Project number: 101111888
Project acronym: SHIMMER
Project duration: 09/2023 – 08/2026
Project Coordinator:
Andrea Alvarado Shmueli, SINTEF AS – Institute SINTEF Industry

Co-funded by the European Union

Horizon Europe Framework Programme (HORIZON)
HORIZON-JTI-CLEANH2-2022-05-03

Clean Hydrogen Partnership

Safe hydrogen injection management at network-wide level: towards European gas sector transition

Safe Hydrogen Injection Modelling and Management for European gas network Resilience

Deliverable 2.4.

Scope and limitations of standards for testing and qualification of materials and components for hydrogen service

VERSION	DATE	TYPE	DISSEMINATION LEVEL
Version 1.0	28-October-2024	Report	Public

ABSTRACT
This deliverable provides a review of the standards for testing and qualification of metallic materials for hydrogen gas and includes a gap analysis in the context of blending of hydrogen into the natural gas grid. The review revealed that while existing standards for qualifying metallic materials for hydrogen service offer a solid foundation, they also exhibit significant gaps and ambiguities, particularly because they are not specifically designed for hydrogen blending in existing gas grids. Some testing standards also lack clarity or detail, affecting the robustness of material performance assessments in hydrogen environments. The need for harmonization across standards is crucial for streamlining the assessment process and ensuring consistent criteria and understanding across Europe and globally. Our report also proposes several fields for further research, to help close these gaps.

AUTHORSHIP AND APPROVAL INFORMATION

AUTHOR(S) Marcos Sánchez, Nevena Marinova, Elena Silveira, Nicolas Larrosa / TECNALIA	**DATE / SIGN** Nevena Marinova Nevena Marinova (Nov 4, 2024 15:24 GMT+1)
REVIEWED BY WP2 LEADER Oded Sobol/ BAM	**DATE / SIGN** Sobol
APPROVED BY COORDINATOR Heiner Schümann / SINTEF	**DATE / SIGN** Heiner Schümann Heiner Schümann (Nov 4, 2024 20:06 GMT+1)

Release history

VERSION	DATE	VERSION DESCRIPTION
0.1	06-09-2024	First version with main content
1.0	28.10.2024	Final version

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The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

List of Abbreviations

Table 1: List of some of the abbreviations

Term	Explanation
C(T)	Compact Tension
CC(T)	Centre Crack Tension
CE	Carbon equivalent
CTOD	Crack tip opening displacement
DCPD	Direct current potential drop
FAL	Failure Assessment Line
FAD	Failure Assessment Diagram
FCG	Fatigue crack growth
FGGR	Fatigue crack growth rate
HAZ	Heat-Affected Zone
HCF	High-cycle fatigue
HE	Hydrogen embrittlement
K_t	Stress concentration factor
LCF	Low-cycle fatigue
PSL	Product specification level
PWHT	Post-weld heat treatments
RA	Reduction in area
RRA	Relative reduction of area
RTNS	Relative notch tensile strength
SCC	Stress corrosion cracking
SE(B)	Single Edge Notch Bend
SE(T)	Single Edge Notch Tension
SMYS	Specified minimum yield strength
SPT	Small punch test
SSRT	Slow strain rate method
SY	Yield strength
UC	Unloading compliance

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Executive Summary

Hydrogen is expected to be a crucial element in reaching the goal of decarbonization set by the European Union. However, developing a dedicated hydrogen transportation network can be expensive and timely, which poses a challenge for incorporating renewable hydrogen into hard-to-decarbonize sectors. To address this issue, blending hydrogen with natural gas in existing pipelines has emerged as a potentially short-term solution. This approach can help meet decarbonization goals more quickly by allowing the transport of hydrogen into the gas transportation infrastructure. Therefore, ensuring the safe operation of the natural gas grid when incorporating hydrogen is a central focus of numerous studies and projects. Ongoing discussions highlight the need to establish clear guidelines and practices to address this challenge effectively.

This report reviews current standards for qualifying metallic materials for hydrogen environments. It identifies and analyses technical and regulatory gaps that hinder the assessment whether the existing natural gas grid infrastructure is ready for hydrogen blends. It highlights limitations in material guidelines and regulatory practices, aiming to provide recommendations to ensure the infrastructure's ability to safely and effectively transport hydrogen.

The report is organized into several sections, starting with a short introduction of pipelines steels (Section 2) followed by revision of Standards for materials testing (Section 3), Standards for qualification based on mechanical testing (Section 4), Codes and standards for design (Section 5), and Codes and standards for assessment (Section 0). It is important to note that, although the standards are categorized this way for clarity of this document, many standards across different sections overlap significantly, sharing similar considerations, testing methods, and evaluation parameters. This overlap is highlighted throughout the document. Section 7 outlines the main gaps identified and Section 8 proposes several fields for further research, which could potentially close the gaps.

The report shows that existing standards for qualifying metallic materials for hydrogen service provide a solid foundation, but also significant gaps and ambiguities are detected, particularly because the standards are not tailored for hydrogen blending in existing gas grids. Some testing standards also lack clarity or detail, affecting the robustness of material performance assessments in hydrogen environments. The need for harmonization across standards is crucial for streamlining the assessment process and ensuring consistent criteria and understanding across Europe and globally. Furthermore, our report identifies critical gaps, related to insufficient understanding of vintage pipeline properties and the lack of a comprehensive classification system.

This report sets the stage for advancing the work in WP3, which focuses on further research into assessment procedures for evaluating the readiness of natural gas infrastructure to accommodate hydrogen. Additionally, some of the proposed research may serve as a framework for developing future approaches, not only within this initiative but also in other blending-related projects. These approaches aim to establish clear guidelines and accessible methods for assessing the existing gas grid's capability to transport hydrogen blends.

About the project: The European natural gas infrastructure provides the opportunity to accept hydrogen (H_2), as a measure to integrate low-carbon gases while leveraging the existing gas network and contributing to decarbonisation. However, there are technical and regulatory gaps that should be closed, adaptations and investments to be made to ensure that multi-gas networks across Europe will be able to operate in a reliable and safe way while providing a highly controllable gas quality and required energy demand. Aspects such as material integrity of pipelines and components, as well as the lack of harmonisation of gas quality requirements at European level must be addressed in order to facilitate the injection of H_2 in the natural gas network.

In this context, the SHIMMER project (Safe Hydrogen Injection Modelling and Management for European gas network Resilience) was selected for funding as part of the 2023 Clean Hydrogen Partnership programme. SHIMMER aims to enable a higher integration of low-carbon gases and safer H_2 injection management in

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multi-gas networks by strengthening the knowledge base and improving the understanding of risks and opportunities in H_2 projects.

It will do this by:

- Mapping and assessing European gas T&D infrastructure in relation to materials, components, technology, and their readiness for hydrogen blends.
- Defining methods, tools and technologies for multi-gas network management and quality tracking, including simulation, prediction, and safe management of network operation in view of widespread hydrogen injection in a European-wide context.
- Proposing best practice guidelines for handling the safety of hydrogen in the natural gas infrastructure and managing the risks.

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1 Introduction

1.1 Purpose of the document

The climate action and the promotion of renewable energies have become one of the fundamental pillars in addressing development since the Paris Agreement of 2015 and the adoption of the United Nations 2030 Agenda. The European Union has emerged over the past decades as a power with a leadership vocation in the energy and ecological transformation of economies. An important milestone in this process is the European Green Deal, a set of initiatives and legal frameworks aimed at "responding to climate and environmental challenges," but also envisioned as "a new growth strategy intended to transform the European Union into a fair and prosperous society," with an efficient economy and no net greenhouse gas emissions by 2050, proposing a reduction of between 50% and 55% by 2030 compared to 1990 levels. [1]

Hydrogen, whether in gaseous or liquid form, is considered a crucial energy carrier and storage medium for the energy transition and industrial decarbonization.[2,3] Hydrogen is considered a green energy carrier because it offers clean combustion, producing only water as a by-product without emitting carbon dioxide or other pollutants, making it an environmentally friendly alternative to fossil fuels. Its versatility allows it to be used in electricity generation, transportation, industrial processes, and heating, with high efficiency.[4] Hydrogen can be produced from renewable energy sources through electrolysis, which involves splitting water into hydrogen and oxygen using electricity from wind, solar, or hydro power, thus making the hydrogen produced renewable. Additionally, hydrogen serves as an effective energy storage medium, storing excess energy generated from intermittent renewable sources and releasing it when needed, thereby balancing supply and demand and enhancing grid stability. Thus, its use helps reduce greenhouse gas emissions, particularly in hard-to-decarbonize sectors like heavy industry and long-haul transport, supporting global efforts to mitigate climate change.[5] Furthermore, hydrogen can be part of a circular economy, contributing to resource efficiency and sustainability by being produced from waste materials or industrial by-products. These benefits position hydrogen as a crucial element in the transition to a low-carbon economy, supporting sustainable development and reducing dependence on fossil fuels.[6]

A proposed hydrogen economy would necessitate dependable technologies for producing, storing, transporting, and converting hydrogen into heat, electricity, and useful chemicals. Methods for transporting hydrogen include using vessels filled with gaseous or liquid hydrogen on trucks, freight trains, or ships, as well as hydrogen gas pipelines. Currently, around 3000 km of carbon and low alloy steel dedicated hydrogen pipelines exist in Europe and the United States most of them operated by industrial gas companies.[7,8] However, developing hydrogen transportation networks could be costly, posing a challenge for using renewable hydrogen in sectors that are difficult to decarbonize. To address this issue, blending hydrogen into existing natural gas networks has emerged as a potentially cost-effective solution which can contribute to the decarbonization goals in relatively short terms. This approach allows for the transport of hydrogen for various end-use applications, either by using the blended gas directly or by separating pure hydrogen downstream.[9]

The established natural gas network in many countries consists of gathering lines that transport gas from wells to central collection points, transmission lines that carry the gas over long distances at high pressure, and distribution lines that operate at lower pressure to connect consumers to the network. Nevertheless, using infrastructure originally designed for natural gas to transport hydrogen or blends presents integrity challenges, as new damage mechanisms can be introduced, or the kinetics of existing ones can be altered. Under pipeline operating conditions, hydrogen can dissociate and penetrate the metallic network and as a consequence can affect the mechanical properties of the materials. [7] This phenomenon is known as "hydrogen embrittlement" (HE) and particularly affects high-strength steels and alloys, causing a permanent loss of ductility that can lead to component failure at loads well below the expected limit. For the HE phenomenon to occur, the following conditions must be met (Figure 1):

1. Susceptible material

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2. Hydrogen-containing media
3. Mechanical stress

When metals are exposed to a hydrogen gas atmosphere, in many cases the hydrogen molecules undergo physisorption on the metallic surface, direct dissociation to hydrogen atoms if there is an active site, or surface diffusion and then dissociation to atoms. The efficiency of this process will depend on the catalytic activity of the specific surface sites (presence of traps) and the character of any oxide film present.[10] In other words the amount of hydrogen absorbed by the metal will depend on the efficiency of the dissociation process that, in turn, depends on the condition of the metal surface.[11] The dissolution and diffusion of atomic hydrogen into steels can degrade mechanical properties, Hydrogen reduces typical measures of fracture resistance such as tensile strength, ductility, and fracture toughness, accelerates fatigue crack propagation, and introduces additional material failure modes. In particular, steel structures that do not fail under static loads in benign environments at ambient temperature may become susceptible to time-dependent crack propagation in hydrogen gas.[12]

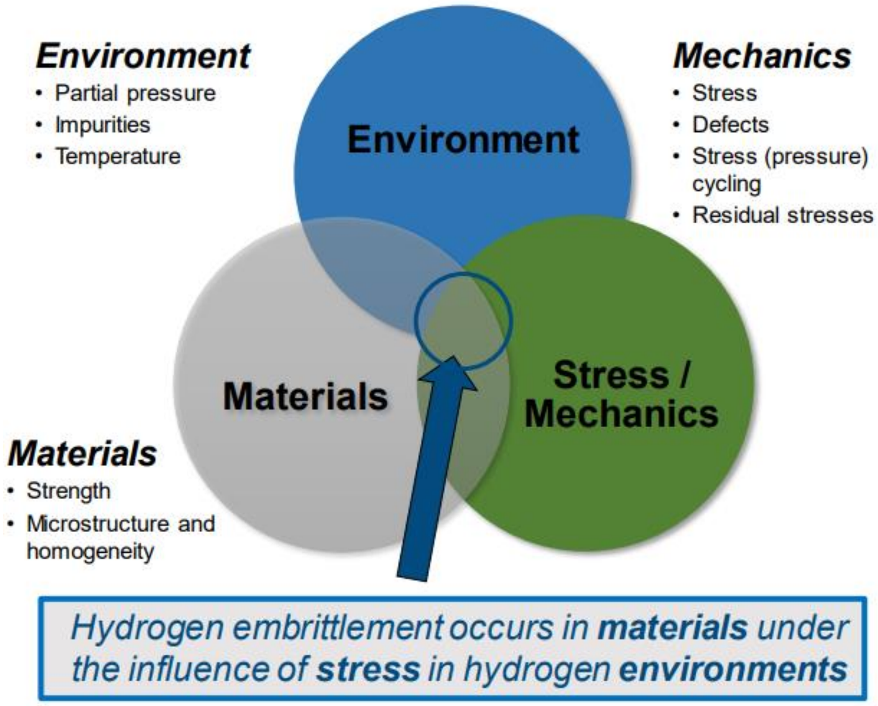

Figure 1: Factors which trigger the phenomenon of Hydrogen embrittlement. [13]

Hydrogen pipelines are not a new concept. The first hydrogen pipeline was reportedly built in Germany in the 1930s, and today there are over 4,500 km of hydrogen pipelines in operation.[14] Similarly, natural gas pipelines are well established, with over 2,000,000 km worldwide. Most of these pipelines, whether for hydrogen or natural gas, are made from carbon-manganese steel and typically adhere to the same base specifications, such as API 5L.[15] This might suggest that materials proven reliable for natural gas could also be suitable for hydrogen. However, many hydrogen pipelines are specifically designed and manufactured according to stringent hydrogen codes, like ASME B31.12 [16], which impose stricter material requirements than those for natural gas pipelines, such as limits on chemical composition and allowable strength levels. As a result, materials suitable for natural gas pipelines may not be appropriate for hydrogen service, indicating that existing natural gas pipelines might not be suitable for hydrogen.[17]

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The transportation of hydrogen via pipelines poses significant technical challenges, particularly due to the phenomenon of hydrogen embrittlement, which might degrade the mechanical properties of steels commonly used in pipeline infrastructure. Current standards and guidelines used for natural gas pipelines do not address issues related to hydrogen transportation and are not appropriate for ensuring the safe and efficient operation of the gas grid with hydrogen. This highlights the critical need for more comprehensive and hydrogen-specific technical documentation and codes. As industry and regulatory bodies foster the repurposing of existing natural gas pipelines for hydrogen service at an accelerated pace, cross-industry research on hydrogen pipeline integrity is advancing rapidly as well. However, standards are struggling to keep pace with these developments, particularly in addressing issues related to historical defects of vintage pipelines, pre-existing damage, and the long-term integrity management of pipelines exposed to hydrogen. The absence of detailed guidelines for managing these risks once pipelines are placed in hydrogen service further emphasizes the need for updating the standards.[18]

Additionally, when repurposing pipelines, existing codes recommend conducting destructive testing of material samples at a minimum frequency of one sample per mile. It has been shown that the mechanical property and chemical composition requirements for hydrogen pipelines are significantly more stringent than those for natural gas pipelines. Consequently, there is a high likelihood that the destructive test results will not meet the requirements for hydrogen service. The codes currently lack guidance on how to address such situations.[17]

Moreover, detailed mechanical data for existing pipelines, such as fracture toughness, is often unavailable. Besides, many vintage pipelines lack basic information like Charpy impact energy values because such data was not required at the time of construction. Standard tests for assessing mechanical properties of the base metal and welds typically need large steel samples. If representative samples from the pipeline's base metal, welds, and Heat-Affected Zone (HAZ) are not available, they must be extracted directly from the pipeline. In this context development of miniaturized testing methods for evaluating mechanical properties, which does not compromise the integrity of the infrastructure, could be a good solution useful for the integrity programs of repurposed or blended pipelines. [7]

The purpose of this document is to review the technical standards available at the moment the document is written and identify gaps and specific fields which need further investigation in order to adapt the normative for safe transportation of hydrogen in the natural gas grid.

This report is a part of the Task 2.2. *State of the art of all the normative related and/or have impact on the H2 injection into the gas grid*, part of Work package 2.

1.2 Intended readership

The content of this deliverable is of interest to a wide range of stakeholders, particularly those involved in technical and scientific activities. This includes testing laboratories, which rely on standards for ensuring accuracy in their methodologies, as well as research institutions engaged in research related to compatibility of metallic materials with hydrogen. Furthermore, technical committees responsible for standardization will find the data useful for establishing uniform practices across the industry. Finally, gas operators, who oversee the day-to-day management and safety of gas systems, can find useful information in the recommendations presented, enabling them to enhance efficiency and comply with and understand better the regulatory requirements.

1.3 Relationship with other deliverables

The methods and standards described in this document in this document will provide inputs to deliverable D3.2 – Assessing the compatibility of the existing NG infrastructure with H2-NG blends.

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2 Pipelines steels in the gas grid

Minimum technical requirements for pipeline steels are listed in international standards, such as API Specification 5L [15] or ISO 3183 2019 [19]. Specifications for pipeline steels currently used for natural gas transmission are carbon contents up to 0.28 wt.% and manganese up to 1.8 wt.%, although actual contents in modern pipelines are typically much lower. The limits depend on the grade specified minimum yield strength (SMYS), the product specification level (PSL) and the manufacturing process (i.e., welded pipe or seamless). Current SMYS of pipelines ranges from 175 MPa to 830 MPa. SMYS is indicated in the grade name, for example, an API 5L X65 has a yield strength (SY) greater or equal to 65 ksi (450 MPa). In the corresponding ISO standard, SMYS is indicated in the steel grade in MPa units, for instance, the equivalent grade to API 5L X65 would be L450.

