Position Paper

Hydrogen Europe Research

Compatibility of polymer-based materials

for the hydrogen transport infrastructure

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Abstract

Hydrogen is central to Europe's decarbonization strategy, yet the safe and cost-effective transport remains a critical challenge. Polymer-based materials are increasingly considered for pipelines, storage vessels, seals, gaskets, and flexible connectors due to their corrosion resistance, lightweight properties, and cost advantages. However, their long-term performance under hydrogen exposure—especially under high pressures, fluctuating temperatures, and cyclic loading—remains insufficiently understood. Unlike metals, polymers do not chemically react with hydrogen, but they are subject to permeation, swelling, and rapid gas decompression damage, which can compromise integrity and safety. Existing qualification standards, often inherited from the oil and gas sector, are not fully suited to hydrogen applications. This position paper outlines the state of knowledge on hydrogen–polymer interactions, identifies research gaps, and proposes priorities for advancing material qualification. Key needs include standardized accelerated testing protocols, reliable lifetime prediction models, and the development of PFAS-free sealing solutions. Establishing shared databases and coupling experimental benchmarks with modelling approaches will be essential to accelerate innovation. Addressing these challenges will enable safer and more efficient hydrogen transport, reduce costs, and strengthen public confidence in hydrogen technologies, thereby supporting Europe's clean energy transition.

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1

Introduction

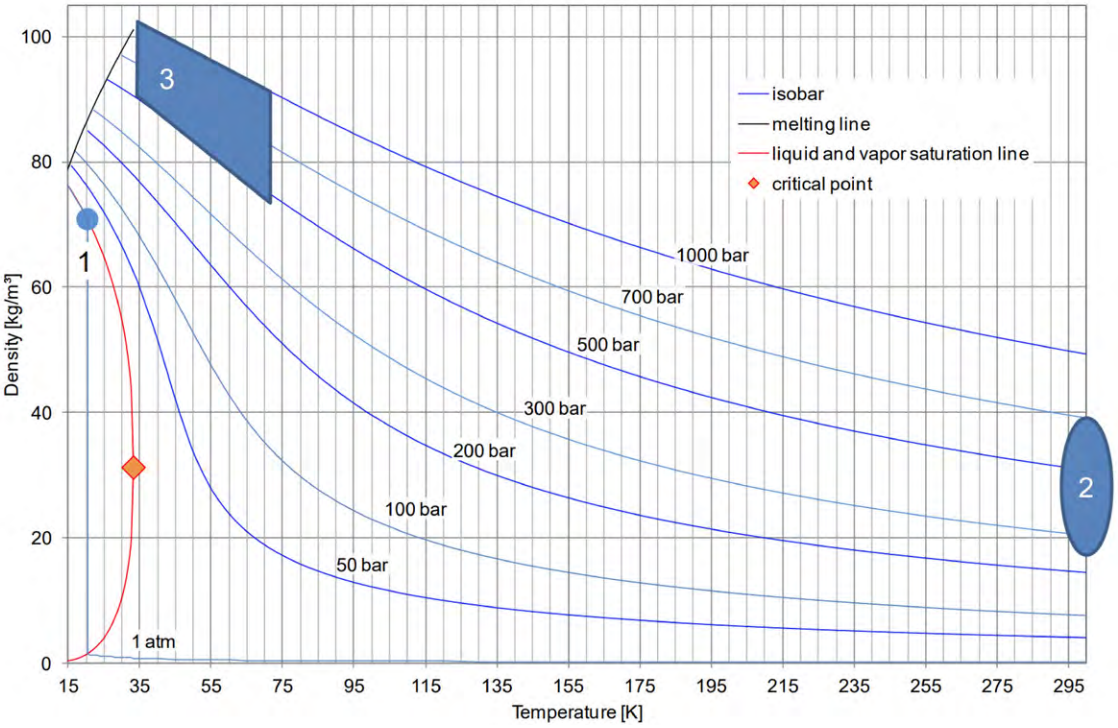
As the global energy landscape shifts toward decarbonization, H_2 is emerging as a key enabler of a low-carbon economy. Its versatility as an energy carrier and feedstock offers compelling solutions for sectors such as transportation, power generation, and industrial manufacturing. However, the widespread deployment of hydrogen infrastructure poses significant materials challenges, particularly in the safe and efficient transport of hydrogen gas under varying pressure and temperature conditions. The transition towards H_2 as an energy carrier is already gradually progressing, with low-medium concentrations of H_2 blended with natural gas (NG) being trialled on small scales to decarbonise gas supplies in Germany, France, UK and Denmark[1]. Further implementation will be dictated by the confidence in technology, as well as economic and regulatory drivers. In the *Clean Hydrogen to Europe* project, which is part of the Zero Carbon Energy Hub, blending hydrogen into NG for pipeline distribution from 2030 is considered for a transition period to reduce upfront investment costs. Nevertheless, to ensure safe and reliable H_2 transport and storage, the performance of the materials used in the infrastructure must be well understood.

