National Gas, 2024). The first test produced a flow rate of around 25 kg/s and ignited spontaneously after around 100 ms. The observed thermal radiation and overpressures were in line with expectations.

If a flammable cloud of hydrogen is ignited, it leads to deflagration or detonation. The term explosion covers these two phenomena, as well as other types of explosions, such as physical explosion. A deflagration is a subsonic combustion process where the pressure build-up is limited. Detonations on the other hand can generate substantial overpressures and the combustion process is supersonic (Molkov, 2015). Hydrogen is known to detonate under certain conditions. The risk for detonation is increased with increasing confinement (Kotchourko, 2022). For gas transmission pipelines, the level of confinement after release would typically be low, reducing the risk for detonation. Confinement can exist at metering stations, compressor stations, etc.

Large-scale explosion experiments conducted as part of the NATURALHY project revealed that hydrogen-air mixtures yielded significantly higher overpressures as compared to methane-air mixtures (Shirvill et al., 2019). These experiments were conducted in a congested region constructed of interconnected pipes. They also concluded that a hydrogen-methane blend of up to 25% hydrogen did not produce significantly higher overpressures compared to pure methane.

4.2.1 Explosive atmosphere

Hydrogen and natural gas are both flammable gases and their handling are therefore subject to ATEX regulation (directives 2014/34/EU and 1999/92/EU). The two directives relate to equipment used in potentially explosive atmospheres and reduction of risk to workers in such atmospheres. Hydrogen is classified as gas group IIC and temperature class T1. Natural gas is classified as gas group IIA and temperature class T1. The gas group and temperature class set the requirements for the equipment allowed in the different zones. This means that equipment designed for natural gas environments may not be suitable for use with hydrogen due to their different classifications. The extent of zones will also change with the conversion of the pipeline system to hydrogen, both because of hydrogen having different leak behaviour, and the higher pressures foreseen with hydrogen (Blanchetiere et al., 2022). Possibly also the type of zone (indicating the likelihood of the presence of an explosive atmosphere) will change as hydrogen can be more prone to leak in certain situations.

Hydrogen may also lead to leaks, which extend further away from the source of the leak compared to natural gas. Distance from the point of release to the lower flammability limit (LFL) may increase up to 100% (Blanchetiere et al., 2022). This leads to a necessary extension of the zones (0, 1 and 2) where an explosive atmosphere may occur. In certain cases, this may create to a situation where the zone extends beyond the facility boundary.

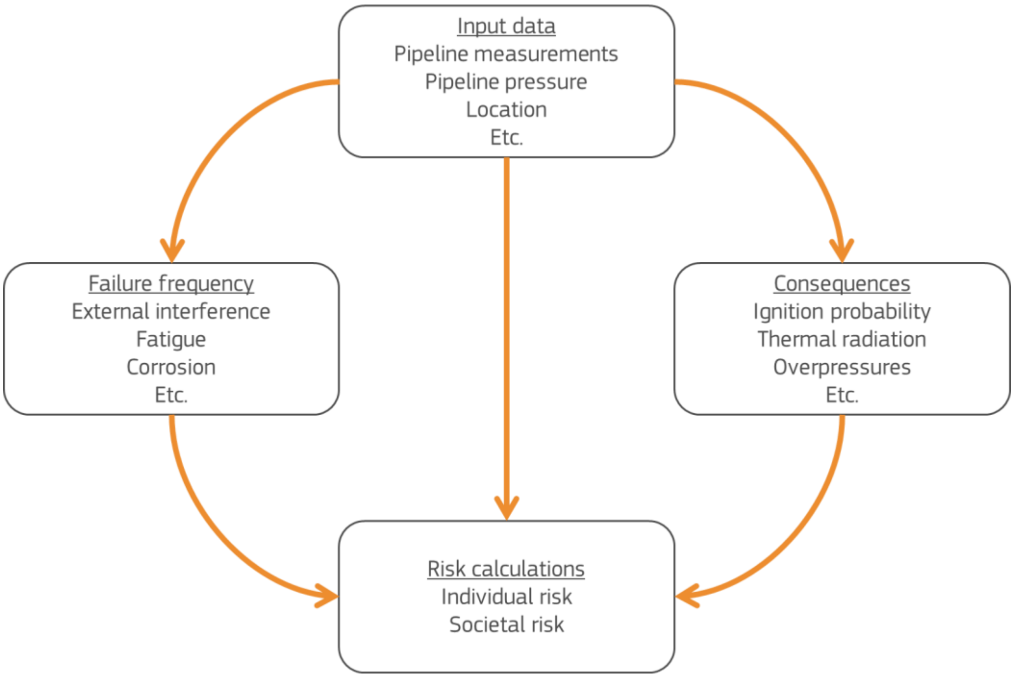
4.3 Risk assessment approaches

Risks related to the operation of gas pipelines are addressed through several activities. The risks related to the integrity of the pipeline are handled in the Pipeline Integrity Management System (PIMS, see section 4.1.3) where the integrity of the pipeline is monitored and maintained through inspections, assessments, and repairs. The risks to the public related to release of gas from the pipeline are addressed through quantitative risk assessments (QRAs) or pre-determined safety distances. The latter represents a more simple approach to risk management.

The determination of safety distance usually relies on the identification and evaluation of a certain hazardous event, which might be correlated for example to pipeline diameter, pressure, and type of surroundings. In the UK for example, the safety distance (Building Proximity Distance (BPD)) is based on the calculation of a natural gas pipeline failure with subsequent fire (Simpson et al., 2024). The safety distance is then calculated as the distance until the level of radiation is lower than 32 kW/m^2. As hydrogen emits less radiation, and the potential overpressure from delayed ignition is higher as compared to natural gas, this approach needs to be re-evaluated.

A schematic representation of a QRA process is displayed in Figure 7. The level of risk can be presented in various ways. Societal and individual risks are two common measures. Societal risk refers to the potential harm or danger posed to a community or population as a whole, whereas individual risk refers to the likelihood of harm or danger to a single person, often based on a distance from the risk source. For conducting a comprehensive QRA, it is necessary to also include the Pipeline Integrity Management System (see section 4.1.3) in the assessment.

Figure 7. Typical QRA process as applied to hydrogen pipelines.



Source: (JRC, 2024)

The risk related to the operation of a gas pipeline can be addressed in several different ways. The pipeline itself can be designed and operated so that the risk for catastrophic releases is minimised. This includes for example operating the pipeline at low pressures, minimising the risk for plastic collapse and also reducing the possible release rate in case of failure. It can also include the installation of the pipeline far below the surface to minimise the interference with excavation equipment. Another possibility is to limit the exposure to the hazard, for example by not allowing the construction of buildings closer than a certain distance to the pipeline. This is commonly referred to as safety distance as discussed above. Lastly, barriers can be implemented, such as physical fire-rated barriers, concrete slabs to protect the pipeline from excavation equipment interference, or detection and isolation functionality. Hence, an increase in risk level in one aspect can be compensated by a reduction of risk level in another, so that the total risk is kept at an acceptable level.

The location factor F given in ASME B31.12 is one example of a risk reducing measure. The location factors for hydrogen are lower than for natural gas (comparing ASME B31.8 with ASME B31.12). As risk is driven partly by pipeline pressure, a reduction in pipeline pressure results in a reduction of risk. The design code used, which dictates amongst other things the maximum operating pressure, has a significant influence on the risk level as shown in a case study on natural gas comparing ASME B31.8 to IGE/TD/1 (Goodfellow & Haswell, 2006).

The QRA methodology applied in the UK for natural gas pipelines is described in IGEM/TD/2. There is currently no equivalent for hydrogen in the UK. More details about risk assessment methods in various codes, standards and guidelines are also available in section 5.

In the Netherlands, the QRA methodology for gas pipelines is described in module V of *Rekenvoorschrift omgevingsveiligheid* (RIVM, 2020) (previously BEVB (RIVM, 2022)). RIVM conducted a study in 2021 to give further guidance for hydrogen pipelines (RIVM, 2021). Based on the fulfilment of 14 prerequisites, RIVM concluded that failure frequencies for natural gas (Module A in BEVB) could also be used for hydrogen.

In a recent study, the UK's *Model for the estimation of Individual and Societal risk from Hazards of Pipelines* (MISHAP) methodology was adapted and applied to a hydrogen transmission pipeline case study (Aslan & Curson, 2021). Adaptations were done mainly for the fire modelling and ignition probability to account for the characteristics of hydrogen gas. Results showed that the level of risk was higher close to the pipeline for hydrogen transport as compared to methane. The opposite was true when distance to the pipeline increased. This was attributed to hydrogen's higher ignition probability and lower thermal radiation. However, the result of any QRA study relies heavily on the assumptions made, which are inherently uncertain when there is little to no data to back it up.

In any QRA, assessments of failure frequency and failure consequence are both central aspects. In a recent review of QRAs of hydrogen transmission pipelines (Yang et al., 2024) several research gaps were identified. It was found that most studies considered the consequence part of the QRA, but less attention was generally given to the probability part of the QRA (Yang et al., 2024).

Froeling et al. (2021) conducted a quantitative risk analysis of transmission pipelines, in which only jet fire consequence was considered. Comparing results for natural gas and hydrogen, it was found that hydrogen generally yielded a lower individual risk. The difference became greater as the distance from the pipeline increased. The difference was attributed mainly to the lower thermal radiation of the hydrogen jet fire. For smaller pipelines (16 inch diameter), the individual risk close to the pipeline was higher for the hydrogen pipeline compared to the natural gas equivalent. This was attributed to the higher ignition probability of hydrogen. The same initial failure frequency was used for both hydrogen and natural gas pipelines.

