Project number: 101111888
Project acronym: SHIMMER
Project duration: 09/2023 – 08/2026
Project Coordinator:
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Co-funded by the European Union

HORIZON 2020: Horizon Europe Framework Programme (HORIZON)
HORIZON-JTI-CLEANH2-2022-05-03
Safe hydrogen injection management at network-wide level: towards European gas sector transition

Clean Hydrogen Partnership

Shimmer

Safe Hydrogen Injection Modelling and Management for European gas network Resilience

3.1. Identification of critical material properties and component factors

VERSION	DATE	TYPE	DISSEMINATION LEVEL
Version 2.0	27-10-2025	Report	Public

ABSTRACT

This Deliverable provides a comprehensive analysis of how hydrogen affects the performance and reliability of materials and components used in natural gas transmission and distribution networks. It examines hydrogen-induced failure modes and degradation mechanisms in both metallic and non-metallic materials under hydrogen exposure. The report consolidates experimental data from research studies, project results, and relevant standards to evaluate material behaviour in hydrogen-containing environments especially in the context of hydrogen blending in the gas grid. It also discusses the compatibility of various materials and components with hydrogen service, providing insights to support decision-making for the safe integration of hydrogen into existing gas infrastructure. The findings serve as a foundation for guiding future research, testing, and operational practices, aiding the transition toward hydrogen-enriched energy systems.

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Release history

VERSION	DATE	VERSION DESCRIPTION
01	15-10-2025	Main content of the document
02	27.10.2025	Copyright information updated and included

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

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List of Abbreviations

Table 1. List of abbreviations

Term	Explanation
H2	Hydrogen
Al	Aluminium
BCC	Body-centered-cubic
BCT	Body-centered tetragonal
CR	Polychloroprene
da/dN	Crack growth rate
EL	Plastic elongation
EPM & EPDM	Ethylene-Propylene
FCC	Face-centered-cubic
FCGR	Fatigue crack growth rates
FFS	Fitness for service
FKM	Fluoroelastomer
FPM	Perfluoroelastomer
HAF	Hydrogen-assisted fatigue
HAZ	Heat affected zone
HCP	Hexagonal close-packed
HDPE	High-Density Polyethylene.
HE	Hydrogen embrittlement
HEDE/AIDE	Hydrogen-enhanced decohesion
HEI	Hydrogen embrittlement index
HELP	Hydrogen-enhanced localized plasticity
HIC	Hydrogen induced cracking
Kmat	Fracture toughness
MDPE	Medium-Density Polyethylene
NBR	Butadiene-Acrylonitrile Rubber
Ni	Nickel
NR	Natural rubber
NPS	Nominal Pipe Size
NTS	Notch tensile strength
PA	Polyamide
PE	Polyethylene
PEEK	Polyetheretherketone
PTFE &FTE	Polytetrafluoroethylene
PWHT	Post-Weld Heat Treatment
R	Stress ratio
RA	Reduction in area
SBR	Butadiene-Styrene
SI &FSI	Silicone and Fluorosilicone
SMYS	Minimum specified yield strength
S–N	stress-amplitude vs. cycles-to-failure

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Term	Explanation
SSRT	Strain tensile rate test
Ti	Titanium
UTS	Ultimate tensile strength
YS	Yield strength
ΔK	Stress intensity factor variation

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Executive Summary

The report focuses on identifying critical material properties and hydrogen-induced failure modes affecting metallic and non-metallic materials commonly used in gas grid components, with the aim of supporting safe and reliable hydrogen blending in natural gas networks.

Key experimental evidence including slow strain rate testing, fracture toughness assessments, fatigue crack growth, and fatigue life data underpin the evaluation of materials' susceptibility to hydrogen embrittlement, hydrogen induced cracking, and hydrogen assisted fatigue. The findings inform best practices for materials selection and infrastructure adaptation essential for maintaining integrity and operational safety under hydrogen exposure.

The document is structured in the following sections:

- 1: Introduction — Defines the purpose, scope, and intended readership of the report, outlining the strategic importance of hydrogen blending and the goals of this deliverable.
- 2: Goals and Scope — Details the objectives and content coverage of the study, setting the framework for the materials and components assessment.
- 3: Metallic Materials and Hydrogen-Induced Failure Modes — Presents an in-depth discussion on hydrogen embrittlement, hydrogen induced cracking, and hydrogen assisted fatigue in metallic materials, supported by experimental test results and establishing critical property criteria for hydrogen service.
- 4: Non-Metallic Materials — Examines polymers used in pipelines and components, assessing their behaviour and compatibility in hydrogen-natural gas blends.
- 5: Gas Network Components — Analyses the main components of the gas grid—including pipelines, flanges, gaskets, and valves—regarding their susceptibility to hydrogen-related degradation and operational challenges.
- 6: Conclusions
- Annex A: Provide tables with gas grid materials as indicate in the relevant standards and materials compatibility evaluation.
- Annex B: Provide list of the standards used in this document and other complementary or equivalent standards related to components in the gas grid

This deliverable serves as a foundational piece within the SHIMMER project, linking previous database development outputs and feeding into future assessments of the European natural gas infrastructure's readiness for hydrogen blending. It offers critical insights and guidance for researchers, industrial stakeholders, and regulators to facilitate a safe transition towards decarbonised multi-gas networks.

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 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.

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- 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

As hydrogen blending or 100% hydrogen operation of the existing natural gas infrastructure becomes more likely, it is essential to understand the effect of hydrogen on materials and components, identify which material properties and components are mostly affected and the extend of it for ensuring long-term integrity and establish operational limits for ensuring adequate safety margins. The purpose of this document is to provide a structured analysis of how hydrogen affects the mechanical properties of materials, and the performance, reliability, and safety of components currently employed in natural gas grids.

More specifically, this document aims to:

- Support decision-making by highlighting key material properties that are influenced by hydrogen, such as ductility, toughness, and fatigue resistance.
- Identify hydrogen-induced failure modes (embrittlement, cracking, and higher fatigue crack growth rates, blistering etc.) that may compromise metallic and non-metallic materials in gas networks.
- Evaluate component-level considerations for pipelines, valves, gaskets, compressors, and other critical elements in the network.
- Provide reference data from experimental results under hydrogen exposure, including slow strain rate testing, fracture toughness, fatigue crack growth, and fatigue life curves.
- Assess the compatibility of materials used in gas grid components and indicate the relative suitability for hydrogen service.

This deliverable aims to indicate the extent to which materials and components are susceptible to degradation when hydrogen is introduced into the natural gas grid. The findings are intended to support ongoing assessments of infrastructure readiness and to guide future research, testing, and standardization activities.

1.2 Authorship and Intellectual Property Rights (IPR)

The preparation of this report was led by Tecnalia, who were responsible for compiling and structuring the findings. Following its preparation, the report was circulated to all consortium members for review and revision, ensuring that the perspectives, expertise, and feedback of the entire partnership were incorporated.

1.3 Intended readership

This report is intended to inform and guide a broad set of stakeholders involved in the development and deployment of hydrogen blending technologies. Academic and research institutions can leverage the identified material properties and component to advance scientific understanding and experimental validation. Industrial stakeholders, including natural gas pipeline operators, hydrogen producers, equipment manufacturers, and energy companies, are expected to benefit from the findings by integrating them into design, maintenance, and operational practices to ensure safe and efficient infrastructure adaptation. Regulatory and standardization bodies, such as government energy agencies and international organizations, may also draw upon the outcomes to support the formulation of safety codes, certification frameworks, and policy measures. In this way, the report provides leadership in bridging scientific research, industrial application, and regulatory development to enable the secure and effective adoption of hydrogen blending.

1.4 Structure of this document

The document is organized into several sections to provide a comprehensive overview of material and component considerations for hydrogen blending. First, the critical properties of metallic materials are discussed, with a focus on how they are affected by hydrogen exposure. This is followed by an analysis of polymeric materials commonly used in the gas grid and their performance under blending conditions. The report then examines the main components of the gas grid in the context of hydrogen–natural gas mixtures, highlighting potential challenges and limitations. Finally, the document concludes with an Annexes that

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presents tables of relevant standards, indicating the materials typically used for different components in the gas grid and providing an indicative assessment of their hydrogen compatibility.

1.5 Relationship with other deliverables

Materials properties discussed in this deliverable are supported by the findings in deliverable:

D2.4. - Scope and limitations of standards for testing and qualifications of materials and components for H2 service

The materials for pipelines and valves in this document receives inputs from the following deliverables:

- D2.1.– Information fed into the database
- D2.2. - Database prototype structure developed (Beta version)
- D2.3. - Developed database (release version)

The results here serve as input to deliverable 3.2. - Assesing the compatiblity of the existing NG infrastructure with H2-NG blends

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2 Goals and Scope

2.1 Goals

The primary goal of this deliverable is to identify and analyse the critical material properties and component factors that determine the performance, reliability, and safety of existing natural gas grid infrastructure when exposed to hydrogen or hydrogen–natural gas blends. The work seeks to establish a solid scientific and technical basis for assessing material suitability and to support the development of adaptation strategies for integrating hydrogen into gas networks.

The specific objectives are to:

1. Characterize material behaviour under hydrogen exposure: Present reference data from experimental studies, such as slow strain rate testing, fracture toughness, fatigue crack growth, and fatigue life assessments, that illustrate hydrogen-induced degradation in metallic materials relevant to the natural gas grid. For polymeric materials, the findings are based on research data, compatibility data and results from previous projects.
2. Identify hydrogen-induced failure modes: Analyse the main degradation mechanisms, including hydrogen embrittlement, hydrogen-induced cracking, hydrogen-assisted fatigue, and degradation in polymers etc. and assess their implications for infrastructure integrity.
3. Indicate component-specific issues: Assess the compatibility and relative suitability of materials employed in pipelines, valves, flanges, gaskets, and other key gas grid components when subjected to hydrogen service.
4. Contribute to infrastructure readiness and safety: Provide robust technical evidence and compatibility assessments that can support infrastructure evaluation, risk management strategies, and future standardization activities.
5. Support for subsequent project stages and related deliverables, such as infrastructure compatibility evaluations and risk management frameworks.

2.2 Scope

The scope of this deliverable is limited to:

- Evaluation of existing materials and components used in European natural gas transmission and distribution infrastructure, with a focus on their behaviour under hydrogen and hydrogen–natural gas blend conditions.
- Assessment of material compatibility under typical operational pressures, temperatures, and environmental conditions encountered in gas grids.
- Identification of hydrogen-related issues in the analysed components, highlighting vulnerabilities that may affect performance and integrity.
- Provide an indicative assessment based on existing experimental data, literature, standards, and project results, rather than exhaustive new testing.

The scope of the document regarding types of materials focuses on metallic materials used in natural gas and hydrogen infrastructure, including various steels such as plain carbon steel, low and medium carbon steel, low alloy steel, high alloy steel (including stainless steels like ferritic, martensitic, austenitic, and duplex), tool steels, high strength steels, and cast iron. It also considers non-metallic materials, particularly polymers, as well as aluminium, copper, cobalt, nickel, and titanium alloys.

Regarding components, the document covers typical elements found in natural gas networks such as pipelines, piping flanges, gaskets, valves (including ball, plug, gate, and butterfly valves), and compressors. It evaluates their performance and compatibility when exposed to hydrogen blending or substitution, aiming to identify vulnerabilities and support safe adaptation of the existing infrastructure.

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3 Metallic materials used in Natural Gas grid and hydrogen induced failure modes

In metallic components typical of natural gas infrastructure, the principal hydrogen-related degradation modes are hydrogen embrittlement (HE) under monotonic/quasi-static loading, hydrogen-induced cracking (HIC) associated with wet, sulfide-containing (sour) environments, and hydrogen-assisted fatigue (HAF) under cyclic loading. These concerns motivate hydrogen-specific integrity rules (e.g., defect-tolerant assessments for gaseous H2 pipelines according to ASME B31.12 [1]) and, separately, sour-service qualification for H_2S environments (e.g., NACE MR0175/ISO 15156 [2]). HIC is not expected in dry, high-pressure gaseous hydrogen, where HE/HAF are the principal risks [3].

3.1 Hydrogen embrittlement (HE)

HE is the loss of ductility and fracture toughness, together with an increased susceptibility to cracking, that occurs when diffusible atomic hydrogen is present in a metal during deformation and fracture. Various mechanistic explanations have been proposed in the literature to describe HE. Two mechanisms have the strongest support:

- Hydrogen-enhanced localized plasticity (HELP): hydrogen facilitates dislocation motion and localizes slip near the crack tip.
- Hydrogen-enhanced decohesion (HEDE): hydrogen lowers cohesive strength at interfaces (lattice, grain boundaries, or inclusions), promoting quasi-cleavage or intergranular separation.
- Adsorption-induced dislocation emission (AIDE) also results in brittle fracture appearance but involves localized dislocation activity at the crack tip rather than pure bond breaking.

Hydrogen trapping (reversible/irreversible) and diffusion, often described using Oriani's local-equilibrium framework, govern how much mobile hydrogen reaches de fracture zone [4–6].

In the pipeline context, several variables effect HE severity: hydrogen pressure (fugacity), stress/strain concentration features (e.g. localised corrosion pits, gouges, dents), temperature, cyclic strain rate/frequency, microstructure (e.g., ferrite/pearlite fraction, segregation banding, inclusions), weld/HAZ (heat affected zone) hardness, residual stresses, and surface condition. In practice, HE effects may lead to a re-rating of the pipeline due to the more severe operational conditions relative to natural gas operation, the extent of which depending of the level of expected degradation, mainly depending on the percentage of hydrogen used (e.g., blending or pure H2), the material grade used, the quality of welds and the pressure of the pipeline [4].

3.2 Hydrogen induced cracking (HIC)

HIC is an internal, planar cracking mode that occurs in susceptible low-to-medium-strength steels without externally applied stress, when hydrogen is generated at the steel surface by corrosion in aqueous H2S-containing environments. Hydrogen atoms enter the steel, accumulate at traps (e.g., inclusions, voids), and can form blisters; stepwise linkage of these features yields through-thickness cracking. When tensile stresses (applied or residual) assist the linking, the damage is termed stress oriented HIC (SOHIC).

In H2S solutions the sulfide ions poison the recombination of adsorbed H atoms into H_2 at the surface, so more hydrogen remains available to diffuse into the steel—raising subsurface concentrations and cracking risk. An "internal pressure" model (hydrogen molecules pressurizing cavities at inclusions) is often used to rationalize blistering and HIC.

Industry commonly classes service as "sour" when the H_2S partial pressure exceeds ~0.3 kPa; under such conditions HIC/SSC (sulfide stress cracking) become central integrity threats and materials are qualified to sour-service standards. In contrast, dry gaseous H_2 service does not produce HIC; instead, HE/HAF dominate [3].

HIC susceptibility increases with elongated MnS and other inclusions; inclusion control (e.g., Ca treatment to spheroidize sulfides) and thermo-mechanical controlled processing (TMCP) to refine/condition microstructure improve resistance [7].

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HIC/SOHIC are specific to wet, H_2S-containing conditions and are included here to distinguish sour-service risks from those in dry gaseous hydrogen pipelines.

3.3 Hydrogen assisted fatigue (HAF)

Under cyclic loading, gaseous hydrogen markedly accelerates fatigue crack growth rates (FCGR) compared with air, often by orders of magnitude in the Paris regime for ferritic steels (typically used in pipelines).

Fatigue crack acceleration tends to increase with ΔK (stress intensity factor variation), it is typically stronger at lower cycling frequencies (more time for hydrogen to reach the crack tip) and depends on stress ratio (R). Base metal, weld metal, and HAZ (heat-affected zone) metal may exhibit different sensitivities. Acceleration generally increases with hydrogen pressure/fugacity, motivating pressure-dependent design curves [8,9].

Another effect of hydrogen reported in literature is the reduction of fatigue crack growth thresholds (ΔKth) [10]. This threshold indicates the smallest ΔK at which a fatigue crack will propagate. A lower ΔKth in hydrogen means that cracks can grow under smaller cyclic driving forces than in air.

The ASME B31.12 code and related technical bases provide pressure-sensitive FCGR rules for ferritic steels in gaseous hydrogen, calibrated against multi-laboratory datasets and expressed in power-law forms with environmental factors. These rules support defect-tolerant life assessments and inspection planning for hydrogen pipelines and pressure boundaries [1,11].

3.4 Critical materials properties affected by hydrogen gas.

This section synthesises and analyses the principal effects of gaseous hydrogen on mechanical properties based on experimental evidence reported in the literature. Given the breadth of available data, the discussion is organized by alloy family and microstructure. The classification used (see Figure 1) reflects materials commonly found in gas-network infrastructure and includes plain-carbon steels (the dominant pipeline materials), low-alloy steels, stainless steels, cast irons, and non-ferrous alloys.

For steels in particular, microstructure matters: the hydrogen uptake, trapping, and crack-tip processes (e.g., HELP/HEDE) depend strongly on whether the steel is ferritic–pearlitic, bainitic, martensitic, austenitic, duplex, or precipitation-hardened. Explicitly identifying the microstructural condition is therefore essential for interpreting hydrogen sensitivity. This framework provides a consistent basis for qualitatively comparing hydrogen-induced changes in ductility, toughness, and fatigue-crack growth across material classes and for drawing indicative implications for pipeline integrity. However, since these properties are highly dependent on the specific testing conditions, and for simplicity they have been considered together in this study, the results should not be interpreted as directly quantitative or strictly comparable.

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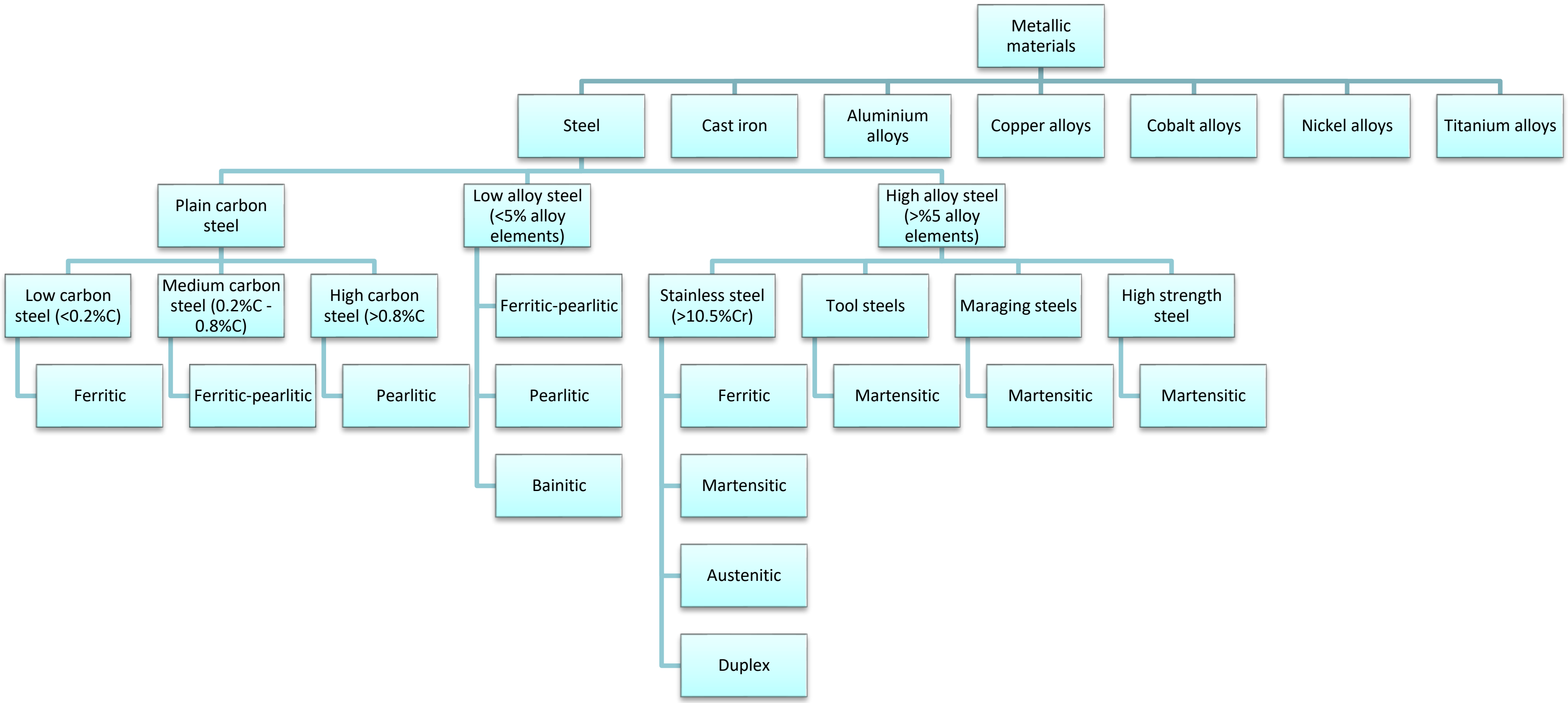

Figure 1. Metallic material classification relevant to natural gas and hydrogen infrastructure.