API 5L sets two different product specification levels (PSL 1 and PSL 2). PSL 2 pipes have stricter requirements than PSL 1 pipes, like both minimum and maximum levels for the actual Sy and ultimate tensile strength (UTS), limits on the carbon equivalent (CE) and lower allowable contents of carbon, sulfur and phosphorous. They also have requirements on minimum energy absorbed in Charpy impact tests of base metal, HAZ and welds (for welded pipes). For PSL 2 pipes, letters after the SMYS indicate the delivery condition, as rolled, normalized, thermos-mechanically rolled, quenched and tempered, etc. For example, an API 5L X65Q is delivered in the quenched and tempered condition.

Weldability is a key property for pipeline steels because they are longitudinally or spirally welded in pipe mills and girth welded in the field. In modern steels, the weldability is controlled by reducing the carbon content while maintaining the strength levels with the introduction of alloying elements such as Cr and Mo and very low additions (less than 0.1 wt.%) of Nb, Ti and V. The effect of different alloying elements on the weldability is evaluated using the carbon equivalent (CE). Depending on the carbon equivalent (CE) and the thickness of the material, preheating, stricter control of welding variables, and possibly post-weld heat treatments (PWHT) might be needed to temper HAZ and ensure proper performance.

The biggest growth in the transmission pipeline network occurred alongside the introduction of key technologies that improved the structure and properties of pipeline steels, such as sulfide shape control with calcium and rare earth microalloying, continuous casting, and controlled rolling. As a result, both "modern" and "vintage" steels are used in the current natural gas pipeline network. Modern pipelines have lower carbon content and CE than older pipelines of the same grade, which means they tend to have lower hardness in the HAZ. Additionally, it wasn't until 2000 that impact testing for a minimum level of absorbed energy was required by the API 5L Specification for PSL 2 pipes. Therefore, many steels in existing natural gas pipelines have never been impact tested.[7]

According to the EGIG database which used the API 5L designation, the European gas grid consists of different material grades as the predominant are Grade B, X52, X60 and X70 (Figure 2).[20]

This data is consistent with the information gathered in SHIMMER and other projects related to inventory of the European gas grid.[21] Furthermore, plastic pipes are also used, more specifically in the distribution network which is operating at much lower pressure compared to transition network. Plastic pipes are considered to be immune even to pure hydrogen under the operating conditions of the distribution network,[22] therefore, the scope of the current report is limited to testing and qualification of metallic materials.

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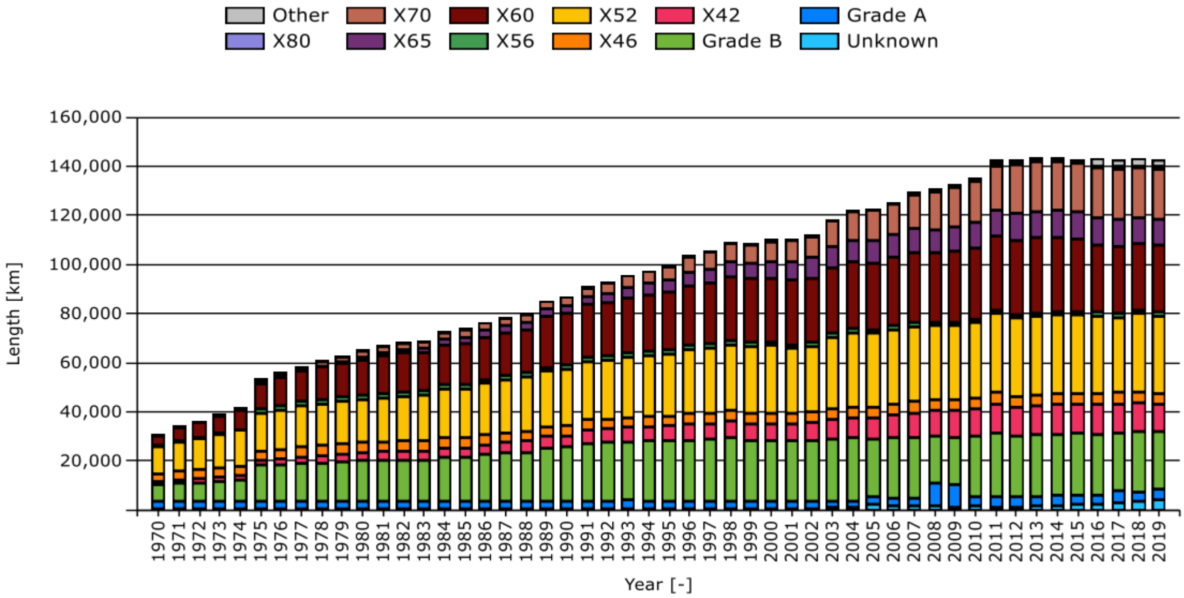

Figure 2: Total pipe length per grade of material. [20]

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3 Codes and Standards for materials testing in hydrogen gas

3.1 Uniaxial testing tests

Plastic elongation and reduction in area (RA) both quantify the material's capacity to deform plastically. Hydrogen effects are evaluated by the ratios of these properties measured in a hydrogen containing atmosphere versus a control environment (air, nitrogen, argon). Usually, relative changes in RA are larger than for the rest of the parameters measured during a tensile test. The RA parameter is attractive because it does not depend on specimen gauge length, and it can be used for both smooth and notched specimens. The decrease in mechanical properties is dependent on the materials strength level, microstructure, and environmental parameters. Additionally, the extension rate is also important, and it must be low enough to allow absorption, diffusion, and interaction of hydrogen with defects. It indicates that a full characterization of hydrogen embrittlement might require tests at higher or lower values. [7]

The slow strain rate test is the simplest, fastest, and most affordable test, but it does not allow performing structural integrity assessments. Its usefulness is limited to ranking materials in each environment or ranking the severity of different environments.

These tests are usually used primary as a screening method to determine:

- Quasi static tensile properties in gaseous hydrogen relative to in air (or other reference environments).
- Notch sensitivity in gaseous hydrogen.
- Assess the risk for a time-delayed failure.

3.2 Slow Strain Rate Test (ASTM G142, ASTM G129)

ASTM G142 [23] and ASTM G129 [24] describe the testing employing the Slow Strain Rate Test (SRRT), as the first one is specifically for high pressure and/or high temperature. ASTM G142 describes test procedures for determining the tensile properties of metals in environments containing high-pressure and/or, high-temperature gaseous hydrogen, accommodating both smooth and notched specimens. It applies universally to all material types and forms, including wrought and cast materials. This method assesses the materials' susceptibility to hydrogen embrittlement by comparing their standard mechanical properties (such as yield strength, ultimate tensile strength, notched tensile strength, reduction in area, elongation) in hydrogen-containing environment against those in a non-embrittling environment (control test). This comparison serves as a fundamental indicator of the material's tendency to crack under hydrogen exposure compared to its typical mechanical performance. This test method is also listed in the standard CSA ANSI/CSA CHMC 1- Test methods for evaluating material compatibility in compressed hydrogen applications – Metals. [25]

3.2.1.1 Smooth specimen

The smooth specimen is depicted in Figure 3.

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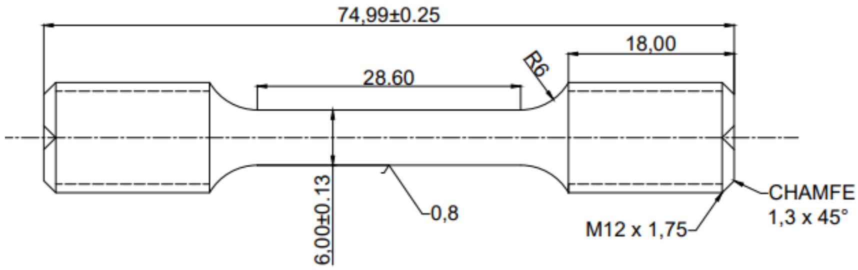

Figure 3: Smooth tensile specimen as recommended by ASTM G142, dimensions are shown in mm.

Specimens shall be machined to have a minimal amount of cold work on the gage or notch surfaces. Total metal removed in the last two passes shall be limited to a total of 0.05 mm and have a surface finish of 0.25 µm (10 µin.) or better.

When testing in hydrogen, the tensile testing speed is usually low and the test duration long to allow for sufficient time for the hydrogen to interact with materials deformation mechanisms. As loading rate is known to effect test results it is imperative that the same loading rate is employed for all tests of a screening campaign. For smooth tensile specimen the loading rate should be measured in the gauge length and rate requirements are as follows:

- ASTM G142: 0.002 mm/s, hence strain rate depends on the specimen geometry used. A deviation by 10% is acceptable.
- ASTM G129: Allows 10^{-4} to 10^{-7} in/s and recommends testing below 10^{-5} in/s. The achieved strain rate then depends on the specimen geometry.
  - ANSI/CSA CHMC 1: 10^{-5} /s between yielding and maximum force. A deviation by a factor of 2 is acceptable.

The most commonly evaluated parameter for smooth specimen is the relative reduction of area (RRA, Equation 1) derived by dividing the reduction of area under the influence of hydrogen RA_H by that measured in a reference state or atmosphere (air or an inert gas) RA_R.

$$\mathbf{RRA = RA_H/RA_R} \qquad \textbf{Equation 1}$$

The standard, however, does not provide guidelines how to interpret the result quantitatively and the main application of tensile tests is screening materials for hydrogen embrittlement susceptibility depending on e.g., temperature or heat treatment. ANSI standard ANSI/CSA CHMC 1 considers an aluminium or stainless steel alloy compatible with gaseous hydrogen if RRA is above 0.9 (See chapter 4.2 for more details).

3.2.1.2 Notched specimen

The sample geometry for notched specimen indicated by ASTM G142 is shown in Figure 4. When notched specimens are used CHMC-1 also refers to recommended geometries in ASTM G142 or alternative designs with a stress concentration factor K_t greater than 3.

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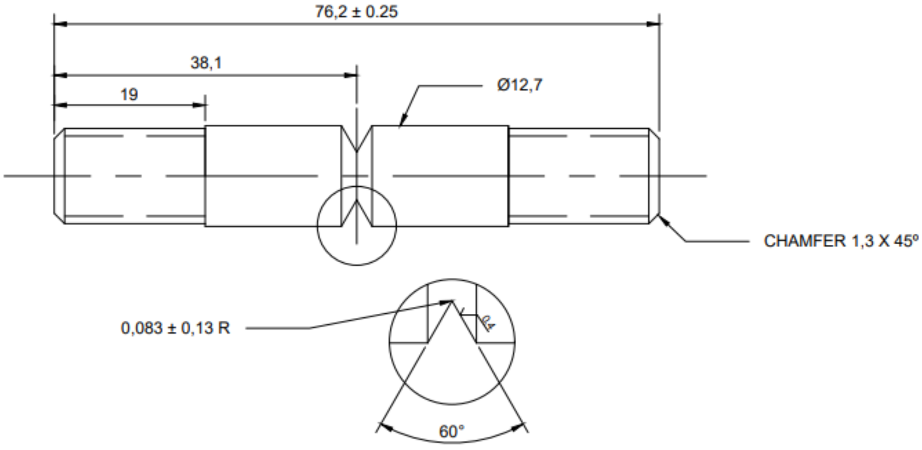

Figure 4: Notched SSRT specimen as recommended by ASTM G1412, dimensions are shown in mm.

The actual strain rate for notched specimens is difficult to measure accurately because the strain is concentrated at the notch. Strain rate can be controlled by either adjusting the crosshead or actuator displacement or by measuring it over a specific distance cantered around the notch. The following requirements apply:

- ASTM G142: 0.02 mm/s cross head displacement. A deviation by 10% is acceptable.
- ANSI/CSA CHMC 1: 10^{-6} /s measured over a 1 inch length centered on the notch. Alternatively, actuator displacement can be used if calibrated by a smooth specimen in the same setup. A deviation by a factor of 2 is acceptable.

For notched specimens the relative notched tensile strength (RNTS) is usually evaluated. Similar to RRA, if RNTS is above 0.9, the standard ANSI/CSA CHMC 1 considers an aluminium or stainless steel alloy compatible with gaseous hydrogen. Further details on the application of the testing results for materials qualification are described in Section 4.2.5.

3.2.1.3 Step loading testing (ASTM F1624)

ASTM F1624 [26] uses either "irregular geometry-type specimens" from ASTM F519 or a fracture mechanics-based specimen as described in ASTM E399. The irregular geometry specimens include notched tensile specimens from ASTM F519 (Figure 5) as well as bending geometries and C- and O-rings. Additionally, ASTM G129 permits the use of pre-cracked specimens in accordance with ASTM E399.

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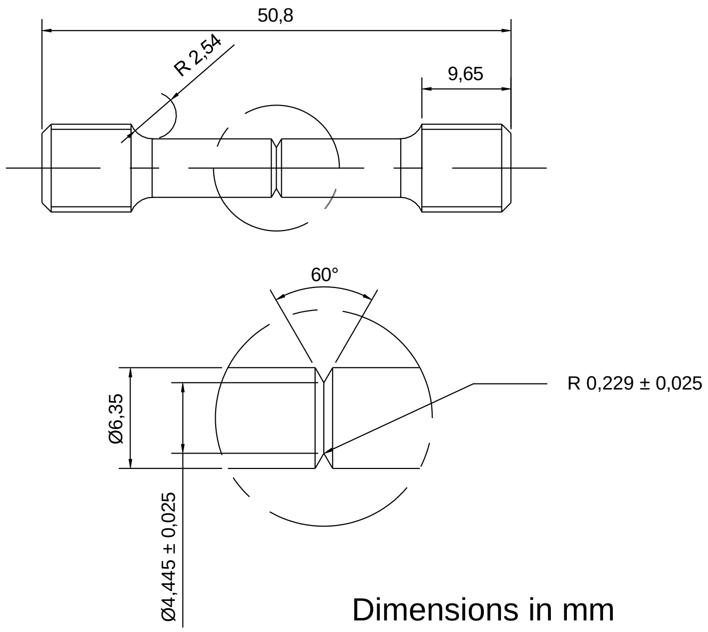

Figure 5: Type 1a.1 specimen as described in ASTM F519; dimensions shown in mm.

ASTM F1624 employs an incremental step load technique. Load levels are held for a time between 1 and 4 hours, depending on the load profile which in turn depends on material hardness (Figure 6). Load changes are done with a load rate between 10^{-5} and 10^{-8} /s which, since the test is done in force control, is translated to a force rate via the elastic modulus.

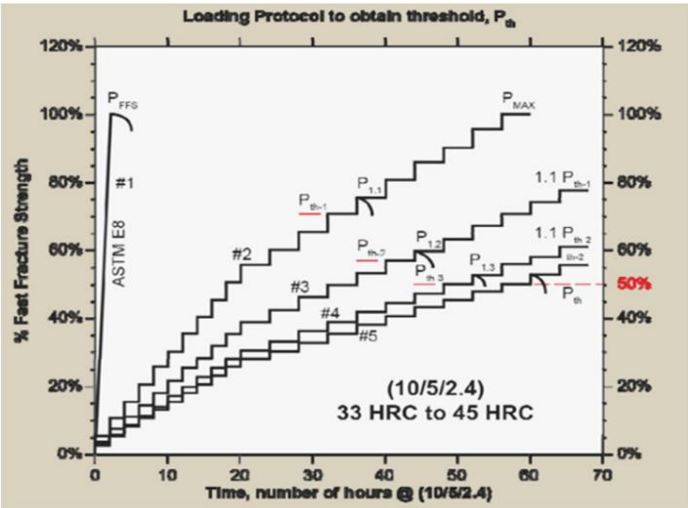

Figure 6: Suggested Protocol for a Loading Profile to Determine Threshold. Taken from ref [27].

3.2.1.4 Effect of gas composition, temperature, and pressure on uniaxial testing

- **Gas composition:**

ASTM G142 states that when testing in hydrogen containing environments, susceptibility to hydrogen embrittlement typically increases with decreasing oxygen content of the test environment. Therefore, the standard recommends using reagent grade chemicals and ultralow oxygen gases (<1 ppm) to be used in all tests unless the test environment is derived from a field or plant environment. Furthermore, ASTM G142 recommends strict procedures for deaeration followed by recording the oxygen content and sampling of the test environment at the start of the testing and again hen any element of the test procedure or test system has been changed or modified.

- **Temperature:**

To ensure safety, tests are typically conducted at specific or multiple temperatures to identify the temperature at which maximum hydrogen embrittlement occurs. For pipeline steels, this critical temperature is generally assumed to be around room temperature.

- **Pressure:**

For purposes of standardization, ASTM G142 suggests standardized pressures testing at 7 MPa, 35 MPa, and 69 MPa. For materials evaluation for specific applications, the test pressure should be equal to or greater than that which represents the service conditions.

The ASTM F1624 is not specifically intended for gaseous hydrogen and therefore does not specify any requirements.

3.3 Fracture mechanics tests

Fracture toughness is a critical mechanical property that reflects the material's resistance to failure in presence of a crack when is subjected to a monotonic loading. At certain load levels, and particularly steels, some degree of plastic deformation can occur at the crack tip, which serves to blunt the crack and reduce the stress intensity. This plastic deformation absorbs energy and mitigates further crack propagation.

However, the presence of hydrogen can significantly reduce or even preclude plastic deformation to occur, leading to decreased energy absorption at the crack tip. This results in lower fracture toughness values ($K_{IH} \leq K_{IC}$) and increases the risk of catastrophic (brittle) failure if the stress intensity factor reaches a critical value, i.e., $K_I \geq K_{IH}$. Although various mechanisms have been proposed to explain the phenomenon of hydrogen embrittlement, none have been fully demonstrated yet [28].

In practice, fracture toughness values are used in design codes, such as ASME B31.8, ASME B31.12 Option B and in ASME BPVC Section VIII, Division 3. These values are also required in structural integrity assessment procedures, such as API 579 and BS 7910, which are used to evaluate flaw tolerance assessment, primarily by assessing critical flaw sizes and margins of safety against failure under real operational and postulated (i.e., beyond design) conditions. In the context of the Shimmer project, it is crucial to assess the impact of hydrogen on properties such as fracture toughness and fatigue crack growth rates to determine the suitability of the current gas network for operating in hydrogen-rich environments, for which it was not originally designed.

Fracture toughness testing standards were developed to ensure the determination of lower-bound toughness values, independently of specimen size and geometry. Organizations such as ASTM, BSI and ISO have developed standardized test methods for measuring initial toughness and crack growth resistance curves using deeply cracked specimens. These specimens present a high level of constraint at the crack tip, ensuring conservative values of fracture toughness and flatter tearing resistance curves.