Table 1. Main polymers used in H_2 transport[2,3,19].

Typical Thermoplastics	Applications
Polyethylene (HDPE/UHMWPE)	High/low pressure pipes, valve seats, coatings, composites
Polyamides (PA6, PA66, PA12)	
Polyphenylene sulfide (PPS)	
Polyaryletherketones (PAEK)	
Fluoropolymers (PTFE, PVDF)	
Polyvinyl chlorides (PVC/CPVC)	
Typical Elastomers	**Applications**
Ethylene propylene diene monomer (EPDM)	Overmoulded or loose O-rings, gaskets, energized seals
Fluoroelastomers (FKM, FFKM)	
Nitrile butadiene rubbers (NBR)	
Chloro-rubbers (CR, ECO)	
Typical Thermosets	**Applications**
Epoxy resins (e.g. FBE)	Flow coatings
Phenolic resins (VER)	
Polyurethanes (TSU)	

Polymer-based materials have received increasing attention for their vital roles in hydrogen transport systems, especially in pipelines, storage vessels, seals, gaskets, and flexible hoses (Table 1). High-density polyethylene (HDPE) and polyamides (PA) are commonly used in H_2 storage tanks and as liner material in H_2 pipelines (> 100 bar). Polypropylene (PP) or polyvinyl chlorides (PVC/CPVC) are typically used in low-pressure H_2 pipelines.

Figure 1: H_2 storage conditions: (1) liquid H_2 around 20 K at low pressure, (2) pressurised H_2 at pressure range between 250 and 700 bar at room temperature, and (3) cryogenic compressed H2 around 500 – 1000 bar. Reproduced from [5].



Fluoropolymers (PTFE/PVDF), polyether-etherketones (PEEK/PEKK) and fluoroelastomer (FKM) are common sealing materials in valves, while PTFE is also used as a material for low temperature seals. More generally, elastomeric materials are widely used in sealing components and for example, control valves, flexible hoses, and connectors, which are also directly exposed to high-pressure H_2 conditions. Here, materials such as ethylene propylene copolymer (EPM), silicones and neoprene (CR) are applied.

Compared to metals, polymers offer advantages such as corrosion resistance, ease of fabrication, reduced weight, and cost-effectiveness. However, while the damaging embrittlement effects of H_2 on metals has been the subject of many research projects[4], much less is known about the effects of H_2 on polymer and composite materials. Nonetheless, their interaction with hydrogen involves complex phenomena, including permeation, physical or chemical aging, and potential degradation under high-pressure cyclic loading, all of which could compromise long-term performance and safety.

Especially challenging for the application of polymer-based materials along the H_2 value chain is the wide range of temperature and pressure that the materials can potentially experience as indicated in Figure 1[5]. For example, conditions can range from cryogenic storage at medium pressure though at very low temperatures (<35 K and 5-15 bar) to pressurised H_2 storage at 250 to 1000 bar. A typical temperature range for gaseous pressurised H_2 systems is 233 K (-40 °C) to 358 K (85 °C), but temperatures as high as

473 K (200 °C) can be reached in some compressors, while in the cryo-compressed range polymers can potentially be exposed to 35-75 K at pressures between 700-1000 bar.