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3.4.1 Slow strain rate test results under hydrogen gas pressure.

Hydrogen effects on metals are commonly assessed using low strain tensile rate test (SSRT). This is a first screening approach where specimens, smooth or notched, are tested in both inert and hydrogen environment to obtain tensile parameters such as are notch tensile strength (NTS), plastic elongation (EL), reduction in area (RA), yield strength (YS) and ultimate tensile strength (UTS). In order to quantify the hydrogen effect, the so-called hydrogen embrittlement index (HEI) is used [12], defined as:

$$\text{HEI (\%)} = \frac{\text{Property}_{\text{air}} - \text{Property}_{\text{H}_2}}{\text{Property}_{\text{air}}} \times 100$$

In this sense, positive values denote degradation in hydrogen environment (loss of properties relative to air) and negative values a slight improvement or negligible effect.

Figure 2 to Figure 6 report HEI for these tensile properties as box and whisker plots, grouped by material family. These plots summarise central tendency and dispersion, but it is important to take into account that it should be read as trends rather than absolutes values, substantial scatter is expected due to differences in alloy composition, heat treatment, specimen geometry, strain rate, hydrogen pressure and other testing conditions.

Figure 2 shows the NTS for different materials groups. HEI NTS quantifies the loss of notched load-bearing capacity in gaseous hydrogen relative to air. Because a notch elevates stress triaxiality and constraint conditions, this metric is especially sensitive to hydrogen-assisted damage at the notch root and is therefore widely used as a conservative screening tool for hydrogen compatibility.

Based on Figure 2, a family ranking can be made:

1. Aluminium (Al) and copper alloys present medians near zero or even slightly negative (≈ -10% to 0%). Thus, these FCC (face-centered-cubic) non-ferrous alloys show negligible degradation in NTS.
2. Austenitic stainless steels show small but positive medians (≈ 6 %). AISI 3xx grades, which present FCC crystal structure, generally performs well in gaseous hydrogen. However, HEI may increase with strain-induced martensite phenomena for grades with lower equivalent Ni content, which stabilises austenite (e.g. AISI 301 and 304)
3. Titanium (Ti) alloys and plain carbon steels present moderate medians (≈ 10-15%). Titanium alloy typically present alpha phase with HCP (hexagonal close-packed) structure and beta phase with BCC (body-centered-cubic) structure. On the other hand, plain carbon steel present a combination of BCC ferrite and cementite. In plain carbon steels normally HE severity increases with strength level (i.e., grade / UTS).
4. Cobalt alloys and low alloy steel present significant HEI medians (≈ 25-30%). Co-based alloys, despite strengthened FCC matrices, often exhibit significant HE. Low-alloy steels, with a typical BCC structure, show wide dispersion because properties depend strongly on heat treatment, and again, higher strength materials tend to show higher HEI.
5. Nickel (Ni) alloys and ferritic stainless steels present higher medians (≈ 35-45%). although the HE levels are similar in both material’s type, Ni alloys often present precipitation-hardened FCC structure and ferritic stainless steel a BCC structure. Although the absolute levels are similar, the underlying causes differ: Nickel alloys commonly possess complex, precipitate-strengthened microstructures that promote planar slip and interface decohesion, yielding high variability; ferritic stainless steels present the fast hydrogen transport and localization typical of BCC matrices.
6. Martensitic stainless steels and high-alloy steel group have the highest medians (≈ 75-85%), with comparatively negligible scatter. These families are consistently the most penalized in NTS by gaseous hydrogen. These steels typically present a martensitic microstructure with a BCT (body-centered tetragonal) crystal structure.

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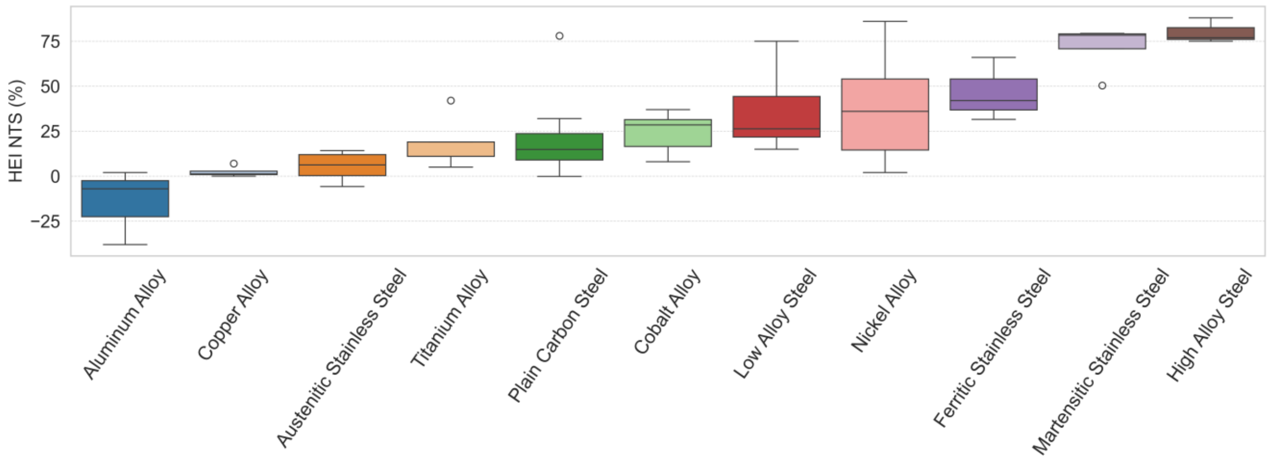

Figure 2. Hydrogen embrittlement index based on notch tensile strength [13,14]**.**

Figure 3 presents HEI based on EL, which quantifies the loss of uniform plasticity in smooth bars tested under gaseous hydrogen relative to air. Because uniform plastic elongation is governed by the material's strain-hardening capacity, this metric is an excellent proxy for how hydrogen alters the crack-free plastic flow that precedes instability.

Based on Figure 3 metrics, some observations can be made:

- Copper and aluminum alloys and austenitic stainless steel medians cluster near zero (≈0-2%). These values indicate minimal or negligible loss of uniform elongation under hydrogen pressure. For austenitic stainless steel, variability increases when the austenite is metastable or cold-worked because strain-induced martensite and planar slip promote localization.
- Titanium alloys and plain carbon steel present moderate medians (≈12-25%). In Titanium alloys, hydrogen degrades slip compatibility across α/β interfaces; in plain-carbon steels, hydrogen-enhanced localized plasticity in BCC ferrite accelerates instability.
- Low-alloy steels and ferritic stainless steels present large medians (≈30-36%). Low-alloy steels exhibit substantial scatter, reflecting sensitivity to strength/hardness level, segregation, and inclusion content; embrittlement generally increases with yield strength.
- Nickel alloys present high median (≈50%) and scatter. This scatter is consistent with planar slip and damage at precipitate/matrix interfaces that erode work hardening.
- Martensitic stainless steels and high alloy steels show the highest medians (>90%) with relative tight boxes. For these steels the uniform elongation is nearly extinguished in hydrogen. Lath martensite, high dislocation density, and carbide interfaces foster intense HELP/HEDE synergy, causing very early instability.

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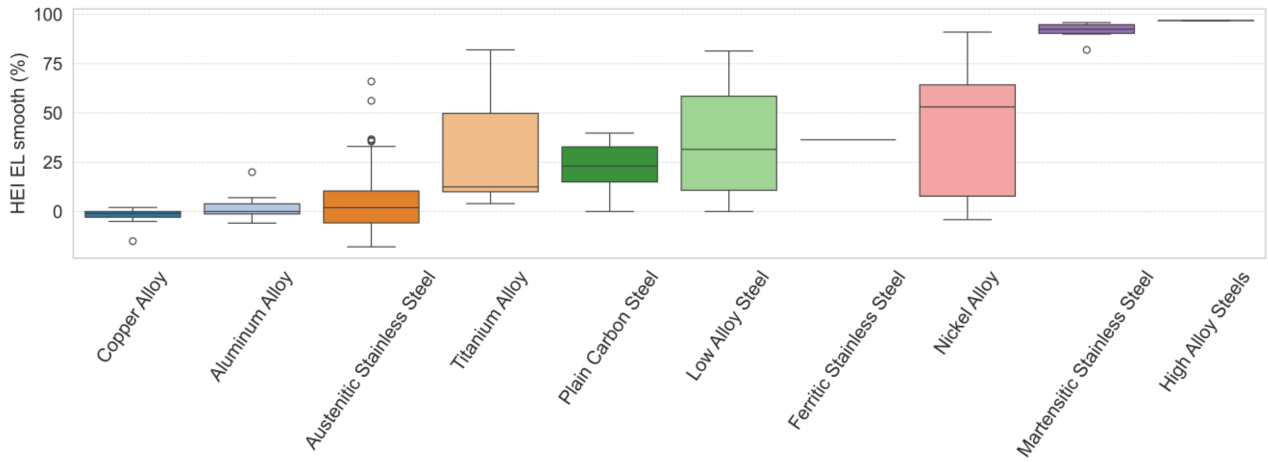

Figure 3. Hydrogen embrittlement index based on plastic elongation [13,14]**.**

Figure 4 show the HEI based on RA, which measures the ductility after the onset of necking. It is primarily governed by void nucleation, growth and coalescence. Among standard (smooth specimen) tensile properties, RA is typically the most sensitive to hydrogen. A higher HEI RA indicates greater loss of post-uniform ductility in H2. Based on the analysis of Figure 4, the following conclusion can be made:

- Copper and aluminum alloys and austenitic stainless steel medians cluster near zero (≈0-2%).
- Titanium and cobalt alloy present moderate medians (~15-30%).
- Plain-carbon steels and ferritic stainless steel present severe median (~40-45%).
- Low-alloy steels and nickel alloys have severe median (~55-65%).
- High-alloy steels and martensitic stainless steels present the hight and most consistent medians (85-95%). Post-uniform ductility is almost exhausted in H2.

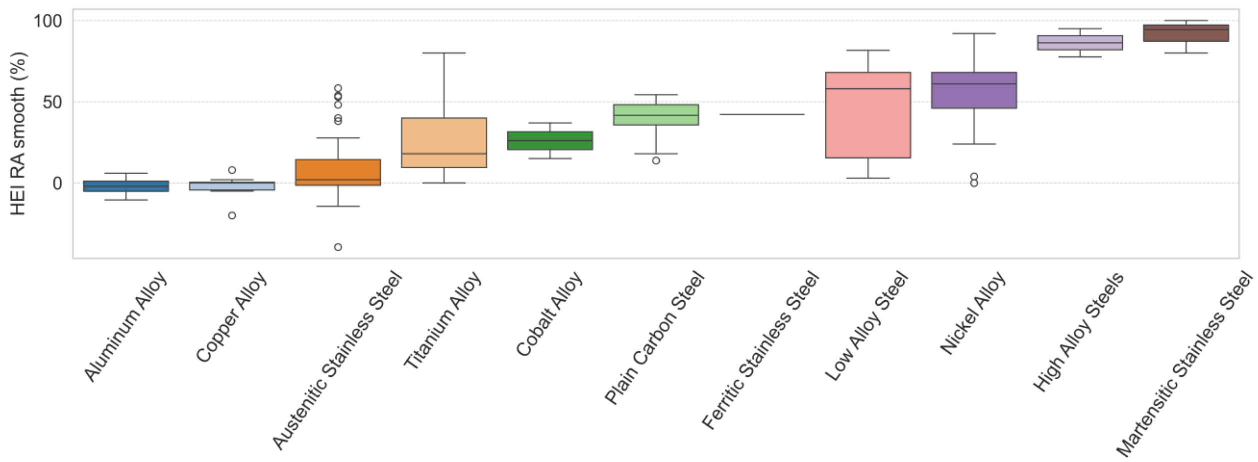

Figure 4. Hydrogen embrittlement index based on area reduction [13,14]**.**

Figure 5 shows the influence of hydrogen in YS values. Since yielding precedes damage, hydrogen usually has a small or even negligible effect of YS.

In general, most families cluster within ±5%, confirming that YS is relatively insensitive to gaseous H2. Two clear exceptions appear in this dataset: aluminum and copper alloys show the larger degradation in YS (Al ≈10-12%, Cu ≈20-25%).

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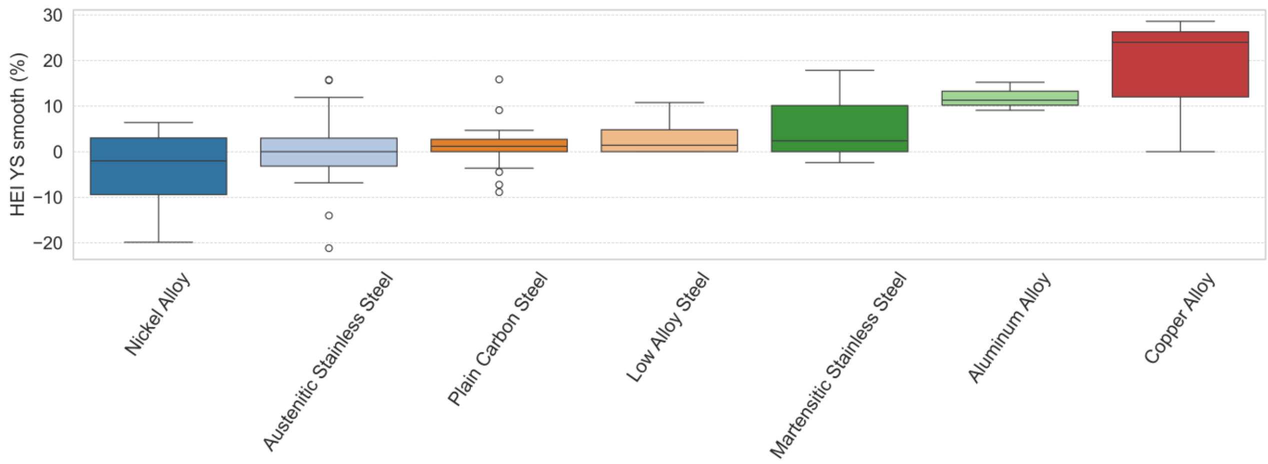

Figure 5. Hydrogen embrittlement index based on yield strength [13,14]**.**

Figure 6 shows the HEI based on UTS values, which measures the peak load after uniform plastic flow and just before the onset of pronounced necking. It is therefore influenced by both the early hardening response and the point at which strain localizes. Hydrogen usually lowers UTS by degrading work-hardening and triggering earlier instability, but the effect is still smaller than for RA or EL. In general, most material families cluster between 0-5% with relatively small scattering, confirming that UTS is comparatively insensitive to gaseous H2. Some exceptions may be highlighted: aluminium alloys have modest degradations (≈8-10%). Given their small EL/RA degradation observed for aluminium alloys, these UTS shifts are likely rate or temperature dependent rather than intrinsic to all aluminium alloys. High-alloy steels have moderate medians (≈10-15%). On the other hand, martensitic stainless steels present the largest drop UTS (≈50-60%). Early instability in lath martensite, amplified by hydrogen-assisted slip localization and interfacial decohesion, reduces the attainable peak load.

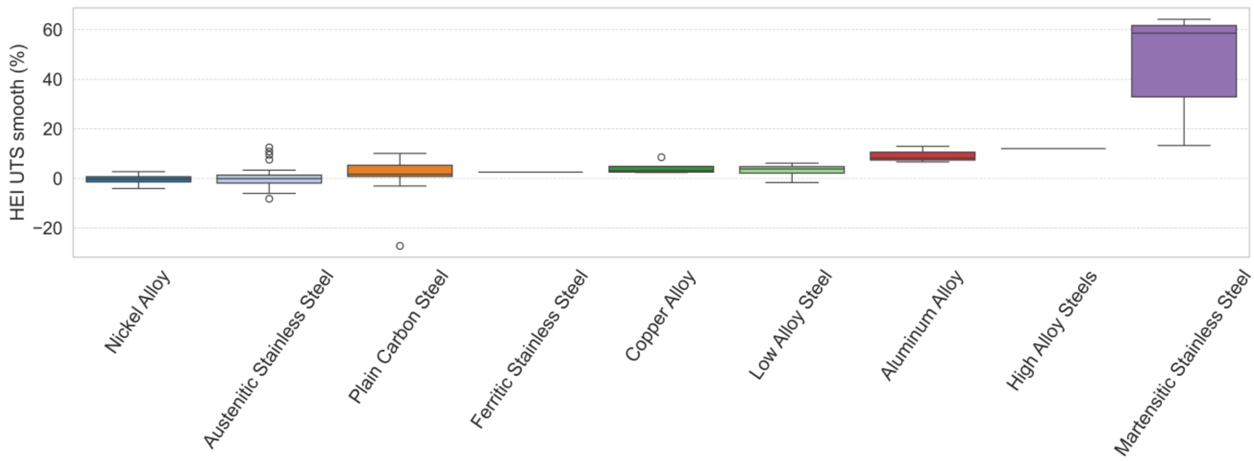

Figure 6. Hydrogen embrittlement index based on ultimate tensile strength [13,14]**.**

3.4.2 Fracture toughness results under hydrogen gas pressure.

Fracture toughness (e.g., Kmat) is determined from precracked specimens loaded under quasi-static, rising load conditions. This property is pivotal for fitness for service and damage tolerant assessments as it has a strong influence on the critical defect size (constant load) and maximum operating load/pressure (constant defect size)

In recent years, the volume of gaseous hydrogen testing has grown substantially, resulting in large datasets for several alloy families, mostly focused on pipeline steel, (e.g., API 5L steels), austenitic stainless steel and low alloy steel.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Figure 7 summarises the HEI for fracture toughness by material family. The data show a clear reduction in Kmat for plain carbon steels, low alloy steels and martensitic stainless steels with medians HEI values around 45-70%. Besides the large scatter in the results reflects the HE dependency on strength level (steel grade), heat treatment, cleanliness/segregation and hydrogen pressure. On the other hand, austenitic stainless steel exhibit a modest but non-negligible reduction of around 10%. This is noteworthy because their tensile HEI is typically small, underscoring the decoupling between tensile metrics and fracture toughness. For nickel alloys, the median degradation appears near zero in the present dataset; however, this interpretation should be treated with caution given the limited literature coverage and the diversity of precipitation-hardened microstructures within that family.