The most common fracture parameters used are the critical stress intensity factor (K_{IC}), critical J-integral (J_{IC}) and the critical crack tip opening displacement (CTOD). These parameters are obtained through tests conducted according to detailed and systematic experimental procedures. For doing that, it is important to ensure small-scale yielding and plane strain conditions at the crack tip, which are mainly influenced by the testing configuration, including specimen size and geometry, crack depth and loading type). Table 2 summarizes the most relevant fracture toughness standards for H_2 testing.

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Table 2. Relevant fracture toughness standards used for H_2 compatibility.

Standard	Loading method	Purpose	Ref.
ASTM E1820	Quasi-static	Determines fracture toughness at the onset and during ductile crack propagation or instability	[29]
ASTM E399	Quasi-static	Determines plane-strain fracture toughness	[30]
ASTM E1681	Constant load or displacement	Determines threshold stress intensity factor	[31]
ASTM F1624	Step loading	Assesses susceptibility of steel to time-delayed failure.	[26]
ISO 12135	Quasi-static	Similar to ASTM E1820	[32]
ISO 15653	Quasi-static	Similar to ISO 12135 but for testing welds	[33]
ISO 11114-4	Quasi-static (method B), Constant load or displacement (method C)	Similar to ASTME E1820 and ASTM E1681, specifically for transportable gas cylinders	[34]
BS8571	Quasi-static	Similar to ISO 12135 but for SE(T) specimen	[35]
ISO 7539-9	Quasi-static	Similar to ASTM E1820	[36]

As shown in the table above, fracture toughness standards can be divided based on the loading method used. Three different loading types are commonly employed: quasi-static loading (where a slow, rising load is applied), constant load or displacement, and step loading. Tests under rising displacement are used to determine the critical stress intensity factor in hydrogen environments (K_{IH}). On the other hand, when a material is tested under constant load or displacement, the crack arrest (or threshold) stress intensity factor (K_{TH}) is obtained.

ASTM E1681 is a standardized method designed to assess the threshold stress intensity factor for materials under conditions that promote stress corrosion cracking (SCC). This standard outlines procedures for evaluating the threshold stress intensity factor, K_{IEAC}, particularly in materials subjected to constant-load or constant-displacement testing over extended periods. The standards allow the use of precracked SE(B) specimens and C(T) specimens for testing by dead weight loading or bolt-loaded compact tension (MC(W)) specimens for constant load tests. The validity criteria in ASTM E1681 ensure that the specimens meet plane strain conditions and exhibit predominantly elastic behaviour, adhering to the size requirements specified in the ASTM E399, otherwise the material is characterized by a size-dependent parameter, K_{EAC}. The initial applied stress intensity factor is set above the expected threshold value for SCC. As the crack propagates over time under the influence of the corrosive environment, the stress intensity factor decreases, and K_{TH} (equivalent K_{EAC} in hydrogen conditions) is defined as the stress intensity level after a specified duration, often extending up to 10,000 hours. The test is designed to capture the critical threshold where sub-critical crack growth initiates and proceeds, providing a measure of the material's resistance to SCC. While ASTM E1681 offers a robust framework for determining K_{TH} , the extended duration and stringent loading conditions required can present practical challenges, especially in establishing critical fracture toughness for materials with high yield strengths, such as those exceeding 1200 MPa.

ASTM F1624 measurements are conducted by rapidly loading a fatigue pre-cracked specimen in the environment of interest to a prescribed load level via displacement control, followed by a hold period where the displacement is maintained constant for a set time duration. This rise/hold sequence is repeated for incrementally larger loads until crack growth occurs, which is generally indicated by a greater than 5% decrease in the applied load. K_{TH} is then defined based on the K calculated at the highest load preceding the step where crack growth was first observed. In order to ensure that the loading scheme is slow enough to prevent hydrogen diffusion, the protocol is replicated using different hold times and/or number of holds.

Fracture toughness properties are typically measured using a slow rising loading method. In this case there are several standards that can be used depending on factors such as material behaviour, geometry configuration or regulatory requirements. In the context of pipeline steels, which the material generally exhibits stable crack propagation, fracture toughness is characterized by a crack propagation curve (R-curve or J-R curve) that represents the tearing response of the material. From this curve, the fracture toughness at the onset of stable crack propagation (J_{IC}) can be obtained.

For the rising test, several specimen geometry configurations can be used. For example, ASTM E1820 allows for various specimen geometries, with the compact tension (C(T)) and single edge notch bend (SE(B)) specimens being the most common. Alternately, the BS8571 provides the procedure for testing single edge tension (SE(T)) specimen, which offer a lower constraint specimen that reproduces more realistic the actual constraint conditions of the pipelines.

The loading rate is relatively harmonized between the rising loading standards, with a load-line displacement rate of 0.2-3 MPa √m/s.

Both ASTM E1820 and ISO 12135 provide two methodologies for determining fracture toughness values. The first one is a multi-Specimen Approach (Basic Procedure in ASTM E1820). This method involves testing several nominally identical specimens without employing crack extension measurement equipment. Each specimen is loaded to a pre-selected displacement level, which corresponds to different values of the J-integral and varying amounts of stable (ductile) crack extension (Δa). Each specimen yields an individual [J, Δa] data point, which is subsequently used to construct the J-R curve and determine the critical fracture toughness. However, this approach is rarely utilized in combination with hydrogen due to the significantly longer testing times required in the expensive pressurized hydrogen test setup, and the difficulty in pinpointing the exact initiation of crack growth. Second method is a single-specimen approach (Resistance Curve Procedure in ASTM E1820): In this method, crack extension measurement equipment is employed to derive a complete J-R curve and the corresponding critical toughness from a single specimen. It is essential to validate that the predicted crack extension closely matches the measured value when using indirect techniques. An example of a J-R is given in the Figure 7. In order to measure the crack extension, two common techniques are used. The unloading compliance (UC) technique involves partially unloading and reloading the specimen at specified displacement increments during the test. The quasi-linear unloading slopes are then used to estimate the crack length through analytical elastic compliance formulas. Measurements can be taken either from load-line displacement or crack mouth opening. On the other hand, the direct current potential drop (DCPD) method passes a constant current through the specimen, creating a potential difference across the crack plane that increases as the crack grows.

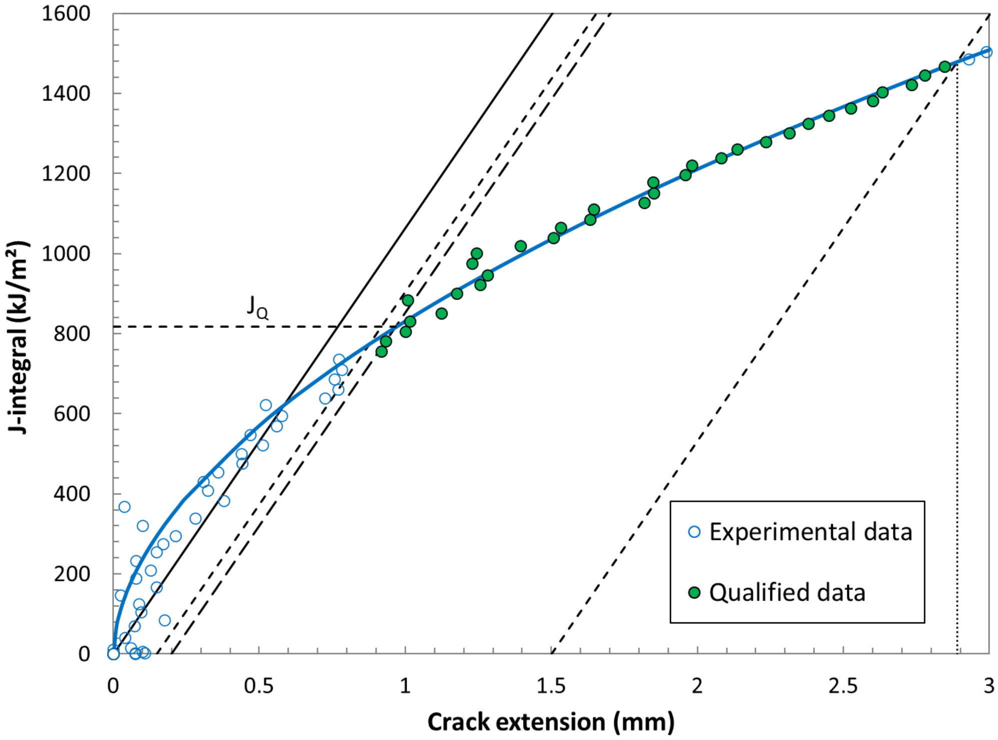

Figure 7: Example of J-R-curve used for fracture mechanics characterization.

Since all these methodologies involve fracture mechanics characterization, it is crucial to have a pre-existing sharp crack in the specimen. To achieve this, the specimens are subjected to a fatigue pre-cracking step before any of the aforementioned tests are applied. ASTM E1820 notes that experience has shown that it is impractical to obtain a reproducible, sharp and narrow notch that adequately simulates a crack by machining only. For fracture toughness tests conducted in air, various standards provide guidance and prescribe limitations on how to obtain a suitable crack through fatigue loading prior to testing. In case of fracture toughness testing of welds, ISO 15653 provides additional pre-cracking guidance.

Besides, it is recommended to apply the side grooves after pre-cracking. However, for shallow cracks the ISO standard allow the option to apply shallow side grooves before pre-cracking and deepen them afterwards.

ISO 11114-4 is a standard containing fracture toughness test methods for selecting steels for transportable hydrogen gas cylinders. In addition to the disc rupture tests (method A) , it describes fracture toughness tests similar to those in ASTM E1681 (method B) and ASTM E1820 (method C), referencing the ISO7539-x series of test standards for stress corrosion testing. Further information about this standard can be found in Section 4.5.

The European Pipeline Research Group has recently released a draft of guidelines for small-scale laboratory fracture toughness testing of carbon steel pipeline materials in hydrogen environments. The guidelines build on ASTM E-1820 and refining and supplementing the guidance of ANSI/CSA CHMC-1 by detailing specimen preparation, apparatus setup, environmental controls, test execution with crack monitoring, and result analysis. The following points are highlighted:

- The guidance does not recommend pre-soaking samples in hydrogen gas, as local adsorption at the crack tip is sufficient to initiate hydrogen-assisted cracking.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

- A significant part of the guidelines addresses crack growth measurement, recommending the potential difference method (DCPD or ACPD) to monitor crack growth in real time, providing continuous data without the need for mechanical unloading.
- The guidance also introduces the concept of using the J at Δa=0.0 mm and Δa=0.05mm to determine the fracture toughness threshold when using DCPD and unloading compliance methods, respectively.

At the time of writing this report, EPRG is planning an interlaboratory study to evaluate the effectiveness of the guidelines and identify potential gaps in their application. This study would involve a broader range of test providers (25 laboratories), allowing for a comprehensive assessment of the guidelines across various laboratories. By sampling a wider spectrum of test providers, the study aims to ensure consistency in test results, validate the robustness of the guidelines, and highlight any areas that may require refinement for broader industry application.[37]

3.4 Fatigue tests

Fatigue is an important phenomenon which involves the initiation and propagation of cracks in components subjected to variable stresses over time. This process is classified as subcritical because it occurs prior to complete fracture and may ultimately lead to it. In fatigue testing, a cyclic tensile or bending stress is applied to the test specimen. These tests are essential for assessing the resistance of the material or component to fatigue failure during its service life. Depending on the presence of cracks in the material, the analysis can be conducted using the methodologies explained in Section 4.4.1. If no cracks are present, the alternatives approaches described in Section 4.4.2 can be used.

3.4.1 Fatigue crack growth test methods.

The methods and procedures for fatigue crack growth (FCG) testing, including the associated specimen geometries and requirements, are well-documented in standards such as ASTM E647 [38] and ISO 12108 [39]. The most commonly used specimen geometries in FCG testing that allow for these both standards are:

- Compact Tension (C(T)): This geometry is widely used due to its material efficiency and comprehensive guidelines provided by ASTM E647. However, it subjects the crack to asymmetrical loading, which may not accurately represent the actual loading conditions in pipelines.
- Single Edge Notch Bend (SE(B)): these specimens are particularly suitable for testing in corrosive environments, offering a robust option for such conditions.
- Single Edge Notch Tension (SE(T)): these specimens are favoured for their resemblance to actual loading conditions in pipelines, making them a preferred choice in pipeline testing.
- Centre Crack Tension (CC(T)): this geometry is symmetrical, which helps in avoiding crack closure issues, providing a balanced approach to FCG testing.

When selecting a specimen geometry for practical applications, several criteria should be considered:

- Material Availability: C(T) specimens require less material, making them ideal when sample availability is limited.
- Testing Conditions: SE(B) and SE(T) specimens are more conducive to testing in corrosive environments and better simulate actual pipeline loading conditions.
- Specimen Machining: Although machining SE(T) specimens can be complex, they offer significant advantages when testing girth welds in pipelines.

Pre-cracking serves the critical purpose of introducing a sharpened fatigue crack, ensuring that any effects from a machined starter notch are removed. This step is essential for accurate K-calibration and for eliminating influences on subsequent crack growth data, such as changes in crack front shape or pre-crack load history.

During pre-cracking, the maximum stress intensity should not exceed the initial maximum stress intensity applied during the FCGR test, in accordance with the standard requirements of ASTM E647 and ISO 12108 for K-increasing tests. For K-decreasing tests, it is recommended to use the lowest stress intensity range possible, with pre-cracking growth rates below 10^-8 m/cycle.

Achieving crack initiation at low K_{max} values can be challenging. In such cases, ISO 12108 suggests using a lower load ratio (R) than that employed in the actual FCGR experiment. Both ISO 12108 and ASTM E647 recommend using a higher initial K_{max} for crack initiation, followed by a stepwise reduction in the maximum pre-cracking force.

Specific standards outline detailed requirements for defining crack extension and force steps during testing. Crack monitoring during FCGR testing is typically conducted using methods such as Unloading Compliance or DCPD, as was mentioned in Section 3.3 for fracture mechanic tests.

3.4.2 Fatigue life test

When testing materials without pre-existing cracks, fatigue is predominantly governed by the initiation phase. The most common method for assessing fatigue life involves using smooth cylindrical or rectangular specimens to generate fatigue curves in both low-cycle fatigue (LCF) and high-cycle fatigue (HCF) regimes. These curves capture both the crack initiation and propagation phases.

In LCF, cyclic loading is applied at stress levels above the material's elastic limit but below its ultimate tensile strength. The total fatigue life in LCF is typically less than 10,000 cycles, depending on the material. Crack initiation usually occurs at multiple sites on the surface, leading to the generation of an ε-N curve, which plots alternating strain amplitude (ε) against the number of cycles to failure (N). The procedures and testing methods for LCF are standardized in ASTM E606 [40].

In HCF, the material is subjected to cyclic loading while maintaining stress levels below its yield strength. Fatigue life in HCF typically ranges from 10^4 to 10^7 cycles, with cracks generally initiating at a single location on the surface. This testing regime produces an S-N curve, which plots alternating stress amplitude (S) against the number of cycles to failure (N). The procedures and testing methods for HCF are standardized in ASTM E466 [41].

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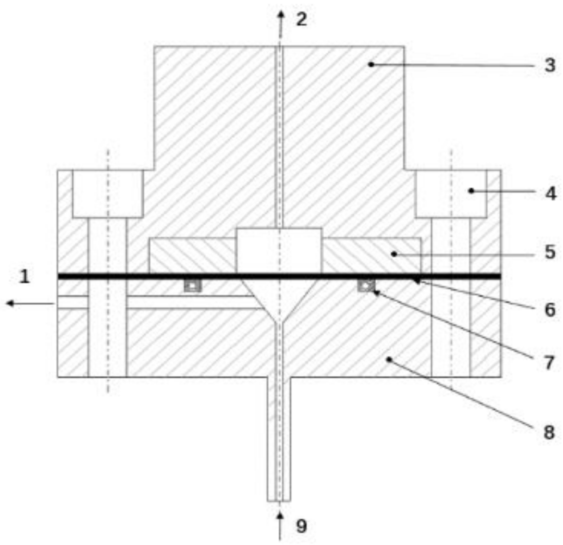
4 Codes and standards for qualification of materials for hydrogen service

4.1 ISO 11114-4 (2017) Transportable gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 4: Test methods for selecting steels resistant to hydrogen embrittlement

ISO 11114-4 Transportable gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 4: Test methods for selecting steels resistant to hydrogen embrittlement [34] specifies material test methods and material qualification metrics for transportable seamless steel gas cylinders at pressures greater than 5 MPa. Since this standard is the only ISO standard in this field, it is often misquoted as a standard to determine hydrogen susceptibility in general. It shall be emphasized here, that ISO 11114-4 should not be used for other applications without a careful consideration of the requirements of the other application. For all tests methods, the maximum allowable oxygen impurity is 1 ppm (and less than 3 ppm H_2O), which complies with ASTM G142 and ANSI/CSA CHMC 1.

4.1.1 Method A

In this method a disk of the material to be tested (diameter 58 mm, thickness 0.75 mm) is biaxially deformed by a hydrogen gas pressure until rupture. The testing equipment is shown in Figure 8. The result is a burst pressure in hydrogen, which is compared with a burst pressure in an inert control gas, usually helium. The resistance of material to hydrogen embrittlement is evaluated by the ratio between hydrogen blasting pressure P_{He} and helium blasting pressure P_{H2}. The standard states that if the maximum value of the aforementioned ratio is less than or equal to 2, the material should be considered suitable for high pressure hydrogen gas cylinders [34,42]. This test does not provide basic material properties.



1. Port for evacuation and flow adjustment
2. Discharge port
3. Upper flange
4. Bolt hole
5. High strength steel ring
6. Test disc
7. O-ring
8. Lower flange
9. Gas inlet

Figure 8: Test apparatus for Method A ISO 11114-4.[43]

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

4.1.2 Method B

Method B describes the determination of the fracture toughness in hydrogen (K_{IH}) through a step load test using C(T) specimens. The procedure begins with a defined pre-crack, after which the specimen is loaded with a stress intensity factor of 1 MPa√m and maintained for 20 minutes. If no crack growth is detected by the end of this holding period, the load is increased and held for an additional 20 minutes. This procedure continues until fracture occurs. Finally, K_{IH} is calculated according to ISO 7539-6 [36]. If K_{IH} is equal to or greater than 60/950 x UTS, the material is qualified up to this ultimate tensile strength (UTS).