The scope of this position paper on the “Compatibility of polymer-based materials for the hydrogen transport Infrastructure” is to guide research efforts and align priorities for future advancements in the use of polymer-based materials along the hydrogen value chain. The position paper highlights the current state of research and introduces research challenges.

2

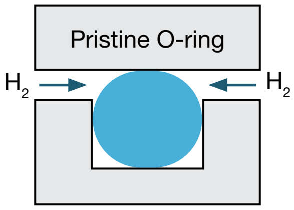
Current State of Research

In contrast to metals that can react with hydrogen and form brittle metal hydrides, polymers are basically chemically inert to hydrogen, with the exception of few peculiar cases (e.g., acrylonitrile butadiene rubber[6] (NBR) and HDPE[7]). Nevertheless, the most significant effects are due to dissolved hydrogen that can interact physically with polymers[8] and any damage to the polymer is believed to primarily result from mechanical failure related to the absorption of hydrogen[9]. It is widely accepted that most damage to polymers in hydrogen applications occurs during sudden decompression of high-pressure hydrogen, commonly referred to as explosive decompression failure (XDF) or rapid gas decompression (RGD) damage. In addition to decompression damage effects, other hydrogen effects are related to physical stability (dimensional and property changes), dynamic frictional wear, rapid temperature cycling effects and issues related to material contamination. Furthermore, permeation (hydrogen fugitive emission) needs to be specifically assessed, especially under high pressure and temperature, and to be guaranteed over time. Polymers are indeed inherently permeable to small molecules and gases and these represent a drawback which must be addressed. In particular, semicrystalline polymers such as polyamides (and PA6 in particular) or HDPE have been mainly considered in order to meet the leak rates suggested for the different applications[10],[11]. For this reason, in the open literature many studies are available which focus on the characterization of hydrogen permeability in these polymers.

For PAs, Humpenoder[12] measured hydrogen permeability and diffusivity in an undefined polyamide between -10 and 30 °C while, Kanesugi *et al*.[13] considered the same quantities in PA6, PA12 and PA11 at 30 °C. Tests for PA 11 were then extended to high pressures up to 900 bar. Similar pressure range was also considered by Dong et al.[14] who measured the variation of H_2 permeability in PA6 at pressure ranging from 150 and 900 bar for different temperatures (35–85 °C). The increase of barrier properties related to the addition of different fillers such as carbon fibers or nanoclays was also considered and estimated by different authors[15],[16]. In the case of HDPE, Humpenöder[11] measured hydrogen permeability and diffusivity at temperatures ranging between -10 and 30 °C. Smith and Anovitz[17] pointed out that the permeability of hydrogen in HDPE is affected by the forming process and pressure, while more recently Fujiwara *et al.*[18],[19] measured hydrogen transport properties in HDPE and other polyethylenes at 30 °C and pressures up to 900 bar. General results shows that PA, and PA6 in particular, has lower permeability with respect to HDPE despite the lower crystallinity. It is therefore preferred as barrier for hydrogen storage applications. In particular, liner thicknesses in the order of 1-3 mm allow to fulfil the EU regulation for hydrogen storage on vehicles[20],[21].