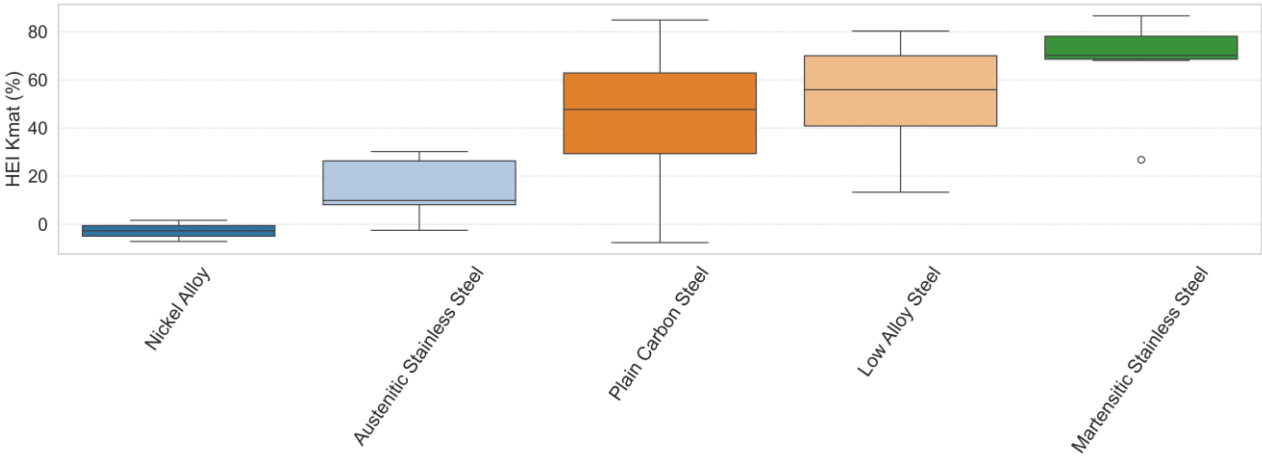

Figure 7. Hydrogen embrittlement index based on fracture toughness [15]**.**

3.4.3 Fatigue crack growth rate results under hydrogen gas pressure.

Figure 8 compares da/dN-ΔK curves at R=0.1 (frequency as indicated in each graph) for six alloys: 25Mn TWIP, AISI 304, Inconel 718, API 5L X52, Zeron 100 duplex stainless, and 4130 low-alloy steel. In every case, exposure to gaseous H2 shifts the Paris regime upward relative to air. For most materials the H2 and air trends are approximately parallel, consistent with a multiplicative acceleration in crack growth at a given ΔK. The magnitude of this acceleration depends on alloy class and microstructure.

Table 2 reports the acceleration factor evaluated at ΔK = 10 MPa√m. The ratios span ~5× (25Mn TWIP, Inconel 718) to 22-29×(4130), with intermediate values for 304, X52, and Zeron 100. On average, the data indicates typical accelerations of order 10×, acknowledging that the exact value depends on frequency, tensional ratio, hydrogen pressure (fugacity), microstructure, and the selected ΔK.

These results are critical for design: even alloys that appear tolerant in tensile or monotonic fracture can experience substantially faster crack growth under cyclic loading in hydrogen. Components subject to pressure fluctuations therefore require fracture-mechanics-based integrity assessments in the hydrogen environment, ideally using environment-specific Paris parameters or pressure-dependent rules as provided in hydrogen design guidance (e.g., ASME B31.12). Using air data with a generic knock-down may not be conservative.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 2. Example of fatigue crack growth ratios for a fixed ΔK = 10 MPa√m.

Material	$\frac{(da/dN)_{H_2}}{(da/dN)_{air}}$
25Mn TWIP	5
304	9
Inconel 718	5
X52	10
Zeron 100	6
4130 (a)	29
4130 (b)	22

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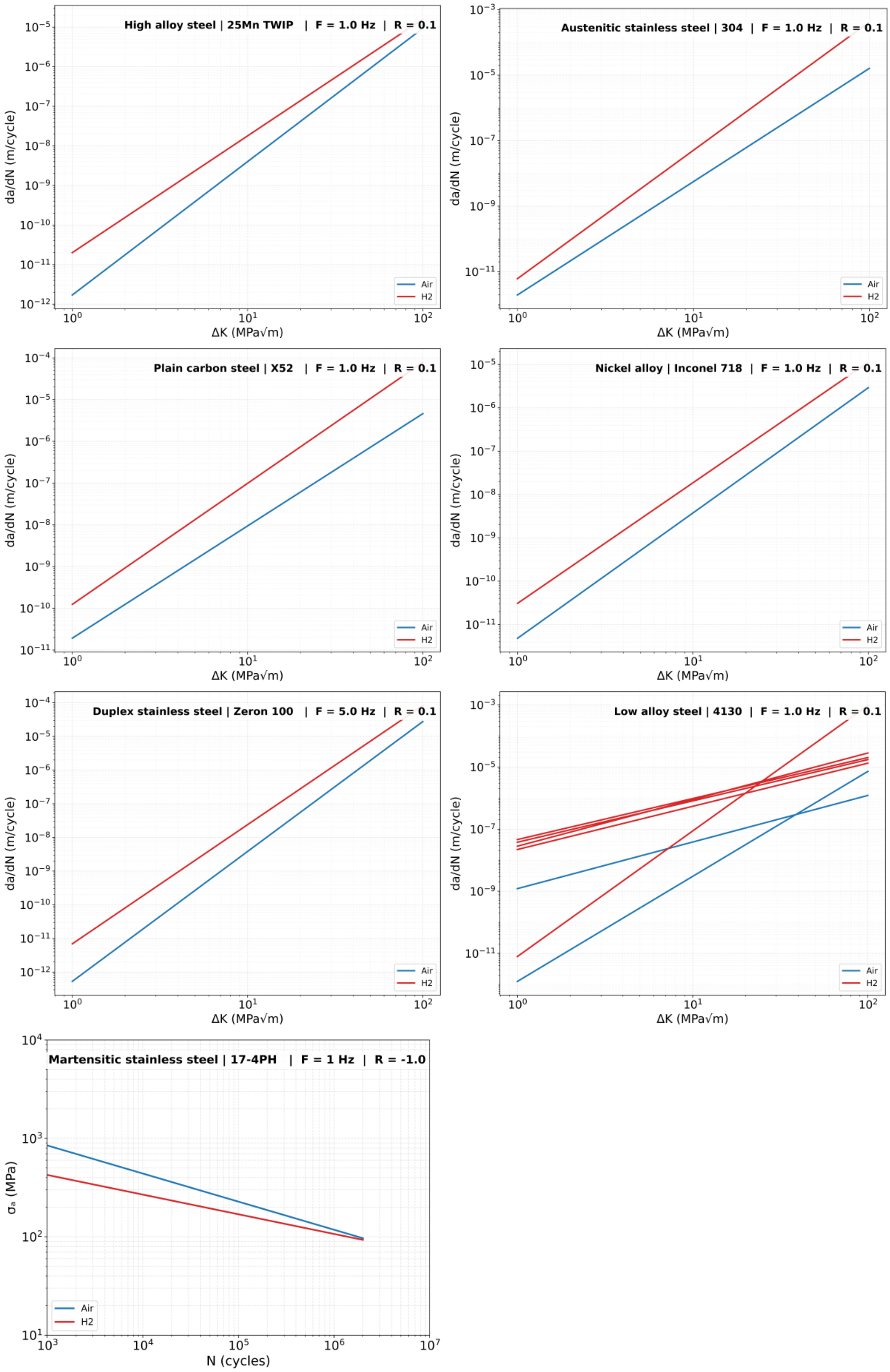

Figure 8. Fatigue crack growth curves under hydrogen pressure for different materials [10].

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

3.4.4 Fatigue life curves

This subsection compares stress-amplitude vs. cycles-to-failure (S–N) curves in air and in gaseous H2 for representative alloys: 17-4PH martensitic stainless, AISI 304 austenitic stainless, Inconel 718 (Ni-base, precipitation-hardened), SCM435 (Cr–Mo low-alloy steel), and API 5L X80 (pipeline steel). As can be seen in Figure 9, the test conditions vary (frequency and stress ratio), and they are indicated on each plot. It should be noted that S-N curves are not usually generated in gaseous H2, therefore the literature in this regard in quite limited. A downward shift of the H2 curve at a fixed N (number of cycles) reflects reduction in fatigue strength, while a steeper slope indicates a faster loss of strength over the component's life.

According to literature [10], following consideration can be done:

- Hydrogen slightly reduces the fatigue life compared to air. This means that for a given stress amplitude, the number of cycles to failure is reduced. This slightly reduction is not systematic and highly depends on the material type, tests conditions, pressure, etc.
- The endurance limit (considered at 2 x10^6 cycles) seems not to be affected by hydrogen. The endurance limit must be interpreted with caution because (here) is not a fatigue limit, i.e., material may fail with a lower stress level. In this sense, it is not clear if hydrogen may decrease the fatigue limit or even eliminate this threshold (as usually happens in corrosive environments).

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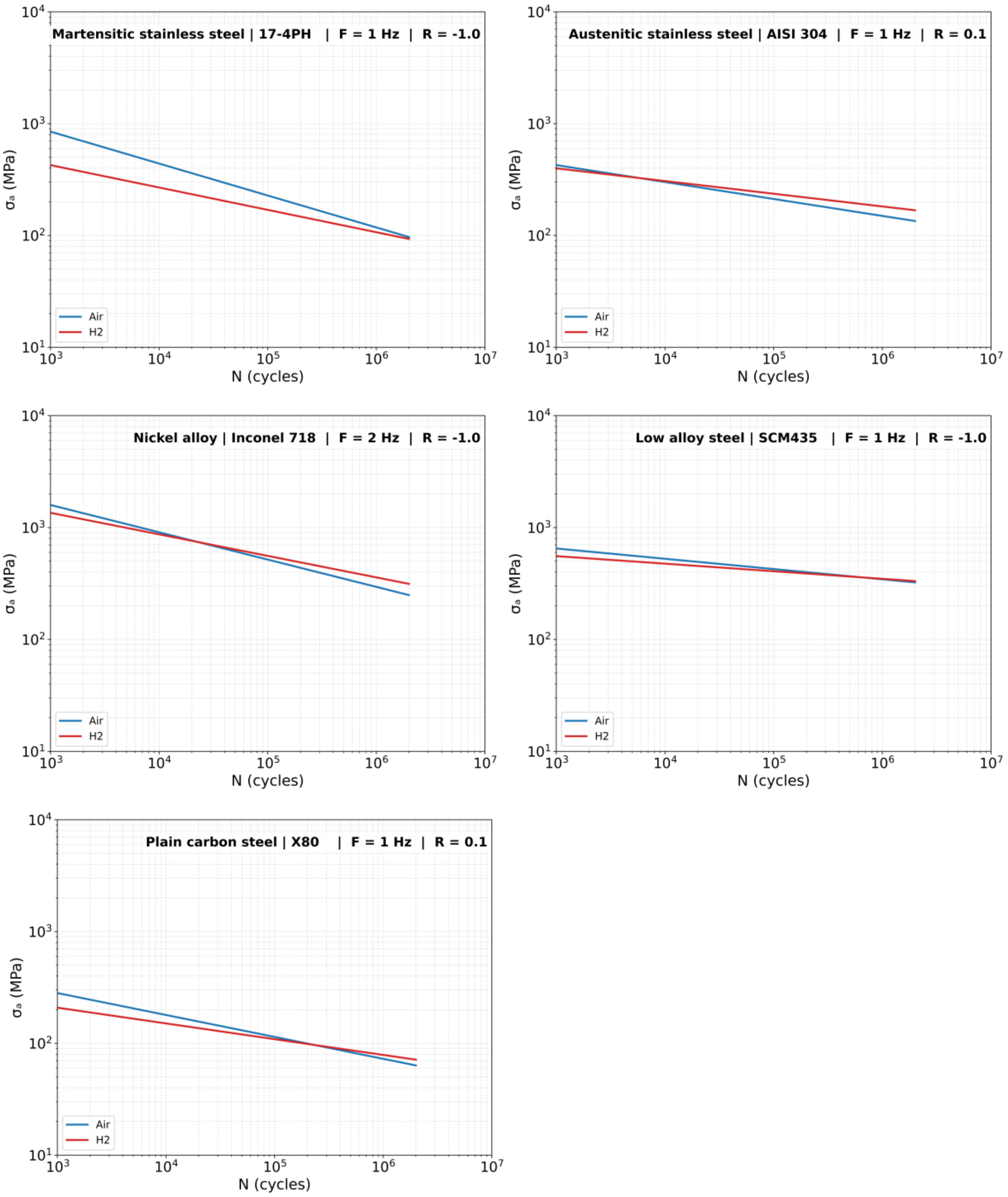

Figure 9. Fatigue life curves under hydrogen pressure for different materials [10]**.**

3.4.5 Conclusion

The most critical material properties in gaseous H2 are summarized as follows

- Fracture toughness is the primary discriminator. The analysis shows large median losses of Kmat for plain-carbon and low-alloy steels and for martensitic stainless steels, with modest but non-negligible loss for austenitic stainless steels and little change, on average, for Ni-base alloys. This confirms that fracture toughness controls hydrogen tolerance more strongly than strength shifts.
- NTS tracks notch/constraint sensitivity. HEI NTS clearly separates martensitic and high-strength ferritic steels (severe penalties) from stable FCC families (small penalties). As a conservative screen it correlates well enough with the observed Kmat trends

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- Ductility changes are large but YS and UTS remain largely unaffected. EL and RA show substantial degradation for martensitic/high-strength ferritic steels and for precipitation-hardened FCC systems; YS and UTS shift little for most families, so strength is a poor proxy for compatibility
- Fatigue is a critical consideration. All families exhibit hydrogen-accelerated FCGR (often 10x on average), so components that are "safe" in monotonic loading can still be life-limited in cyclic service. In this sense, in all cases, despite material type, it is highly recommended to perform a fatigue analysis of all components subjected to pressure fluctuations, such as pipelines.

3.4.6 Hydrogen material compatibility criteria

This subsection provides a traffic-light screening for metallic materials used in pressure-containing components in gas network. It translates the hydrogen effect on mechanical properties discussed above into practical selection guidance. It is a screening tool, not a substitute for code compliance (e.g., ASME B31.12) or project-specific qualification.

For the assessment of the hydrogen compatibility the criteria employed is described in Table 3

Table 3. Hydrogen compatibility criteria used in this study

Colour code	Meaning
Green	Generally suitable for hydrogen service using the standard code rules (e.g., ASME B31.12); no additional testing normally required beyond routine qualification. Despite that, fatigue crack growth testing is recommended also in these cases.
Yellow	Conditionally usable. It requires a H2-specific structural integrity assessment (e.g., fitness for service (FFS) / engineering critical assessment (ECA)) under the real working conditions. Also, it is necessary to perform fracture/fatigue tests as inputs of these integrity assessments. This colour code is also used when contradictory results have been reported in literature
Red	Not usable/recommended for hydrogen service due to safety reasons, even for low pressure parts. Replacement of the component is highly recommended. In case of using any of these materials due, for example, budget constraint, a structural integrity assessment is mandatory

Table 4 summarises the recommendations for each material family. This table and criteria are employed in the Annex A section to review the hydrogen compatibility of the specific materials employed in the different components of the gas infrastructure. The tables in the Annex A contain 4 different columns: the standard specification, the material family (type), grades, and hydrogen compatibility, based on Table 4 and the criteria described Table 3.

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Table 4. Hydrogen material compatibility for pressure applications.

Material family	Hydrogen service	Comments
Austenitic stainless steel	Green	Generally tolerant in H2. Modest Kmat loss and small NTS penalties. Important to avoid strain-induced martensite (limit cold work/ use grades with nitrogen (e.g., 316LN)).
Ni-alloys	Yellow	Kmat near zero loss but very limited results. NTS presents high variability with moderate penalties. Alloy composition and microstructure highly affect HE severity.
Duplex stainless steel	Yellow	Highly affected depending on austenite and ferrite mix.
Plain-carbon steel	Yellow	Kmat and NTS penalties moderate–large; FCGR strongly accelerated. Worse when is high strength. Quality requirements are usually less controlled.
Low-alloy steels	Yellow	Similar to plain carbon steel. Normally subjected to thermo-mechanical treatments to increase strength.
Ferritic stainless steel	Yellow	BCC matrix shows NTS/EL/RA penalties; Kmat reductions warrant FFS.
Martensitic stainless steel; high alloy steel	Red	Highest HEI susceptibility in all mechanical properties. Avoid in hydrogen service, especially for pressure applications.
Titanium alloys	Yellow	Moderate EL/RA penalties, but hydride formation under some conditions of pressure and temperature.
Aluminium alloys	Yellow	Generally good performance in H2 but limited strength at high pressure. In addition, there is a noticeable lack of fracture toughness data.
Copper alloys	Yellow	Minimal HE penalties when oxygen-free copper is employed. Practical limits are strength/permeation. In addition, there is a noticeable lack of fracture toughness data.
Cobalt alloys	Yellow	NTS penalties are moderate. Application limited as hardfaces/overlays. Very limited results in literature.
Cast iron	Red	Poor fracture toughness and ductility. Cast iron is forbidden by ASME B31.12 for safety reasons.

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4 Non-metallic materials in the Natural gas grid

4.1 Polymers

Polymeric materials are widely used in both TSO and DSO networks. They can be found as pipelines or as parts of components.

Hydrogen is expected to be inert in the presence of most polymers but its effects under high pressure rises some concerns. Polymers do not undergo hydrogen induced degradation in the same manner as metals (hydrogen embrittlement). For polymers exposed to high-pressure gaseous hydrogen, key failure and degradation mechanisms include blistering from rapid decompression, ageing, and microstructural deterioration. [16]

4.1.1 Polymeric pipelines

Polyethylene (PE) has become the material of choice for pipelines in modern DSO networks, thanks to its proven reliability and low maintenance requirements. Its key advantages include resistance to corrosion, the ability to form fully weldable systems, high ductility, and excellent performance at low temperatures.[17] Since DSO networks operate at relatively low pressures, PE provides a durable and corrosion-resistant alternative that is gradually replacing old cast-iron pipes. [18]

Short-term mechanical testing on PE pipelines has shown that hydrogen at low pressures does not significantly alter mechanical properties, whereas, at higher pressures, a minor reduction in tensile strength and failure strain is observed [19] There are some data available on hydrogen effects on physical properties of PE material, such as degree of crystallinity and density. The data show small changes in these properties with hydrogen exposure, although the trend between different grades of PE materials is not similar. [20] Aging of PE in laboratory have shown that aging effect of hydrogen on PE pipe materials is not significant. [21]

A four-year pilot study in Denmark concluded in 2010 [17] tested PE pipes from the gas distribution grid (PE80 MDPE - Medium-Density Polyethylene , PE100 type I HDPE - High-Density Polyethylene., and PE100 type II HDPE), some of which had already been in service for up to 20 years with natural gas, under continuous exposure to pure hydrogen at ~4 barg and 8 °C. The evaluation program included analysis of structural integrity, antioxidant consumption, tensile properties, slow crack growth resistance, and surface oxidation.