4.1.3 Method C

Method C describes the determination of a stress intensity in hydrogen through a constant displacement test using C(T) specimens. The procedure initiates with a defined pre–crack, after which the specimen is loaded at a specific displacement rate (V) until reaching a defined stress intensity factor (K_{IAPP}). At K_{IAPP}, the crack grows until the stress intensity decreases to a lower bound, resulting in crack arrest (K_{arrest}). Formulas for both V and K_{IAPP} are given in ISO 11114-4. The steel is qualified up to its UTS if either (i) the measured crack growth does not exceed 0.25 mm or (ii) the measured crack growth exceeds 0.25 mm and K_{arrest} is equal to or greater than 60/ 950 x UTS.

4.2 ANSI/CSA CHMC 1 (2014) ANSI/CSA CHMC 1 Test methods for evaluating material compatibility in compressed hydrogen applications - Metals (2014)

ANSI/CSA CHMC 1 “Test methods for evaluating material compatibility in compressed hydrogen applications – Metals” [25] provides uniform test methods for measuring material properties in gaseous hydrogen environment. The standard is divided into three parts:

Clause 4 *General Requirements* defines the specific environmental variables within which the material will be qualified, specifically these variables are temperature, hydrogen gas pressure and hydrogen gas purity. This chapter provides a procedure for the selection of optimal testing temperature. For all tests methods, the maximum allowable oxygen impurity of 1 ppm complies with ASTM G142 and ANSI/CSA CHMC 1 provides further information and guidance on how to obtain the required gas purity during testing.

- Gas purity: Hydrogen 99.999%; CO_2+CO 2 ppm; N_2 2ppm; O_2 1 ppm; H_2O 3.5 ppm.
- Propose a purge equation.
- Includes recommended test temperatures for select alloy classes.
- Test pressure: use minimum the service conditions

Clause 5 *Test methods* provides specific methods for conducting mechanical property measurements in gaseous hydrogen. The results of these tests are considered valid only within the bounding conditions of temperature, hydrogen gas pressure, hydrogen gas purity described in Clause 4.

Clause 6 *Material Qualification* provides procedures which indicate how to use the test results from Clause 5 for qualification of the material.

Testing methods and qualification procedures are described below.

4.2.1 Slow Strain Rate test

For this testing the standard refers to ASTM G142 smooth and notched specimen shown in Section 3.2. When notched specimen is used, the specimen shall be designed according to ASTM G142 or alternatively the stress concentration factor K_t shall be greater than 3 ($Kt > 3$).

For smooth specimen tensile tests, ANSI/CSA CHMC 1 specifies testing in constant extension rate mode which translates to a nominal strain rate of $d\varepsilon/dt = 10^{-5}$/s. This does not exactly comply with ASTM G142 where the specified nominal strain rate is slightly higher. For notched specimens, “tests shall be conducted at

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applied displacement rates such that the effective strain rate measured over 25.4 mm, centered over the notch, is nominally 10^{-6}/s. This is one order of magnitude slower than the specified rate for the standard smooth specimen using the same test fixtures. This is in contradiction to ASTM G142 where the extension rate of the notched specimen tensile test is one magnitude faster (0.02 mm/s) compared to the smooth specimen tensile test (0.002 mm/s). In the future revision of both standards, it is important to synchronize the testing conditions to avoid confusion.[44]

4.2.2 Hydrogen assisted cracking stress intensity factor K_{IH} or J_{IH}

This test procedure is based on the ASTM E1820 the standard using the recommended C(T) and SE(B), see Section 3.3. ANSI CSA CHMC 1 standard on the other hand recommends a load-line displacement rate giving a K rate of 0.0017 – 0.017 MPa√m/s in the elastic range. With this loading rate a K of 60 MPa√m is reached within 1 to 10 hours.

4.2.3 Fatigue Crack Growth Rate

For fatigue crack growth testing (ΔK_{th}, *da/dN*), ANSI/CSA CHMC 1 allows C(T) specimens, middle tension (M(T)) specimens and eccentrically loaded single edge crack tension specimens (ESE(T)) according to ASTM E647.[38] The specified test parameters are a R = 0.1, a frequency of 1 Hz and a triangle or sine waveform. That is, a test frequency of 1 Hz appears to be a good compromise between test duration and test result conservatism.

4.2.4 Fatigue life test

For load–controlled fatigue life tests (S–N curves), ANSI/ CSA CHMC 1 allows specimens in accordance with ASTM E466.[41] When using notched specimens, the stress concentration factor K_t shall be equal or greater than 3 ($K_t \geq 3$). For strain–controlled fatigue life tests, ANSI/CSA CHMC 1 allows specimens in accordance with ASTM E606 [40]. The specified test parameters are:

- R-ratios of 0.1 (notched specimens, load-controlled) or -1 (smooth specimens, strain-controlled)
- Frequencies of less than 1 Hz (low cycle fatigue regime with less than 10^5 cycles) or less than 20 Hz (high cycle fatigue regime with more than 10^5 cycles)
- Triangle or sine waveform. As for the fatigue crack growth tests, the same rationale for a test frequency of 1 Hz applies for the fatigue life tests.

4.2.5 Materials qualification

ANSI/ CSA CHMC 1 proposes to use relative material properties for the qualification process. The procedure proposed by the standard is shown in Figure 9.

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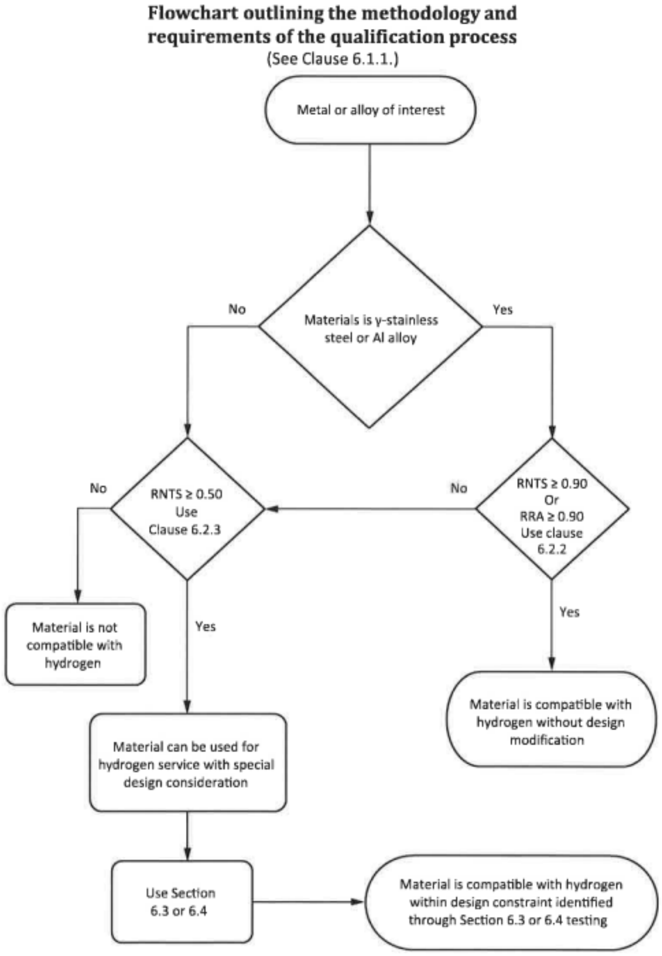

Figure 9: Flowchart for qualification material process based on Slow Strain Rate tests results.
(Source: Figure 2, ANSI/CSA CHMC 1-2014 (R2023), Test methods for evaluating material compatibility in compressed hydrogen applications - Metals. © 2014 Canadian Standards Association)

The procedure begins with a screening test, similar to the one proposed in ASTM G149, which will depend on the type of material to qualify. If the compatibility is verified for aluminium and austenitic stainless steels, the material is accepted when the relative notch tensile strength (RTNS) exceeds 0.9 or when the relative reduction of area (RRA) exceeds 0.9. It is noteworthy that satisfying either of these criteria independently qualifies the material as compatible, even if the other criterion is not fulfilled.

On the other hand, any type of metal, including aluminium and austenitic steel, is classified as not compatible with hydrogen if the RNTS is less than 0.5. If the RTNS falls within the range of 0.5 to 0.9, the material may still be used in hydrogen applications when additional requirements are used. One approach is to apply a hydrogen safety factor (SF) and a second one is to qualify the material for a specific application by testing.

The determination of a hydrogen safety factor is carried out using load-controlled fatigue life testing in the low cycle fatigue regime with notched specimens. Specifically, four SF are calculated at 1, 10^3, 10^4 and 10^5 cycles, where SF = SR/SH. Here. SR is the fatigue strength in reference atmosphere and SH is the fatigue strength in hydrogen (Figure 10). The hydrogen safety factor is the largest of the four ratios.

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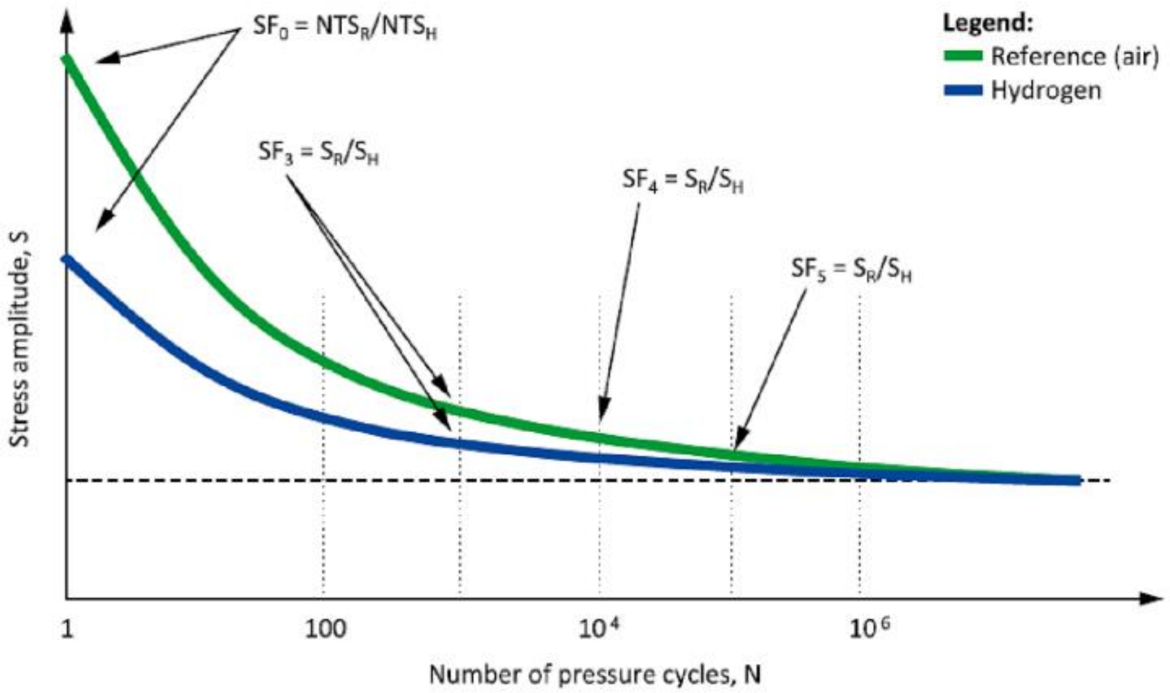

Figure 10 Material qualification using the safety multiplier method according to ANSI/CSA CHMC 1. (Source: Figure 3, ANSI/CSA CHMC 1-2014 (R2023), Test methods for evaluating material compatibility in compressed hydrogen applications - Metals. © 2014 Canadian Standards Association)

Alternatively, a material can be qualified by fulfilling the requirements for stress or strain-based fatigue testing and fracture mechanic testing.

4.2.6 Testing of hydrogen-precharged specimen

The standard also includes an annex for testing ex-situ of hydrogen-precharged specimens. However, it is stated that the testing of precharged specimen is not equivalent to testing specimens concurrently exposed to hydrogen.

The recommended practice is thermal precharging in hydrogen gas. This method however is recommended only for materials that exhibit limited egress at room temperature. High diffusivity alloys such as ferritic steels should not be tested using this approach since substantial hydrogen egress prior and during tesitng might lead to not realistic results.

Based on thermodynamic data the standard indicates the required duration and temperature for thermal recharging for austenitic and nitrogen strengthen austenitic alloys (Table 3).

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Table 3. Precharging times for common metals and geometries according to ANSI/ CSA CHMC 1. (Source: Table E-2, ANSI/CSA CHMC 1-2014 (R2023), Test methods for evaluating material compatibility in compressed hydrogen applications - Metals. © 2014 Canadian Standards Association)

			Temperature				
			100°C	150°C	200°C	250°C	300°C
Precharging time (days)	3 mm diameter cylinder	300 SS	625	80	15	4	2
		N-SS	1000	125	25	8	3
	6 mm diameter cylinder	300 SS		300	65	15	6
		N-SS		500	100	25	9
	6 mm semi-infinite plate	300 SS		650	140	35	12
		N-SS		1050	250	60	20
	12 mm semi-infinite plate	300 SS			540	140	50
		N-SS			850	250	80

5 Codes and recommended practice for the design of hydrogen-natural gas pipelines

5.1 ASME Boiler and Pressure Vessel Code - Section VIII - Div. 3 – Article KD-10 (2021)

The article KD-10 of the ASME BPVC Section VIII, Division 3, provides specific requirements for pressure vessels operating in hydrogen conditions. This article stablished that the vessels fatigue life and fracture toughness must be evaluated through specific conditions.

The article is mandatory for nonwelded vessels operating below 95°C when hydrogen partial pressures exceed 41 MPa or for vessels made from materials with an ultimate tensile strength (UTS) exceeding 945 MPa when the hydrogen partial pressure exceeds 5.2 MPa. For welded vessels operating below (95°C), the requirements are mandatory if hydrogen partial pressures exceed 17 MPa or if the vessel is made from materials with a UTS exceeding 620 MPa when the hydrogen partial pressure exceeds 5.2 MPa. The requirements are nonmandatory for vessels operating above 95°C. However, if vessels are exposed to hydrogen at temperatures above 95°C and subsequently operate at colder temperatures, the rules of this article should be considered, especially concerning brittle fracture risks during startup and shutdown cycles.

The article also sets limitations on the maximum design temperature for different materials. For carbon and low alloy steels, the maximum design temperature is governed by the curves of API RP 941 and should not exceed 65°C for hydrogen partial pressures between 90 MPa and 100 MPa. For pressures above 100 MPa, the temperature limit remains 65°C. Additionally, vessel parts in direct contact with hydrogen should have an ultimate tensile strength not exceeding 950 MPa unless the sum of maximum stress intensity factor and residual stress intensity factor (K_{Imax} + K_{Ires}) is less than or equal to zero.

Article KD-10 establishes a fatigue life assessment (KD-1010) based on fracture mechanics. This methodology is also used in the ASME B31.12 and will be further explained in Section 5.2.3. Moreover, this article provides guidelines for material test qualification to be used in the subsequent fatigue life assessment.

The evaluation of the threshold stress intensity factor in hydrogen conditions (K_{IH}) must be conducted using specimens from the largest wall thickness. Three measurements in the final heat treatment condition are required for the base material, weld material, and the HAZ. Each different welds of the vessel must be recharacterized for both the weld material and the HAZ. Ideally, specimens should be extracted from the

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pipeline in TL direction (see ASTM E399 for more details [30]). If this is not possible for the weld material and the HAZ, specimen extraction in LT direction is also allowed. The lowest K_{IH} value obtained in the tests must be used in the fracture mechanics assessment. The determined values are also applicable to similar materials with the same or similar specifications, chemical composition, heat treatment and material strengths, provided these properties do not exceed the values of the material used in the qualification test by more than 5 %.

This article proposes to determine K_{IH} based on the ASTM E1681 [31], see Section 3.3. Initially, a fatigue pre-cracked is introduced in the specimen in air conditions. Subsequently, the specimen is tested in a pressurized gaseous hydrogen environment at room temperature. At maximum, the gas impurity levels on the tests must be: O_2 < 1 ppm, CO_2 < 1 ppm, CO < 1 ppm, and H_2O < 3 ppm, typically achieved using 99.9999% hydrogen. Specimen loading can be applied using either the constant load or constant displacement method. For the constant load test, a C(T) specimen is commonly used, typically loaded by a weight or a servo-controlled actuator with an applied stress intensity of (K_{IAPP}) greater than K_{IH} (e.g., 55 MPa√m or from previous experiments or Table 4). In the constant displacement method, a modified bolt-load compact specimen is pre-strained to apply a stress intensity of $1.5 \cdot K_{IH} < K_{IAPP} < 198$ MPa√m. Table 4 gathers suitable starting K_{IAPP} values depending on yield strength, according to Article KD-1045. In addition, it is important to take into account that for the constant displacement method a glovebox with an inert environment must be used to apply the K_{IAPP} and to introduce the specimen inside the autoclave.

The specimen must be kept in the autoclave under the desired H_2 pressure during a minimum test duration of 1000 hours for ferritic and martensitic steels, or 5000 hours for stainless steels. In case the specimen does not fracture during the test, either due to crack arrest or time, it is subsequently broken through fatigue or by inducing brittle fracture by cooling the specimen. Then, the crack propagation is observed, if any. If the crack propagation increment from the pre-existing fatigue crack is less than 0.25 mm, the characterized material is qualified for using in pressurized gaseous hydrogen components. In this case, $K_{IH} = K_{IAPP}$ for the constant load method, and $K_{IH} = 0.5 \cdot K_{IAPP}$ for the constant displacement method. Consequently, as ASME B31.12 requires a minimum K_{IH} of 55 MPa√m, it is common practice to set K_{IAPP} at 110 MPa√m for the constant displacement method. Additionally, all the specimens must satisfy the constraint validity check according to ASTM E1681 in order to ensure plain-strain conditions and linear elastic behaviour.

In order to perform the fracture mechanics assessment, the plane-strain fracture toughness (K_{IC}) is also determined according to Article KM-250, under the required gaseous hydrogen conditions. The testing procedure follows the guidelines of ASTM E399 standard (see Section 3.3 for further details). Here, it is important to note that article KD-10 uses the term K_{IC} to refer to rising load fracture toughness test under H_2 environment, rather than K_{IH}, which is more commonly used in other standards and codes.

Table 4. K_{IAPP} estimated values in function of the yield strength for ferritic steels.