A similar study by Kim et al. (Kim et al., 2024) included also overpressure effects from explosions in the evaluation. Similarly, they assumed the same initial failure frequency for both natural gas and hydrogen. They found similar individual risk levels for both hydrogen and natural gas transmission pipelines, with slightly lower individual risk levels for hydrogen at medium distances, and slightly higher risk levels at longer distances from the pipeline.

The above references discuss mainly the risk to the public from hydrogen pipelines. There is also a risk related to the end use of hydrogen. The HyDelta 2 project conducted a QRA (van den Noort & Zwanenburg, 2023) for the distribution grid in The Netherlands, comparing natural gas and hydrogen. The focus was mainly on the use of hydrogen in homes. They found that the risk from explosion was greater for hydrogen, but that the overall risk was lower compared to natural gas. The main reason for this is the risk of CO poisoning, which is a big contributing factor to the natural gas risk. A QRA was also conducted as part of the UK based H21 project phase 2c (H21, 2023) considering the hypothetical conversion of the UK gas distribution grid to hydrogen. They found that the societal risk for the hydrogen case was roughly twice as much the one for the natural gas case, even considering fatalities from CO poisoning. Although these studies are on the same topic, the results are not easily comparable due to the many methodological differences and assumptions that were used.

5 Requirements, codes, standards and guidelines for hydrogen pipelines

There are only a few codes and standards that define material requirements specifically for hydrogen pipelines. Most notable is the ASME B31.12 that builds upon the pre-existing ASME B31.3 that applies to natural gas pipelines. Most other codes with material requirements specific for hydrogen are built upon ASME B31.12. Material requirements in terms of chemical composition, strength and toughness are common. This section covers only codes, standards and guidelines that give material requirements specifically for hydrogen pipelines.

5.1 ASME B31.12-2023

ASME B31.12 is probably the most used code when it comes to hydrogen pipelines. Although it is an American standard, it is often used as a reference also in other countries. Apart from pipelines, the code also covers industrial piping.

An important note is that there is currently an ongoing work to transfer the hydrogen pipeline requirements from ASME B31.12 to an exception chapter of ASME B31.8. Following this change, the technical requirements of ASME B31.12-2023 have been reviewed and new consensus engineering requirements (CER) have been proposed in the context of a project developed by the Emerging Fuels Institute (EFI) of the Pipeline Research Council International (PRCI) (Shaw et al., 2024). Some notable proposed updates are the use of Engineering Assessment/Engineering Critical Assessment (EA/ECA) for design, the removal of material performance factors, decoupling hardness and toughness, and the introduction of material equivalence. The following review is based on the current ASME B31.12-2023 and does not consider the changes proposed from the above mentioned project.

The chemical composition of the pipeline steel allowed under ASME B31.12, pipeline section, is required to align with the API 5L PSL 2 specifications. This restricts the maximum carbon equivalent to 0.43. In the non-mandatory appendix G which provides guidelines for higher fracture toughness steel, the maximum carbon equivalent is further restricted to between 0.15 and 0.17 depending on steel grade. API 5L PSL restricts the maximum carbon content to 0.16%-0.24% depending on steel grade. Non-mandatory appendix G restricts it further to 0.07%. API 5L PSL 2 specifications and non-mandatory appendix G contain further requirements not covered here.

The code gives two options for the design of hydrogen pipelines. Option A is a prescriptive approach in which the hoop stress is limited to 50% of SMYS for steel grades equal to or below X52 and the least restrictive location class[5]. For X70 steel the hoop stress is restricted to between 39% and 30% of SMYS depending on operating pressure. Steel with SMYS up to 480 MPa (70 ksi) is allowed under design option A. Design option A uses material performance factors which effectively reduce the maximum operating pressure (or demand thicker pipe walls) for higher strength steel.

[5] Location class describes the number and proximity of building intended for human occupancy. Highly populated areas are classified as more restrictive location class and vice versa.

Design option B requires more material testing to determine the fracture toughness of the material. If design option B is used, hoop stress is allowed up to 72% of SMYS, irrespective of grade. Steel with SMYS up to 550 MPa (80 ksi) is allowed under design option B.

For API 5L steels with grade X65 or higher, Maximum Operating Pressure (MOP) is not allowed to be higher than 10 MPa according to ASME B31.12. This is irrespective of design option.

ASME B31.12 design option B requires the measurement of material fracture toughness in air according to the rising displacement method described in ASTM E1820. It requires also the measurement of the threshold stress intensity for hydrogen assisted cracking (K_{IH}) according to the constant displacement or constant load method described in ASTM E1681. Lastly, it requires fatigue crack growth testing in gaseous hydrogen as described in ASTM E647. Fatigue crack growth testing can be omitted if values for fatigue crack growth properties given in ASME B31.12 are used instead.

For design option B, a minimum fracture toughness (threshold stress intensity factor) of 55 MPa*m$^{1/2}$ when tested in 100% hydrogen at design pressure is required. Testing should be conducted as specified in KD-1040 in ASME BPVC.VIII.3.

ASME B31.12 limits the ultimate tensile strength to 110 ksi (760 MPa) for design option B and 100 ksi (690 MPa) for design option A. This restriction applies to both base metal and weld metal. ASME B31.12 also limits hardness to less than 237 BHN for installation inspection of welds (ASME, 2023). API 5L (API, 2018), which is the material specification for pipeline steel, allows quite big and hard zones (up to 345 HV, 50mm in any direction), meaning that these can be expected in hydrogen pipelines.

5.2 DVGW G 464

The DVGW G 464 is a German standard that applies to hydrogen steel pipelines with operating pressures exceeding 16 bar. It covers the fracture mechanical assessment of such pipelines. As such, it is not a complete design code as it is the case for ASME B31.12.

DVGW G 464 requires the measurement of the threshold stress intensity factor for hydrogen assisted cracking (K_{IH}) in gaseous hydrogen according to the rising displacement method described in ASTM E1820. It also requires fatigue crack growth testing in gaseous hydrogen following ASTM E647. Alternatively, the code allows for the use of the Paris law as indicated in ASME B31.12 as well as the use of material values from the SyWeSt H2 project report (Steiner et al., 2023). As such, DVGW G 464 could theoretically be applied without the need for additional material testing.

5.3 IGEM/TD/1 Supplement 2

IGEM/TD/1 is a UK standard covering the design, construction, inspection, testing, operation and maintenance of steel pipelines. In supplement 2, specific guidance for hydrogen pipelines is given.

Appendix 3 of IGEM/TD/1 contains a high-level description of a risk assessment procedure similar to EIGA IGC Doc 121/14. More detail is given in IGEM/TD/2 but this only applies to natural gas pipelines.

Supplement 2 restricts the hoop stress to maximum 50% of SMYS for hydrogen pipelines (for other pipelines covered by IGEM/TD/1, hoop stress can be allowed up to 72% or 80% of SMYS). Additionally, Supplement 2 defines material performance factors similar to ASME B31.12, which further restricts operating pressure for pipeline grades higher than X52.

Grades over X70 are not allowed in IGEM/TD/1 Supplement 2 unless the pipe and weld metal are qualified for the intended service. The qualification involves defining and demonstrating acceptable fracture toughness of the material. Furthermore, maximum tensile strength of pipe and weld metal is restricted to 690 MPa. Compared to API 5L PSL 2 specifications, only grade X46 is required to have a maximum tensile strength lower than 690 MPa. Material testing similar to ASME B31.12 design option B is allowed in order to relax these restrictions. Hardness is restricted to 250 HV10.

Two options are given for determining fracture toughness in hydrogen service. One option is to conduct testing similar to what is described in ASME B31.12 design option B. The other option is to conservatively assume fracture toughness in hydrogen service from Charpy impact energy. In the latter, you are required to assume a fracture toughness equal to the lowest of 27 J or 50% of the specified value. These values can then be converted to fracture toughness values using the correlation given in Appendix J of BS 7910-2019.

Supplement 2 contains requirements related to the definitions of fatigue life. It is highlighted in the standard that fatigue is a bigger issue in hydrogen service compared to other fluids. Two approaches are given. First is a simplified approach that can be used when daily pressure fluctuations are constant. This method does not consider pre-existing flaws but simply the constant amplitude stress range and the number of cycles. The second method is based on Paris law equation and the constants for determining fatigue crack growth are given in the standard. The recommended fatigue crack growth threshold is 2 MPa*$m^{1/2}$.

5.4 EIGA IGC Doc 121/14

The European Industrial Gases Association (EIGA) has published guidelines for hydrogen pipeline systems in the document IGC Doc 121/14 (EIGA, 2014). The document is not intended to be a mandatory standard or code. It is said to contain a summary of current industrial practices and is based on the experience and knowledge of the authors. The guideline covers aspects related to the design, operation and maintenance of hydrogen pipeline systems.

As it is not a design code, it does not provide complete guidance on establishing the MOP for hydrogen pipelines. It gives some guidance for specific situations as described below.

EIGA guidelines recommend restricting hoop stress to <30% of SMYS or <20% of SMTS, mainly to reduce effects of third-party damage, but the restriction is also said to ensure resilience towards hydrogen embrittlement.