Results showed no adverse effects of hydrogen exposure on either PE80 or PE100 pipes, with no significant changes in mechanical, oxidative, or structural properties. Even pipes with a combined service history of 24 years (20 years natural gas + 4 years hydrogen) performed equally well as new pipes. Overall, the study concluded that MDPE PE80 and HDPE PE100 are suitable for use as pipes in hydrogen transport. It can be concluded that PE exhibits mechanical and chemical resistance that is considered adequate for hydrogen applications. [17]

A recent study on PE100 in hydrogen environments show that hydrogen permeation at 4 MPa (40 bar) and room temperature (22 °C), with hydrogen blends up to 100%, does not significantly affect tensile, creep, or relaxation performance, meaning PE100 is suitable for medium- to low-pressure hydrogen pipelines. Temperature (14–50 °C) reduces PE100's mechanical performance, but this effect is independent of hydrogen, as results in pure hydrogen and pure nitrogen were nearly identical.[22]

Another potential concern is the hydrogen leakage through the polymeric pipelines. The permeation coefficient of hydrogen is four to five times higher in plastic pipe than the permeation coefficient of natural gas.[23] Leakages through pipeline joints can also cause concern, though to a lower degree than leakage through polyethylene pipe walls. While studies on the topic are limited, it is generally agreed that the one issue of polymeric pipelines could be their higher permeability, which can result in gradual, continuous leaks, rather than sudden failures from a complete breach of the material.[19] Despite this, reports indicate that the gas permeation loss is negligible (0.066% per year for service conditions of 320K and pressure of 10 bar as calculated in reference [24]) and does not pose concerns from safety, economic, or environmental perspectives.[21] Other report mentions that main safety risks from hydrogen leakage in distribution systems arise at end-use locations, particularly in confined or poorly ventilated spaces, where there is a risk of fire or

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explosion. Consequently, the report emphasizes the importance of leak detection sensors and/or hydrogen odorization. [20]

In general, plastic pipes from DSO network are considered compatible for blends even up to 100% hydrogen for the operating conditions in DSO network. [25] However, further research is needed to assess long-term effects on materials of blends, leakage through pipe joints, and pipe wall permeation[20,24].

4.1.2 Polymers in components

Polymeric materials used in transmission and distribution grids are usually used in O-rings, diaphragms, gaskets, boots, flanges, valve seats, quad seals etc.[20,21] These materials are present in relatively small quantities within the infrastructure, and it is believed that their replacement, if needed, would be comparatively easy. [19]

Examples of polymers which can be found in the components of TSO and DSO network and their compatibility with hydrogen are shown in Table 5. The data on the polymers are gathered primarily from references [16,19–21,26–28] and supplemented with information from the Shimmer Consortium. The information about the compatibility is gathered from different sources indicated in the table. Further compatibility and hydrogen permeation data can be found also in references [16,21,29].

Polymers used in the natural gas grid are mainly elastomers and thermoplastics, which differ in their structure and properties. Elastomers are highly elastic materials that can deform under stress and return to their original shape, making them ideal for seals, gaskets, and other flexible components that must maintain tight sealing under varying pressures, examples include NBR, EPDM, silicone and fluorosilicone.

Thermoplastics, in contrast, are rigid materials at room temperature, which soften when heated and can be reshaped multiple times. They provide chemical resistance, mechanical strength, and long-term stability, examples include polyamides, SBR, PTFE.

Hydrogen has a higher permeation coefficient in elastomers than in other polymeric materials. However, leakage through pipeline walls still accounts for the majority of gas loss due to the much larger surface area exposed.[21]

Failure criteria for polymers are mainly linked to swelling and permeability, which can cause reductions in strength, modulus, hardness, and sealing performance. Structural changes from crosslinking, chemical bonding, fluid ingress, or additive extraction may shift the glass transition temperature, making polymers either brittle or overly rubbery. While failure related to glass transition is well defined, swelling and related property changes must be correlated with real component-level performance tests. An additional uncertainty is potential leakage from gas permeation or changes in sealing properties of the polymeric the component.[34]

In the case of high-pressure hydrogen and blends the main damage mechanism expected is blistering, which is irreversible damage caused to the polymer where the saturated gas absorbed at high pressure becomes supersaturated upon decompression, coming out of the polymer matrix and nucleating at microscopic voids (defects) in the material or at interfaces between polymer and filler particles. Multiple cycles and rapid decompression can lead to eventual failure. [27]

A study from 2012 investigated the coupling between gas diffusion and mechanical behaviour of two semicrystalline polymers (PE) and polyamide 11 (PA11), under hydrogen exposure. Short-term in-situ tensile tests in hydrogen atmospheres up to 3 MPa (30 bar) showed no measurable effect of hydrogen on the mechanical response of either polymer. Long-term aging tests (up to 13 months) at hydrogen pressures of 2–5 MPa (20-50bar) and temperatures below above the glass transition temperature of both polymers similarly revealed no degradation of mechanical properties or microstructure in PE or PA11. Variations observed in PA11 were attributed primarily to testing near its glass transition rather than hydrogen exposure. Overall, the results confirm that PE and PA11 maintain their mechanical integrity and microstructural stability under prolonged hydrogen exposure.[35]

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 5. Polymers used in the natural gas grid and their compatibility with hydrogen gas

Polymeric material	Other/Trade Name	Acronym	Application	Compatibility with Hydrogen	
				From Ref [30]*	Other sources
Butadiene-Acrylonitrile Rubber	Buna-N; Nitrile; Perbunan; Nytek	NBR	O-rings, gaskets, valve fittings and seals	1	Excellent [31]
Polychloroprene	Neoprene; Bayprene; Chloroprene	CR	Valve seals and gaskets	1	Excellent [31]
Ethylene-Propylene	Nordel; Royalene; Dutral	EPM & EPDM	Valve seals and gaskets	1	Excellent [31]
Polyamide (11 and 12)	Rilsan; Vydyne; Plaskin; Nylon	PA11 & PA12	Valve seats, seals and gaskets		Excellent (to 48°C) [32]
Silicone and Fluorosilicone	Polysiloxanes; Cohrlastic; Green-Sil; Parshiled; Baysilone; Blue-Sil	SI &FSI	Valve seals and gaskets	3	Poor [31]
Fluoroelastomer	Viton; Fluorel; Technoflon	FKM	O-rings, gaskets, valve fittings	1	Excellent [31]
Perfluoroelastomer	Kalrez; Chemraz; Kel-F	FPM	O-rings, gaskets	1	Excellent [31]
Polytetrafluoroethylene	Teflon, Halon	PTFE &FTE	O-rings, gaskets, fittings, valve seats. Compressors seals and coatngs		Excellent [31]
Polyetheretherketone		PEEK	Seals and gaskets. Compressors seals and coatngs		Excellent [33]
Butadiene-Styrene	Buna-S; GR-S	SBR	No specific data found	2	Good [31]
Natural rubber	Gum	NR	No specific data found	2	

*1 - Satisfactory 2 - Fair (usually OK for static seal) 3 - Doubtful (sometimes OK for static seal) 4 - Unsatisfactory

A study of SNADIA laboratory [36] have shown that high pressure hydrogen can cause damage in polymers. The study evaluated two elastomers (NBR, Viton A) and two thermoplastics (HDPE, PTFE) after static hydrogen exposure at 100 MPa and ambient temperature for one week. Results showed clear differences between thermoplastics and elastomers due to their distinct microstructures. Thermoplastics, with higher crystallinity, exhibited low hydrogen permeability and minimal changes in properties, aside from slight increases in tensile strength and modulus. Elastomers, with greater free volume and chain mobility, showed higher sensitivity and swelling: Viton A displayed significant changes in modulus, compression set, and volume, while NBR showed similar but less pronounced effects. Overall, the study highlights how polymer microstructure governs hydrogen compatibility and stresses the importance of such understanding for material

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selection and testing in hydrogen infrastructure applications. It should be noted, however, that the tests were conducted at 100 MPa (1000 bar) well above the maximal operating pressures in natural gas grids (about 16 bar for DSO networks and 80 bar for TSO networks), therefore the study conditions were considerably more extreme than those normally encountered in natural gas grid.

Additionally, hydrogen permeation can reduce the tensile strength of elastomers, potentially increasing leakage over time. [19] Outdoor exposure to sunlight, ozone, and oxygen can degrade elastomers, leading to surface cracking, discoloration, and loss of mechanical properties. Purely mechanical damage is rare and usually occurs after chemical degradation. Elastomers become brittle below their glass transition temperature, which can result in fracture.[21]

Recent experimental work further quantified the influence of hydrogen–methane mixtures on elastomer sealing materials under rapid decompression. In a 2024 study, FKM- and HNBR-based O-rings were exposed to CH_4/H_2 mixtures (3–10 vol.% H_2) at 15 MPa and 100 °C, following ISO 23936-2 procedures. The results showed that the fluoroelastomer FKM26 exhibited excellent resistance to rapid gas decompression (average damage level < 0.5), whereas HNBR and FKM246 suffered severe internal cracking (damage level $\approx$ 3.5–4). These findings highlight how gas solubility and diffusivity directly influence blistering susceptibility and confirm that material selection for sealing applications is critical when adapting natural gas components for hydrogen service.[37]

Experience from previous pilot projects related to polymeric materials in blends:

HIGGS No damage in polymeric materials (valve seals, seats etc.) due to hydrogen was observed. During the second experimental campaign involving a hydrogen mixture (20 mol% H_2 with trace H_2S and CO_2), significant leakages were found in the line with flanged valves. These were attributed to incorrect reassembly of valves after the first campaign, suggesting that future reassembly should be done by the manufacturer.

Inspection of components such as valves and pressure regulator after exposure to various hydrogen mixtures showed no apparent damage, except for blistering observed in a pressure regulator valve seat during the 30 mol% H_2 campaign. This blistering was not present at 100 mol% H_2, making it difficult to establish a clear link between hydrogen concentration and damage. [38]

H2SAREA The evaluation of non-metallic materials, particularly polyethylene pipes and various gaskets, focused on their durability when exposed to hydrogen-natural gas (H_2-NG) mixtures. Polyethylene pipes showed strong resistance to hydrogen exposure, with no significant degradation across different grades. However, elastomeric gaskets, especially those made from NBR and EPDM, displayed mixed results—some maintained integrity, while others experienced swelling or reduced elasticity, indicating the need for further study to ensure long-term reliability.

NBR rubber seals were notably vulnerable under high-pressure hydrogen environments. When exposed to 100% hydrogen at 16 bars, they exhibited surface blistering and cracking, while a 20% hydrogen–80% methane mix caused similar but less severe degradation (Figure 10). These issues were linked to hydrogen supersaturation in polymer defects, especially near metal meshes, leading to blister formation during decompression. The findings highlight the importance of understanding gas-material interactions and suggest future research should aim to improve polymer formulations and design strategies to enhance seal performance in high-pressure hydrogen applications. [39]

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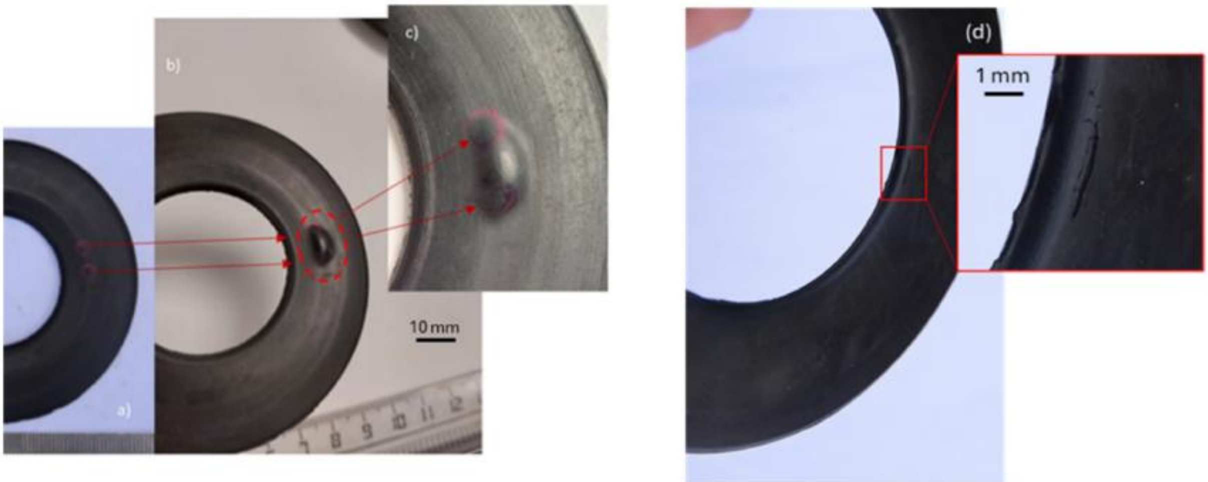
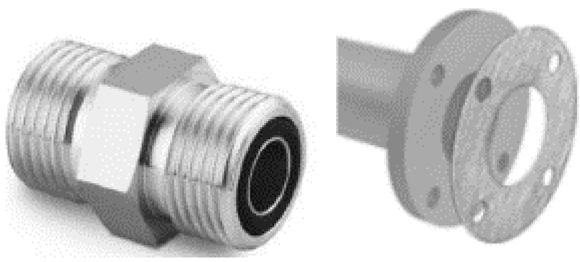


Figure 10. Evidence of blistering on the NBR seal DN25 PN 10 40. (a) Immediate inspection post-exposure shows small blisters near the metal mesh. (b) Larger blisters observed 24 h post-exposure. (c) Close-up view of a blister (d) Crack on the inner lower edge of the NBR seal observed immediately post-exposure.

NYSEARCH program in 2022 investigated whether hydrogen–methane blends affect elastomers commonly used in gas distribution. Phase I tested virgin SBR and NBR with pure hydrogen at one temperature, finding no significant impact. Phase II expanded testing to virgin and field-extracted materials, with blends up to 30% H_2 in methane, multiple temperatures, and even natural gas with higher hydrocarbons plus 20% H_2. Results showed that in unrestrained conditions, hydrogen blends did not affect shrink, swell, creep, or stress relaxation of SBR and NBR cubes, indicating no measurable degradation under the studied conditions.

Currently, an ongoing phase aims to determine whether blending hydrogen into fuel gas alters the properties of elastomers used in O-rings and flange gaskets studying the complete assembly (Figure 11). Two identical test rigs were built—one for O-ring seals and one for gasket seals—allowing six assemblies to be exposed simultaneously to 20% hydrogen in methane or 100% hydrogen at three temperatures (0 °C, 16 °C, 49 °C). Assemblies are saturated under different compression levels after which small coupons are cut and analysed using thermomechanical analysis (TMA). The TMA measures shrinkage, swelling, creep, and stress relaxation to assess hydrogen effects. Gasket seal testing in 100% hydrogen is ongoing, with full completion of testing is expected by Fall 2025.[40]


A

B

Figure 11. A O-Ring (Left) and Flange Gasket (Right); B Testing Rig, image reproduced from https://www.nysearch.org/tech-brief-pdfs/NYSEARCH-Tech-Brief-Book-2025.pdf

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

5 Components of the gas network

Transitioning natural-gas networks to hydrogen requires a component-by-component assessment of both materials and operating conditions. In this sense, the first step, and the scope of this work, is to identify the key components of the network (pipelines, flanges, valves and compressors) and to map the typical materials used in their manufacture.

The following sections review the main types of components relevant to the structural integrity and safety of the gas grid, with particular attention to potential issues such as material incompatibility and degradation under hydrogen exposure. The analysis highlights how different component families may respond to hydrogen and identifies where risks of performance or durability may arise. Complementing this discussion, the Annex A provides detailed tables listing the specific materials currently used in these components, as indicated in the corresponding standards, and includes a traffic-light compatibility rating for ease of interpretation, as described in Table 3.

Importantly, since TSOs operate at high pressures (often exceeding 70 bar) with larger and more frequent fluctuations, TSO gas grid conditions are significantly more severe for materials and components than those in DSOs. As a result, certain materials or geometries that may not be suitable for hydrogen blending in high-pressure transmission pipelines could still operate safely in distribution networks. Therefore, the compatibility assessment here presented should be regarded as indicative rather than universal, since operating conditions, component geometry and possible defects, must always be taken into account when selecting materials.

5.1 Pipelines

Pipelines are the most common and frequently encountered components in European gas grids, forming the backbone of both transmission and distribution networks. Among all infrastructure components, they are also the most thoroughly documented in terms of material inventory, geometry, installed length, year of installation etc. Several projects and initiatives [41–43], have compiled relatively detailed pipeline inventories, providing data on pipeline diameters, metallic materials, installation periods, operational parameters etc. This relative abundance of information means that evaluations of existing pipeline materials, particularly regarding their compatibility with hydrogen blending, can be carried out in a more realistic and representative way.

Figure 12 shows the total installed length by API 5L grade from the SHIMMER database. The most prevalent grades are X60 (~34%), X70 (~25%), X65 (~17%), X42 (~13%), and X52 (~4%). Because these are ferritic steels, hydrogen service requires reassessment beyond B31.8 assumptions. Structural integrity assessments based on fracture mechanics and fatigue crack growth curves are required to establish the proper working conditions under which steel pipeline may be used. It is important to take into account that HE generally increases with strength (e.g. HE of X80 > X70 > X60 >X52 > X42). This trend for fracture toughness is shown in Figure 13.

As shown in Figure 12, the dominant presence of X60–X70 steel implies that FFS evaluation (e.g., B31.12/BS 7910/API 579 methodologies) are highly recommended before introducing hydrogen in the infrastructure.

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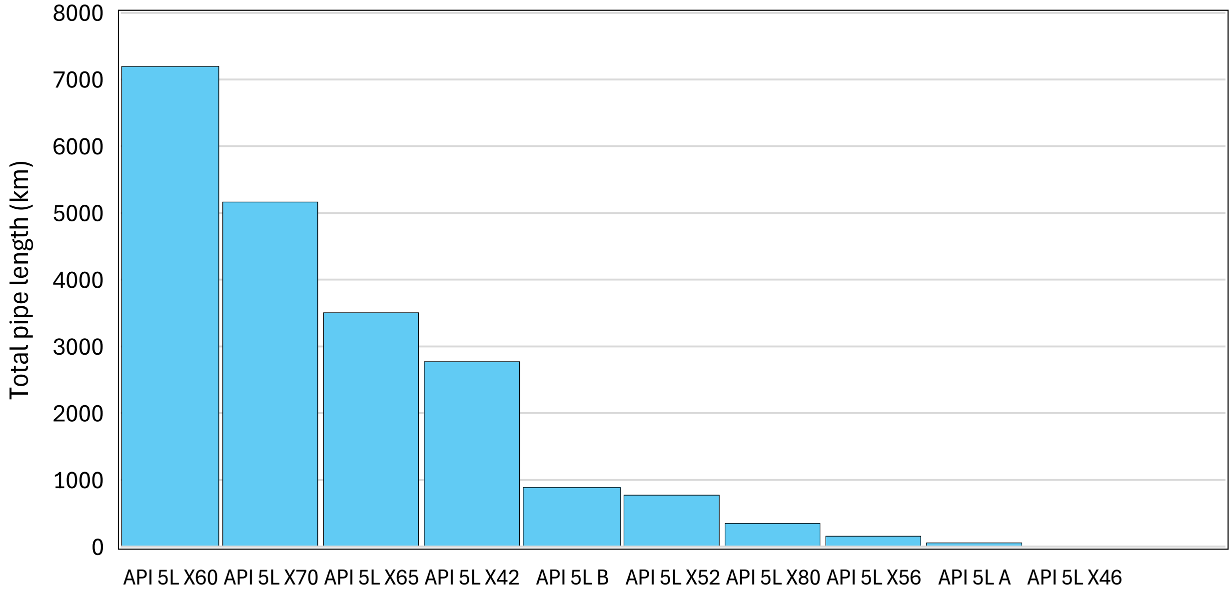

Figure 12. Pipeline length installed by API 5L grade according to SHIMMER database [44].