Yield strength (MPa)	K_{IAPP} (MPa√m)
621	159 to 198
759	93 to 159
897	71 to 115

Another important experimental campaign involves characterizing fatigue crack growth under H_2 conditions. The testing conditions and specimen orientations are identical to those used for the fracture characterization. The general guidelines for conducting a da/dN testing are provided in ASTM E647. The load ratio is selected based on the service conditions of the component. Additionally, the test frequency is also adopted to the operation conditions, whereby the cycle frequency should not be faster than f = 0.1 Hz.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

5.2 ASME B31.12 (2023)

Hydrogen emerges as a key component in transitioning to a sustainable energy system, making crucial the development of reliable infrastructure. ASME B31.12 Hydrogen Piping and Pipelines is a worldwide recognized standard for piping and pipeline construction in hydrogen service. Originally developed in 2008, this code addresses one of the main issues associated with hydrogen transportation: the well-known hydrogen embrittlement. This code stablishes the standards for piping and pipelines used for handling of gaseous hydrogen and hydrogen mixtures, as well as for piping in liquid hydrogen service. ASME B31.12 is structured in three main parts: Part GR, General Requirements, Part IP, Industrial Piping and Part PL, Pipelines; and two additional appendices. With all this, the standard provides the framework to ensure the safe and reliable construction and operation of hydrogen piping and pipelines, including guidelines about:

- **Design**: Specific design criteria for hydrogen service conditions such as pressure, temperature, material compatibility and safety.
- **Construction**: Welding process, inspection techniques and installation practices.
- **Operational and maintenance**: Safe practices, periodic inspections, testing, maintenance protocols.

While ASME B31.12 provides a robust framework, some limitations and considerations can make it excessively conservative. One example is the hardness requirement, which is derived from standards for sour service pipelines (handling H_2S). This requirement may be overconservative since pipelines exposed to H_2S present significantly higher levels of atomic hydrogen than those exposed to pure H_2.[18] Another example of this conservatisms is the recommendation to extract specimens from existing pipelines for regular testing, which in many cases can be impossible or impractical.

Considering these constraints, there is a need for more precise and customized design codes, material property specifications, and testing procedures that truly reflect real-world conditions for hydrogen pipeline transportation. The following paragraphs will provide an overview of the application limitations, materials, design standards, and testing requirements as outlined in ASME B31.12.

- **Material Selection Criteria**: ASME B31.12 outlines criteria for selecting materials based on their chemical composition, mechanical properties, and resistance to hydrogen embrittlement.
- **Testing and Qualification**: Materials must undergo rigorous testing and qualification procedures to ensure they meet the standard's requirements for hydrogen service conditions.

In practice, engineers and designers refer to ASME B31.12 to select materials that strike a balance between performance, cost-effectiveness, and safety in hydrogen piping and pipeline applications.

5.2.1 Application limits and materials

The application limits of ASME B31.12-2023, including criteria such as steel grade, maximum allowable operating pressure (MAOP), and temperature are described in Table 5.

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Table 5. Application limits of ASME B31.12.

Parameter	Criteria/Application Limit
Steel grade	≤ X80 ≤ X70 (for Option A and σ_H/SMYS > 40%)
MAOP	3000 psi (≈ 206 bar) for new pipes, steel grade < X65 2200 psi (≈ 151 bar) for existing pipes, steel grade < X65 1500 psi (≈ 103 bar) for all pipes, steel grade ≥ X65
Temperature	Pipeline systems with temperatures between 232°C and -62ºC
Blending with NG	Pipeline systems with hydrogen-containing gas mixtures that have been demonstrated to not adversely affect the integrity of the pipeline systems.

The most commonly used pipes for gas transportation, described in ASTM or API codes, are also considered in ASME B31.12. Table 6 gathers the material specification index for pipelines components included in ASME B31.12.

Table 6. Material specification index for pipelines considered in ASME B31.12.

Material specification index for pipelines	
ASTM specifications	**API 5L specifications**
Electric resistance welded pipes: - Spec. A53, Grades A and B - Spec. A135, Grades A and B - Spec. A333, Grades 1, 6 and 10	Electric resistance welded: - Spec. X42 to X80, Grades A and B
Seamless pipes: - Spec. A106, Grades A, B, and C - Spec. A333, Grades 1, 6, and 10	Seamless pipes: - Spec. X42 to X80
Double submerged arc welded: - Spec. A381, Classes Y-35 to Y-65	Double submerged arc welded: - Spec. X42 to X80, Grades A and B
Electric fusion welded pipes: - Spec. A139, Grades A, B, C, D, E	-

For pipelines operating at different levels of hoop stress, ASME B31.12 outlines specific material selection criteria referencing API 5L standards:

- **Pipelines Operating at Hoop Stress Below 40% of SMYS:**

  Standard product quality such as Product Specification Level 1 (PSL1) of API 5L is acceptable.

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- **Pipelines Operating at Hoop Stress Above 40% of SMYS:**

  The material must meet the tensile requirements of Product Specification Level 2 (PSL2) of API 5L, which has stricter requirements to ensure higher reliability and strength under increased stress levels.

- **Additional Material Requirements:**

  ASME B31.12 also imposes further limitations on material tensile characteristics for qualification in fracture control and arrest, which depends on the pipeline design approach selected (see Section 5.1.2).

A summary of the applicable requirements for material grade and strength listed in ASME B31.12 is given in Table 7, where parameters such as the maximum yield strength (SMYS) and the minimum and maximum ultimate tensile strength (UTS) are reported. Refer to Section 5.2.2 for a detailed explanation of Option A and Option B provided in ASME B31.12.

Table 7. Summary of the applicable requirements for material grade and strength in ASME B31.12 (both for Option A and Option B).

Strength class	Max SMYS (MPa)	Min UTS (MPa)	Max UTS (MPa)	Option A	Option B
A25 (L175)	-	310	-	✓	✓
A (L210)	-	335	-	✓	✓
B (L245)	450	415	655	✓	✓
X42 (L290)	495	415	655	✓	✓
X46 (L320)	525	435	655	✓	✓
X52 (L360)	530	46	760	✓	✓
X56 (L390)	545	490	760	✓	✓
X60 (L415)	565	520	760	✓	✓
X65 (L450)	600	535	760	✓	✓
X70 (L485)	635	570	760	✓	✓
X80 (L555)	705	825	825	✗	✓

5.2.2 Pipeline design approaches

ASME B31.12-part PL presents the design criteria for pipelines under specific conditions, which can be summarize as follows: the hydrogen content must exceed 10% by volume, the total gas pressure shall be less than 21 MPa (3000 psi), temperatures range between -62 °C and 232 °C, and the water content is below 20 ppm. The code proposes to calculate either the design pressure (p) or the pipeline thickness (t) using the following equation:

$$p = \frac{2\,St}{D} FETH_f \qquad \textbf{Equation 2}$$

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Where S is the specified minimum yield strength (SMYS) of the material, D is external diameter, F is the design factor, which varies between 0.04 and 0.72 depending on the design approach, E is the longitudinal joint factor ranging between 0.8 and 1, T is the temperature derating factor, which considers temperature above 121 ºC, and H_f is the material performance factor in gaseous H_2, varying between 0.542 and 1 depending on the design pressure and SMYS.

In order to ensure the structural integrity of both new and repurposed pipelines, those designed to operate at a hoop stress (σ_h) exceeding 40% of the SMYS must be subjected to a fracture control and arrest criterion. In this sense, ASME B31.12 proposes two different design approaches (Option A and Option B), each with different material performance and design factors. These options are summarized below.

5.2.2.1 Option A: Prescriptive design approach

Option A is a prescriptive design approach that utilizes conservative safety factors and Charpy energy measurements to ensure pipeline integrity. This approach limits the design pressure so that the hoop stress levels never exceed 50% of SMYS. The maximum allowable SMYS and ultimate tensile strength (UTS) for both pipe and weld materials are 483 MPa and 690 MPa, respectively. Consequently, these requirements restrict the use of steels up to a grade X70 (L485), following API 5L specifications. It is important to mention that impact testing is not required for pipe sizes with and outer diameter less than 114.3 mm, following API 5L testing procedures.

In order to apply the option A, several qualifications and requirements must be met:

1. Brittle fracture control: The test temperature must be the colder of 0°C or the lowest expected metal temperature during service or pressure testing. The average shear value of the fracture appearance from three Charpy specimens per heat must not be less than 80% for full-thickness Charpy specimens, 85% for reduced size Charpy specimens, or 40% for drop weight tear testing specimens.
2. Ductile fracture control: The average Charpy energy values must meet or exceed the requirements specified by the following equation:

$$CVN\ (J) = 1.83\ \times 10^{-5}(RT)^{0.39}\sigma_h^2 \qquad \textbf{Equation 3}$$

   Where $CVN(J)$ is the full-size specimen Charpy energy in Joules, R is the radius of the pipe in mm, t is the nominal pipe wall thickness in mm, and σh is the hoop stress due to design pressure in MPa.
3. Weld procedure qualification by Charpy test: Three specimens from weld metal and three specimens from HAZ shall be tested and the test temperature shall be 0°C or the lowest expected metal temperature during service or a specific table for not standard specimens. The minimum Charpy energy should meet the following criteria:

   (a) 27 J for full-size CVN specimens (or 0.338 J/mm^2 for subsize CVN specimens for pipe OD ≤ 1422 mm).
   (b) 40 J for full-size CVN specimens (or 0.509 J/mm2 for subsize CVN specimens for pipe OD > 1422 mm).

5.2.2.2 Option B: Performance-based design approach

Option B is a performance-based design approach that allows higher design pressure, up to 72% of SMYS. In this approach, the material performance factor (H_f) is assumed to be 1.0, and a design factor (F) is necessary to be incorporated. The design factors for Option B are tabulated in the ASME B31.12 and vary depending on the location class. The maximum allowable SMYS and ultimate tensile strength UTS for both pipe and weld materials are 552 MPa and 758 MPa, respectively. Besides, the phosphorous content of the pipeline material

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shall be less than 0.015 wt.%. As a result, these criteria restrict the selection of steels to API 5L grade X80 (L555) or lower.

As this method allows higher hoop stresses, the material qualification process is more exigent than in Option A. In this sense, both base (pipe) and weld materials must be tested in H_2 gas at or above the design pressure and at ambient temperature, following the testing guidelines provided in Article KD-10 of ASME, Section VIII, Division 3 [45], as seen in Section 5.1.

In addition to fulfil all the requirements already specified for Option A, the following criteria must also be satisfied:

- Fracture toughness test: The fracture toughness under H_2 condition (K_{IH}) must be evaluated using the procedures provided in Article KD-10. The material must be tested in its thickest section and in the final heat-treated condition that will be used in pipe manufacturing. Specimens must be extracted from three critical locations: the base metal, the weld metal, and the heat-affected zone (HAZ) of welded joints. The specimens should be oriented in the TL direction, representing the through-thickness orientation relative to the longitudinal direction of the pipe. If TL specimens cannot be obtained from the weld metal or HAZ, LT specimens may be used. The lowest K_{IH} value obtained from these tests is then used in the pipeline design analysis, ensuring a conservative approach to fracture resistance.
- Fatigue analysis: If specific fatigue crack growth rate (FCGR) properties are not experimentally measured, Equation 4 may be used. Note that the material constants for FCGR properties are applicable only for carbon steels in gaseous hydrogen service up to 20 MPa (3000 psi) and with stress ratio R ($K_{IA,min}/K_{IA,max}$) of less than 0.5.

$$\frac{da}{dN} = a_1 \Delta K^{b1} + \left[\left(a_2 \Delta K^{b2} \right)^{-1} + \left(a_3 \Delta K^{b3} \right)^{-1} \right] \qquad \textbf{Equation 4}$$

Where $a1$, $b1$, $a2$, $b2$, $a3$, $b3$ are constant values, shown in Table 8. *da/dN* is the crack growth rate, expressed in (mm/cycle), $K_{IA,max}$ is the maximum applied stress intensity factor (MPa√m), $K_{IA,min}$ is the minimum applied stress intensity factor (MPa√m). The K_{IA} value is calculated considering the solutions proposed in the API-579 procedure, see Section 6.1. Additionally, the ASME B31.12 require that the calculated value of K_{IA} is lower than the K_{IH} value. Under no circumstances K_{IH} should be less than 55MPa√m (i.e., 50 ksi√in).

Table 8. Constants of fatigue design curve according to ASME B31.12.

Material constants	Values (SI units)
a1	4.08×10^{-9}
b1	3.21
a2	4.09×10^{-11}
b2	6.48
a3	4.88×10^{-8}
b3	3.61

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5.2.3 Pipeline fatigue life assessment according to ASME B31.12/KD-10

The ASME B31.12 code, particularly when using the design Option B, proposed a fatigue life assessment based on fracture mechanics calculations. This assessment references directly the Article KD-10 of the ASME BPVC-VIII.3. At the same time, article KD-10 refers to article KD-4 for determining the number of load cycles. The main parameters for the fatigue life assessment are summarized in Table 9.

In the fracture mechanics assessment, the critical number of cycles (N_{crit}) is calculated using Equation 4, once the critical crack size (a_{crit}) has been determined. This procedure allows for two alternative methods to define the critical crack size: 1) a_{crit} = 0.25t and l_{crit} = 2c_{crit} = 1.5t; and 2) using the FAD approach according to the API 579-1 procedure. For calculating the allowable final crack size (a_{allow}), the code refers to Article KD-412. Two options are provided for determining a_{allow}:

1. When the crack depth reaches 25% of the pipe wall thickness, yielding $a_{allow(1)}$ = 0.25t, and the corresponding allowable number of load cycles, $N_{allow(1)}$.
2. When the crack depth has growth 25% of the distance from the initial crack size (a_0) to the critical crack size a_{crit}, resulting in $a_{allow(2)} = a_0 + 0.25(a_{crit} - a_0)$, and the corresponding allowable number of load cycles, $N_{allow(2)}$.

The allowable number of load cycles N_{allow} is then determined by selecting the minimum value from both options. In this sense, the final design lifetime is calculated as the minimum of N_{allow} and half of N_{crit}, expressed as: $N_{design} = \min(0.5N_{crit}, N_{allow})$.

Table 9. Concepts used for the fracture mechanics assessment according to the ASME B31.12 and the Article KD-10

Parameter	Application
Standards	BPVC-VIII-3 / Article KD-10 / ArticleKD-4 / API 579-1
Idealise crack geometry	Semi-elliptical crack in cylinder axially oriented
Initial crack depth (a_0)	Not defined. Determined with NDT methods
Initial crack length (c_0)	Defined by aspect ratio: a_0/c_0 = 2/3
Stress intensity factor (K_I)	API 579-1
Critical crack size (a_{crit})	KD-412: a_{crit} = 0.25t and $2c_{crit}$=1.5t or KD-401: Level 2 FAD of API 579-1
Fatigue crack growth curve (da/dN)	Experimentally Article KD-1050: ASTM E647[(1)] or ASME B31.12 design curve
Fatigue threshold value (ΔK_{th})	KD-430: min[G(1-H·R)] but no less than 1.1 MPa√m
Yield strength definition (σ_{YS})	Chapter 9.3.5 of API 579-1
Plane fracture toughness (K_{IC}) (air)	Articles: KD-1021 with ref. to KM-250 with ref. to KD-4 Standards: ASTM E399 and E1820
Fracture toughness in H_2 conditions (K_{IH})	Experimentally using ASTM E1681 with a minimum of 55 MPa√m
Allowable crack size (a_{allow})	KD-412 : $a_{allow(1)}$ = 0.25t; $a_{allow(2)} = a_0 + 0.25(a_{crit}-a_0)$
Load history	Not explicitly regulated

[(1)]Conditions: minimum testing at pressure design. f≤1 Hz. R = 0.5.

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5.2.4 Hardness

ASME B31.12, which pertains to hydrogen piping and pipelines, specifies hardness criteria to ensure the integrity and safety of materials used in hydrogen service. In accordance with ASME B31.12, hardness testing is required for:

- welding procedure qualification (WPQ),
- hot and cold bent formed piping,
- pipe components,
- production weldments.

In order to qualify the welding procedure, the code established that the material cannot exceed the Vickers Hardness established for distinct type of materials, as gathered in Table 10 after the required PWHT (post weld heat treatment). The test method follows the ASTM E92.

On the other hand, the production weldments hardness must be controlled in the following cases:

1) Non-PWHT (as-welded condition) BM Group P-1, CS weldments made using SAW and FCAW process.
2) Non-PWHT (as-welded condition) weldments containing CS filler metal with minimum 1.6% Mn.
3) Any weldments that have been subjected to PWHT.

For these cases, the code stablished a maximum hardness of 237 BHN (Brinell Hardness Number), which is equivalent to 250 HV10 (Vickers Hardness). The test is performed in accordance with ASTM E92 for welding procedure qualification and ASTM E833 or ASTM E110 for production weldments (using portable hardness testers).

Table 10. Hardness testing acceptance criteria according to ASME B31.12

Base metal P-Nº	Base Metal Group	Max HV 10
1	Carbon steel	235
3	Alloy steels, Cr ≤ 0.5%	235
4	Alloy steels, 0.5% ≤ Cr ≤ 2 %	235
5A. 5B	Alloy steels, 0.5% Cr ≤ 10 %	248

5.3 DVGW Technical Rule G 464 (2023)

The DVGW technical rule G 464 [46], published in March 2023, introduces a fracture mechanics assessment for steel pipelines used in hydrogen transportation, applicable within limits presented in Table 11. This guideline also defined a procedure for predicting pipeline lifetime based on fracture mechanics. Table 12 presents the main parameters that are necessary for conducting a fatigue analysis. Once the material properties and the initial conditions are established (e.g., K_{IH}, a_0), the subsequent step involves the determination of the critical crack length (a_{crit}), which is calculated using the FAD methodology (see Section 6.1 for further details). The critical number of load cycles (N_{crit}) is then derived from a_{crit} using a FCGC, which can be determined

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either experimentally or directly with the design fatigue equations (see Table 12). This code proposed the following fatigue design curves obtained from experimental results under H_2 conditions:

$$\frac{da}{dN} = 4.4 \times 10^{-13}(1 + 3R)\Delta K^7 \sqrt{pH_2} \text{ for } \Delta K \le \left[3.6667 \times 10^{-6} \sqrt{pH_2}^{-0.25}\right] \text{MPa}\sqrt{\text{m}} \quad \textbf{Equation 5}$$

$$\frac{da}{dN} = 1.2 \times 10^{-7}(1 + 3R)\Delta K^3 \sqrt{pH_2} \text{ for } \Delta K \ge \left[3.6667 \times 10^{-6} \sqrt{pH_2}^{-0.25}\right] \text{MPa}\sqrt{\text{m}} \quad \textbf{Equation 6}$$

The allowable crack depth (a_{allow}) is determined either by dividing a_{crit} by a safety factor (S_a) of 1.5, or when the crack depth reaches half the wall thickness ($0.5t$), whichever is smaller. S_a accounts for fabrication tolerances and other potential deviations. The predicted lifetime (N_{pred}) is defined as the point at which the crack depth reaches a_{allow}. To ensure pipeline's reliability, a technical expert must verify the fracture mechanics assessment after a specific period or after a certain number of load cycles (N_{veri}), which is set by dividing the N_{pred} by a verification safety factor (S_{veri}) of minimum 5. The difference respects the initial assessment is that for the verification analysis the real operational pressure fluctuations are used for determining the operating load spectrum, and the subsequent equivalent constant amplitude loading.