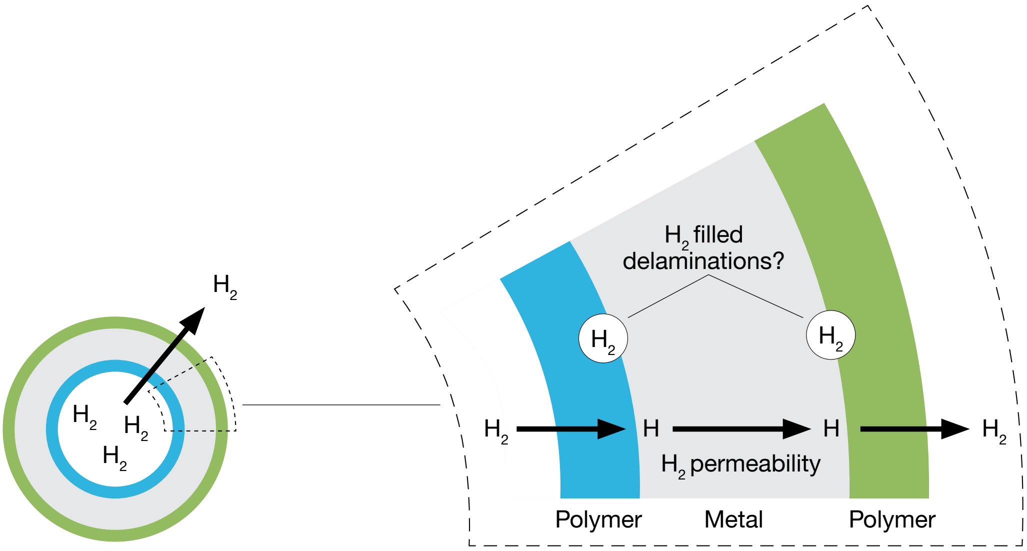
Polymer based materials used today in oil and gas distribution are often based on those qualified use in that industry (e.g. NORSOK M710 or ISO 23936-2), but not designed for transport of pure or blended H_2 or H_2 carriers, like MeOH or NH_3. Even though the solubility of H_2 in polymers is low in view of its very low condensability, swelling of 70-80 % has been reported in elastomer compounds exposed to high pressure H_2[22], which clearly risks seal extrusion (Figure 2) and tearing[23]. Even though massive swelling is often seen, it should not be forgotten that such changes are often less relevant for H_2 compared to other gases, and observed to be reversible (in case no explosive decompression or tearing damages have occurred).

Figure 2: O-ring extrusion due to H_2 swelling. Adapted from Balasooriya, 2022.



On depressurisation, this absorbed H_2 can then cause rapid gas decompression (RGD) damage, in which gas absorbed under pressure (in polymer free volume or in pre-existing pores) expands to tear the elastomer. For example, it has been reported that elastomeric seals can contain 3 % voids, often <40 µm, which may act as inflation points[5]. Pre-existing defects may act as nucleation sites for decompression damage, also known as blister fracture, which were measured in EPDM by Yamabe and Nishimura using atomic force microscopy[24]. Alternatively, gas under pressure can create new pores under depressurization by nucleating at defect sites such as at polymer-filler interfaces. The degree of inflation of bubbles within the polymer has been reported in literature, allowing a prediction of damage based on polymer properties and depressurisation parameters[25]. The toughness of the polymer will influence the effect of this damage; less tough polymers (for example, polymers below their glass transition temperature, or elastomers with high shear modulus, high crosslink densities or which have become more brittle due to aging effects[26] or embrittlement by plasticizer extraction/blooming[7]) are more likely to tear or fracture. In addition, the volumetric swelling caused by H_2 absorption has been shown to enable phase separation of unbound additives (*e.g.* plasticizers). This phase separation can cause local changes in mechanical properties, further reducing tear resistance. This has for example been shown to occur for EPDM under high pressure hydrogen cycling[27]. Regarding thermoplastic materials, such RGD damages have also been evidenced experimentally, the severity of the phenomenon depending on material properties (strength and transport properties) as well as environmental conditions (pressure delta, decompression speed, number of cycles, simultaneous mechanical loading)[28,29]. Experiments have supported the establishment of models able to predict the probability of the occurrence of RGD damages[30]. Since thermoplastics are often used when structural properties are needed, the major damage risk is at the interface between materials, due to cyclic (de-)pressurizations, and rapid expansion mismatches with the non-polymer counterparts. In the case of fibre reinforced thermoplastics, fibre-matrix and ply interface damage reduces load transfer

Figure 3: Diffusion of H_2 through a polymer-metal multimaterial structure (pipe wall).



efficiency, lowering the mechanical properties and enhance leak path creation[31]. Graphite has long been studied for fuel-cell applications[32], but the influence of hydrogen exposition on graphite-based fibre-reinforced polymers has hardly been investigated up to now. In the case of multi-material structures comprising metals and thermoplastics (e.g. polymer-metal laminates in combined power/hydrogen transport umbilicals, or coated metal structures) interfacial delamination may lead to shortcuts through the polymer, increasing overall leakage. Since the diffusion of gases through metals is slower than through most polymers or polymer-based composites, high pressure gas accumulation at defects at the polymer-metal interface (e.g. due to manufacturing defects or progressive damage) are a particularly complex scenario to understand, but are a key part of failure modes of these structures (Figure 3). In the long term, the effects of H_2 on polymers and multi-material structures with polymers have not been comprehensively determined; further research is needed to investigate progressive failure modes.