Steels used for hydrogen pipelines are recommended to have a hardness less than 22 HRC/250 HB, which is equivalent to a tensile strength of 800 MPa (116 ksi). This limit also applies to welds and Heat Affected Zones (HAZ), so the base metal would be restricted in hardness even further. 500 MPa is given as a guidance.

In general, API 5L X52 and lower strength grades, and ASTM A 106 Grade B are recommended steels. The recommendation is based on previous experience where these grades have been used with few reported problems. It is also said that, for API 5L steels, the PSL 2 specification level is preferred.

EIGA (EIGA, 2014) specifies the maximum carbon equivalent (CE) to be 0.43 for carbon steels. For micro alloyed steels, the maximum CE is 0.35. The reason for limiting CE is to avoid the formation of excessively hard untempered martensite during welding (EIGA, 2014). The limit given in API 5L PSL 2 for maximum CE is 0.43. Compared to the API 5L PSL 2 specifications, EIGA also puts stricter requirements for sulphur (0.01% compared to 0.015%) and phosphor (0.015% compared to 0.025%) for microalloyed steels.

In microalloyed form, EIGA only allows for API 5L grades X42 and X52.

In section 4.6 of the guideline, a high-level description of a hazard analysis and risk assessment procedure is given. It contains recommendations on which threats and event scenarios need to be considered, recommendations on how to evaluate the hazard, and suggestions for mitigation measures. It does not give enough details in order to establish a safety distance or equivalent for a specific pipeline. The method is referenced in ASME B31.12 (ASME, 2023) as a suitable risk assessment method for hydrogen pipelines.

6 Testing facilities on hydrogen pipelines

This section gives an overview of the testing facilities on hydrogen pipelines worldwide. Those are used for full-scale pipeline testing, material integrity testing, or metering devices/grid components testing. This compilation is not meant to be exhaustive, but to identify the main entities working on the subject and their capabilities.

6.1 DNV – Spadeadam – Great Britain

DNV is a worldwide company with different business areas, including oil and gas. DNV has a research centre based in Spadeadam, where a testing facility has been built in collaboration with National Gas: the FutureGrid high-pressure test facility.

FutureGrid is a testing facility constructed from a representative range of decommissioned National Transmission System (NTS) assets of different types, sizes, and material grades (National Gas, 2024). Tests can be carried out in a purpose-built offline test facility, as well as in stand-alone test modules. These stand-alone tests include material permeation testing, pipe coating and cathodic protection testing, flange testing, asset leak testing, fatigue testing, and rupture testing. For the fatigue testing, a 36 inch X60 pipelines with welds were pressure cycled 75 000 times to simulate over 200 years of service life. Tests have been performed on hydrogen-natural gas blends at 2%, 5%, 20% and 100% hydrogen concentrations.

Figure 8. View of the FutureGrid facility.

Source: (National Gas, 2024).

The facility has been used to verify whether the pipelines and assets of the gas NTS could be used safely and reliably to transport hydrogen gas. The results of the study are available in a report published in July 2024 (National Gas, 2024).

The phase 2 of the FutureGrid project focuses on deblending and purification of hydrogen in natural gas, and on compression aspects.

DNV is also in charge of assessing the viability of blending hydrogen into the South Korea's gas transmission network (DNV, 2023). Further details on the assessment are currently unknown.

6.2 Rosen group – Lingen – Germany / Newcastle – Great Britain

Rosen group is a global technology company, which delivers asset integrity management solutions for different sectors, including oil and gas. Rosen has two test centres, located in Germany and in Great Britain (ROSEN, 2024).

In 2022, the Rosen group test centre in Lingen, Germany, expanded its existing material testing capabilities to material testing in hydrogen environment according to ASME B31.12. In its other test centre in Newcastle, Great Britain, the Rosen group conducts a wide range of analyses on new and existing products of the gas infrastructure, for instance, pipe ring testing, fatigue or burst tests on full-scale pipelines (diameters from 3" to 56"). More information about the Rosen group laboratories and their capabilities is available on their website[6]:

Figure 9. Partial view of the Rosen testing facility in Lingen, Germany

Source: (ROSEN, 2024)

6.3 Rina Consulting Centro Sviluppo Materiali SpA – Cosenza – Italy

Rina Consulting Centro Sviluppo Materiali SpA is a company that provides a wide range of services, including consulting, engineering, testing, inspection, and certification, primarily in the fields of energy, infrastructure, and industry[7].

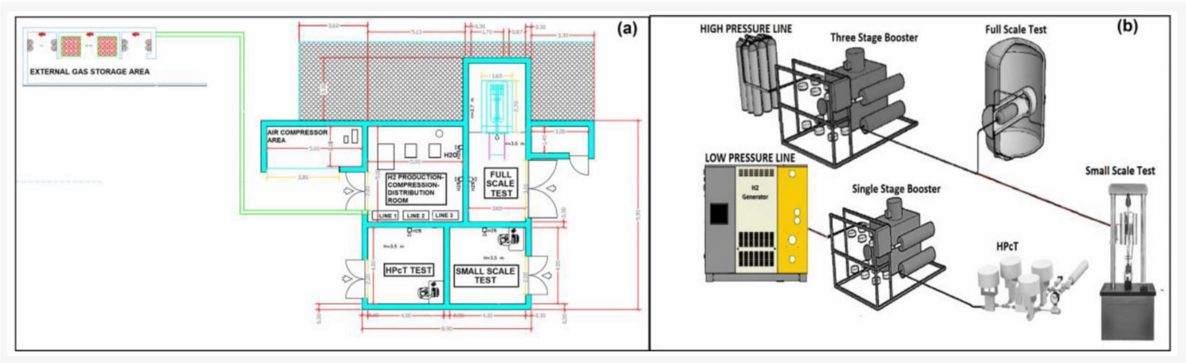
In 2016, Rina created the Delta H Laboratory in collaboration with the University of Calabria. The Delta H Laboratory is dedicated to the assessment of the performance of materials and components in the presence of gaseous hydrogen at high pressure. The laboratory is divided in three units: a small-scale testing unit, a large-scale testing unit and a solid state material testing

[6] https://www.rosen-group.com/en/expertise/testing/testing-facilities

[7] https://www.rina.org/en

unit. In the large-scale testing unit, tests on real-scale materials and components can be performed, and pressure cycling tests can be carried out on full-scale tanks or vessels at pressures up to 1000 barg (Mecozzi & Di Vito, 2022). The possible dimensions of the tested samples are not known.

Figure 10. (a) Map of the Delta H laboratory and (b) simplified diagram of the large scale testing unit.



Source: (RINA, 2021)

In April 2020, Rina and Snam, the main Italian operator for the transport and distribution of natural gas in Italy, formed a joint working group to study and test the compatibility of the Italy's existing gas transport infrastructure for hydrogen. At the end of 2023, 1513 km of the Italy's gas transmission network were certified H_2-ready by Rina (Snam, 2024).

Rina has also a full-scale pipeline testing facility in Sardinia, Italy, in which a wide variety of tests (burst tests, bending tests, etc.) are conducted at high-pressure hydrogen on large diameter steel pipelines (RINA, 2024).

6.4 Energinet – Varde – Denmark

Energinet is an independent public enterprise owned by the Danish Ministry of Climate and Energy. Energinet owns, operates and develops the transmission systems for electricity and natural gas in Denmark[8].

In 2014, Energinet has launched a project with different partners with the purpose of testing a blend of hydrogen and natural gas in the Danish network. The aim was to acquire knowledge and anticipate possible challenges related to leaks, safety equipment, etc. For the tests, a closed loop of the existing grid between two metering and regulating stations (M/R) has been used.

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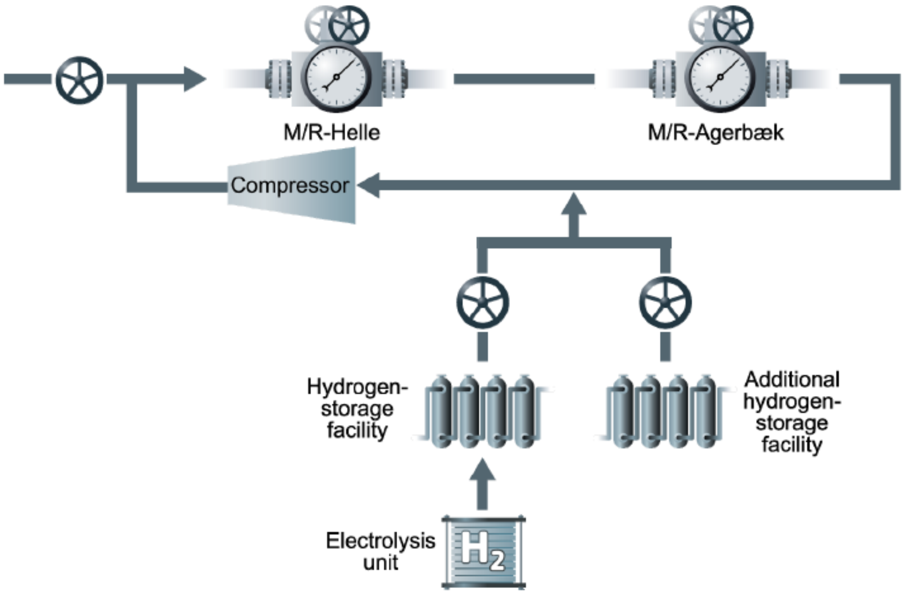
8 https://en.energinet.dk/about-us/

Figure 11. Scheme of the Energinet testing facility.