Table 11. Applicability of DVGW G464 Guidelines.

Parameter	**Specification**
Nominal Pipe Diameter (DN)	100 to 1400 mm
Design Pressure (DP)	> 16 bar
Wall Thickness (t)	≥ 3.6 mm
Pipe Joining Method	Butt welds
Specified Minimum Yield Strength (SMYS)	Up to 555 MPa
Hydrostatic Testing Pressure	At least 1.3 × DP
Fracture mechanics assessment for new pipelines	Mandatory with one exception*
Fracture mechanics assessment for repurpose existing pipelines	To be verify case-by-case
Applicability for Pipelines with Minor Hydrogen Content	Applicable analogously
Applicability for Pipelines with Detachable Connections/Sockets	Applicable analogously with DP up to 16 bar

* SMYS ≤ 360 MPa, utilization factor $f_0 \le 0.5$ and predominantly static loads (≤ 1 equivalent load cycle with 100% MOP per year)

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Table 12. Concepts for the fracture mechanics assessment according to the DVGW G464.

Parameter	Application
Standards	Not specified. Recommendations: BS7910 /API579-1 / FKM guideline
Idealise crack geometry	Semi-elliptical surface flaw in (infinite) plate + crack face pressure + bulging factor for pipe curvature
Initial crack depth (a_0)	5% or 10% of wall thickness according to DVGW G463
Initial crack length (c_0)	$2c_0$ = 50 mm
Stress intensity factor (K_I)	API 579-1 / BS7910
Critical crack size (a_{crit})	FAD assessment API 579-1 / BS7910
Fatigue crack growth curve (da/dN)	Experimentally using ASTM E647[(1)] or ASME B31.12 design curve or DVGW G464[(2)] design curve
Fatigue threshold value (ΔK_{th})	6.5 MPa√m
Yield strength definition (σ_{YS})	R_{EH} or $0.5(Rt_{0.5} + R_m)$
Plane fracture toughness (K_{IC}) (air)	Not required
Fracture toughness in H_2 conditions (K_{IH})	Experimentally using ASTM E1820 and ASTM E399 with a minimum of 55 MPa√m
Allowable crack size (a_{allow})	$a_{allow} = \min(a_{crit}/S_a, 0.5t)$ (S_a =1.5)
Load history	Miner ruler

(1)Conditions: minimum testing at MOP. Recommended 100 bar. f≤1 Hz. R = 0.5.
(2)DVGW G464 design curve is dependent of pressure and load ratio.

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6 Codes and recommended practices for the assessment of hydrogen-natural gas pipelines

Ensuring the structural integrity of pipelines in hydrogen (H_2) environments is critical due to the severe consequences of potential failures, including loss of life, environmental damage, and economic costs. Hydrogen's corrosive and embrittling effects can penetrate the metal lattice, causing embrittlement, cracking, and ultimately catastrophic failure. High-pressure and high-temperature conditions in H_2 pipelines further accelerate these degradation mechanisms, necessitating robust structural integrity procedures to detect, assess, and mitigate potential failures.

One significant challenge addressed by the scientific community and gas suppliers is the compatibility of materials used in current natural gas pipelines for the safe introduction of hydrogen. It is important to note that the calorific value of H_2 is one-third that of natural gas. Therefore, either the pressure or the flow rate of H_2 must be increased, or a blend of natural gas and H_2 must be used to provide the same energy output as natural gas. This results in harsher operating conditions, which, combined with the susceptibility of steels to hydrogen embrittlement, demands more exhaustive integrity assessments. In fact, the future ASME B31.8 code, which will replace the actual ASME B31.12, will require fatigue life assessments for the design of new pipelines.

Furthermore, it is important to assume that no structure or component is free from cracks or defects with a certain notch radius. For example, in pipelines, defects commonly arise from material heterogeneities, scratches, or delamination along weld seams.[2] Additionally, the mechanical properties of pipeline steels are significantly degraded when transporting H_2 due to the embrittlement effect. Specifically, the fatigue crack growth becomes more pronounced, as H_2 has been demonstrated to significantly accelerate this process. Moreover, the fracture toughness is significantly reduced under H_2 exposure [47]. For these reasons, combined with the increased frequency and higher-pressure cycles, it is necessary to assess the pipeline service life using a fracture mechanics-based approach. As previously mentioned in Section 5.2.2, the most used design code so far is ASME B31.12 [16], which proposes two design options: Option A, a more conservative approach based on Charpy specimens, and Option B, a less conservative method based on article KD-10, using fatigue curves and fracture mechanics. Additionally, the recently published German code DVGW G464 [46] also proposes a fatigue design based on fracture mechanics (see Section 5.3). Both codes recommend using structural integrity procedures to calculate the critical crack size and, consequently, the number of cycles required for pipeline failure. ASME B31.12 specifies using the API 579-1/ASME FFS-1 procedure, [48] while DVGW G464 is less restrictive, allowing the use of recognized procedures such as BS 7910 [49], API 579-1 [48] or the FKM guideline [50]. In the following section a brief introduction to the BS 7910 and API 579-1 is carried out.

6.1 Structural integrity procedures: BS 7910 and API 579

In the context of pipelines and pressure vessels in non-nuclear context, the structural integrity assessment of components containing crack-like defects is typically performed using procedures such as BS 7910 [49] and API 579-1 [48]. These procedures offer different generic routes of assessment, each depending on the quality and detail of the material property data available. Higher levels of analysis require more accurate and specific input data and involve more complex calculations, whereas lower levels of analysis yield more conservative results.

These procedures are generally based on Failure Assessment Diagrams (FADs), which allow a simultaneous analysis of fracture and plastic collapse processes through two normalized parameters, K_r and L_r:

$$K_r = \frac{K_I}{K_{mat}}$$ **Equation 7**

$$L_r = \frac{P}{P_L} = \frac{\sigma_y}{\sigma_{ref}}$$ **Equation 8**

where K_I is the stress intensity factor, K_{mat} is the material fracture toughness in stress intensity factor units, P is the applied load, P_L is the limit load, σ_y is the material yield stress, and σ_{ref} is the reference stress. Assessment procedures such as BS 7910 and API 579-1 provide analytical solutions for K_I and σ_{ref} for a variety of components and crack geometries.

From **Equation 7** and **Equation 8**, it can be inferred that K_r evaluates the component against fracture, and L_r evaluates the component against plastic collapse, with both parameters defining the resulting assessment point within the FAD. The location of this point is then compared with the critical conditions defined by the Failure Assessment Line (FAL). When the assessment point is located above the FAL, the component is considered to be in unsafe conditions. If the assessment point is located between the FAL and the coordinate axes, the component is considered to be in safe conditions. Failure (critical) conditions are achieved when the assessment point lies on the FAL. Figure 11 shows a typical FAD definition illustrating the three different possible situations when assessing a fracture initiation analysis.

The FAL follows expressions that are functions of L_r:

$$K_r = f(L_r)$$ **Equation 9**

These $f(L_r)$ functions are essentially plasticity corrections to the linear-elastic fracture assessment (K_r=1). Their rigorous analytical solution is:

$$f(L_r) = \sqrt{\frac{J}{J_e}}$$ **Equation 10**

where J is the applied J-integral and J_e is its corresponding elastic component. This analysis is additionally limited by the cut-off, which corresponds to the load level causing the plastic collapse of the analysed component. This cut-off is defined by the maximum value of L_r ($L_{r,max}$), which depends on the material flow stress, generally defined as the average value of the material yield stress and ultimate tensile strength.

The definition of $f(L_r)$ following the rigorous analytical solution generally requires finite element analysis (FEA). Although structural integrity assessment procedures include this possibility, they also provide approximate solutions that can be easily defined through the tensile properties of the material. These solutions are usually provided hierarchically, with higher levels of material stress-strain curve definition leading to solutions that are more approximate to the rigorous analytical solution.

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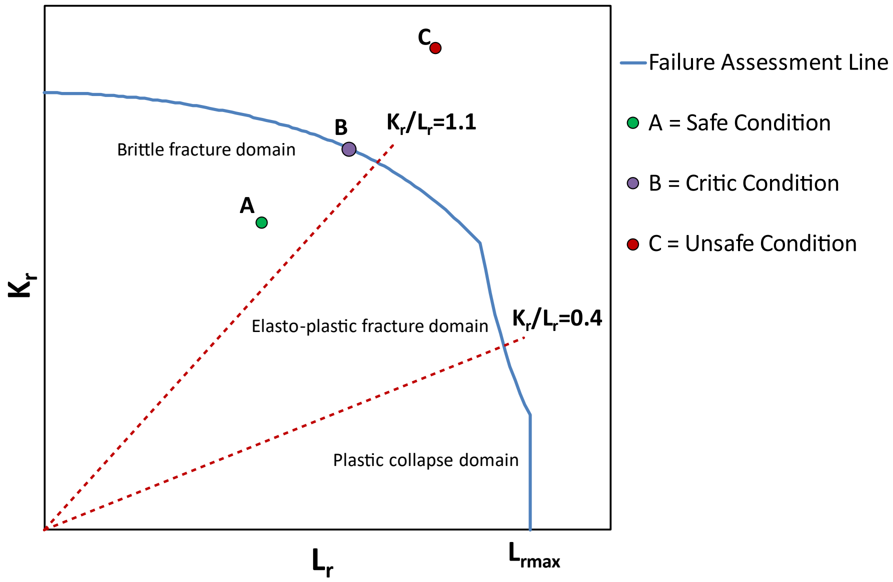

Figure 11: Definition of failure assessment diagram (FAD).

The first procedure introduced here is the well-known BS 7910 (2019). This British Standard provides guidance on methods for assessing the acceptability of flaws in metallic structures. It is widely used in various industries, including offshore, nuclear, and petrochemical, to ensure the structural integrity of components subjected to different loading conditions. BS 7910 covers the assessment of flaws such as cracks, inclusions, and voids in welds and base materials. It is applicable to a broad range of structures including pipelines, pressure vessels, and structural steelwork. BS 7910 offers three alternative routes, known as “Options”, to carry out fracture assessments:

- **Option 1**: It requires basic information and is divided into continuous or discontinuous yielding material. It is the simplest and most commonly used analysis option. For materials exhibiting continuous yielding behaviour, Option 1 is defined by Equation 11-16:

$$K_r = f(L_r) = \left[1 + \frac{1}{2}(L_r)^2\right]^{-1/2} \cdot \left[0.3 + 0.7 \cdot e^{-\mu \cdot (L_r)^6}\right] \qquad L_r \le 1 \qquad \textbf{Equation 11}$$

$$K_r = f(L_r) = f(1) \cdot L_r^{\frac{N-1}{2N}} \qquad 1 < L_r \le L_{r,max} \qquad \textbf{Equation 12}$$

$$K_r = f(L_r) = 0 \qquad L_r = L_{r,max} \qquad \textbf{Equation 13}$$

$$\mu = min\left[0.001 \cdot \frac{E}{\sigma_Y}; 0.6\right] \qquad \textbf{Equation 14}$$

$$N = 0.3 \cdot \left(1 - \frac{\sigma_Y}{\sigma_u}\right) \qquad \textbf{Equation 15}$$

$$L_{r,max} = \frac{\sigma_Y + \sigma_u}{2 \cdot \sigma_Y} \qquad \textbf{Equation 16}$$

- **Option 2**: This requires full stress-strain data for the material under consideration. It is defined by the Equation 17 and Equation 18:

$$K_r = f(L_r) = \left(\frac{E\varepsilon_{ref}}{L_r\sigma_y} + \frac{L_r^3\sigma_y}{2E\varepsilon_{ref}}\right)^{-1/2} \quad \text{for } L_r < L_{r,max} \qquad \textbf{Equation 17}$$

$$K_r = f(L_r) = 0 \quad \text{for } L_r > L_{r,max} \qquad \textbf{Equation 18}$$

- **Option 3**: Recommended for specific cases as an alternative to the previous options, this approach requires both elastic and elastic-plastic analysis, supported by numerical analysis to derive crack driving forces. It corresponds to the exact solution of the Failure Assessment Line (FAL), as provided by Equation 9 and Equation 10, with the cut-off following the same definition as in Options 1 and 2.

For the determination of the assessment point, BS 7910 provides analytical solutions for K_I and σ_{ref} (or P_L) in the annexes M and P, respectively.

The second structural integrity procedure introduced here is the API 579-1/ASME FFS-1 (2016), commonly referred to as API 579. This standard, developed by the American Petroleum Institute (API) and the American Society of Mechanical Engineers (ASME), provides guidelines and methodologies for evaluating the fitness-for-service (FFS) of equipment, including pipelines, that are subject to various types of degradation.

The API 579 (2016) offers three "Levels" of assessments based on available material properties and inspector expertise:

- **Level 1**: This assessment procedure provides conservative screening criteria that can be applied with minimal inspection or component information. This level of assessment is completely different than the BS 7910 Option 1 assessment. It consists of a series of allowable flaw size curves.
- **Level 2:** This more sophisticated analysis employs a generic FAD. At this level, stresses are expressed in terms of membrane and bending components, and partial safety factors are applied to the independent variables to account for uncertainty. In this case, the cut-off ($L_{r,max}$) points may be defined by six different options. The generic FAL equation is as follows:

$$K_r = f(L_r) = [1 + 0.14(L_r)^2] \cdot \left[0.3 + 0.7 \cdot e^{-0.65\cdot(L_r)^6}\right] \qquad L_r \leq L_{r,max} \qquad \textbf{Equation 19}$$

$$K_r = f(L_r) = 0 \qquad L_r = L_{r,max} \qquad \textbf{Equation 20}$$

- **Level 3:** This level is a more advance analysis that offers a substantial amount of flexibility by including five methods:
  - ✓ Method A: Level 2 assessment with user-generated partial safety factors or a probabilistic analysis.
  - ✓ Method B: Material-specific FAD, similar to BS 7910 option 2.
  - ✓ Method C: J-based FAD obtained from elastic-plastic finite element analysis, similar to BS 7910 Option 3.
  - ✓ Method D: Ductile tearing assessment.
  - ✓ Method E: Use a recognized assessment procedure, such as R6 or BS 7910.

When comparing BS 7910 Option 1 and API 579 Level 2, they are equivalent in terms of required data. It is worth noting that the BS 7910 FAL equation depends on material properties, whereas the API 579 procedure relies solely on the parameter L_r. Parametric studies have revealed the influence of Young's modulus, yield stress-to-ultimate tensile stress ratio, and yield stress on the FAD shape. Generally, the BS 7910 FAD curve tends to be slightly lower for $0 < L_r < 0.8$, higher for $0.8 < L_r < 1$, and lower for $L_r > 1$ compared to API 579.[51] This implies that BS 7910 allows for potentially larger flaws just before plasticity, while API 579 applies greater conservatism when $L_r > 1$. Figure 14 shows the FAL curves using the Equation 16 as the cut-off point for both procedures.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

6.2 Structural integrity assessment in pipelines

For the assessment of flaws, the first step involves the idealization of the crack geometry. Here, for simplicity, two common crack geometries used in pipeline assessment are considered. The first geometry, as per ASME B31.12, assumes an internal, axially oriented semi-elliptical crack within a cylindrical pipe. The second geometry, recommended by the DVGW G464 code, consist of a semi-elliptical surface flaw in a plate, where the width of the plate is (typically) significantly larger than the crack length, allowing the plate to be considered infinite. Figure 12 shows these two crack configurations for the cylinder and the plate. In this figure, the crack depth is a, the crack length is $2c$, the angle along the crack front is ϕ, the inner radius is R_i, and the thickness is t.

The structural integrity assessment requires that the applied load, which in this context is the internal pressure, to be expressed in terms of membrane stress and bending stresses. Therefore, the thin-walled cylinder solutions are used to compute the membrane stress (σ_m) (Equation 21) and through-wall bending stress (σ_b) (Equation 22) components of the primary stress at the centre of the uncracked cylinder:

$$\sigma_m = \frac{P \cdot R_i}{t} \qquad \textbf{Equation 21}$$

$$\sigma_b = \frac{P \cdot R_0^2}{R_0^2 - R_i^2}\left[\frac{t}{R_i} - 1.5\left(\frac{t}{R_i}\right)^2 + 1.8\left(\frac{t}{R_i}\right)^3\right] \qquad \textbf{Equation 22}$$

Where P is the internal pressure and R_0 the outer radius. The next steps involve determining the stress intensity factor and the reference stress. The relevant formula for both procedures and crack geometries are listed in Comparison of solutions of stress intensity factors and reference stresses [52,53]. For simplicity, other parameters influencing these equations are not defined here, but references to the corresponding sections in API 579 and BS 7910 are included. Additionally, Figure 13 shows the range of applicability of the K_I solution given in each procedure for a cylinder and a plate. It is noticeable that API 579 covers a wide range of dimensions for the cylinder, whereas BS 7910 has a broader range for the plate case.