With the development of H_2 as an energy vector, its delivery and transport from the production site to the end user remains an issue. Hydrogen blending in natural gas networks is gaining momentum as a strategy to decarbonize energy systems. This approach involves mixing hydrogen, typically up to 20% by volume, into existing natural gas pipelines, leveraging current infrastructure to reduce carbon emissions. In other cases the blending with up to 60 vol.% H_2 (H2NG) is investigated. For example, the EU-funded THyGA project[33] "Testing Hydrogen for Gas Applications" investigated the impact of blends of natural gas and hydrogen on end use applications, specifically in the domestic and industrial sectors. The key challenge to overcome for the existing pipeline network is the higher H_2 permeation through existing polymer infrastructures used for natural gas distribution. As the amount of hydrogen injected into the natural gas grid increases, the elastomeric materials used in fittings and gaskets may be challenged to withstand H_2 permeation. As a result, sealing difficulties may occur at fittings that are effective with natural gas but not in the presence of hydrogen. Also, due to its higher solubility, the co-existence of high pressure (>150 bar) CH_4 could cause significant swelling, affecting the polymer free volume and so reducing the barrier properties. Klopffer *et. al.* investigated the permeation of pure hydrogen and mixtures with natural gas (20% of CH_4 and 80% of H_2) in pipeline materials[34]. In this work the permeability of both hydrogen and methane has been found independent of gas composition, which makes direct comparison possible in spite of the various experimental conditions. Also, within the FP6 project NATURALHY[35] (*Preparing for the hydrogen economy by using the existing natural gas system as a catalyst*), key issues of blending hydrogen into the natural gas pipeline networks were investigated. With respect to H_2 permeation through PE, an increase in gas loss with hydrogen content was seen, partially as expected because of the higher H_2 permeation rate compared to CH_4. No clear change in either the hydrogen or methane permeability was observed as function of gas composition. The EU-funded HIGGS project[36] also aimed to identify and bridge knowledge gaps on the impact of high amounts of H_2 on the high-pressure gas infrastructure and its components. To reach its aim, it has mapped technical, legal and regulatory barriers, helped determining the economic viability of hydrogen injection into the gas grid, and tested various technical solutions. The tightness and compatibility of different components and equipment of the existing high-pressure gas grid up to 100% H_2 was evaluated. All valves remained tight for the duration of the test, with just minor hydrogen losses due to hydrogen leakage through the main body of the valves. Finally, no apparent damage was found on the different parts of the valves, pressure regulator, cartridge filter and turbine gas meter components after their exposure to hydrogen. According to the results, the high-pressure natural gas grid would be ready for its repurpose, aiming for the large-scale transport of 100% hydrogen.

3

Research Challenges

As exemplified in section 1 and 2, the use of polymeric materials in the H_2 value chain has knowledge gaps, complicating material selection. An increased understanding of properties and failure modes will greatly advance material qualification and standardization, which are both of great industrial importance. One focus is thus to relate short-term accelerated testing of H_2-induced polymer aging to the long-term effects of H_2 on the polymers and multi-material structures, setting the basis for the future material qualification. Ongoing research focuses on multilayer structures and polymer composites to improve barrier properties and mechanical strength. Long-term durability data is limited, especially for cyclic loading, wear and aging effects in hydrogen-rich environments. Moreover, the influence of environmental impurities on their behaviour has to be considered to assess the reliability of their use. The effect of some parameters such as temperature, material crystallinity or internal stresses is however little to not documented in the literature. As such parameters can have competitive positive-detrimental influence on the initiation of RGD-induced damages, such understanding would benefit the establishment of clear guidelines for the test parameters to adopt in a procedure to assess the compatibility of polymers for hydrogen applications. Accurate benchmarks need to be developed to study the behaviour of novel components and seals in operating conditions to strengthen their reliability. As part of these studies, particular attention must be paid to assembly techniques and as a consequence to heterogeneous interfaces, focusing on the risks of leakage and maintaining their integrity in a hydrogen environment subject to external stresses. Using exhaustive databases and instrumented benchmarks, these experimental works must also be coupled with numerical and mechanistic modelling studies in order to offer a better understanding of their behaviour in service, to support new developments and lifetime prediction.