Source: (Energinet, 2020)

The phase 1 of the project was finalised in February 2020 with a long-term test of 12% hydrogen in natural gas and short-term test of 14% hydrogen in natural gas. A report presenting the main conclusions and the perspectives has been published in 2020 (Energinet, 2020). For the phase 2 of the project, Energinet aims to test up to 25% blend of hydrogen in natural gas (Energinet, 2020).

6.5 KIWA – Apeldoorn – The Netherlands

KIWA is a global specialist in testing, inspection and calibration. In the recent years KIWA has been active at national and international levels for technical assistance, testing, inspection and certification of solutions dedicated to the hydrogen supply chain[9].

In its different hydrogen testing facilities, KIWA is able to carry out a wide range of tests, from hydrogen material compatibility assessment to high-pressure components testing. In its Hydrogen Tank and High Pressure Components Test Laboratory, it carries out lifecycle and functional testing of hydrogen fuelled products and associated appliances and systems[10] up to 1050 bars hydrogen, in various environmental conditions. KIWA is also active in the field of hydrogen transportation and distribution studies. In this regard, in collaboration with Alliander, an energy network operator, it has built the Hydrogen Experience Centre[11]. The Hydrogen Experience Centre is built as a residential home heated by a hydrogen boiler and aims to demonstrate how, in practice, natural gas could be replaced by hydrogen in residential areas. The demonstration facility includes a local gas

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9 https://www.kiwa.com/en/about-kiwa/

10 https://www.kiwa.com/en/markets/energy-and-power-generation/hydrogen/hydrogen-specials/laboratory-facilities/

11 https://www.kiwa.com/nl/en/themes/energy-transition/hydrogen-revolution/hydrogen-house/#:~:text=The%20Hydrogen%20Experience%20Centre%20is,for%20heating%20mechanics%20and%20engineers.

distribution system. The centre is also used as a training location for engineers working in those fields.

6.6 Fundación Hidrógeno Aragón – Huesca – Spain

The Fundación Hidrógeno Aragón is a foundation which supports the development of strategic projects in the field of hydrogen and fuel cell technologies[12].

To support the European project HIGGS (Hydrogen in Gas Grids), a testing facility has been built in Huesca, Spain. The purpose of this facility is to assess the behaviour of real components, such as valves, pipelines, seals, or couplings, after having been exposed to hydrogen under real life conditions. The facility is divided in two sections. The first section is a static section to perform tightness and permeation tests. In this section, the gas lines are fed to a given pressure, and then isolated for a given time (e.g. 3000h at 80 barg). The second section is a dynamic section where the tested elements are exposed to flowing hydrogen. The dynamic section is used to study the hydrogen embrittlement of grid components (Sánchez-Laínez et al., 2024).

Figure 12. View of the dynamic (left) and static (right) sections of the testing facility.

Source: (Fundación Hidrógeno Aragón, 2023)

The HIGGS project started in 2020 and ended in 2023. A brochure summarising the most important results and experiences that have been performed at the facility during the HIGGS project has been published in November 2023 (Fundación Hidrógeno Aragón, 2023).

6.7 Sandia National Laboratory – Albuquerque - USA

Sandia National Laboratory (SNL) is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC. SNL has been very active in the field of material compatibility with hydrogen (Ronevich et al., 2023; San Marchi & Ronevich, 2022b; San Marchi & Somerday, 2012; Topolski et al., 2022).

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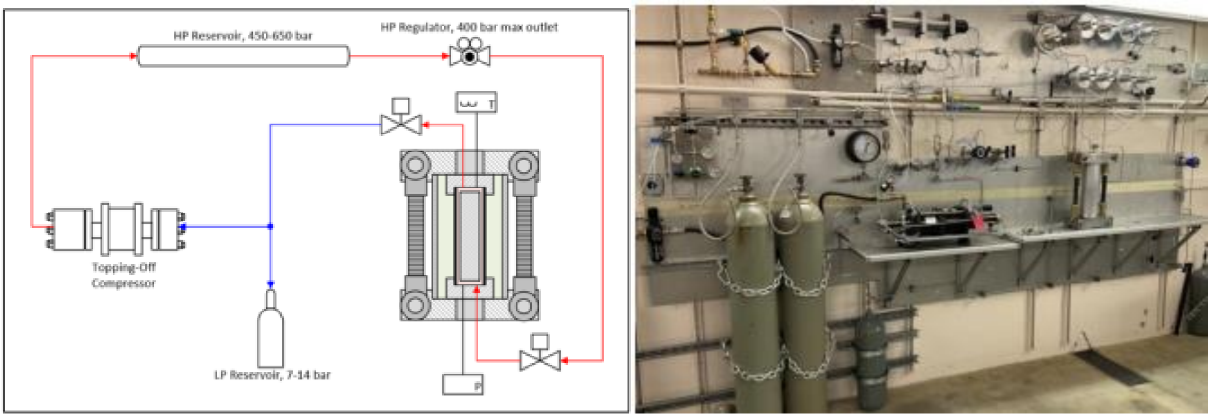
[12] https://hidrogenoaragon.org/en/the-foundation/mission-vision-values/

To provide scientific basis to verify safety of piping and pipelines for hydrogen service, Sandia has developed a subscale pipe testing platform to pressure cycle 60 mm diameter pipes (Simmons & San Marchi, 2023).

Figure 13. (Left) Simplified scheme of Sandia subscale pipe testing platform and (right) picture of the same platform.



Source: (Simmons & San Marchi, 2023).

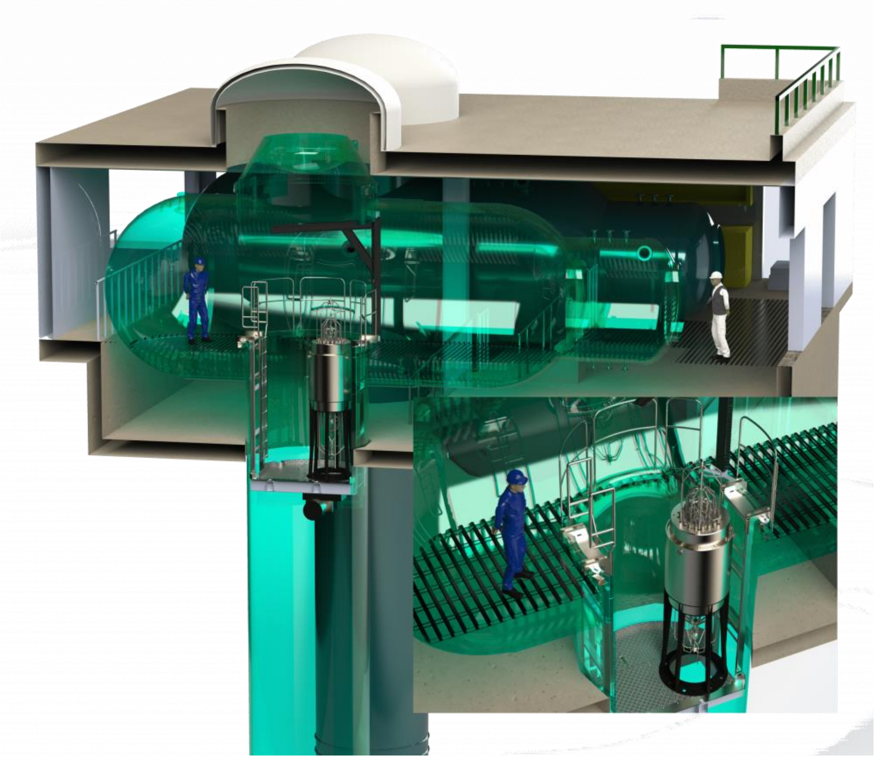
6.8 C-FER Technologies – Edmonton – Canada

C-FER Technologies is a company specialised in the improvement of safety, operational efficiency and environmental performance in the energy and oil and gas industries. C-FER Technologies helps developing new industry standards for hydrogen-ready equipment and is supporting the update of industry codes and standards to ensure a safe transition to hydrogen[13].

To investigate the feasibility of converting existing natural gas pipelines to hydrogen, C-FER Technologies has set up a facility to perform advanced testing on systems and components in hydrogen environment, such as material integrity testing, small-scale tests with continuous exposure to hydrogen, or static or cyclic pressure loading tests on full-scale pipelines (C-FER Technologies, 2024). C-FER Technologies full-scale testing system allows to test pipeline cross-sections up to 711.2 mm in diameter and 700 mm in length in hydrogen environment.

[13] https://www.cfertech.com/company-overview/

Figure 14. Cut away view of the C-FER Technologies full-scale testing system.