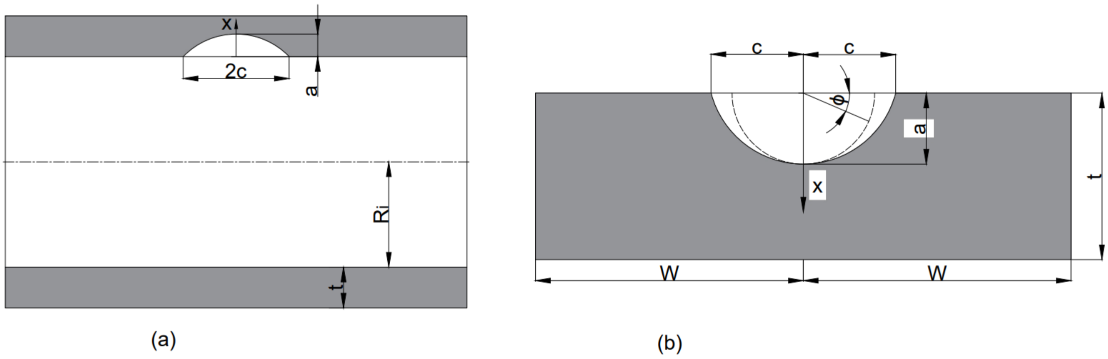

Figure 12: (a) Semi-elliptical internal flaw oriented axially in a cylinder and (b) semi-elliptical surface flaw in a plate. Figure drawn according to API 579-1[52]**.**

Table 13. Comparison of solutions of stress intensity factors and reference stresses [52,53]**.**

Procedure	**Cylinder**	
API 579 (9C.5.9)	$\sigma_{ref} = \dfrac{gP_b + [(gP_b)^2 + 9(M_s \cdot P_m \cdot (1-\alpha)^2)^2]^{0.5}}{3(1-\alpha)^2}$	**Equation 23**

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BS 7910 (P.8.2)	$$\sigma_{ref} = M_s P_m + \frac{2P_b}{3(1-\alpha'')^2}$$	**Equation 24**
Plate		
API 579 (9C.3.4)	$$\sigma_{ref} = \frac{gP_b + [(gP_b)^2 + 9P_m^2(1-\alpha)^2]^{0.5}}{3(1-\alpha)^2}$$	**Equation 25**
BS 7910 (P.6.1)	$$\sigma_{ref} = \frac{P_b + \left[{P_b}^2 + 9P_m^2(1-\alpha'')^2\right]^{0.5}}{3(1-\alpha'')^2}$$	**Equation 26**
Cylinder		
API 579 (9B.5.10)	$$K_I = \frac{pR_o^2}{R_o^2 - R_i^2}\left[2G_0 - 2G_1\left(\frac{a}{R_i}\right) + 3G_2\left(\frac{a}{Ri}\right)^2 - 4G_3\left(\frac{a}{R_i}\right)^3 + 5G_4\left(\frac{a}{R_i}\right)^4\right]\sqrt{\frac{\pi a}{Q}}$$	**Equation 27**
BS 7910 (M.7.2.2)	$$K_I = Mf_w\{k_{tm}M_{km}M_mP_m + k_{tb}M_{kb}M_b[P_b + (k_m - 1)P_m]\}\sqrt{\pi a}$$	**Equation 28**
Plate		
API 579 (9B.3.4)	$$K_I = (M_m(\sigma_m + p_c) + M_b\sigma_b)\sqrt{\frac{\pi a}{Q}}$$	**Equation 29**
BS 7910 (M.4.1)	$$K_I = Mf_w\{k_{tm}M_{km}M_mP_m + k_{tb}M_{kb}M_b[P_b + (k_m - 1)P_m]\}\sqrt{\pi a}$$	**Equation 30**

In Table 13: a is crack depth dimension; σ_m, P_m , are the primary membrane stresses; σ_b , P_b are the primary bending stresses; Q is the defect shape parameter; M is the bulging correction coefficient; f_w is the correction term of stress intensity factor of elliptical defect; k_{tm} is the membrane stress concentration factor; k_{tb} is the bending stress concentration factor; M_m , M_b , M_{km}, M_{kb} are the stress intensity amplification factor; k_m is the stress amplification factor caused by misalignment; p is the internal pressure ; G_0 , G_1 , G_2 , G_3 , G_4 are the influence coefficient of internal and external surface cracks; R_0 , R_i are the external radius and internal radius of the vessel, respectively; α,α'' are the reference stress parameter; g is a reference stress bending parameter.

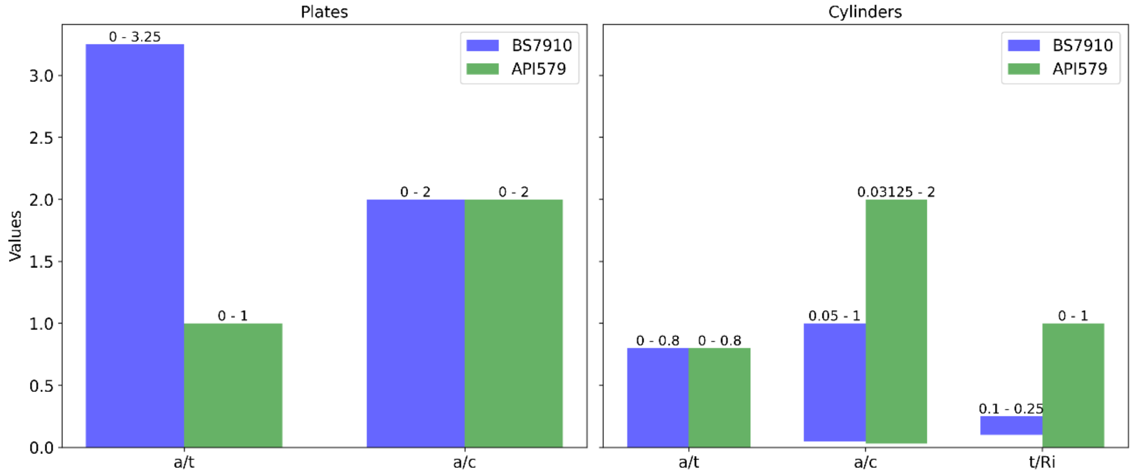

Figure 13: Validity range of crack sizes used for FAD according to BS 7910 and API 579.

In order to compare both geometries and procedures, the example given in the DVGW G464 (Appendix A.1) was used. The pipeline had an outer diameter of (D_o) of 610 mm, and a wall thickness (t) of 8 mm. The maximum allowable operating pressure (MAOP) was 70 bar (0.7MPa). The material selected was the L485 (X70) with a yield strength (σ_{YS}) of 485 MPa and an ultimate tensile strength (σ_{UTS}) of 570 MPa. External factors such as secondary bending stresses and residual stresses interacting on the pipeline tubes were neglected. The fracture toughness was assumed to be the minimum viable value of K_{IH} = 55 MPa√m. The crack had a semi-elliptical shape oriented in the axial direction with an initial depth (a_0) of 0.8 mm and an initial length ($2c_0$) of 50 mm.

Figure 14 and Figure 15 present the FAD assessment for the example case using both API 579 and BS 7910 procedures. The red squares and circles represent the plate and cylinder configurations assessed using API 579, whereas the blue squares and circles correspond to those assessed using BS 7910. Figure 14 shows the initial assessment points (i.e., a_0, $2c_0$). The solutions provided by both procedures for the plate and cylinder geometries are comparable, with only slightly higher K_r and L_r ratios for the cylinder evaluation using API 579. Besides, the clustering of these points below their respective FALs indicates safe situations of the initial points. Note here that strictly the BS 7910 solution is outside the validity range of *a/c* but is included for comparison purposes. On the other hand, Figure 15 presents the scenario when the crack depth growths until reach the critical situation (i.e., intersects the FAL). Here, the differences in the plate solutions are minimal, with an a_{crit} = 3.70 mm. However, larger differences are observed between procedures for the cylinder solutions, with a_{crit} = 3.15 mm and a_{crit} = 3.90 mm for the API 579 and BS 7910, respectively. Therefore, the cylinder solution of the API 579 provides the most conservative assessment. These differences between the solutions outlined in API 579 and BS 7910 are well-documented in the literature, with these discrepancies leading to significant variations in structural assessments [54–57]. Oesterling et. al [2] studied the differences in lifetime predictions for pipelines using these two procedures. They observed that, while both codes provide similar frameworks for assessment, notable differences exist in the allowable cycles and conservatism levels. Specifically, fatigue life assessments based on API 579 typically allowed a higher number of cycles compared to those based on BS 7910. Besides, solutions for plates yielded more conservative results, allowing for fewer number of cycles than those derived from cylinder solutions. Ultimately, the authors concluded that the most important parameters to reduce conservatism in structural integrity assessments are a precise understanding of the expected defect size (both length and depth), together with the use of material-specific fatigue crack-growth curves.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

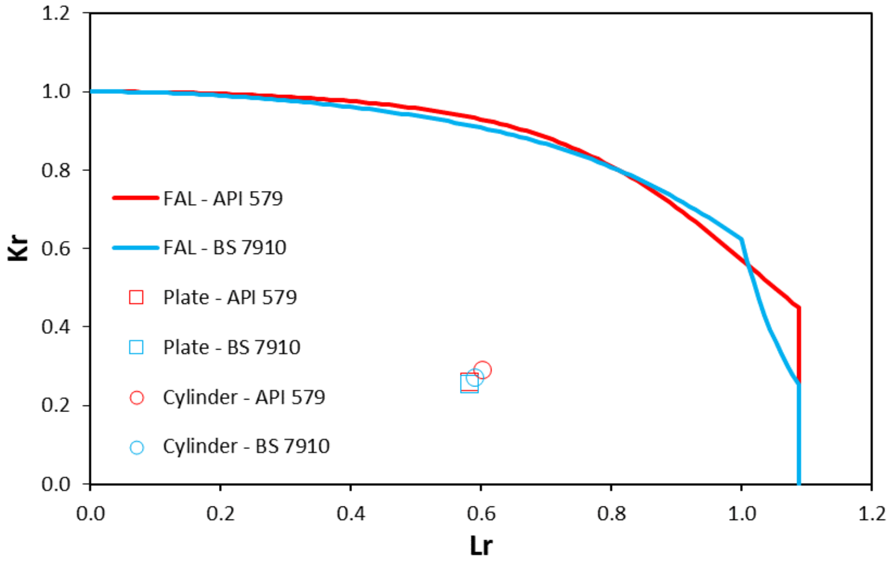

Figure 14 Comparison of solutions provided by the API 579 and the BS 7910.

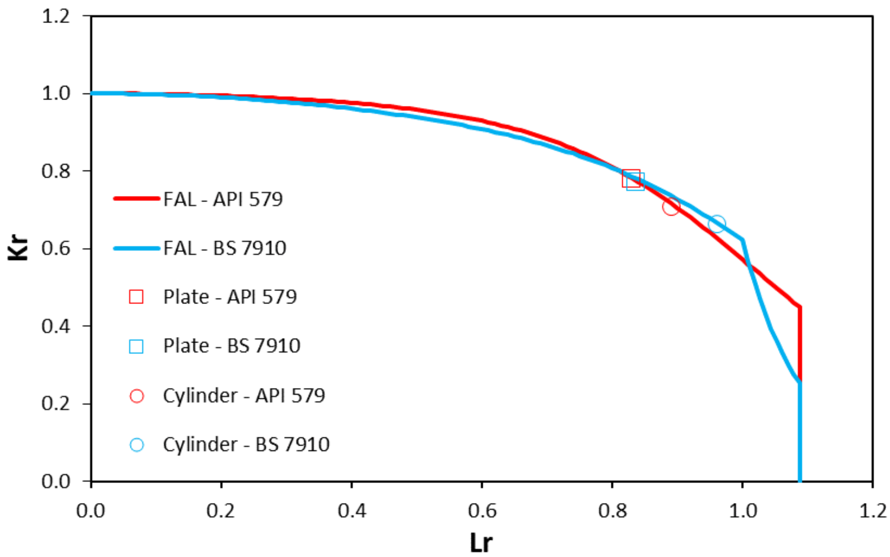

Figure 15 Comparison of critical crack depths (a_{crit}) by applying the API 579 and the BS 7910.

6.3 Structural integrity assessment in H2 environment.

As mentioned in sections below, the fracture toughness of pipelines operating under H_2 environments can decrease by approximately 50% or more compared to values measured in air. However, the effect of H_2 on yield strength and ultimate tensile strength is considered negligible. When using FAD assessments to estimate the critical load (e.g., critical internal pressure), the impact of H_2 is shown in Figure 16. It is evident that there is a significant reduction in the safe zone (i.e., below the FAL) when fracture toughness measured in a hydrogen environment (i.e., $K_{mat} = K_{IH}$) is considered.

Another important effect of introducing H_2 into the pipelines is the presumed increase in operating pressure compared to natural gas. In a FAD assessment, this pressure increase results in an increment in both L_r and K_r. This increment is proportional, as both σ_{ref} and K_I increase with pressure. Therefore, the pressure increments

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will follow a line passing through the origin. The slope of this line is controlled by material properties such as σ_{ys} and K_{IH} as well as pipeline geometry and flaw dimensions. For example, If K_{IH} is 50% of the K_{mat} (in air), the slope of this line doubles after hydrogen introduction. The shape of the FAD curve affects the sensitivity of the critical load for H_2 service (see Figure 16). This sensitivity is highest in the brittle failure zone, where a 50% decrease in fracture toughness due to hydrogen results in a 50% decrease in critical load. The sensitivity decreases in the elastoplastic zone, and eventually, the critical load becomes independent of fracture toughness in the collapse zone, where steel strength controls critical load.

The discussion in the previous paragraph suggests that, generally, a flawed pipeline would not tolerate a hydrogen blend without a corresponding decrease in operating pressure. Otherwise, the hydrogen blend would cause failure or a decrease in safety factors. This issue was discussed by Kappes et al. [7], who studied how an assessment in the fracture domain region (see Figure 11) could represent the condition of vintage pipelines with large defects and inferior microstructure. In such cases, hydrogen injection would make those materials worse, promoting brittle failure. On the other hand, an assessment in the collapse domain region would represent the condition of modern pipelines with high strength and very small defects. The authors concluded that the main limitation of this methodology is the determination of K_{IH} for an existing pipeline. Here, the development of small-scale specimens (e.g., small punch test or mini-C(T) specimens[58]) would be particularly beneficial for the structural integrity assessment of both current and future pipelines.

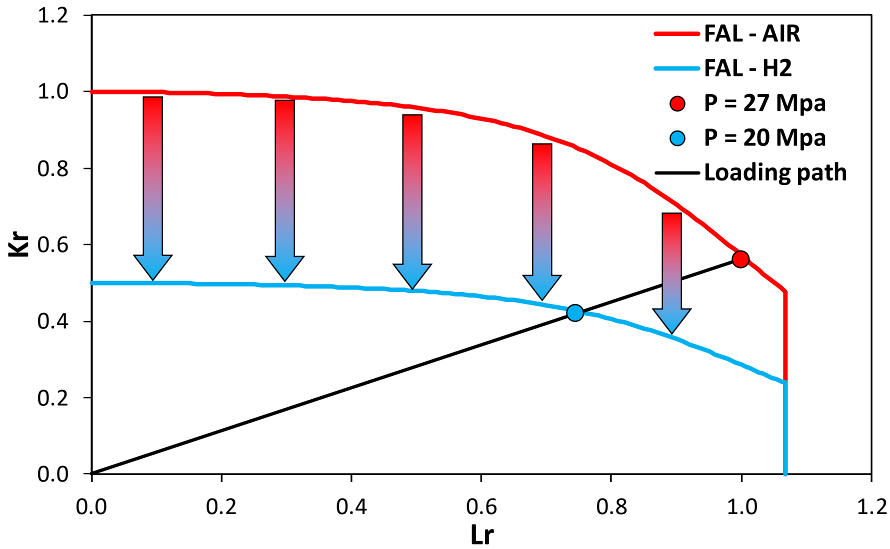

Figure 16: Effect of H_2 embrittlement in the FAD assessment.

Another comprehensive study conducted by Kappes et. al analysed the relationship between the failure pressure (P_{fail}) and the fracture toughness for five semi-elliptical flaws of different sizes.[59] The study identified the existence of a threshold hydrogen-affected fracture toughness (denoted as K_{IH}*) above which the P_{fail} for hydrogen is equivalent to that for an inert gas. Figure 17 shows the relationship between P_{fail} and K_{mat} for the different crack sizes. As previously pointed out, there is a linear relationship when the material has low toughness (typically below 50 MPa√m, brittle fracture domain in FAD). Beyond this point, the relationship becomes non-linear (corresponding to the elastic-plastic domain in FAD) until the material's fracture toughness is high enough to maintain a constant P_{fail} (corresponding to the collapse plastic domain in FAD).

Therefore, if $K_{IH} > K_{IH}$*, pipelines can operate with hydrogen blends without reducing operating pressure while maintaining the same safety factor. For example, this occurs for the flaw #1 in Figure 17. The safety factor is defined by the ratio of P_{fail} to the maximum allowable operating pressure (MAOP) (i.e., $f = P_{fail}/MAOP$). On the other hand, if $K_{IH} < K_{IH}$*, the safety factor decreases because the failure pressure in hydrogen service is lower. In order to achieve equal safety factors in both hydrogen and natural gas services, the MAOP in hydrogen service must be reduced accordingly. It is important to consider that K_{IH}* depends on flaw size and location. Larger flaws and flaws in welds would require a higher K_{IH}*, potentially exceeding the hydrogen-affected fracture toughness of pipeline steels.

Additionally, failure pressure decreases with increasing flaw size at a given fracture toughness. Therefore, the critical flaw size is smaller in hydrogen service compared to natural gas service, indicating higher susceptibility to failure in hydrogen environments.