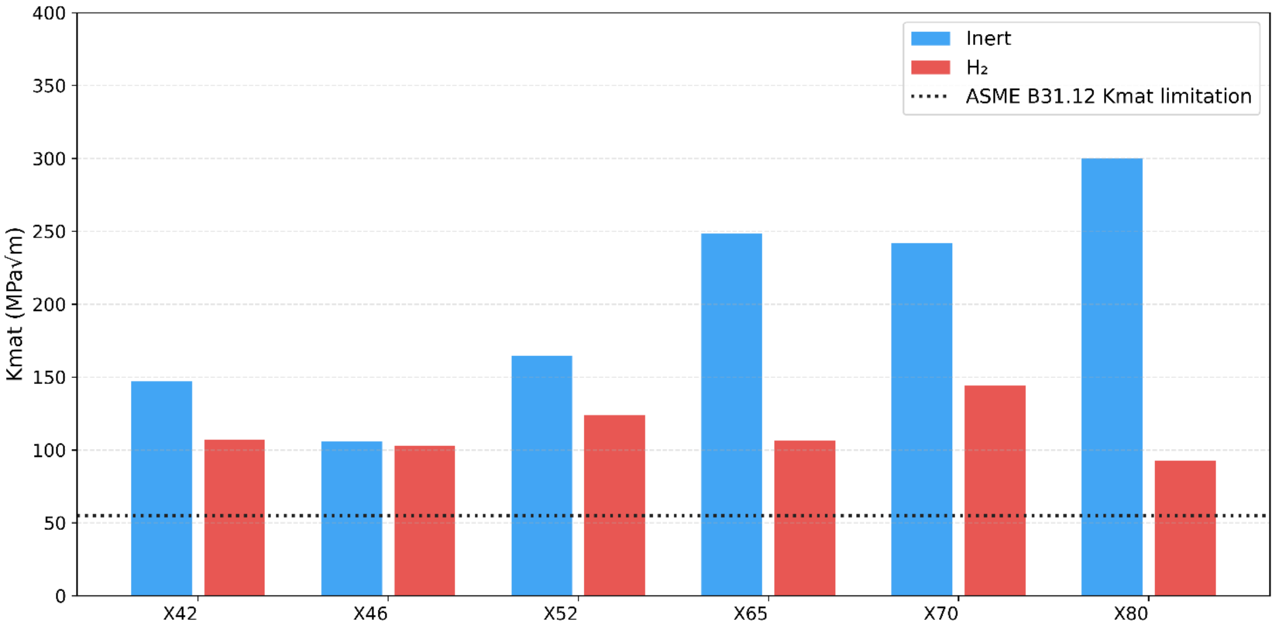

Figure 13. Fracture toughness degradation of common pipeline API 5L carbon steels

On the other hand, IGC Doc 121/14[29] recommends that, for hydrogen service, connections between pipes are made with welds wherever is possible to minimize potential leak sources. Threaded connections which are seal welded are considered as welded connections for this purpose. Either seamless or longitudinally welded pipe and wrought or machined fittings shall be used except in exceptional circumstances. In case that welded connections are not practical, the next best choice are flanges, which are going to be discussed in the section below (section 5.2).

Welds in pipelines deserve special attention in the context of hydrogen blending, because they often contain defects such as lack of fusion, porosity, inclusions, or regions of low cohesive strength etc. Combined with high residual stresses and surface roughness compared to the base metal, these imperfections make welds more susceptible to crack initiation and growth. For this reason, the fatigue properties of welds must be carefully

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

assessed in addition to those of the base material. However, knowledge of the fatigue crack growth behaviour of pipeline welds and the HAZ in hydrogen environments remains limited, with even fewer data available under pressurized hydrogen gas [23].

Table 8 summarizes pipeline materials permitted by ASME B31.8, the principal design code for natural-gas transmission and distribution and provides an indicative assessment of their compatibility with hydrogen using a traffic-light code. In practice, most line pipe follows API 5L and consists of plain carbon steel designated A25, A, B, X42, X52, X60, X70, X80, etc. In the X-grade system, the numeral denotes the minimum specified yield strength (SMYS) in ksi (e.g., X70 ≈ 70 ksi ≈ 483 MPa). Pipe is manufactured as seamless or welded (ERW/SAW), and supplied as rolled or heat-treated (e.g., normalized or Quenched and Tempered).

From a structural integrity perspective, pipelines are considered critical components because they constitute the main element of the gas grid, operate over extensive lengths, and their failure could have severe consequences for infrastructure, the environment, and public safety. For this reason, careful assessment that takes into account material properties and operating conditions is essential.

5.2 Piping flanges

Flanges are widely used in gas grids to connect pipes, valves, and equipment, particularly in larger-diameter piping. They provide a bolted joint that allows disassembly for maintenance, but their sealing performance depends strongly on design, gasket material, and assembly quality. In the context of hydrogen blending, flanges are of particular interest because they represent potential leakage points and therefore require careful consideration of both geometry and material compatibility.

A flanged joint comprises two mating flanges, a gasket, and bolting; tightening the bolts compresses the gasket to create a seal. ASME B16.5 provides the dimensional system and pressure–temperature ratings for NPS (nominal pipe size)½–24 (≈ DN 15–600) flanges and flanged fittings. ASME B16.47 extends this system to large-diameter steel flanges, NPS 26–60 (≈ DN 650–1500). This section focuses on the body part of the flanges, due to its importance, gaskets are revised in the section 0.

The pressure-temperature rating of a flange is defined by its class designation. ASME B16.5 assigns ratings of Class 150, 300, 400, 600, 900, 1500, and 2500; for each class, the allowable pressure decreases as temperature increases and depends on the material group. The flange class (e.g., Class 150, 600) is a standardized pressure-temperature rating that indicates how much internal pressure a flange of a given material can safely withstand at a specified temperature: higher classes mean higher allowable pressure. For instance, a Class 150 carbon steel flange is rated at about 19.7 bar at 38 °C, while a Class 600 of the same material can handle about 102.0 bar at 38 °C. The allowable pressure decreases as the temperature increases, and the exact limits also depend on the material group of the flange. ASME B16.47, which covers larger flange sizes, uses Class 75, 150, 300, 400, 600, and 900 under the same principles. In both cases, ratings apply to the assembled joint (flanges + bolting + gasket) when installed and tightened correctly.

Another important choice is the face type of the flange because it will impact on the performance and service life. The standards classify the faces variants as (see Figure 14).

- Raised Face (RF) and Flat Face (FF): are the most common.
- Tongue-and-Groove (T&G) and Male-and-Female (M&F): capture the gasket by geometry.
- Ring-Type Joint (RTJ): uses a machined grooved face for metal ring gaskets (R/RX/BX).

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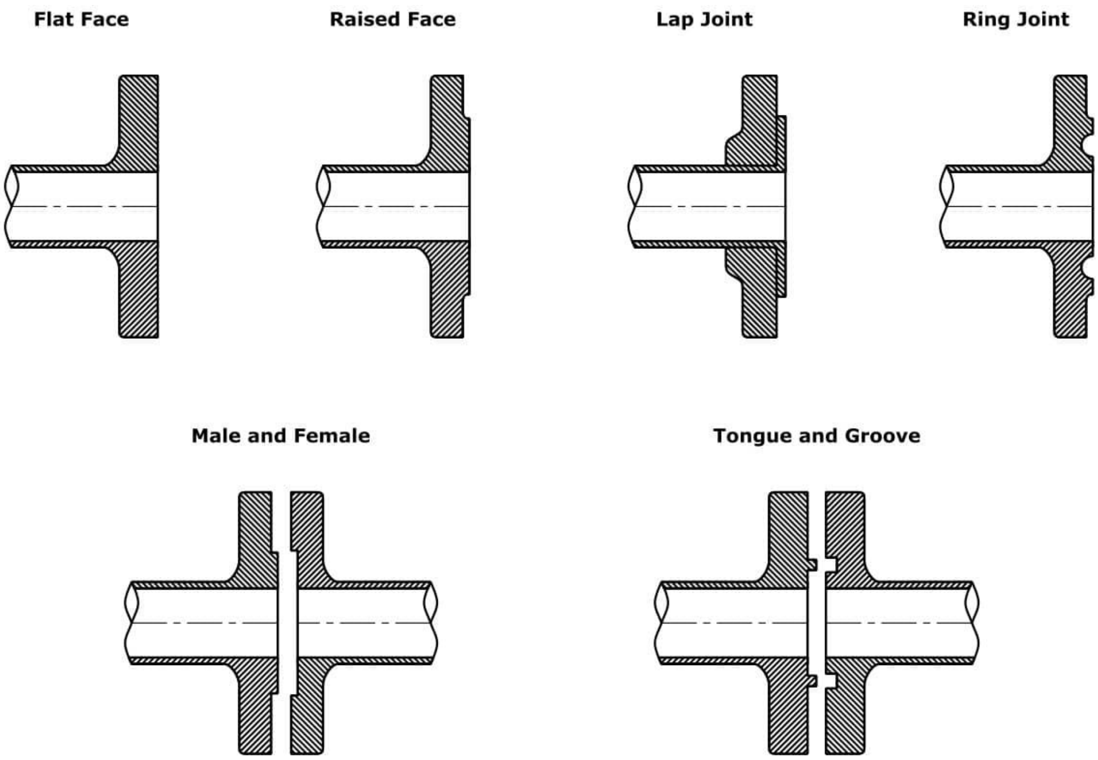

Figure 14. Typical flanges face: Flat face (FF), raised face (RF), Lap joint (LJ), ring joint (RTJ), male and female (M&F) and tongue and groove (T&G) Image reprinted with permission from saVRee ltd. Original image: [Flange Faces Explained (Flat, Raised, etc) - saVRee](#) [45].

In the natural gas infrastructure different types of flanges can be found (shown in Figure 15, Figure 16, Figure 17, Figure 18, Figure 19, Figure 20, images are reproduced from https://www.hlc-metalparts.com/news/what-is-a-flange-what-you-need-to-know-about-77306387.html):

- Welding Neck (WN): tapered hub for butt-weld to pipe, preferred for severe service.
- Slip-On (SO), Socket-Weld (SW), Threaded (TH): simpler installation envelopes; bores/counterbores and tolerances are specified.
- Lap-Joint (LJ) with stub-end: used where frequent disassembly is needed; LJ flanges are flat-face and rely on the stub-end lap as the sealing face.
- Blind (BL): closes a line; special facing guidance given. Straight-Hub WN is a standardized variant.

An important difference is that ASME B16.5 includes the full family flanges (WN, SO, SW, TH, LJ, BL), but ASME B16.47 limits the type to welding neck and blind.

Among the common flange types, the internal surfaces are in direct contact with the conveyed gas (e.g., H2) in all cases except the lap-joint configuration. In a lap-joint assembly, the stub end welded to the pipe is the wetted sealing surface, while the loose backing flange is not wetted. Because the flange bore is normally exposed to the gas, the flange body material shall form part of the hydrogen-compatibility assessment. By contrast, bolts, nuts, and washers lie outside the pressure boundary and are not in contact with the gas. They are, therefore, not usually evaluated for compatibility with hydrogen. But they remain critical to leak tightness through proper preload and assembly practice.

Table 11 and Table 12 compile the permitted flange body materials in ASME B16.47 and ASME B16.5, respectively. These standards establish dimensions, tolerances, and material specifications that may be used, but they do not select a material for a specific fluid; that choice must be made by the user based on the intended pressure, temperature, environment, and performance targets.

As shown in Table 11 and Table 12, both standards list broadly similar families: plain-carbon and low-alloy steels, austenitic stainless steels, and duplex/superduplex stainless steels. A notable difference is that ASME B16.5 (≤ NPS 24) also includes nickel-base alloys, whereas ASME B16.47 (NPS 26–60) is limited to steels.

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Figure 15. Welding neck flange [46]**.**

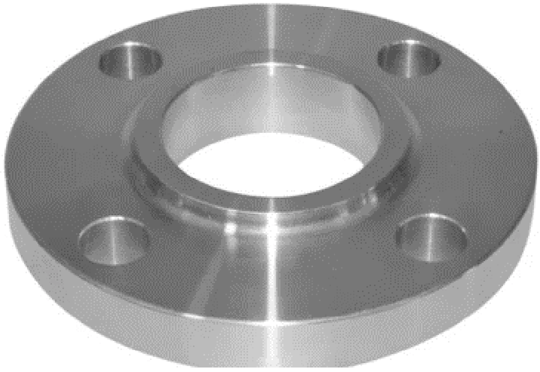

Figure 16. Slip on flange [46]**.**

Figure 17. Threaded flange [46]**.**

Figure 18. Socket weld flange [46]**.**

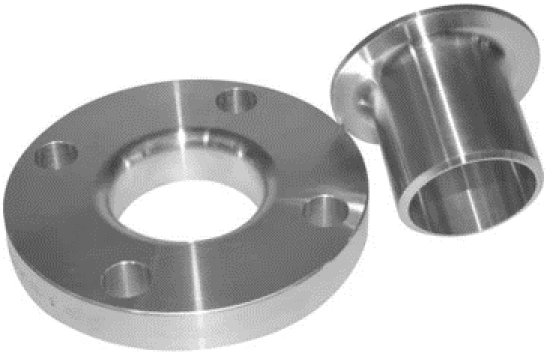

Figure 19. Lap joint flange [46]**.**

Figure 20. Blind flange [46]**.**

From a structural integrity perspective, flanges are generally less critical than pipelines or welds, since they are not load-bearing over long distances and failures rarely lead to catastrophic rupture. However, they represent important connection points in the gas grid where leakage is more likely to occur, particularly under hydrogen service. For this reason, the design of flange connections, the choice of gasket materials, and proper assembly practices are essential to ensure tightness and safety.

5.3 Piping gaskets

In a flanged piping system, a gasket is a replaceable sealing element installed between two flange faces. When the flange bolts are tightened, the gasket is compressed and conforms to small surface irregularities, producing a leak-resistant joint, as can be seen in Figure 21.

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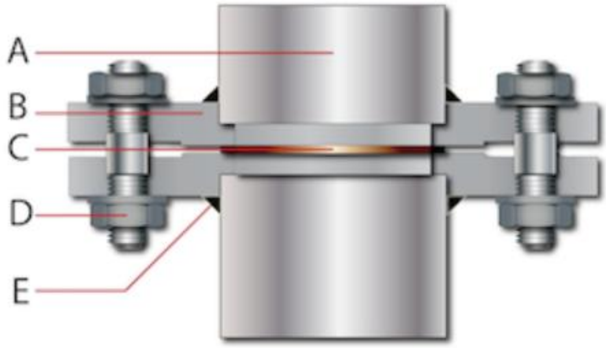

Figure 21. Pipe flange joint parts: A) Pipe, B) Flange, C) Gasket, D) Bolting and E) Weld. Image reproduced with permission from Tameson, source https://storage.tameson.com/asset/Articles/general/pipe-flange-example.png [47].

ASME B16.20 standardizes metallic gaskets: their types, dimensions, tolerances, markings, and material categories, for use with standard pipe flanges. The standard applies to three gasket families, all dimensionally compatible with flanges in ASME B16.5 and ASME B16.47:

1. Ring-joint (RJ) gaskets: they are made of a solid metal ring with oval or octagonal cross-sections, identified by R, RX and BX numbers tied to NPS/pressure class and the reference flange standards. The seal under bolt loads the ring plastically embeds into the flange groove to make a line-contact seal. Regarding the materials employed the user selects the alloy for the service; the standard sets maximum hardness (ring must be softer than the groove) and surface-finish limits for the sealing faces. Marking rules identify material and type. The list of materials allows by the ASME B16.20 is listed in Table 13, covering plain carbon steels, low-alloy steels, martensitic steel and austenitic steel.
2. Spiral-wound (SW) gaskets are form by alternating metal windings and flexible filler, usually with a centering ring (positions the gasket) and often an inner ring (stability/leak control at the bore). Dimensions, ring roles, and identification are standardized. SW seal because compression creates a resilient, conformable sealing band; the inner ring helps protect the filler at the gas bore. ASME B16.20 list some metallic options, which are gathered in Table 14. Similar analysis can be made, the martensitic steel should be avoided, and the rest of materials should be carefully revised with exception of austenitic stainless steels The non-metallic filler used for these gaskets are PTFE, flexible graphite, vermiculite, phlogopite (magnesium mica) and ceramic.
3. Grooved metal with covering layers (GM) (also known as Kammprofile gasket) is form as a concentrically grooved metal core with thin cover layers (e.g., graphite or PTFE) on both faces, plus a centering ring. Thicknesses, tolerances, and (for large sizes) permitted welding details are specified. In order to seal, the grooved core concentrates gasket stress; the cover layers conform to flange surfaces. The material selection for both metallic and non-metallic materials is the same as for SW gaskets (see Table 14).

In the natural gas network, gaskets are used wherever a flanged connection is required, such as between pipelines, at pipeline-to-valve interfaces, and on flanged nozzles of equipment in compressor and pressure regulation stations (filters, meters, heat-exchangers, etc.).

The analysis of ASME B16.20 gaskets are quite relevant for hydrogen service and compatibility since they are directly in contact with hydrogen gas. By design, the inside diameter of the gasket aligns with the flange bore, so the gasket's sealing element is exposed on the process side. This is explicit in the dimensional figures for SW and GM gaskets (inside/outside diameters, radial clearances) and is implicit for RJ rings seated in the groove at the bore. Therefore, material compatibility with the conveyed gas (e.g., hydrogen or blends) is directly relevant.

On the other hand, gaskets may be non-metallic. In these cases, ASME B16.21 defines non-metallic flat gaskets for flanged joints: their types (full-face and flat ring), dimensions, tolerances, and markings. These gaskets are dimensioned to fit standard flanges in ASME B16.1, B16.5, B16.24, B16.47, and MSS SP-51; selection is by NPS and pressure class matching the mating flange. Non-metallic gaskets are installed between two flange

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faces anywhere a flanged joint exists (pipe-to-pipe, pipe-to-valve, pipe-to-equipment). B16.21's sizing philosophy explicitly prevents the gasket from projecting into the flow, meaning its inside diameter aligns with the flange bore; consequently, the gasket is exposed on the process side and contacts the contained gas (including H2). Two designs are proposed in this case:

1. Full-face gaskets: for flat face flanges, covering the full flange face and bolt circle.
2. Flat-ring gasket: for raised face flanges that sits inside the bolt circle on the raised face.

The dimensions for both types are tabulated in flange standard, NPS and class. Regarding materials, ASME B16.21 allows resilient or pliable non-metallic materials, included composites reinforced/filled with metallic or non-metallic material, but do not explicit any material. Some examples of typical material can be found in Table 6.

Table 6. Examples of materials in non-metallic gaskets according ASME B16.21.