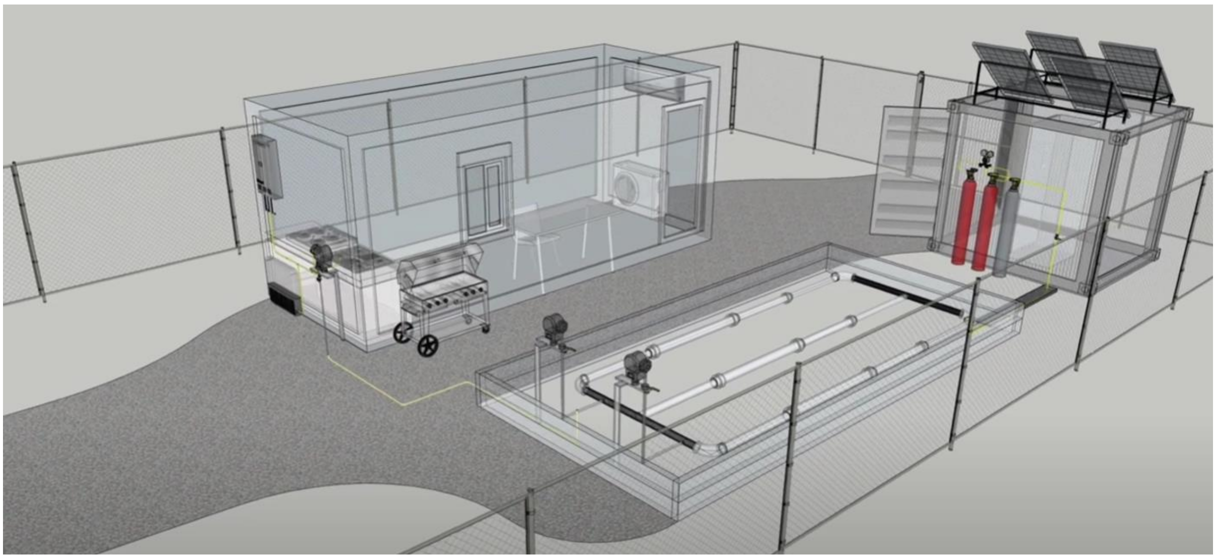
Source: (C-FER Technologies, 2024).

6.9 Canberra Institute of Technology – Canberra – Australia

Evoenergy, one of the gas network owner in Australia, and the Canberra Institute of Technology built a hydrogen testing facility at the Fyshwick campus that opened in December 2018. Hydrogen interaction with distribution grid materials (polyethylene and nylon pipes), work practices for hydrogen service, and equipment systems and components have been studied at the facility. The project was split in 2 phases: in a first phase, existing Australian gas network components were tested, and construction and maintenance practices with 100% hydrogen were developed, then appliances for use in hydrogen were tested (Evoenergy, 2024). More information are available on the Evoenergy website[14].

[14] https://www.evoenergy.com.au/Future-energy/Hydrogen-Test-Facility

Figure 15. 3D view of the Evoenergy/Canberra Institute of Technology hydrogen testing facility.



Source: (Evoenergy, 2024).

The network compatibility with 100% hydrogen has been assessed over a period of 2 years, and no major issues have been detected. An article presenting the project and its main outcome was published in 2021 (Gaykema et al., 2021).

In July 2020, the installation was upgraded with the installation of a gas mixer, thus allowing testing on blends of hydrogen and natural gas (Evoenergy, 2024) .

6.10 Kyushu University – Fukuoka – Japan

Kyushu University is engaged in a wide range of research subjects linked to the utilisation of hydrogen (Kyushu University - International Research Center for Hydrogen Energy, 2024). Its scope of research includes the construction of safe and low-cost hydrogen storage, transportation and supply systems. At its Ito campus, the Kyushu University has several hydrogen testing facilities, including a high-pressure hydrogen strength testing laboratory, and a high-pressure hydrogen exposure testing laboratory. Further information on its research topics is available on the Kyushu University website[15].

[15] https://h2.kyushu-u.ac.jp/english/

7 The High-Pressure Gas Testing Facility (GasTeF) of the European Commission's Joint Research Centre (JRC)

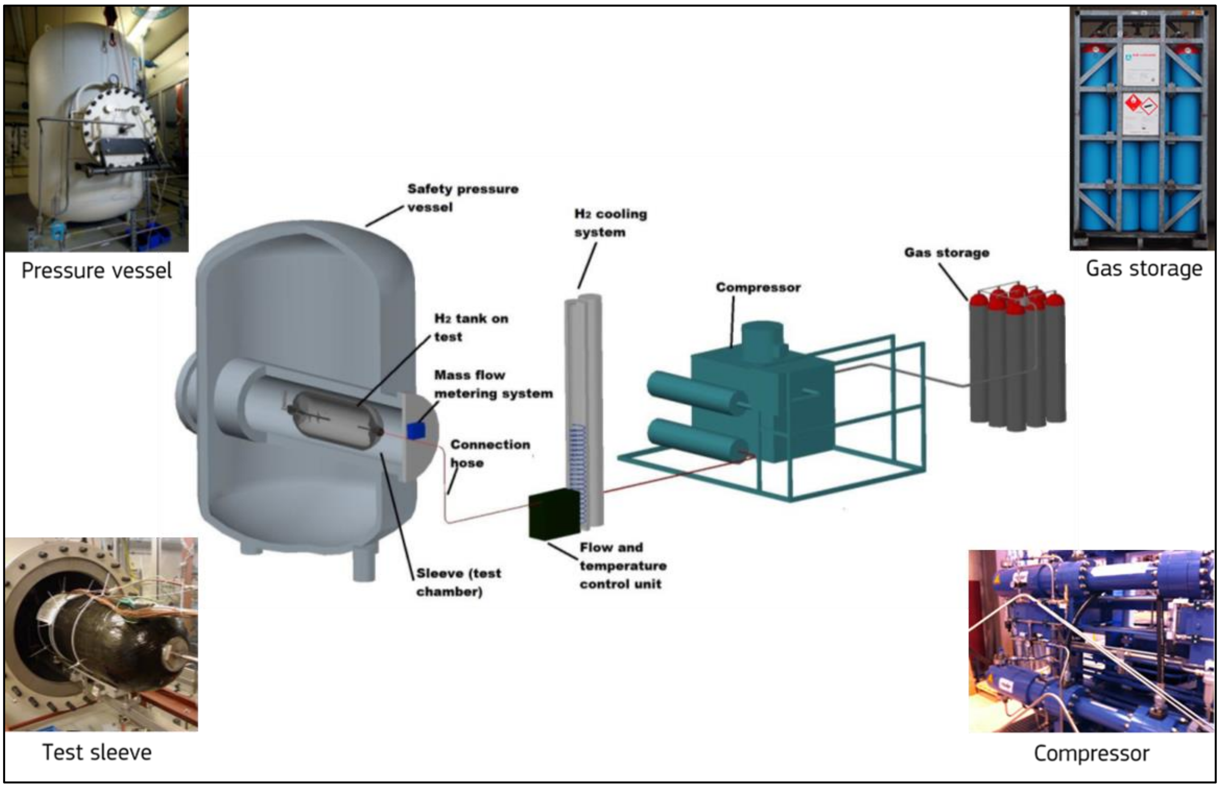
7.1 Description and technical characteristics

The High-Pressure Gas Testing Facility (GasTeF) of the European Commission's Joint Research Centre (JRC) in Petten, The Netherlands, is used for the experimental assessment of the safety and performance of systems and components under pressurised hydrogen. The facility is designed to perform permeation tests, emptying and filling in cycles and fast filling experiments. It has been used previously to test gaseous hydrogen storage tanks for automotive applications (De Miguel et al., 2015; Ortiz Cebolla et al., 2023).

The GasTeF facility consists of a half-buried concrete bunker connected to gas bundles stored in a gas storage area. The utilised gases (helium, nitrogen, and hydrogen or methane) are stored in standard bundles of cylinders at pressures of 200 or 300 barg. In addition, a liquid nitrogen reservoir is used to operate the hydrogen pre-cooler, to actuate the pneumatic equipment in the facility, for purging off lines and chimneys, and for the removal of oxygen from the bunker (bunker inertisation) when tests with hydrogen are being carried out. The facility is complemented with a control room situated in an adjacent building from where the tests are remotely monitored and controlled.

The inside of the bunker is divided into four parts: an entrance area with the control cabinets, a service room, a compressor room and a test room. The test room hosts the safety pressure vessel and a sleeve, which contains the sample, and the equipment for hydrogen pre-cooling. The configuration of the GasTeF facility is shown in Figure 16.

Figure 16. Configuration of the GasTeF facility.



Source: (JRC, 2024)

The facility is composed of a gas bundle (located in the gas storage area), an 880 barg compressor, a gas cooling system, a safety pressure vessel and a sleeve, which contains the sample. It can perform pressure cycles with hydrogen from 20 barg up to 880 barg. The facility has measurement capabilities to measure the temperature and pressure of the flowing gas, the temperature at different locations of the sample, the permeation/leak of hydrogen, and the surface strains induced on the sample from the gas pressure.

7.2 Earlier experimental results

The GasTeF facility has contributed to various research projects, including the Fuel Cell and Hydrogen Joint Undertaking funded project MATHRYCE 'Material Testing and Design Recommendations for Components Exposed to Hydrogen Enhanced Fatigue', which investigated the hydrogen-enhanced effect on the fatigue life of metallic vessels (de Miguel et al., 2017). The GasTeF facility has also been used to analyse out-of-specifications circumstances during the refuelling of hydrogen vehicles (De Miguel et al., 2015). Its test results have provided insights for understanding the behaviour of high-pressure hydrogen storage systems under various conditions, including fast filling and defueling.

Considering the lack of guidance for setting up a hydrogen permeation test for composite reinforced vessels, a dedicated permeation test campaign was performed using the GasTeF facility (Ortiz Cebolla et al., 2023). The aim of this test campaign was to provide complementary guidelines to the applicable regulations and standards. Indeed, even if the existing literature at the time was giving information about the experimental setup, the test protocol and the results, there was no particular guidance on how to execute the permeation test, and how to reliably measure and calculate the permeation rate. The outcome of this study provided an analysis of the overall process to carry out permeation tests, and guidelines to test providers.