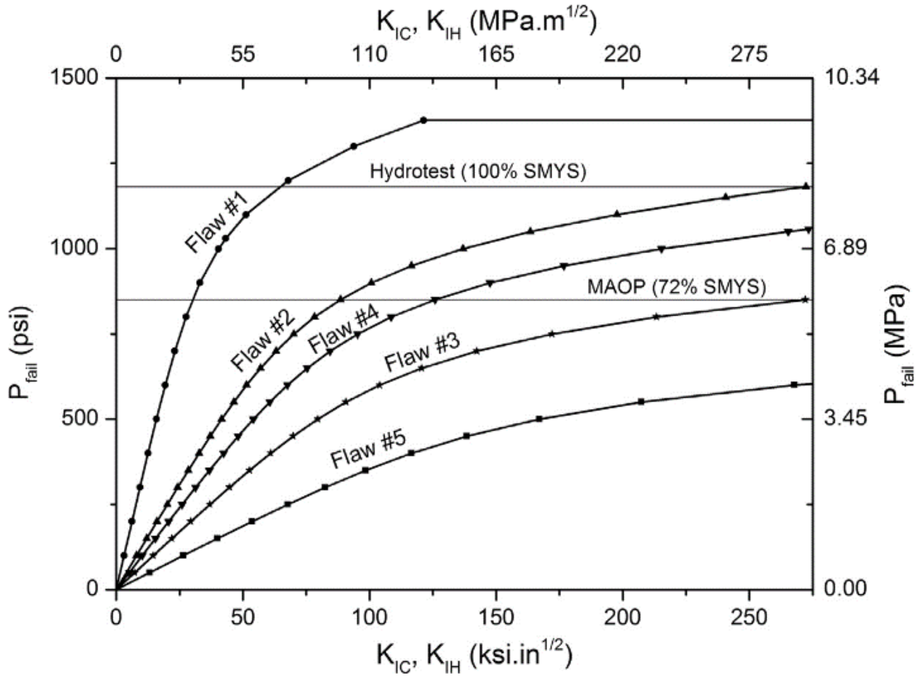

Figure 17: The relationship between failure pressure (P_{fail}) and fracture toughness (K_{IC}, K_{IH}). Taken from [60]**.**

7 Gap analysis

Numerous reviews, technical reports, and R&D projects have identified significant gaps in existing codes and standards when applied to hydrogen within existing natural gas infrastructure. The lack of standardized assessment methods for evaluating the compatibility of hydrogen with vintage pipeline infrastructure is a significant challenge in this respect. This issue is critical because the materials and construction methods used in older pipelines may not have been designed to handle the unique properties of hydrogen, such as its small molecular size, high diffusivity, and potential to cause embrittlement in certain metals.

Another significant issue is the absence of detailed specifications in many codes regarding the range of natural gas composition concentrations and the effects of various constituents on pipeline materials. Most existing standards focus on testing materials in high-purity hydrogen atmospheres. However, in practice, the blend composition may vary, containing different hydrogen content levels and other additives that could impact material behaviour. Although some projects have attempted to fill this gap by conducting testing campaigns employing blends with varying hydrogen concentrations,[61] these efforts have highlighted a significant challenge: the lack of standardized testing methods. This deficiency results and inhomogeneous and difficult-to-generalize findings, making it challenging to apply these results broadly across different types of infrastructure.

The main issues identified in the current review are the following:

1. Existing assessment methods may vary, and there is not a universally accepted standard and criteria for evaluating the compatibility of hydrogen with vintage infrastructure.
2. Many older pipelines lack detailed historical records of their material composition, manufacturing methods, and in-service conditions, making it difficult to assess their current suitability for hydrogen transport.
3. Vintage pipelines might be more susceptible than new pipelines to hydrogen-induced material degradation, including embrittlement, which can compromise the structural integrity of the pipeline. However, it is not clear which conditions (maximal hydrogen concentration and pressure) are still safe for operation.

To address these challenges, the development of a standardized approach for assessing hydrogen compatibility with vintage pipelines is crucial. This would involve:

1. **Comprehensive Material Testing:** Establishing protocols for testing the materials used in vintage pipelines under hydrogen service conditions, including long-term exposure tests to assess the potential for embrittlement and other forms of degradation.
2. **Historical Data Analysis:** Developing guidelines for evaluating the available historical data of pipelines to determine their current state and predict their performance when exposed to hydrogen.
3. **Risk Assessment Framework:** Creating a risk assessment framework that accounts for the age, condition, and material properties of vintage pipelines, providing a clear methodology for deciding whether a pipeline can be safely repurposed for hydrogen transport. Some possible solutions might be developing classification of vintage pipelines, based not only on steel grade, but also considering composition, fabrication methods, structure, hardness of the welds etc. and thus accounting for the effects introduced by modern and vintage methods of fabrication, aging etc. This framework should be supported by thorough experimental and numerical data.

The following sections highlight specific gaps identified in the standards for testing and qualification of materials and components used in hydrogen service identified in the scope of SHIMMER as well as indicated by previous projects. These gaps include not only the gaps detected throughout the work the SHIMMER project, but also gaps indicated by other similar projects.

7.1 Harmonized material testing protocols

The current lack of harmonized testing protocols for materials and components in hydrogen, coupled with discrepancies in testing guidelines across different standards for the same type of testing, might result in inconsistencies in the results obtained. Some of the issues detected are listed below.

- For smooth specimen tensile tests, ANSI/CSA CHMC 1 specifies testing in constant extension rate mode which translates to a nominal strain rate of $d\varepsilon/dt = 10^{-5}$/s. This does not exactly comply with ASTM G142 where the specified nominal strain rate is slightly higher. For notched specimens, tests shall be conducted at applied displacement rates such that the effective strain rate measured over 25.4 mm, centered over the notch, is nominally 10^{-6}/s. This is one order of magnitude slower than the specified rate for the standard smooth specimen using the same test fixtures. This is in contradiction to ASTM G142 where the extension rate of the notched specimen tensile test is one magnitude faster (0.02 mm/s) compared to the smooth specimen tensile test (0.002 mm/s). In the future revision of both standards, it is important to synchronize the testing conditions to avoid confusion since it is well known the displacement rate affects the results of SSRT.
- Currently samples are tested without pre-charging, however the pre-charging of the specimen might affect the testing results. By incorporating a (prolonged) pre-charging period, where hydrogen is allowed to penetrate the material sample before testing, the test conditions could become more representative for real-world scenarios. This approach may lead to more conservative and reliable results, as it better simulates the long-term exposure of materials to hydrogen, potentially revealing vulnerabilities that might not be evident under shorter or no pre-charging conditions.
- It would be necessary to publish a standard about testing protocols for industry hydrogen applications, indicating properly how to control the test environment (e.g., H_2O and O_2). Besides, it would be important to revise the small-scale specimen commonly used in laboratories to better reproduce the real conditions of pipelines and reduce conservatism. An example of that would be implement lower specimen constraints such as shallow cracked specimens and SE(T) specimens.

Furthermore, the test methodologies developed must be designed to be as universally applicable as possible while maintaining a degree of conservativeness. Additionally, they must offer the necessary representativeness to ensure accurate fitness-for-purpose analyses.

7.2 Harmonized evaluation criteria

- Few standards indicate clear acceptance criteria and not all of them can be universally applied. The values RRA obtained from SSRT for instance are recommended for ranking purposes only and according to ANSI/CSA CHMC 1 only for austenitic and aluminium alloys an RRA value ≥ 0.9 could serve as an acceptance criterion. This greatly limits the applicability of the method.
- In ANSI/CSA CHMC 1 a material is classified as “not compatible with hydrogen” when the relative notched tensile strength (RNTS) is less than 0.5. However, a rationale for this boundary of 0.5 could not be identified and there might be applications where materials with RNTS less than 0.5 can be safely used in hydrogen applications, e.g., for unloaded or very low loaded parts. On the other hand, a material is classified as “compatible with hydrogen” when RNTS ≥ 0.9 or RRA ≥ 0.9. Importantly, this assessment from tensile testing cannot be generalized, i.e., when a material is classified as “compatible with hydrogen” in tensile tests, this does not automatically mean that said material would be categorized accordingly in fatigue life tests, fatigue crack growth tests or fracture toughness tests.
- ISO 11114-4 for instance specify the acceptance criteria, for all 3 methods used, however this standard is not universally applicable. This method appears to generate specific data for the qualification of steels for the given application and does not yield fundamental material properties. Consequently, this qualification requirement seems tailored to the specific application and may not be transferable to other contexts without careful assessment.

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- In ASME B31.12 the Design Method (option A) for pipeline sizes larger than 114.3 mm includes three Charpy impact tests for each material heat according to the API 5L Annex G. For welds, also three specimens from the weld material as well as from the heat affected zone are characterized in Charpy impact tests and have to guarantee specimen size dependent Charpy impact energies. Annex G of API 5L also specifies that the Charpy tests shall be performed “in the environment of pipeline application”, which means that Charpy tests should be conducted in pressurized hydrogen gas.[44] It is important to note that, currently, there is no technological possibility to conduct Charpy tests under hydrogen conditions.[18]
- ASME B31.12 proposes a criterion to qualify the welding material procedure based on hardness levels, with a maximum of 235 HV for carbon steels. It is not clear how this hardness criteria were defined and if it aligns well with a pipeline under hydrogen service or should be revised.
- ASME B31.12 design method highly depends on accuracy to measure crack sizes, improving non-destructive methodologies (NDT) to detect small cracks would lead to reduce the conservatism of this code.

7.3 Classification and consideration related to the actual state of vintage materials

- There is a lack of understanding about the real state of vintage infrastructure and there is limited and non-systematic data on the actual conditions of the existing gas grid. There is a need to establish a classification system which groups the materials not only in terms of metallurgical grades, but also considers age, carbon content, microstructure, fabrication methods, mechanical properties etc. and also take into account the defect and degradation of the pipes and components.
- Current standards prohibit the use of cast iron for hydrogen service, however, cast iron is used in the gas grid piping and valves in many countries. It is not clear whether cast iron can be safely used for low pressure distribution pipelines, or they need to be replaced as well.

Table 14. ASME B31.12 Materials compatibility table.

Material	H_2 Gas	H_2 Liquid
Aluminium and aluminium alloys	Acceptable	Acceptable
Austenitic stainless steels with greater than 7%	Acceptable	Acceptable
Carbon steels	Acceptable	Non acceptable
Copper and copper alloys	Acceptable	Acceptable
Gray, ductile, or cast iron	Non acceptable	Non acceptable
Low-alloy steels	Acceptable	Non acceptable
Nickel and nickel alloys	Non acceptable	Acceptable
Nickel steels	Non acceptable	Non acceptable
Titanium and titanium alloys	Acceptable	Acceptable

- In the gas infrastructure there exist many different materials which are not considered in the current standards.

8 Recommendation for future research and development of testing methods

Based on the performed analysis and the detected gaps we propose the following areas for further research.

8.1 Classification of pipelines with similar material properties

To deal with the huge inhomogeneity in terms of pipeline materials and their actual conditions such as microstructure, vintage or modern, fabrication methods, hardness of welds etc. even within the same pipe grade, it is desirable to create a classification system or groups of materials which share similar properties so that all materials within the group can reliably be considered to behave in similar and predictable way when operating with hydrogen and blends. This classification or grouping should be based on reliable experimental data and preferably supported by numeric data. One approach could be to first conduct a systematic experimental assessment of the mechanical properties and current condition (including defects) of decommissioned pipelines and components across Europe. This would provide a more detailed and statistically significant data on the actual state of the infrastructure and would allow for the creation of classification and grouping of similarly performing materials. Once this is done, the requirement to determine material properties of existing infrastructure on every mile of piping could be relaxed.[18] This however requires significant research effort and the involvement of gas operators, research institutions and standardization bodies.

8.2 Potential sources of over-conservatism

Design codes such as ASME B31.12 prescribe stringent safety factors and material properties (e.g., hardness, toughness) requirements which vary with material grade and operating pressure. While these measures aim to provide a margin of safety against failures, they may incorporate an excessive degree of conservatism that does not always align with real-world conditions, such as those involving elastic-plastic fracture scenarios. For example, the ASME B31.12 sets minimum toughness requirements (K_{IH}=55 MPa.m$^{1/2}$). Additionally, the hardness requirements mandated by these codes, similar to those for sour service pipelines exposed to H2S, might not be suitable for pipelines transporting pure hydrogen. The differing levels of exposure to atomic hydrogen in pure H environments compared to H2S environments suggest that these requirements could be overly conservative, leading to unnecessary material specifications or enhancements that do not proportionately increase safety but do raise costs and complexity.

The practical implications of these codes are significant. For instance, ASME B31.12 advocates for testing material specimens from each mile of pipeline to verify unknown material properties. While thorough, this approach may not be practical or cost-effective, particularly for large-scale infrastructure projects. Such overly cautious practices could be revised to better balance ensuring safety with maintaining practicality and economic viability in infrastructure development.

Adjusting the conservatism in design codes could lead to more efficient and economically viable projects. A nuanced, evidence-based approach to revising these codes could help align safety measures with real-world conditions and technological advances, fostering innovation while still prioritising safety.

8.3 Testing techniques

As previously mentioned, mechanical data for an existing pipeline such as KIH is usually not available in reality: for most existing pipelines, not even Charpy impact energy values are known, because they were not required at the time of construction. Standardized tests for characterizing mechanical properties of base metal and welds require large amounts of steel. If representative samples of base metal, weld and HAZ of the pipeline are not available, they must be obtained from the pipeline. The development of tests for assessing mechanical properties using miniaturized specimens, like the small punch test (SPT) [62], will be of particular interest for integrity programs of blended or repurposed pipelines. The small samples required for the SPT could be taken

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from an operating pipeline without compromising its structural integrity.[7] In the following paragraph some testing techniques are described.

- SPT was developed to assess the evolution of the mechanical properties of steels used in the nuclear industry under operational conditions [63]. In scenarios where hydrogen continuously permeates the steel (as it is of interest to the SHIMMER project), a comparable issue arises, allowing for the continuous monitoring of mechanical properties degradation throughout the component service life [64]. A significant advantage of the SPT method is that it enables estimation of actual mechanical properties of operating components or structural materials without affecting their integrity and operational performance. SPT technique is standardized by EN 10371 [65] and is widely used to obtained properties such as tensile strength, creep behaviour or fracture resistance. SPT test involves punching a small, flat specimen, deforming it until fracture, while simultaneously recording the applied force and the displacement of the punch or the lower face of the specimen, depending on the specific setup.

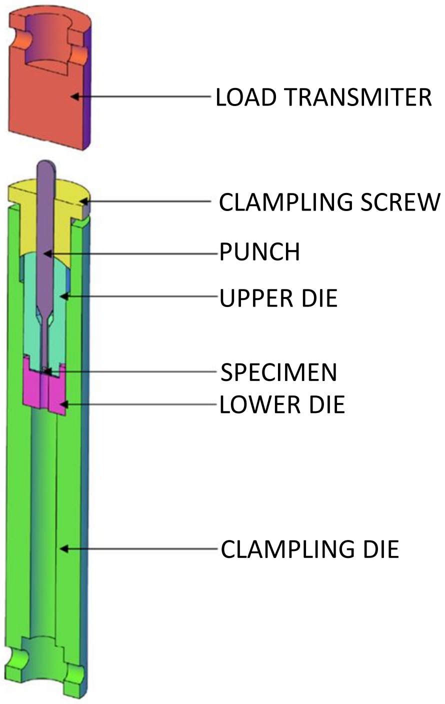

Figure 18: Experimental set-up for small punch test. Taken from [58]**.**

- Another promising miniaturization technique to evaluate the fracture toughness is the miniature compact tension (mini-C(T)) specimen (Figure 19). Similarly, to the SPT, this approach has emerged from the necessity of the nuclear industry to monitor the effects of irradiation dagame in reactor pressure vessel materials [66]. The mini-C(T) specimen has been extensively validated for characterizing the ductile-to-brittle transition range in nuclear grades, together with the Master Curve approach. Notably, efforts on this research can be found in the European project FRACTESUS [67]. However, when dealing with the characterization of the upper shelf regime, the applicability of mini-C(T) specimens remains a challenge. Although research on the upper shelf is limited, existing studies have consistently reported underestimation of the crack resistance curve [68].

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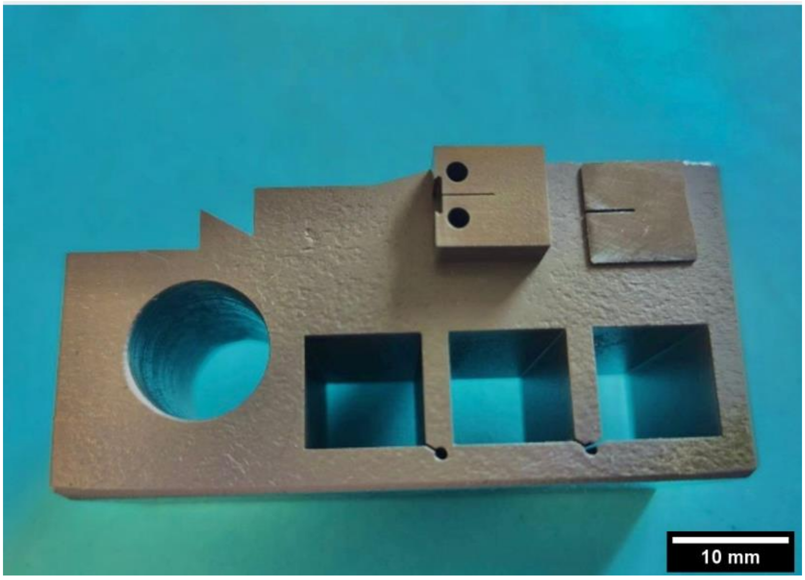

Figure 19: Comparison between mini-C(T) specimen, SPT, and a broken 1T-C(T) specimens. Taken from [58]**.**

- To simplify the testing and avoid the use of autoclaves the Hollow SSRT specimen was proposed. In this type of test, by modifying the geometry of the test piece, the specimen itself acts as a containment for the pressurized gaseous atmosphere. [69] This function is achieved by the fabrication of a longitudinal hole in the center of the sample (Figure 20). The main advantage of this method is simplified testing and much smaller volume of hydrogen needed compared to classical SSRT.

Figure 20: Hollow SSRT specimen, the test assembly, and the corresponding Force-Displacement curve.

9 Conclusions

Existing standards for the qualification of metallic materials in hydrogen service provide a solid foundation, but they present also important gaps and ambiguities in technical guidance. The main reason is because they are not specifically developed for the specific case of hydrogen blending in the existing gas grid. Technical gaps are also detected in some testing standards that could benefit from further clarification to ensure more robust assessments of material performance in hydrogen environments. The need for harmonization across

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standards is essential to streamline the assessment process, establishing consistent criteria and facilitating universal technical understanding across Europe and globally.

While design standards allow for the assessment and repurposing of existing infrastructure, the applicability of the methods they propose is often constrained by high costs and limited scope, impeding a thorough evaluation of system readiness.

Our report identifies several critical gaps within these standards. Conceptually, there is a lack of detailed understanding of the mechanical properties and degradation state of vintage pipelines and components which have been in operation for certain period. Furthermore, there is no comprehensive classification system that considers factors such as material degradation, age-related defects, and operational history, beyond standard material grades.

Research into alternative testing methods and evaluation protocols will be advanced in WP3, where more specific methodologies addressing these gaps will be investigated and detailed, exploring potential solutions to current limitations in material qualification.

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