Grades / Examples
Virgin PTFE, Filled PTFE
Flexible graphite, Reinforced graphite
Mica (phlogopite), Ceramic fiber
Cellulose composites, Rubber, Cork-rubber (SBR)
PTFE + Elastomer, PTFE + Graphite

Based on IGC Doc 121/14, best alternatives for hydrogen service are PTFE or graphite filled spiral wound gasket with a raised face flange or a copper ring with a ring joint flange.[29] However, some reports indicate potential problems for graphite since it is permeable to hydrogen gas and could be ineffective for preventing leakage.[20,48]

From a structural integrity perspective, gaskets are generally not considered critical components. However, in the context of hydrogen blending, gaskets become important for ensuring leak-tight performance and safe operation.

5.4 Valves

Valves in a gas grid provide isolation, control, and protection. They allow operators to start or stop flow, sectionalize a pipeline for maintenance or emergencies, regulate pressure and flow at stations, and prevent reverse flow.

A valve is a complex device: multiple subcomponents perform distinct functions and are often made from different materials. In its simplest form, a valve comprises a body that contains the flow path and the closure element (obturator), which is moved by a stem. The stem passes through a bonnet (or cover) and is operated manually (handwheel/lever) or by an actuator [49].

ASME B16.34 is the principal product standard for flanged, threaded, and welding-end valves. It specifies design, pressure, temperature ratings, markings, and provides the materials for the pressure boundary (body, bonnet/cover, and their bolting). Other internal parts (e.g., stems, discs/gates/balls, seat rings) must be selected so that the complete valve meets the designated rating.

Pressure boundary subcomponents retain pressure but do not by themselves meter the flow. Their allowable materials are governed directly by ASME B16.34 and are catalogued in Table 9 and Table 10. These parts are:

- Body (shell): the main pressure vessel that houses the flow path and internals.

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- Bonnet/Cover: the closure piece bolted or otherwise attached to the body; provides access for the stem and internals.
- Body–bonnet (or cover) bolting: studs/bolts and nuts that clamp the pressure joint.
- End connections: flanged faces, ring-joint grooves, welding ends, or threaded ends—the pressure boundary interfaces to the piping.

In industry practice, and explicitly in API valve standards, trim denotes the internal, process-wetted parts that control flow and make the seal. Table 10 compiles these parts and their base alloys and seating-surface materials (e.g., hard facing overlays), following API 600/603/623/594/602. The main parts are:

- Obturator: Gate/wedge (gate valves), disc/plug (globe/plug valves), ball (ball valves), disc/clapper (check valves). These elements open/close the flow.
- Seat(s) / seat rings: stationary sealing surfaces against which the obturator shuts; may be integral to the body/cover or separate seat rings.
- Seating surfaces/overlays: the finished sealing bands on the obturator and seats; often hard faced (e.g., Co-Cr/Stellite or Ni–Cr) or case-hardened (e.g., nitrided) to improve wear and galling resistance.
- Stem (wetted portion): the lower, smooth section that passes the pressure boundary and connects to the obturator; API 6D classifies the stem as a pressure-containing part and a process-wetted part where it is exposed to the line fluid.
- Backseat and internal bushings/guides (where fitted): internal guides and the backseat bushing that contact the stem inside the pressure envelope.

In addition, there are external hardware that are non-trim are non-wetted. A typical list is actuator/handwheel/lever, yoke, stem nut, position indicator, gear or pneumatic/electric drive, brackets, keys, pins, external fasteners. They are not part of the trim and are usually not limiting for hydrogen compatibility, though they remain important for operability and maintenance.

Depending on their function in the gas grid, valves can be classified into several main categories.

- Isolation valves, such as ball, gate, or plug valves, are used to start or stop the flow of gas.
- Control valves, including globe or needle valves, regulate flow rate or system pressure by partially opening or closing the closure element.
- Safety or relief valves automatically release gas to protect the system from overpressure.
- Check valves allow flow in only one direction, preventing reverse flow that could damage equipment or compromise safety.

Each valve type is selected based on its specific operational role, pressure rating, and required reliability within the gas network. In the following subsections a briefly description of valve types based on their mechanism is provided.

5.4.1 Ball and plug valves

Ball valves incorporate a spherical closure element with a through-hole that rotates 90° to either align with the pipeline for full flow or to obstruct flow completely. This quarter-turn closure mechanism ensures rapid operation and tight sealing, making ball valves widely adopted for on/off isolation in both transmission and distribution pipelines. They are generally not intended for throttling, as partial opening can compromise the sealing surfaces. A simplified scheme of a ball valve is shown in Figure 22.

Plug valves are similar to ball valves but instead of a ball they employ a cylindrical or conical plug that rotates within the valve body to either allow or restrict flow (Figure 23). This robust closure mechanism is particularly suitable for on/off isolation in high-pressure or abrasive gas pipelines, providing reliable sealing under demanding conditions. However, plug valves are rarely employed for flow modulation or throttling.

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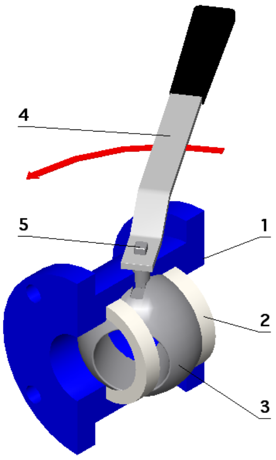

1. Body
2. Seat
3. Floating ball
4. Lever handle
5. Stem

Figure 22. A ball valve components cutaway view, adapted form Wikimedia Commons licensed under CC BY-SA 3.0 https://en.wikipedia.org/wiki/Ball_valve#/media/File:Ball.PNG

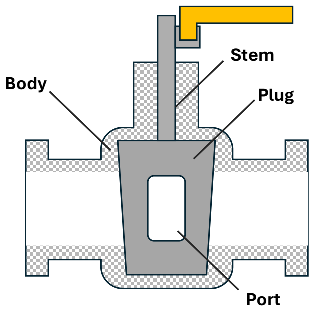

Figure 23. Schematics of plug valve

Both ball valves provide quick operation and reliable sealing, with manual or automatic actuation. They are commonly used for isolation, emergency shutdown, excess flow, and venting or draining, and can serve as control valves where high precision is not required. Ball valves are often full ported (have an internal bore equal to the pipeline diameter) minimizing pressure drop and allowing pipeline inspection tools to pass through. [29]

Common materials used for ball and plug valves are shown in Table 7

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Table 7. Example of materials used in ball and plug valves [50]

Subcomponent	Possible Materials
Body	Carbon steel Stainless steel Weld Overlayed Epoxy/Phenolic lining
Ball	Nickel Coated Carbon Steel Nickel Coated Cast steel
Seat rings	Nickel Coated Carbon Steel Stainless Steels Weld Overlayed
Seat springs	Austenitic Stainless Steel Nickel Alloy
Stem	Nickel Coated Carbon Steel
O-ring seals	Nitrile Synthetic Rubber Nylon Viton
Bolting	Martensitic Steels Low Temperature Alloy Steel Stainless Steel

5.4.2 Gate Valves

Gate valves employ a flat or wedge-shaped gate that moves linearly within the valve body to obstruct or permit the passage of gas. This closure mechanism renders them highly effective for on/off isolation, particularly in high-pressure pipelines, as they offer minimal pressure drop when fully open. However, they are unsuitable for throttling, since partial opening may induce vibration and cause wear to both the gate and seat surfaces. Gate valves are durable, well-established devices primarily used to shut off flow. While they can be automated, they are most commonly operated manually. Their main drawback is that, unless designed with special soft-sealing strips on the disc, they generally do not provide as tight a seal as ball, plug, butterfly, or globe valves. To improve sealing performance, flexible wedges (gates) should be specified. A key advantage of gate valves is that they allow internal pipeline inspection tools to pass through them.[29]

5.4.3 Butterfly Valves

Butterfly valves employ a rotating disc mounted on a central shaft as the closure element. By rotating the disc 90°, the valve can be fully opened or closed. Their compact and lightweight design makes them ideal for on/off isolation in large-diameter pipelines, with certain designs allowing limited throttling in medium- to high-pressure systems. Butterfly valves can be operated manually or automatically and may be used as control valves when pressure drop across the valve is not too large. Their main drawback is valve seat vulnerability to particulate damage, so double-eccentric, bubble-tight designs are recommended. Because the disc and pin remain in the flow path, they cannot accommodate pipeline inspection devices.[29]

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5.4.4 Globe Valves

Globe valves utilize a movable disc or plug element that moves perpendicularly to the valve seat in a spherical body, providing precise modulation of flow (Figure 24). This design makes globe valves particularly suitable for throttling and pressure regulation across both low and high-pressure segments of the gas network. They can be manual or automatic. Their precise control characteristics make them ideal for control valves, automated venting, and isolation duties, though they are more common in smaller sizes. In this type of valve, the fluid is forced to change direction, which enables precise control but increases susceptibility to erosion and abrasion. To mitigate this, hardened plug and seat materials are recommended in applications with high pressure drops. Globe valves give precise flow control but cause higher pressure drops than gate valves. For hydrogen, its high sonic velocity makes the gas reach high speeds even at low pressure drops, which accelerates erosion on the valve's plug and seat surfaces more than with other gases. [29]

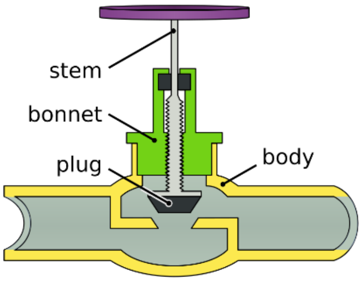

Figure 24. Globe valve schematics, via Wikimedia Commons, https://commons.wikimedia.org/w/index.php?curid=7768001

5.4.5 Check Valves (non-return valves)

Check valves utilize a swinging disc, ball, or lift mechanism that automatically closes in response to reverse flow, thus permitting flow in one direction and to stopping it in the reverse direction (Figure 25). This passive closure mechanism ensures unidirectional flow, hereby protecting equipment and maintaining operational safety in both transmission and distribution networks. Swing and flapper check valves are typically used in larger pipe sizes, while ball or poppet types are preferred for very small sizes (<2”). To minimize backflow when the valve is closed, a soft seat within a metal retainer or carefully lapped metal-to-metal seats are recommended, especially where even a small reverse flow could pose a risk. As with all check valves, correct installation orientation is critical. Check valves are generally less reliable as complete flow stoppers compared to isolation valves and should not be used as a substitute for them. These valves operate without manual intervention. [29]

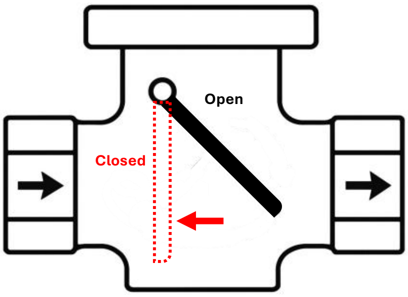

Figure 25. Schematics of a swing check valve (tilting disc check valve) which allows flow only in one direction

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5.4.6 Pressure relief valves (PRV)

PRVs are safety devices designed to prevent overpressurization of systems by automatically venting gas once a predetermined pressure is reached. They operate independently, without requiring operator or control system intervention. In a pressure relief valve, overpressure generates a force on the valve's internal mechanism, usually a spring-loaded disc or piston. When the system pressure exceeds the spring's set force, it overcomes the spring resistance, lifting the valve off its seat and allowing gas or fluid to escape, thereby relieving the excess pressure (Figure 26).

Various types exist, including direct-acting, pilot-operated, and variable backpressure valves. Direct-acting spring-loaded valves are suitable, with internal components made from hydrogen-compatible, corrosion-resistant materials. Valve seats can be metal-to-metal or soft materials in a metal retainer. Metal-to-metal seats are more resistant to damage during valve operation but have a higher risk of leakage when closed. Carbon steel and stainless steel are preferred for valve bodies due to cost-effectiveness and reduced corrosion risk. [29]

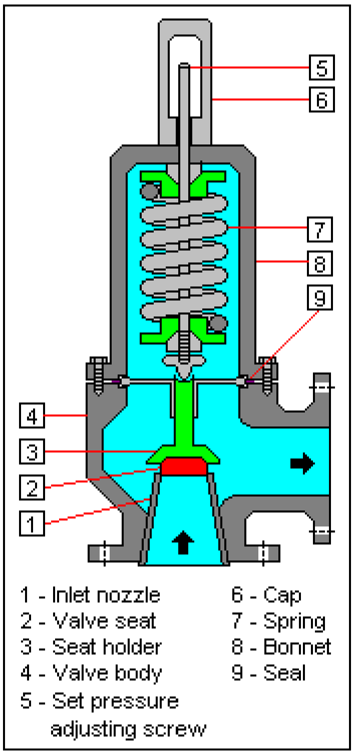

Figure 26. Schematics of pressure relief valve, Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Relief_Valve.png. Licensed under CC BY-SA 3.0.

5.4.7 Hydrogen-Specific Concerns in Valves

Valves play a vital role in natural gas distribution systems, and their integrity is essential for safeguarding both the infrastructure and nearby communities. With hydrogen blending into natural gas posing a higher risk profile, ensuring valve fitness becomes even more crucial.

Some sources indicated that in DSO network with up to 10% hydrogen blended with natural gas, it is expected that existing valves would not need to be modified. [23] Other technical literature points out that most elements of the DSO network can already accommodate H_2–NG mixtures up to 30 vol.-% H_2. With appropriate modifications, nearly all components, including valves, are expected to operate safely across the full range of 0–100 vol.-% H_2. However, further research and development are needed to assess the performance and readiness of excess flow valves at higher hydrogen concentrations.[25] In TSO network, which operates at much higher pressure, the maximum acceptable percentage of hydrogen is limited to 10%

Critical points for the assessment of valves ion the context of H_2–NG blending highlighted by the American Gas Association include [23]:

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

- Valve Type and Design: For applications involving low pressure and a low percentage of hydrogen, welded-body valves with minimal weld seams are generally preferred over bolted-body designs, as they reduce potential leak paths. However, at higher pressures and hydrogen concentrations, welds may be more susceptible to hydrogen-related degradation. In such cases, it may be necessary for valve manufacturers to conduct testing of body weld processes specifically for hydrogen service.[25]
- Materials Selection: Carbon steel is considered acceptable when hydrogen content/partial pressure is relatively low, but at higher hydrogen concentrations, austenitic stainless steel is typically recommended. Cast materials should be avoided due to the risk of porosity and void formation. Many valve designs also incorporate elastomer stem packing, polymer seats, and other internal components, which could be affected by long-term hydrogen exposure. A detailed design evaluation, covering both new and in-service valves, along with additional testing, may be required to determine the durability of these internal components.
- Sealant: The compatibility of sealant materials with H_2–NG blends remains uncertain, highlighting the need for further research.
- Testing: Valve testing standards for H_2–NG blends are limited, with current practice (API 6D) focusing mainly on strength rather than material compatibility. Some utilities recommend fugitive emission tests using helium as a proxy for hydrogen, as described in ISO EN 15484. Helium, being similar in size to hydrogen, is used as a safe to simulate the operating conditions of pure hydrogen service and perform leaks tests.

EIGA recommendations for pure hydrogen service, indicates that the main concern is preventing leakage. Valve leakage can occur through two principal mechanisms. Seat leakage allows hydrogen to flow past the closed valve, with the gas remaining contained within the system. Stem leakage, in contrast, presents a higher safety risk, as it can lead to the uncontrolled release of hydrogen into the atmosphere. Recommended measures include using double seals or packing, hydraulic testing of castings, soft or metal-to-metal seats with positive isolation for maintenance, blocking valve outlets with metallic seats, minimizing flanges or threaded connections, and using full-port mainline isolation valves for inspection and pigging [29]. These recommendations are consistent with earlier guidance on hydrogen valves [48]: Seat leakage in hydrogen service is best prevented using metal-to-metal sealing technology, where a flexible metal disk seals against a stellite hard-faced seat, providing a durable leak-proof seal. Stem leakage prevention relies on careful design, including rotation-resistant packing, highly effective shaft seals, smooth shaft surfaces, and proper contact between packing segments, the stuffing box, and the shaft.

Hydrogen-induced degradation of metallic components can be mitigated through careful valve design. Minimizing sharp edges and abrupt angles reduces stress concentrations that exacerbate hydrogen degradation, while large-radius, uniform-stress designs are preferred for hydrogen service. The forming process also affects performance: cast components avoid welds and sharp edges but may contain voids or porosity, whereas forged steel is generally defect-free but may require welding. Welding should be minimized, as it is a primary site for hydrogen embrittlement. [48]

In addition to the metallic body and internal design, valve sealing performance under hydrogen service strongly depends on the properties of the elastomeric O-rings, which are susceptible to hydrogen-induced degradation such as blistering and rapid gas decompression. These mechanisms and material-specific results are discussed in more detail in Section 4.1.2.

Plastic valves, like metallic ones, are complex assemblies with sub-components often made from different polymers than the main body, while the outer shell and end connections match the piping material (e.g., PE PE). They incorporate seals, shafts, operators, and sometimes lubricants, but unlike many metal valves, plastic valves are usually not designed for disassembly or maintenance. Limited technical data exists on their performance with hydrogen, so further testing is recommended to determine safe limits for hydrogen concentration, pressure, and temperature. While manufacturers select materials for long-term reliability, additional evaluation may be needed to ensure hydrogen does not compromise service life or increase leakage, and utilities may need to conduct their own testing on valves already in service. [23]

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In the case of pressure reducing valves and regulator there are some concerns when the pressure drop across the valve or regulator exceeds 10% of the upstream pressure, because it may create problems in seals and plugs.[20,29]

An additional operational consideration is that many valves are currently operated by actuators powered directly by gas from the pipeline. It is not yet clear whether these actuator types will function properly with hydrogen as the power source, which may require operators to consider alternative actuation technologies.[51]

From a structural integrity perspective, valves are considered important components in the gas grid, as they are designed to contain system pressures and a failure could lead to significant leakage or operational disruption. Hydrogen can increase the risk of leakage or embrittlement under high-pressure conditions. Therefore, careful selection of hydrogen-compatible valve materials, appropriate design, and proper maintenance are essential to ensure safe and reliable operation, particularly in TSO.

Valves are complex components composed of multiple subcomponents and a variety of materials, including metals, elastomers, and plastics. This complexity makes assessing their compatibility with hydrogen particularly challenging, as performance depends not only on the materials themselves but also on the valve's design, assembly, and operational history. To evaluate hydrogen compatibility, it is necessary to consider operating conditions, functionality, the specific materials used in each subcomponent, and the current condition of the valve. Conducting performance tests on multiple valve types and meters across a wider range of operating conditions and configurations would enhance the existing knowledge. Testing elastomers and seals, which are critical to valve and meter performance, would also provide valuable insights.

5.5 Compressors

European gas transmission infrastructure is designed to operate with fossil-based natural gas. The typical gas mixtures transported through these systems have molecular weights ranging from 16 to 18.5 g/mol, primarily due to methane concentrations exceeding 80%. As a general guideline, pipelines are dimensioned to accommodate the required volumetric flow, maintaining a maximum gas velocity of approximately 30 km/h. The average operating pressure across the network typically is between 60 and 70 bar. Flow rate and pressure levels influence the pressure drop caused by friction between the gas and the pipe walls. To counteract this loss and maintain efficient transport, compression stations are strategically placed throughout the network to boost pressure and ensure continuous flow [52].