7.3 Research priorities in the context of hydrogen pipelines

The scope of the GasTeF facility is being widened to include tests of hydrogen pipeline sections to address new research priorities. Due to the configuration of the GasTeF facility, the hydrogen pipeline sections, used as samples, will be closed at their ends in order to resemble gas cylinders. Experiments investigating fatigue and permeation will then be carried out on the hydrogen pipeline sections in the same manner as for on-board and stationary storage vessels.

As highlighted in previous sections, pipeline steel materials exposed to gaseous hydrogen exhibit a reduction in ductility, a reduced fracture toughness, and a decreased fatigue crack growth resistance. Importantly, most of these findings stem from research on small-scale specimens in laboratory environments. While small-scale laboratory tests have provided valuable insights into the effects of hydrogen embrittlement, there is a need for validation of the results using full-scale testing. This is to verify that the findings on small-scale specimens can be accurately extrapolated to real-world pipeline conditions to ensure informed integrity and safety management practices.

The effect of hydrogen on the steel material from pipeline sections under different operating conditions of the pipeline can be investigated using the GasTeF facility. Cycling tests at various hydrogen pressures and flow rates can be performed on the pipeline section to reflect the different operating conditions of the pipeline. Furthermore, the fatigue life of the pipeline as a function of the operating conditions and the type of defects that may be present in the pipeline can be studied. Hydrogen enhanced fatigue and crack propagation can be investigated after the introduction of artificial cracks or other defects under different operating conditions, including high-stress conditions. Cycling tests are to be used as a way to perform accelerated testing of the pipeline over its expected lifetime and beyond.

In addition, evaluation methods of pipeline integrity need to be validated for typical pipeline defects such as dents, gouges and cracks for situations where the gas transported is hydrogen. To accurately predict the behaviour of a pipeline with such defects, full-scale experiments are deemed necessary. Pipeline samples with defects could be tested in the GasTeF facility, and the experimental results be compared with the evaluation methods given in the current regulations, codes, standards and guideline for hydrogen service. Experiments should be conducted both on defects formed before hydrogen exposure, and during hydrogen exposure.

As most studies on crack propagation have been conducted on small-scale specimens and according to test standards such as ASTM E1820, ASTM E1681, and ASTM E647, the behaviour of external cracks during the internal transport of hydrogen has not been studied. The GasTeF facility provides the opportunity to study pipe wall cracks under realistic conditions, where gaseous hydrogen is contained only on the inside of the pipeline.

For polymeric pipelines, permeation has been highlighted as a notable concern, and limited data are currently available on the long-term effects of hydrogen exposure on polymeric materials. In that regard, further research is needed to ascertain the durability and performance of these materials, especially in the context of vintage pipelines and their associated welds and joints. The implications of increased hydrogen leakage through polymeric pipelines, both from an economic and safety standpoint, need to be thoroughly evaluated. The GasTeF facility has previously been used to study permeation of on-board hydrogen tanks (Ortiz Cebolla et al., 2023). With some adjustments, the GasTeF facility could also be used to study the permeation through the pipe walls of polymeric pipelines. Given the design of the GasTeF facility, vintage samples, samples with defects, and samples with welds could all be studied.

8 Discussion

The advancement of hydrogen as a sustainable energy vector is an essential component of the European Union's strategy to achieve a climate-neutral economy. An analysis of the challenges and considerations involved in the transition from natural gas to hydrogen infrastructure, focusing on the repurposing of existing natural gas pipelines for hydrogen transport, has been performed in this technical report. Transporting hydrogen via pipelines is comparatively cheap and safe compared to other alternatives.

For the repurposing of the natural gas assets to be successful, it must be made sure that the assets are compatible for their use with hydrogen. Compatibility entails the economic, environmental and safety aspects (economic aspect - the existing assets need to connect supply with demand, it needs to be able to transport the required volumes of energy; environmental aspect - the assets need to be leak tight to a sufficient extent; safety aspect - the assets need to be able to contain the hydrogen so that the risk of incidents is kept sufficiently low). This technical report has been focusing on the latter aspect: safety and integrity. The interaction between hydrogen and pipeline materials, the integrity and safety of pipeline systems, and the applicability of current standards and codes are all important areas of focus in that frame.

The phenomenon of hydrogen embrittlement is a central concern when considering the transportation of hydrogen through steel pipelines. Hydrogen embrittlement depends not only on the material susceptibility, but also on the specific operating conditions of the hydrogen pipelines. The report's findings indicate that hydrogen embrittlement can lead to significant reductions in key material properties such as ductility, fracture toughness, and fatigue crack growth resistance. These alterations could potentially compromise the structural integrity of pipelines that were originally designed for natural gas.

Although the influence of gaseous hydrogen on material properties such as ductility, fracture toughness and fatigue crack growth resistance has been extensively studied, there are still large variations in reported results. Ductility is reported to be reduced by approximately 20%-80% and fracture toughness by 35%-75%. The reason for those variations is not fully established, but differences can be observed based on for example the test method used and to some extent the material strength. For fatigue crack growth, there are more similarities between materials, which also enable the establishment of ‘master-curves’ such as the one presented in ASME B31.12-2023.

Crack-like defects require particular attention due to the enhanced risk of propagation under the influence of hydrogen. Experimental and numerical results suggest that existing cracks, which may have been stable or latent under natural gas service, could exhibit accelerated growth in a hydrogen environment. This might necessitate a shift in pipeline inspection regimes, with more frequent or advanced monitoring techniques required to detect and address such flaws before they lead to failure. Other integrity threats, such as dents, gouges and corrosion, need also to be reconsidered in the light of hydrogen effects on steel pipeline materials.

Most research activities on hydrogen embrittlement and crack-like defects have been performed using small-scale laboratory experiments. While those small-scale laboratory experiments provide valuable insights into the effects of hydrogen embrittlement and the behaviour of crack-like defects, there is however a need for validation of the results using full-scale testing. Full-scale testing is necessary to verify that the findings on small-scale specimens can be accurately extrapolated to real-world pipeline conditions, especially since the experimental conditions may be different in small-scale laboratory experiments and in real-world pipeline operating conditions. For example, the influence from exposure to gaseous hydrogen may differ in small-scale laboratory experiments and in full-scale experiments, as hydrogen embrittlement is dependent upon the concentration of stresses in the material, the diffusion of hydrogen etc. Depending on the size and the configuration of the sample specimen, the distribution of stresses may differ from that in a pipeline. The type of loading will also differ, where in-field loading will inevitably exhibit some fluctuations. With regard to threat from external defects, where hydrogen first would need to diffuse through the metal, small-scale laboratory experiments, such as the ones specified in ASTM E647, E1681 and E1820, involve exposing the crack directly to gaseous hydrogen, not only through the length of the crack, but also from its sides. Another aspect that may differ between small-scale laboratory experiments and in-field pipelines is the threat from defects inflicted prior to introducing hydrogen. The mitigating effects of oxide layers have been investigated, but it is still unclear as to their long-term effects. Testing facilities having the capabilities to test full- or large-scale pipeline sections in hydrogen environment have an important role to play in the validation of results from small-scale laboratory experiments to ensure informed integrity and safety management practices.

Polymeric materials used in existing natural gas distribution systems behave differently than steel material when exposed to hydrogen, they are not subject to hydrogen embrittlement. The most important concern for polymeric pipelines is their permeation and therefore continuous leaks, rather than the risk of rupture from lost integrity. In addition, more testing is required on the effects of long-term exposure of polymeric materials to hydrogen.

The transition from natural gas to hydrogen also necessitates a re-examination of pipeline inspection and integrity management practices. The report underscores the potential challenges of current inspection technologies, such as in-line inspection tools, to detect any adverse effects of hydrogen. Modifications to these tools, or the development of new inspection technologies, may be required to ensure their continued efficiency in a hydrogen context. Existing inspection methods need to be evaluated for their effectiveness in detecting hydrogen-related damage and, if necessary, modified or replaced with new technologies.

From a safety perspective, the distinctive properties of hydrogen, such as its wide flammability range, low ignition energy, and buoyancy, present unique challenges in comparison to natural gas. Safety protocols, emergency response plans, and risk assessment methodologies need to be rigorously updated to account for these differences. The report emphasises the importance of recalibrating quantitative risk assessments and of establishing appropriate safety distances, taking into consideration the behaviour of hydrogen in the event of a leak or release.

As emphasised in this report, hydrogen embrittlement of pipeline steels will depend upon the environment (hydrogen pressure etc.), the material (steel strength, chemical composition etc.), and the mechanical stresses on the material (maximum operating pressure etc.). There are still many uncertainties regarding how a future hydrogen grid will look like and what the operating conditions will be. This depends, amongst others, on the demands it will have to fulfil. As such, it is very difficult to draw any general conclusions about the compatibility of the current infrastructure at this stage. Most likely, each segment of pipeline will have to be evaluated individually before being deemed safe for use with hydrogen. In some cases, restrictions on operating pressure, line pack capacity, etc. may have to be enforced to ensure that the pipeline can be operated safety.

For the repurposing of the existing natural gas infrastructure for hydrogen transport, European and international codes and standards will need to be updated to include specific requirements on adaptation measures, e.g. safety aspects, choice of material, sealings, and assessment criteria, to make the infrastructure fit for hydrogen purpose and to ensure its safety, operation and maintenance. Such work is underway at the national, European and international level in the responsible national standardisation bodies, CEN-CENELEC and ISO Technical Committees, e.g. American ASME, German DVGW, CEN/TC234 on gas infrastructure, CEN-CLC/JTC6 on Hydrogen in energy systems, ISO/TC197 on Hydrogen technologies. The American ASME B31.12 is currently the most used standard when it comes to hydrogen pipelines. The need to develop a new ISO standard and/or a European standard that is tailored to hydrogen pipeline operation is identified in the European Clean Hydrogen Alliance roadmap on standardisation (European Clean Hydrogen Alliance, 2023).

In summary, the report emphasises the need for an integrated approach to address the identified knowledge gaps discussed above. This approach should encompass research and development efforts to better understand the interaction of hydrogen with pipeline materials, as well as the further development of new standards and guidelines that are specifically tailored to hydrogen service. In order to ensure a successful repurposing and conversion of the existing natural gas grid for hydrogen transport, advancements and information exchange are needed across the entire safety chain from material properties, implications for integrity, and assessment of societal risk.

9 Conclusions

This technical report presents a review of the integrity and safety challenges for the transport of hydrogen by pipeline, and covers in particular the challenges associated to the repurposing of the existing natural gas grid for hydrogen transport. It highlights the interaction between hydrogen and pipeline materials, in particular low carbon ferritic steels and polymers, and the subsequent integrity and safety considerations.

Hydrogen embrittlement of pipeline steels is a well-known issue. Principally, hydrogen embrittlement from gaseous hydrogen in pipeline steel leads to reduced ductility, reduced fracture toughness, and reduced resistance to fatigue crack growth. These alterations are important to assess with regard to the long-term structural integrity of steel pipelines in hydrogen service.

Typical defects found in natural gas pipelines are expected to play an important role for hydrogen pipelines. Therefore the behaviour of these defects need to be investigated under the influence of gaseous hydrogen. These defects include for example cracks, dents, gouges, and corrosion. Hydrogen embrittlement is expected to make the pipeline less resilient to some of these defects.

Most measurements on the effects of hydrogen embrittlement on pipeline steels are from small-scale laboratory experiments that may not be representative of the conditions and behaviours expected for real-size pipeline sections. The report emphasises the need for full-scale validation of small-scale laboratory measurement results to ensure the safe and effective repurposing and design of pipelines for hydrogen transport. Importantly, full-scale testing needs to be performed to investigate the behaviour of defects typically found in gas pipelines under hydrogen service. Testing facilities having the capabilities to test full- or large-scale pipeline sections in hydrogen environment have an important role to play in that regard.

For polymeric materials typically used in distribution pipelines, the primary threat is the permeation of hydrogen through the pipe walls. More research is needed to address the long term effects of hydrogen exposure to polymeric pipelines and their welds so that their suitability for hydrogen transport can be confirmed.

The findings suggest that while hydrogen embrittlement presents an important challenge for pipeline steel material, it can be managed with thorough material compatibility, integrity and safety assessments, and adapted inspection, maintenance and risk mitigation practices. Furthermore, as hydrogen has different safety-related characteristics compared to natural gas, safety and risk assessment procedures need to be revised accordingly.

As more knowledge is generated, it ultimately needs to feed into new codes and standards that are specifically tailored to hydrogen pipeline operation.

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List of abbreviations and definitions

Abbreviations	Definitions
K	Stress intensity factor
ΔK	Stress intensity factor range
ΔK_{th}	Threshold stress intensity factor range
K_{IH}	Threshold stress intensity factor for hydrogen-assisted cracking
K_{TH}	Crack arrest stress intensity factor in the presence of hydrogen
K_{IC}	Plane-strain fracture toughness
FCGR	Fatigue crack growth rate
CNT	Circumferentially notched tensile
CVN	Charpy V-notch
WOL	Wedge opened loaded
HV	Vickers Hardness
CT	Compact tension
BHN	Brinell Hardness Number
HB	Hardness Brinell
QRA	Quantitative Risk Assessment
CE	Carbon equivalents
MOP	Maximum operating pressure
MAOP	Maximum allowable operating pressure
PCI	Project of Common Interest
IPCEI	International Projects of Common European Interest

Abbreviations	Definitions
YS	Yield strength
UTS	Ultimate tensile strength
RA	Reduction of area
FAD	Failure assessment diagram
PIMS	Pipeline integrity management system
TYNDP	Ten Year Network Development Plan

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Annexes

Annex 1. On-going infrastructure and R&D projects

Examples of on-going infrastructure projects in Europe

The ENTSOG Hydrogen Project Visualisation Platform provides an EU-wide, open source, comprehensive database for hydrogen projects (ENTSOG, 2024). With regard to the use of pipelines for hydrogen transport, it provides a visualisation of the newly built hydrogen infrastructure projects (see Figure 17), including the newly built infrastructure for transporting hydrogen, and a visualisation of the retrofitting/repurposing of existing infrastructure projects (see Figure 18). Retrofitting is an upgrade of existing infrastructure that allows the injection of certain amounts of hydrogen into a natural gas stream (blending) while repurposing is converting an existing natural gas pipeline into a dedicated hydrogen pipeline. Table 4 and Table 5 provide more information on the projects related to newly built infrastructure for transporting hydrogen (see Table 4) and on selected projects related to the repurposing of existing infrastructure for transporting hydrogen (see Table 5).

Figure 17. Newly built hydrogen infrastructure projects.

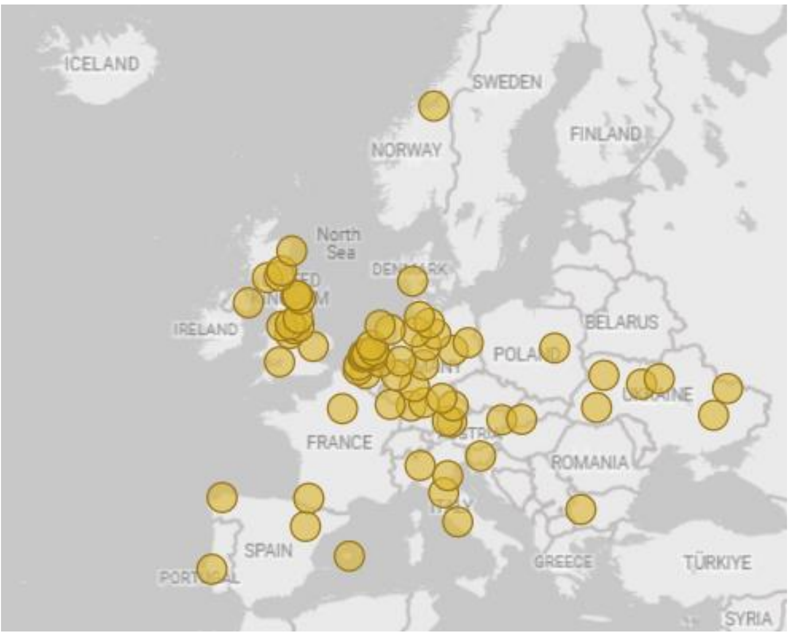
Source: (ENTSOG, 2024)

Table 4. Projects on newly built infrastructure for transporting hydrogen.

Project name	Project promoters	Country	Timeline	Scope & goal
Dow-Yara Point-to-Point Hydrogen transport	Gasunie, DOW, Yara	Netherlands	2018-NA	This regards a commercial activity consisting of 12 km Hydrogen pipe between DOW and Yara. The data and experience are available to Gasunie as well.
H2 transmission system in Bulgaria	Bulgartransgaz EAD	Bulgaria	2022-2029	This is an infrastructure project for transport of pure H2 between the region of Sofia, the Bulgarian-Greek border near Kulata, allowing future expansion to Romania and the Maritsa East Coal Basin.
HyBRIDS	Società Gasdotti Italia (SGI), Società Chimica Bussi (SCB)	Italy	2021-2026	The project envisages the construction of a 2 km hydrogen 8''steel pipeline and facilities connecting the H_2 production plant at SCB chemical complex in Bussi to SGI high-pressure gas network.
The Green Villlage	Alliander, Enexis Groep, Stedin	Netherlands	2016-NA	This consists of a newly built distribution grid to enable research on the possible applications of hydrogen in The Green Village's site at Delft University of Technology. The grid is built with conventional materials used for natural gas grids and connected to heating and cooking appliances.
Zukunft RuH2r	Open Grid Europe (OGE), Enervie Vernetzt, Westnetz	Germany	NA-NA	The project enables a powerful hydrogen supply in the hinge region between the Ruhr Metropolis and South Westphalia.

Source: (ENTSOG, 2024)

Figure 18. Projects on the retrofitting/repurposing of existing infrastructure.



Source: (ENTSOG, 2024)

Table 5. Projects on the repurposing of existing infrastructure.