The compressor stations of the TSO system apart from compressors also house a range of auxiliary components such as regulators, meters, valves, and other parts made from ferrous and non-ferrous metals and various polymers. Some of these materials are in contact with the transported gas therefore they have to be compatible with it. It is well recognized that current gas infrastructure is not suitable for transporting pure hydrogen due to limitations in compressor design, however it is technically feasible to introduce hydrogen in small concentrations as a blend with natural gas [34]

Centrifugal and reciprocating compressors are the primary technologies employed to compensate for pressure drop in transmission pipelines. Centrifugal compressors are typically selected for applications characterized by high flow rates, moderate pressure ratios, and relatively stable operating conditions with limited flow variation. Reciprocating compressors, on the other hand, are preferred in applications involving low flow rates, high pressure ratios, and highly variable pipeline conditions, where their ability to efficiently handle fluctuating operating demands provides a distinct advantage.[20]

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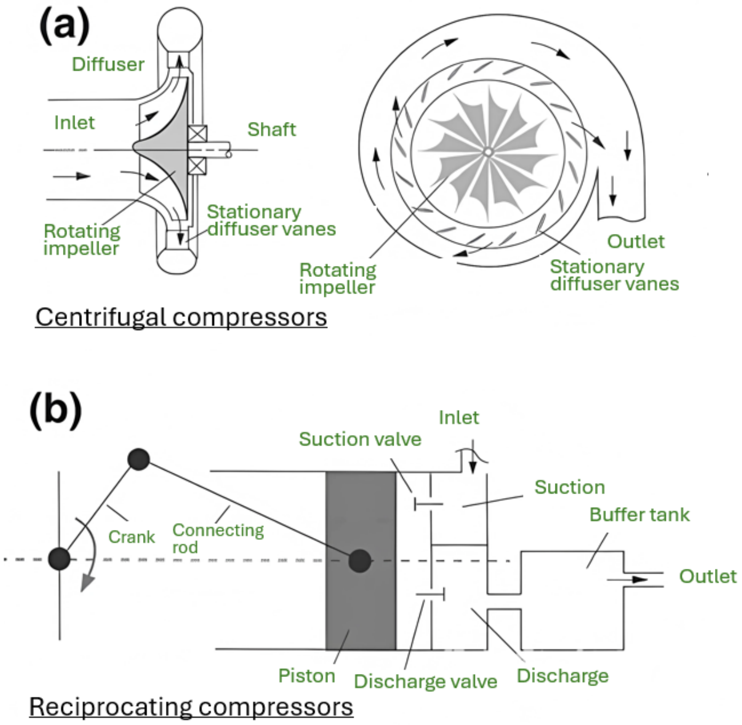

Figure 27. Schematics of compressors (a) Centrifugal compressor (b) Reciprocating compressor. Adapted from original source https://link.springer.com/book/10.1007/978-3-319-66784-3 **[53]. Reproduced with permission from Springer Nature**

5.5.1 Centrifugal compressors

Centrifugal compressors consist of three main parts; the impeller, diffusor and the volute (see Figure 27). Examples of impellers are shown in Figure 28. [53] A centrifugal compressor works by drawing low-pressure gas into the inlet, where it enters the rotating impeller. The impeller blades accelerate the gas outward, increasing its velocity and imparting kinetic energy. The high-velocity gas then passes through the diffuser, where its speed decreases and most of the kinetic energy is converted into pressure. Finally, the gas enters the volute casing, which collects the flow and directs it to the discharge nozzle at a higher pressure. This process allows centrifugal compressors to efficiently handle high flow rates and moderate pressure increases, making them well suited for continuous, steady operating conditions.

For a given impeller tip speed in a turbo-compressor, the pressure increase is directly proportional to the molecular weight of the gas. Hydrogen's molecular weight is approximately 1/8th of methane, which means that achieving a comparable pressure ratio to those of natural gas in an existing pipeline would require much higher impeller tip speeds or a much higher number of compressor stages in several compressor casings. The mechanical strength limits of the impeller are intrinsically linked to its tip speed. As the tip speed increases, the resulting mechanical stresses on the impeller also rise. When compressing hydrogen due to its significantly lower molecular weight compared to methane, achieving the necessary pressure ratios demands higher tip speeds. However, these elevated speeds approach the structural stress limits of the impeller materials well before reaching conditions suitable for 100% hydrogen compression [20,54].

The maximum allowable tip speed of the impeller varies depending on the material used. Typically, these material strength limitations are not a concern when designing compressors natural gas but in the case of low weight gas compositions, like hydrogen, however, they have to be considered, and the impellers' mechanical strength is a limiting factor in the design of hydrogen compressor [55].

The main design code for centrifugal compressor for gas industry is the API 617 [56]. The typical materials used in this type of compressors under API 617 are summarized in Table 15 (API 617 Annex F). For hydrogen gas service, API 617 imposes explicit strength and hardness limits on process-wetted parts (i.e., parts in direct

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contact with the gas such as impellers, the internal surfaces of the casing/diaphragms, labyrinth components, gas-side rotor sleeves, and seal carriers). Materials having yield strength > 827 MPa (120 ksi) or hardness > Rockwell C 34 shall not be used when either: (i) the partial pressure of hydrogen exceeds 0.689 MPa (100 psig), or (ii) the hydrogen concentration exceeds 90 mol% at any pressure.

Because partial pressure is pH2 = xH2 P, the threshold can be crossed with relatively modest blends at high line pressure. For example, at 70 bar(g) transmission pressure, a 10% H_2 blend gives pH2≈7 bar(g), which exceeds the 0.689 MPa (6.89 bar) threshold; at 40 bar(g) the same 10% blend gives pH2≈4 bar(g), which is below it. Thus, compliance depends on both blend fraction and operating pressure rather than blend fraction alone.

Even within these limits, hydrogen can still degrade performance (e.g., reduced toughness and accelerated crack growth), and impeller materials are a well-documented concern for hydrogen embrittlement. Consequently, selection should still favour hydrogen-tolerant families (e.g., austenitic stainless steels) and avoid susceptible ones (e.g., martensitic/PH stainless) for wetted parts, with service-specific verification where needed [52,54,57,58].

Finally, API 617 also requires a radially split casing (axially split casings are not permitted) when the hydrogen partial pressure at maximum allowable working pressure exceeds 1.380 MPa (200 psig). This is a geometric/design requirement intended to enhance joint integrity in high-hydrogen service.

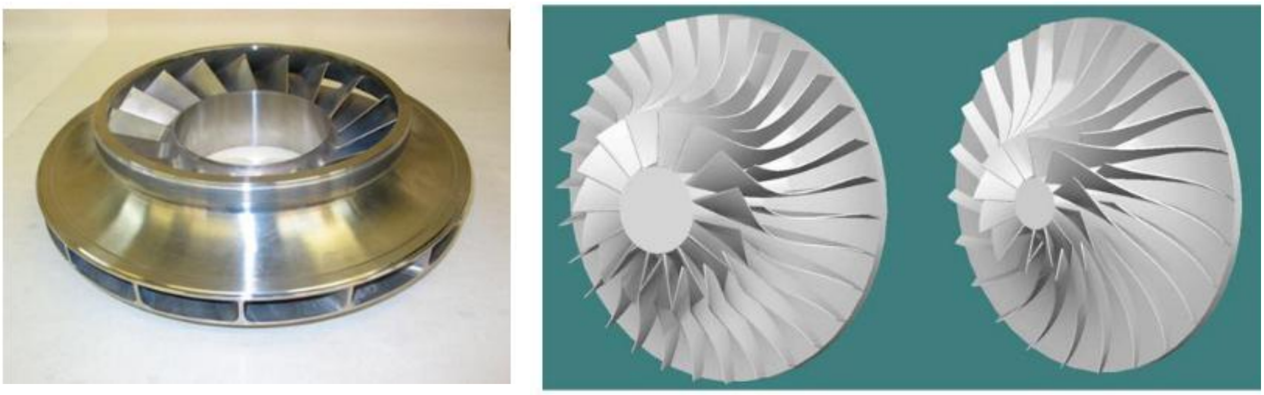

Figure 28. Examples of impellers of centrifugal compressor (left shredded, right open-faced) [57,59]

As a general guideline, it is considered that if blending is below about 10% hydrogen, centrifugal compressors can usually continue operating without major adjustments, though efficiency drops slightly because pressure rise depends on molecular weight of the gas. Between 10% and 40% hydrogen, the compressor housing can still be used, but impellers and gears need to be redesigned. Hydrogen's very low molecular weight reduces achievable pressure ratios per stage, so more stages or higher tip speeds are needed, which pushes impellers toward mechanical strength limits. Above 40% hydrogen, existing natural gas centrifugal compressors cannot be used. The aerodynamic and mechanical limitations are too severe, and new compressors specifically designed for hydrogen are required. [27]

Regarding non-metallic materials, reports indicate that many seals and components in the centrifugal compressor are already compatible with hydrogen. Dry gas seals are typically designed to handle hydrogen concentrations up to 20%. O-rings are generally manufactured from hydrogen-resistant compounds, while shaft seals made of PEEK or PTFE are also suitable for hydrogen service. These materials can typically operate safely at their rated hydrogen concentrations, provided the operating temperature does not exceed 200°C.[58]

5.5.2 Reciprocating compressor

Reciprocating compressors are positive-displacement machines where gas is drawn into the cylinder during the suction stroke and compressed by the piston. A prime mover drives a crankshaft connected to the pistons through connecting rods, producing the reciprocating motion. Once the gas pressure exceeds that of the delivery manifold, the discharge valve opens, and the compressed gas flows out. As the piston begins the next

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suction stroke, the discharge valve closes, the suction valve opens, and the cycle repeats (Figure 27 b) [53]. The main design code for reciprocating compressor for gas industry is the API 618.[60]

Reciprocating compressors are a proven method for compressing hydrogen and are widely used in refineries due to their excellent flexibility for handling gases with different molecular weights (though seals require additional attention for low-molecular-weight gases such as hydrogen). They can be oil-lubricated or non-lubricated, the latter of which is preferred for high-purity hydrogen applications to avoid oil contamination [20].

Regarding materials, Annex G API 618 lists generic classes (e.g., steel, stainless steel, cast iron, aluminium, non-metallics rather than prescriptive grades of materials. The manufacturer must ensure that selected material grades suit the specified service. For a hydrogen service, the focus should be on process-wetted parts, cylinders/heads and valves (seats, plates, springs), pistons, piston rings/rider bands, the gas-side length of the piston rod and pressure packing, and any coolers/separators on the gas side. [60]In these locations, austenitic stainless steels are generally the most tolerant, while plain carbon and low-alloy steels are usable with engineering controls (hardness/strength control, fracture and fatigue assessment, and tight leak integrity). Martensitic/precipitation-hardened stainless steels should be avoided in wetted parts due to embrittlement susceptibility. Although API permits grey/ductile irons for cylinders at limited maximum allowable working pressure, they should not be used for hydrogen pressure components. Non-metallic rings/plates (PTFE/PEEK/PAI families) are generally acceptable for H2 provided temperature and wear limits are respected.

For hydrogen contents below about 10%, natural gas piston compressors can usually operate without major modifications. Leakage risk is limited, and performance is stable. Valves, seals, and materials in the compression station can handle small amounts of hydrogen. When hydrogen content increases up to around 40%, changes are needed in sealing systems, piston rings, and valve materials to handle hydrogen's small molecule size and to avoid accelerated wear or leakage. Lubrication systems may also need adaptation since hydrogen can dissolve in oils. For more than 40% hydrogen, existing piston compressors become inefficient and less reliable. While it is technically possible to redesign them to handle 100% hydrogen, this requires significant changes to materials and sealing technology, so existing machines cannot be used without major upgrades [55,58].

Overall, it is established that most elements of compression, pressure regulation and metering are able to handle hydrogen-NG mixtures in the range of 0-10 vol.-% hydrogen without mitigation measures. Turbo and Piston compressors are a limiting factor and are able to reach 10 vol.-% H2 in H2-NG mixtures with minor modifications. With higher concentration, mitigation measures or replacement are expected, depending on the partial pressure limit of certain materials [25].

Compressors are highly complex machines that operate under demanding conditions, including high pressures and dynamic loading. Some of the materials employed in their construction are susceptible to hydrogen-related degradation, which can affect both performance and durability. In addition, compressors have functional limitations that stem from material constraints, and these become particularly relevant when hydrogen is introduced into the gas stream. Assessing compressor compatibility in detail is beyond the scope of this document; however, the functional limitations of compressors in hydrogen service are well established and widely recognized by the industry. It is also known that even at relatively low hydrogen concentrations, mitigation measures are required, while at higher blending ratios or pure hydrogen service, replacement of existing compressors may be necessary.

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6 Conclusions

This study systematically mapped the primary material families used in natural gas networks, focusing on key components such as pipelines, flanges/gaskets, valves, and compressors. Both metallic and polymeric materials were reviewed, with particular attention to hydrogen-related challenges. To evaluate hydrogen readiness at the component level, a traffic-light compatibility scheme was developed.

For metallic materials, the assessment prioritized fracture toughness (Kmat) as the principal criterion, followed by notch tensile strength and secondary properties such as ductility and other relevant mechanical characteristics. For non-metallic materials, the evaluation was based on available hydrogen compatibility data and insights from previous research projects.

The analysis revealed that many materials of the same type (such as plain carbon steel and low alloy steel) exhibit varying degree of hydrogen susceptibility, due to differences in composition, heat treatment, microstructure, testing conditions etc. For other material types, hydrogen compatibility remains uncertain due to lack of experimental data, such as fracture toughness testing (e.g., Nickel alloys).

Hydrogen readiness of materials and components is highly dependent on operating conditions, especially pressure and hydrogen concentration. Materials or components that may be unsuitable under high-pressure conditions could still perform adequately at lower pressures and reduced hydrogen content. Therefore, a case-by-case assessment is essential. The impact of these findings also depends on the complexity and feasibility of replacing or upgrading affected components. Components that are difficult or costly to replace pose greater challenges and require more critical attention.

From a structural integrity point of view, pipelines (together with their joints and weld) and valves are identified as the most critical components. Pipelines are the main component in gas grid, some pipes (TSO) are subjected to high-pressure, high-pressure variation and most of them are made of plain carbon steels which are not completely immune to hydrogen embrittlement, especially the high strength steel grades. Considering that grades X60, and X70 comprise a significant part of the gas grid, structural integrity assessment using the real working conditions of the pipelines and the current conditions of the pipe (defects) is required. Valves play key role in flow regulation including pressure control and, in many cases, the trim parts are made of high strength materials, such as martensitic steel, which are prone to hydrogen embrittlement. Compressors are also essential for gas grid operation; however, they have well-known operational limitations when hydrogen concentrations exceed approximately 10%, a threshold that will require adaptation, or, at higher hydrogen concentrations, replacement of existing compressor systems to ensure adequate performance.

It should be noted that the information available from previous studies is neither exhaustive nor always consistent. Data on material susceptibility to hydrogen, particularly under varying pressures and concentrations, can be limited or sometimes contradictory. This underscores the need for case-specific assessments and further field studies to reduce uncertainties and support reliable decision-making in the hydrogen-ready adaptation of gas network components.

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The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

8 Annex A: Materials employed in gas grid components and their compatibility with hydrogen

Table 8. Pipeline material list according to ASME B31.8.

Specification	Material type	Grades	Hydrogen compatibility
API 5L	Plain carbon steel	A25, A, B, X42, X46, X52, X56, X60, X65, X70, X80	Yellow
ASTM A53/A53M	Plain carbon steel	Grade A, Grade B	Yellow
ASTM A106/A106M	Plain carbon steel	Grade A, Grade B, Grade C	Yellow
ASTM A134	Plain carbon steel	Not specified	Yellow
ASTM A135/A135M	Plain carbon steel	Grade A, Grade B	Yellow
ASTM A139/A139M	Plain carbon steel	Grade A, B, C, D, E	Yellow
ASTM A333/A333M	Plain carbon steel	Grades 1, 3, 4, 6, 7, 9, 10, 11	Yellow
ASTM A333/A333M	High alloy steel	Grade 8	Red
ASTM A381/A381M	Plain carbon steel	Class Y-35, Y-42, Y-46, Y-48, Y-50, Y-52, Y-56, Y-60, Y-65, Y-70, Y-80	Yellow
ASTM A671/A671M	Low alloy steel	Not specified	Yellow
ASTM A672/A672M	Low alloy steel	Not specified	Yellow
ASTM A691/A691M	Low alloy steel	Not specified	Yellow

Table 9. Valve body and bonnet material list according to ASME B16.34.

Specification	Material type	Grades	Hydrogen compatibility
A105	Plain carbon steel	A105	Yellow
A216	Plain carbon steel	WCB, WCC	Yellow
A352	Plain carbon steel	LCB, LCC, LC2, LC3	Yellow
A350	Plain carbon steel	LF2 Cl.1, LF3 Cl.1, LF6 Cl.1/Cl.2	Yellow
A515	Plain carbon steel	Gr.65, Gr.70	Yellow
A516	Plain carbon steel	Gr.65, Gr.70	Yellow
A537	Plain carbon steel	Class 1	Yellow
A696	Plain carbon steel	Gr.C	Yellow

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A106	Plain carbon steel	Gr.C	Yellow
A672	Plain carbon steel	B70, C70	Yellow
A203	Low alloy steel	Gr.A, B, D, E	Yellow
A204	Low alloy steel	Gr.C	Yellow
A182	Low alloy steel	F1, F5, F5a, F9, F11 Cl.2, F12 Cl.2, F21, F22 Cl.3, F91, F92	Yellow
A217	Low alloy steel	WC1, WC9, C5, C12, C12A	Yellow
A387	Low alloy steel	Gr.11 Cl.2, Gr.22 Cl.2, Gr.91 Cl.2	Yellow
A739	Low alloy steel	B11	Yellow
A335 / A369 / A691	Low alloy steel	P11, P12, P21, P22, P91, P92, FP11, FP12	Yellow
A182	Austenitic stainless steel	F304, F304H, F304L, F316, F316H, F316L, F317, F317H, F321, F321H, F347, F347H, F348, F348H, F309H, F310, F310H, F44	Green
A351	Austenitic stainless steel	CF3, CF3M, CF3A, CF8, CF8M, CF8A, CG8M, CG8MF	Green
A240	Austenitic stainless steel	304, 304L, 304H, 316, 316L, 316H, 316Ti, 317, 317L, 321, 321H, 347, 347H, 348, 348H, 309H, 310, 310H	Green
A312 / A376	Austenitic stainless steel	TP304, TP304L, TP304H, TP316, TP316L, TP316H, TP317, TP317H, TP321, TP321H, TP347, TP347H, TP348, TP348H, TP309H, TP310, TP310H	Green
A479	Austenitic stainless steel	304, 304L, 304H, 316, 316L, 316H, 321, 321H, 347, 347H, 348, 348H, 309H, 310, 310H	Green
A358	Austenitic stainless steel	304, 316	Green
A430	Austenitic stainless steel	FP304, FP304H, FP316, FP316H, FP321, FP347	Green
A182	Duplex stainless steel	F51, F53, F55	Yellow
A351 / A995	Duplex stainless steel	CK3MCuN, CE8MN, CD4MCuN, CD3MWCuN	Yellow
A240	Duplex stainless steel	S31254, S31803, S32750, S32760	Yellow
B462 / B463 / B468 / B473 / B464	Nickel alloys	Alloy 20	Yellow
B564 / B162	Nickel alloys	N02200, N02201	Yellow
B127 / B564	Nickel alloys	Monel 400	Yellow
B168 / B564	Nickel alloys	Inconel 600	Yellow

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A182 / B564 / B409	Nickel alloys	Incoloy 800	Yellow
B462 / B333	Nickel alloys	Hastelloy B-2, Hastelloy B-3	Yellow
B462 / B575 / B443	Nickel alloys	N10276, Inconel 625, Alloy 825, C-22, Alloy 2000, N10001, N10003, N06455	Yellow
B572 / B435	Nickel alloys	Hastelloy X, R30556	Yellow

Table 10. Valves trim materials for gate, glove, check according to API 600, 603, 623, 594, 602. (B): Base; (S): Surface.