Project name	Project promoters	Country	Timeline	Scope & goal
Green H2 Pipeline	IDOM, Redexis	Spain	2020-NA	The aim is a 35 km pipeline of green H_2 and an injection system into Natural Gas Network. A preliminary study of the definition and dimensioning of the necessary equipment (regulation and metering, gas analyser...) for the injection of hydrogen into the natural gas grid and of the hydrogen pipeline which connects the production point to the injection point (35 km between them) was requested.
Green Hydrogen @blue Danube - Connection Port Regensburg	bayernets GmbH, Open Grid Europe GmbH	Germany	2020-2050	The project aims at connecting hydrogen sources with high-demand regions in Bavaria using existing transmission pipelines or pipeline routes.
H21 North of England	Equinor, Cadent	United Kingdom	2019-NA	Developed in partnership with global energy giant Equinor and UK gas distributer Cadent, this project builds on the original Leeds City Gate, presenting a conceptual design for converting the North of England to hydrogen between 2028 and 2035.
H2DeltaNetwork	Fluxys, North Sea Port	Belgium	2021-2025	The project aims at the development of H_2 infrastructure in Belgium part of the North Sea Port.
H2vorOrt	Initiative of 33 distributing network operators who count for more than 50% of the german gas distribution network	Germany	2021-2050	The project partners have developed a transformation path for this infrastructure towards climate neutrality by aggregating and sharing knowledge from Research & Development and practitioners, linking TSO and DSO, promoting application of H_2 in the distribution network.
Hydrogen transmission backbone Netherlands	Gasunie	Netherlands	2024-2030	This is a transmission project, which transports hydrogen to customers and storage.
HyTransPort.RTM	Port of Rotterdam, Gasunie	Netherlands	2021-2024	The realisation of the hydrogen pipeline within the project is a key step forward in establishing Rotterdam as a major European hydrogen hub. The pipeline is being constructed between the areas of Maasvlakte and Pernis and will have a diameter of 60 cm (24 inches). It will be an open access pipeline, which means that any company that wishes to consume or supply hydrogen in the area can connect to the pipeline. In the future, the pipeline will also be linked to the national hydrogen grid that is being realised by Gasunie. It will also be connected with Chemelot in Limburg, the German state of North Rhine-Westphalia and other European regions.
SLOH2 Backbone	PLINOVODI	Slovenia	2022-2028	The project involves the repurposing of two existing natural gas main pipelines and new interconnections for use with hydrogen. The repurposed pipelines will allow transport of natural gas - hydrogen blends as well as pure hydrogen. Repurposed pipelines will be connected with planned new hydrogen ready pipelines and together they will enable hydrogen transit between Slovenia and all neighbouring countries.

Source: (ENTSOG, 2024)

Examples of on-going national, regional and European R&D projects

Research and Development (R&D) projects on pipelines for hydrogen transport are also developed at the national, regional and European levels. Examples of national and regional R&D projects on hydrogen pipelines are given in Table 6.

Table 6. Examples of on-going national and regional R&D projects on pipelines for hydrogen transport.

Project name	Project promoters	Country	Timeline	Scope & goal
Certification of the H2-ready network	Snam, RINA	Italy	NA-NA	Snam and RINA are assessing and certifying the compatibility of each natural gas pipeline of Snam's network to transport up to 100% hydrogen, and are studying and testing the compatibility of industrial burners. Further experiments, analysis and technology scouting in various areas of hydrogen production, storage and distribution are also part of the activity.
FenHYx 1	GRTgaz (RICE)	France	2021-2024	GRTgaz has designed the FenHYx collaborative R&D platform. Its purpose is to test the transmission system equipment and materials under real conditions for different CH_4/H_2 mixtures. FenHYx aims at improving the understanding both of the impact of hydrogen on the gas networks, and of the adaptation required to ensure their safe and efficient operation. New innovations can also be tested in collaboration with partner manufacturers and research centres. The test results will make it possible to adapt the network maintenance and management procedures.
H21 NIC - Phase I	All UK GDNS, DNV-GL, HSE Laboratories	United Kingdom	2021-NA	The aim of the project is to deliver the quantified safety evidence necessary to inform a government policy decision on hydrogen for use in the existing gas network.
H2GAR	ENAGAS, Fluxys, Gasunie, GRTGaz, National Grid, OGE, SNAM	Italy	2020-NA	In that project, the stakeholders are sharing current technical knowledge on H_2 gas asset readiness.
H2I-T	EUSTREAM	Slovakia	2022-2030	The project aims at the construction of a trial site (a closed-loop high-pressure system) for testing of various components of gas transmission grid such as pipes, valves, regulators in relation to material and function. The trial site represents a complete solution including a hydrogen supply generated by electrolysis from solar power.
MatHias	Nordion	Nordic countries	2024-2027	This regional project aims at material and structural integrity assessment for safe Nordic Hydrogen transport infrastructure.

Source: (ENTSOG, 2024)

European R&D projects on pipelines for hydrogen transport are primarily funded by the Clean Hydrogen Partnership, an initiative co-funded by the European Commission. Some relevant examples of currently funded European R&D projects are given in Table 7. The complete list of projects funded by the Clean Hydrogen Partnership is available on their website (Clean Hydrogen Partnership, 2024).

Table 7. European R&D projects funded by the Clean Hydrogen Partnership on pipelines for hydrogen transport.

Project name	Coordinator	Country	Timeline	Scope & goal
PilgrHYm	GRTGaz	France	2024-2027	Pre-Normative Research on Integrity Assessment Protocols of Gas Pipes Repurposed to Hydrogen and Mitigation Guidelines. The project seeks to develop a pre-normative framework to support the development of a European standard. It aims to conduct a comprehensive testing program on small-scale laboratory specimens, focusing on 8 base materials, 2 welds, and 2 heat-affected zones that are representative of the EU gas grids. These specimens will be selected after a thorough review by TSOs to address safety concerns, lack of regulations, codes, and standards, as well as research gaps related to the compatibility of current pipelines with hydrogen.
CANDHy	Fundación Hidrógeno Aragón	Spain	2023-2026	Compatibility Assessment of Non-steel metallic Distribution gas grid materials with Hydrogen. The project aims at testing relevant metallic materials, different from the well-studied steels, with a methodology involving simultaneous test in independent R&D platforms with a common methodology. This will allow obtaining trustful and reproducible results about hydrogen tolerance of materials that have not been considered in previous research but that are an essential part in in low-pressure gas grids. The project aims at enabling hydrogen distribution in low pressure gas grids by consolidated and exhaustive scientific data, coupled with harmonised guidelines for non-steel metallic grid materials.
OPTHYCS	Enagas	Spain	2023-2025	Optic fibre-based hydrogen leak control systems. The project aims at developing new sensor technologies for continuous leak detectors based on optical fibre sensors technologies. This will lead to an increase in the safety level of hydrogen applications, from production to storage and distribution, both in new infrastructure, working with pure H_2, and in natural gas repurposed installations and pipelines, contributing to a safe and economically viable implementation of H_2 production, transport, and storage processes.
SHIMMER	SINTEF	Norway	2023-2026	Safe Hydrogen Injection Modelling and Management for European gas network Resilience. The project aims to enable a higher integration and safer hydrogen injection management in multi-gas networks by contributing to the knowledge and better understanding of hydrogen projects, their risks, and opportunities.

Source: (Clean Hydrogen Partnership, 2024)

The following European R&D project funded through the Research Fund for Coal and Steel, managed by the Research Executive Agency (REA) from the European Commission, is also relevant to pipelines for hydrogen transport (see Table 8).

Table 8. Other European R&D project on pipelines for hydrogen transport.

Project name	Coordinator	Country	Timeline	Scope & goal
SAFEH2PIPE	RINA	Italy	2024-2027	Guidelines for material selection and qualification for safe transportation of H_2-NG mixtures in EU pipelines. Aim of the project is to develop guidelines for material selection and qualification process for safe transportation of H_2 and H_2-NG mixtures for both new and existing pipelines. By means of state-of-the-art engineering studies and testing and adopting a Fitness for Service approach, the present project will provide info and data and guidelines for safe use of future new H_2 pipelines as well as retrofitting of existing ones.

Source: (European Commission, 2024b)

Other international projects of relevance

On the international stage, in addition to Europe, US has been the main player in setting up and implementing R&D projects of relevance for hydrogen transport by pipelines (see Table 9). Japan is also investigating the possibility of using a double-piping system in which a hydrogen pipeline is placed inside an existing pipe buried underground (NTT Anode Energy, 2022).

Table 9. International projects on pipelines for hydrogen transport.

Title	Country	Primary promoter	Scope & Goal
H-Mat Overview: Metals	US	Sandia National Laboratories	H-Mat is a consortium of national laboratories addressing the materials science of hydrogen-induced degradation of materials. In this project focused on metals, its aim is to elucidate the mechanisms of hydrogen-materials interactions in metals to inform science-based strategies to design the microstructure of metals with improved resistance to hydrogen degradation.
H-Mat Overview: Polymers	US	Pacific Northwest National Laboratory	H-Mat aims at addressing the hydrogen compatibility performance of materials to increase the durability of material thereby providing a more reliable and stable performance of systems in the hydrogen infrastructure. In this project focused on polymers, it aims at addressing the following question: Can the effects of hydrogen on polymer systems be reduced to provide a more robust and reliable infrastructure?
HyBlend: Pipeline CRADA Materials R&D	US	Sandia National Laboratories	The project aims at providing a scientific basis to assert safety of piping and pipelines for hydrogen service. It aims to ensure safety of infrastructure for hydrogen service by evaluation/assessment of structural integrity of transmission and distribution pipelines (re-purposed NG pipelines) and by designing probabilistic analysis tools.

Source: (U.S. Department of Energy, 2024)

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