Trim	Disc/Wedge (B)	Disc/Wedge (S)	Seat (B)	Seat (S)	Stem /Backseat bushing (B)	Material type	Hydrogen compatibility
1	13Cr (F6)	Integral	13Cr	Integral	13Cr	Martensitic stainless steel	Red
2	304	Integral	304	Integral	304	Austenitic stainless steel	Green
2S	304	Co-Cr	304	Co-Cr	304	Austenitic stainless steel (Cobalt alloy)	Yellow
3	310	Integral	310	Integral	310	Austenitic stainless steel	Green
4	13Cr (F6)	Nitrided	13Cr	Nitrided	13Cr	Martensitic stainless steel	Red
5	13Cr	Co-Cr	Parent (manufacturer)	Co-Cr	13Cr	Martensitic stainless steel (Cobalt alloy)	Red
5A	13Cr	Ni–Cr	Parent (manufacturer)	Ni–Cr	13Cr	Martensitic stainless steel (Nickel alloy)	Red
5B	13Cr	Co–alloy (R31233)	Parent (manufacturer)	Co–alloy (R31233)	13Cr	Martensitic stainless steel (Cobalt alloy)	Red
6	13Cr	Integral	Cu–Ni seat ring	Integral Cu–Ni	13Cr	Martensitic stainless steel / Copper alloy	Red
7	13Cr	Hardened 13Cr	13Cr	Hardened 13Cr	13Cr	Martensitic stainless steel	Red
8	13Cr	Integral	13Cr or Parent	Co-Cr	13Cr	Martensitic stainless steel (Cobalt alloy)	Red
8A	13Cr	Integral	13Cr or Parent	Ni-Cr	13Cr	Martensitic stainless steel (Nickel alloy)	Red
9	Monel (Ni–Cu)	Integral	Monel (Ni–Cu)	Integral	Monel	Nickel alloy	Yellow

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10	316	Integral	316	Integral	316	Austenitic stainless steel	Green
11	Monel (Ni–Cu)	Integral	Monel (Ni–Cu)	Co-Cr	Monel	Nickel alloy (Cobalt alloy)	Yellow
12	316	Integral	316	Co-Cr	316	Austenitic stainless steel (Cobalt alloy)	Yellow
13	Alloy 20 (Ni–Fe–Cr)	Integral	Alloy 20	Integral	Alloy 20	Nickel alloy	Yellow
14	Alloy 20	Integral	Alloy 20	Co-Cr	Alloy 20	Nickel alloy (Cobalt alloy)	Yellow
15	304	Co-Cr	304	Co-Cr	304	Austenitic stainless steel (Cobalt alloy)	Yellow
16	316	Co-Cr	316	Co-Cr	316	Austenitic stainless steel (Cobalt alloy)	Yellow
17	347	Co-Cr	347	Co-Cr	347	Austenitic stainless steel (Cobalt alloy)	Yellow
18	Alloy 20	Co-Cr	Alloy 20	Co-Cr	Alloy 20	Nickel alloy (Cobalt alloy)	Yellow
19	Nickel (generic)	Integral	Nickel (generic)	Integral	Nickel (generic)	Nickel alloy	Yellow
19A	Alloy 625	Integral	Alloy 625	Integral	Alloy 625	Nickel alloy	Yellow
19B	Alloy C-276	Integral	Alloy C-276	Integral	Alloy C-276	Nickel alloy	Yellow
19C	Alloy 825	Integral	Alloy 825	Integral	Alloy 825	Nickel alloy	Yellow
20	Nickel (generic)	Integral	Nickel (generic)	Co-Cr	Nickel (generic)	Nickel alloy (Cobalt alloy)	Yellow
20A	Alloy 625	Integral	Alloy 625	Co-Cr	Alloy 625	Nickel alloy (Cobalt alloy)	Yellow
20B	Alloy C-276	Integral	Alloy C-276	Co-Cr	Alloy C-276	Nickel alloy (Cobalt alloy)	Yellow
20C	Alloy 825	Integral	Alloy 825	Co-Cr	Alloy 825	Nickel alloy (Cobalt alloy)	Yellow
21	Nickel (generic)	Co-Cr	Nickel (generic)	Co-Cr	Nickel (generic)	Nickel alloy (Cobalt alloy)	Yellow

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 11. Flanges material list according to ASME B16.47.

Specification	Material type	Grade	Hydrogen compatibility
ASTM A105	Plain carbon steel	A105	Yellow
ASTM A216	Plain carbon steel	WCB, WCC	Yellow
ASTM A352	Plain carbon steel	LCB, LCC, LC2, LC3	Yellow
ASTM A350	Plain carbon steel	LF1 Cl.1, LF2, LF3, LF6 Cl.1, LF6 Cl.2	Yellow
ASTM A515	Plain carbon steel	Gr.60, Gr.65, Gr.70	Yellow
ASTM A516	Plain carbon steel	Gr.60, Gr.65, Gr.70	Yellow
ASTM A537	Plain carbon steel	Class 1	Yellow
ASTM A182	Low alloy steel	F1, F2, F5, F5a, F9, F11 Cl.2, F12 Cl.2, F22 Cl.3, F91, F92	Yellow
ASTM A217	Low alloy steel	WC1, WC4, WC5, WC6, WC9, C5, C12, C12A	Yellow
ASTM A204	Low alloy steel	Gr.A, Gr.B, Gr.C	Yellow
ASTM A387	Low alloy steel	Gr.11 Cl.2, Gr.22 Cl.2, Gr.91 Cl.2	Yellow
ASTM A182	Austenitic stainless steel	F304, F304H, F304L, F309H, F310, F310H, F316, F316H, F316L, F317, F317L, F321, F321H, F347, F347H, F44	Green
ASTM A240	Austenitic stainless steel	304, 304H, 304L, 309H, 310, 310H, 316, 316H, 316L, 317, 317L, 321, 321H, 347, 347H	Green
ASTM A351	Austenitic stainless steel	CF3, CF3M, CF3A, CF8, CF8M, CF8A, CF8C, CG8M, CG8MF, CF3A, CH8, CH20, CK20, CK3MCuN	Green
ASTM A182	Duplex stainless steel	F51, F53, F55	Yellow
ASTM A240	Duplex stainless steel	S31254, S31803, S32750, S32760	Yellow
ASTM A995	Duplex stainless steel	CE8MN, CD4MCu, CD3MWCuN	Yellow

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Table 12. Flange material list according to ASME B16.5.

Specification	Material type	Grade	Hydrogen compatibility
ASTM A105	Plain carbon steel	A105	Yellow
ASTM A216	Plain carbon steel	WCB, WCC	Yellow
ASTM A352	Plain carbon steel	LCB, LCC, LC2, LC3	Yellow
ASTM A350	Plain carbon steel	LF1 Cl.1, LF2, LF3, LF6 Cl.1, LF6 Cl.2	Yellow
ASTM A515	Plain carbon steel	Gr.60, Gr.65, Gr.70	Yellow
ASTM A516	Plain carbon steel	Gr.60, Gr.65, Gr.70	Yellow
ASTM A537	Plain carbon steel	Class 1	Yellow
ASTM A182	Low alloy steel	F1, F2, F5, F5a, F9, F11 Cl.2, F12 Cl.2, F22 Cl.3, F91, F92	Yellow
ASTM A217	Low alloy steel	WC1, WC4, WC5, WC6, WC9, C5, C12, C12A	Yellow
ASTM A204	Low alloy steel	Gr.A, Gr.B, Gr.C	Yellow
ASTM A387	Low alloy steel	Gr.11 Cl.2, Gr.22 Cl.2, Gr.91 Cl.2	Yellow
ASTM A182	Austenitic stainless steel	F304, F304H, F304L, F309H, F310, F310H, F316, F316H, F316L, F317, F317L, F321, F321H, F347, F347H, F44	Green
ASTM A240	Austenitic stainless steel	304, 304H, 304L, 309H, 310, 310H, 316, 316H, 316L, 317, 317L, 321, 321H, 347, 347H	Green
ASTM A351	Austenitic stainless steel	CF3, CF3M, CF3A, CF8, CF8M, CF8A, CF8C, CG8M, CG8MF, CF3A, CH8, CH20, CK20, CK3MCuN	Green
ASTM A182	Duplex stainless steel	F51, F53, F55	Yellow
ASTM A240	Duplex stainless steel	S31254, S31803, S32750, S32760	Yellow
ASTM A995	Duplex stainless steel	CE8MN, CD4MCu, CD3MWCuN	Yellow
ASTM B564	Nickel alloys	Nickel 200, Monel 400, Inconel 600, Alloy 825	Yellow
ASTM B162	Nickel alloys	N02200, Nickel 201	Yellow
ASTM B127	Nickel alloys	Monel 400	Yellow
ASTM B168	Nickel alloys	Inconel 600	Yellow
ASTM A182	Nickel alloys	Alloy 800	Yellow
ASTM B409	Nickel alloys	N08800	Yellow

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ASTM B462	Nickel alloys	Hastelloy B-2, Hastelloy B-3, Hastelloy C-276, Alloy C-22	Yellow
ASTM B333	Nickel alloys	N10665, N10675, N10001	Yellow
ASTM B575	Nickel alloys	N10276, N06455	Yellow
ASTM B443	Nickel alloys	Inconel 625	Yellow
ASTM B424	Nickel alloys	Alloy 825	Yellow
ASTM B434	Nickel alloys	N10003	Yellow

Table 13. Ring joint gaskets material list according to ASME B16.20.

Specification	Material type	Grade	Hydrogen compatibility
Not specified - HRB < 56	Plain carbon steel	Soft iron	Yellow
Not specified - HRB < 68	Plain carbon steel	Low-carbon steel	Yellow
ASTM A182 - HRB < 72	Low alloy steel	4–6Cr–½Mo (F5)	Yellow
Not specified - HRB < 86	Martensitic stainless steel	410	Red
Not specified - HRB < 83	Austenitic stainless steel	304, 316, 347	Green

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 14. Spiral wound and grooved metal gaskets material list according to ASME B16.20.

Specification	Material type	Grade	Hydrogen compatibility
Not specified	Plain carbon steel	Carbon steel	Yellow
Not specified	Ferritic stainless steel	430	Yellow
Not specified	Martensitic stainless steel	410, 17-7 PH	Red
Not specified	Austenitic stainless steel	304, 304L, 304H, 309, 310, 316, 316L, 316Ti, 317L, 321, 321H, 347, 347H, 904L, AL-6XN, 254 SMO, Carpenter 20Cb-3 (Alloy 20)	Green
Not specified	Duplex stainless steel	2205, 2507	Yellow
Not specified	Titanium alloy	Ti Grade 2, Ti Grade 7	Yellow
Not specified	Nickel alloy	Monel 400, Nickel 200, Hastelloy B, Hastelloy B-2, Hastelloy B-3, Hastelloy C / Alloy C-276, Hastelloy C-22, Hastelloy C-2000, Inconel 600, Alloy 625 (Inconel 625), Inconel X-750 / X-750-HT, Inconel 718, Alloy 800, Alloy 800H, Incoloy 825	Yellow
Not specified	Copper	Copper	Yellow
Not specified	Tantalum	Tantalum	Yellow
Not specified	Zirconium	Zirconium	Yellow

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 15. Typical materials used in a centrifugal reciprocating according to API 617 (in brackets subcomponents that are wetted).

Component category	Material type	Grades (examples)	Hydrogen compatibility
Pressure-containing	Plain carbon steel	ASTM A216 WCB/WCC; A352 LCB/LCC	Yellow
	Low alloy steel	ASTM A217 WC6/WC9/C5/C12	Yellow
	Austenitic stainless steel	ASTM A351/A743/A744 (CF3, CF3M, CF8, CF8M)	Green
	Cast iron	ASTM A395 (ductile); A278 (gray)	Red
	Aluminum alloy	ASTM A356/A357	Yellow
	Titanium alloy	ASTM B367 (Grades C3/C4)	Yellow
Impeller	Austenitic stainless steel	316/316L, 304/304L; cast CF8M/CF3M/CF8/CF3	Green
	Martensitic stainless steel	CA6NM (13Cr-4Ni), 410/420, 17-4PH	Red
	Nickel alloy	Inconel 718/625, Alloy 825	Yellow
	Aluminum alloy	A356-T6, C355, 7xxx	Yellow
	Titanium alloy	Ti-6Al-4V (Grade 5)	Yellow
Shaft/Rotor components (balance piston, gas-side shaft sections, sleeves under labyrinths)	Low alloy steel	AISI 4140/4340/4320/9310, ASTM A470	Yellow
	Martensitic stainless steel	F6NM/CA6NM, 422, 17-4PH	Red
	Nickel alloy	Inconel 718/625	Yellow
	Titanium alloy	Ti-6Al-4V	Yellow
Labyrinths/Seals	Austenitic stainless steel	304/304L, 316/316L	Green
	Martensitic stainless steel	403/410/416/420	Red
	Nickel alloy	Inconel 625/718	Yellow
Internal mechanisms & structures (non-rotor) (inner barrel, diaphragms, return channels, crossover, diffuser passage)	Plain carbon steel	A216 WCB, A352 LCB	Yellow
	Low alloy steel	A217 WC6/WC9	Yellow
	Austenitic stainless steel	304/304L/316/316L/321/347; CF8/CF8M/CF3/CF3M	Green
	Aluminum alloy	5xxx/6xxx	Yellow
	Nickel alloy	Alloy 625/825	Yellow

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 16. Polymeric materials and their compatibility with hydrogen (based on the references in Table 5 and results from projects)

Polymeric material	Acronym	Application	Hydrogen Compatibility
Butadiene-Acrylonitrile Rubber	NBR	O-rings, gaskets, valve fittings and seals	Yellow
Polychloroprene	CR	Valve seals and gaskets	Green
Ethylene-Propylene	EPM & EPDM	Valve seals and gaskets	Green
Polyamide (11 and 12)	PA11 & PA12	Valve seats, seals and gaskets	Yellow
Silicone and Fluorosilicone	SI &FSI	Valve seals and gaskets	Red
Fluoroelastomer	FKM	O-rings, gaskets, valve fittings	Green
Perfluoroelastomer	FPM	O-rings, gaskets	Green
Polytetrafluoroethylene	PTFE &FTE	O-rings, gaskets, fittings, valve seats. Compressors seals and coatngs	Green
Polyetheretherketone	PEEK	Seals and gaskets. Compressors seals and coatngs	Green
Butadiene-Styrene	SBR	No specific data found	Yellow
Natural rubber	NR	No specific data found	Red
Polyethylene	PE	Pipes, valves	Green

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9 Annex B: Relevant standards

Table 17 Standards relevant to components in the gas grid

Components	Standards used in this study	Equivalent or Complementary Standards
Pipeline	**ASME B31.8** Gas Transmission and Distribution Piping Systems **API SPEC 5L** Line pipe	**EN 1594** – Gas infrastructure – Pipelines for maximum operating pressure over 16 bar – Functional requirements **EN 12007** series – Gas infrastructure – Pipelines for maximum operating pressure up to and including 16 bar Part 1 (General), Part 2 (Specific functional requirements for polyethylene), Part 3 (Specific functional requirements for steel) **EN 1555** series – Plastic piping systems for gaseous fuels – Polyethylene (PE): Parts 1 (General), 2 (Pipes), 3 (Fittings), 5 (Fitness for purpose of the system), and 7 (Assessment of conformity) **EN ISO 3183** – Steel pipe for pipeline transportation systems **EN 10255** – Non-alloy steel tubes suitable for welding and threading. **EN 969** – Ductile iron pipes, fittings, accessories and their joints for gas pipelines – Requirements and test methods **EN ISO 16486** series – Plastics piping systems for the supply of gaseous fuels – Unplasticized polyamide (PA-U) piping systems with fusion jointing and mechanical jointing: Part 1 (General), Part 2 (Pipes), Part 3 (Fittings) **EN 14870-1** – Petroleum and natural gas industries - Induction bends, fittings and flanges for pipeline transportation systems - Part 1: Induction bends (ISO 15590-1) **EN 13480** – Metallic industrial piping

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Valves	**ASME B16.34**. Valves—Flanged, Threaded, and Welding End **API 600, 603, 623, 594, 602, 598** **API Spec 6D** – Specification for valves.	**EN 13942** – Petroleum and natural gas industries - Pipeline transportation systems - Pipeline valves **EN 14141** - Valves for natural gas transportation in pipelines - Performance requirements and tests **EN 1555-4** – Plastic piping systems for gaseous fuels – Polyethylene (PE) – Part 4: Valves **ISO 10434** – Bolted bonnet steel gate valves for the petroleum, petrochemical and allied industries **ISO 10432** – Subsurface safety valves – Design, performance, and testing **ISO 10417** – Equipment for subsurface safety valve systems. **EN 13774** – Valves for gas distribution systems with maximum operating pressure less than or equal to 16 bar **EN ISO 16484-4** – Valves with non-plasticized polyamide body
Flanges	**ASME B16.47** Large Diameter Steel Flanges **ASME B16.5** Pipe Flanges and Flanged Fittings	**ISO 15590-3** – Petroleum and natural gas industries — Factory bends, fittings and flanges for pipeline transportation systems – Part 3: Flanges **EN 1759-1** – Flanges and their joints – Circular flanges for pipes, valves, fittings, and accessories, Class designated – Part 1: Steel flanges, Classes 150 to 2500 **EN 1092-1** – Flanges and their joints – Circular flanges for pipes, valves, fittings, and accessories, PN designated – Part 1: Steel flanges. Part 2: Cast iron flanges **CEN/TC 74** – Flanges and their joints (Technical Committee reference, not a standard)

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Gaskets	**ASME B16.20** Metallic Gaskets for Pipe Flanges	**EN 1514** series – Flanges and their joints – Dimensions of gaskets for PN-designated flanges, Part 1: Non-metallic flat gaskets with or without inserts; Part 2: Spiral wound gaskets for use with steel flanges; Part 3: Non-metallic PTFE envelope gaskets
Compressors	**API 617** Axial and Centrifugal Compressors and Expander-compressors **API 618** Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services	**ISO 10439** – Petroleum, petrochemical and natural gas industries – Centrifugal compressors – Design and testing **ISO 13707** – Petroleum, petrochemical and natural gas industries – Reciprocating compressors – Design and testing **ISO 13631** – Petroleum and natural gas industries – Reciprocating gas compressors – Performance and mechanical testing **EN 12583** – Gas Infrastructure. Compressor stations. Functional requirements
Pressure control and metering stations (not included in this report)	**ASME B31.8** Gas Transmission and Distribution Piping Systems	**EN 1776** - Gas infrastructure. Gas measuring systems. Functional Requirements **EN 12186** - Gas infrastructure. Gas pressure control stations for transmission and distribution. Functional requirements **EN 334** - Gas pressure regulators for inlet pressure up to 10 MPa (100 bar) **EN 12261** - Gas meters. Turbine gas meters.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

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

Clean Hydrogen Partnership

HORIZON 2020: Horizon Europe Framework Programme (HORIZON)

HORIZON-JTI-CLEANH2-2022-05-03

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