While PFAS (per- and polyfluoroalkyl substances) restriction is under discussion, their use is critical for the hydrogen sector because of the strict performance requirements that demand a high level of tightness and limitation of fugitive emissions from sealing devices and processing equipment. R&D works have to be launched on new PFAS-free material solutions and sealing design in order to evaluate the gap to be bridged to fulfil the expected in-service specifications using dedicated characterization equipment and benchmarks.

There is also a need for standardized testing protocols and lifetime prediction models under realistic hydrogen conditions. Recent international standards and guidelines, such as those from ISO and ASTM, are beginning to address hydrogen-specific performance criteria for polymeric components. However, a unified framework for long-term testing and certification under hydrogen exposure is still under development. Furthermore, the identification of a clear and reliable accelerated ageing protocols, for instance, will be of great relevance.

4

Timeline and Resources

The short-term focus of research activities is proposed to lay on the establishment of standardized test-protocols for accelerated material qualification to facilitate rapid deployment of a variety of polymeric or composite materials in the hydrogen economy. Special focus in the short-term should be on the development of a test linking short-term test results to long-term properties under hydrogen atmosphere. Studies should include the investigation of the effect of gas impurities, cyclic loading, wear and tear and initial material properties such as material crystallinity and micro-structure, or internal stresses to enable establishment of comprehensive guidelines.

In the medium-term, focus should be on the qualification of novel sealant materials to replace existing PFAS-based structures to facilitate the envisioned phase-out of PFAS materials in industrial production. Concurrently, establishment of accurate benchmarks for novel components and materials should be developed with particular attention to the assembly techniques.

Complementary to the efforts in the short- and medium-term, establishment of a shared database for the effects of hydrogen on polymers facilitates the long-term utilization of gathered data in numerical and mechanistic studies of new components and their behaviour in service.

5

Rationale for Advancing Research in This Area & Potential Applications

One of the key enablers of societal acceptance of novel technologies such as hydrogen and related infrastructure is the trust of stakeholders in the research processes as well as the institutions involved[37]. A large-scale rollout of hydrogen infrastructure thus requires the active involvement and communication to local communities regarding safety and health risks of planned hydrogen projects. Extensive investigation, assessment and qualification of long-term stability and safety of employed materials prior to deployment is one of the factors for strengthening public trust in hydrogen technologies. As polymer products such as sealings, gaskets, pipes or fibre reinforced tanks are being applied along the whole hydrogen value chain, research clarifying the effects of hydrogen on polymer products paves the way for further implementation and societal integration of the European hydrogen economy. Enabling a rapid qualification of novel materials for hydrogen applications by development of a methodology permitting transfer of short-term experimental results to long-term property predictions shortens the development cycles of new products, thereby improving competitiveness of industry actors. Furthermore, enabling utilization of polymer pipes and tanks for the hydrogen economy facilitates a reduction in transport and installation costs and a subsequent reduction in carbon footprint of the infrastructure needed for deployment. The transition to a hydrogen-based energy system is a cornerstone of Europe’s decarbonization strategy. However, the safe, efficient, and cost-effective transport of hydrogen remains a critical bottleneck. Polymer-based materials, due to their corrosion resistance, lightweight nature, and cost advantages, are increasingly considered for use in hydrogen infrastructure. Yet, their long-term behaviour under hydrogen exposure—especially under high pressure, temperature fluctuations, and cyclic loading—remains insufficiently understood. Offering a cost-effective alternative to metals, polymers may contribute to a massification of new hydrogen usages supporting the reduction of the overall cost of the value chain. Moreover, these developments may support the optimization of hydrogen infrastructure facilitating the compatibility with existing gas networks, reducing capital expenditure and accelerating deployment timelines. The development of advanced materials and testing infrastructure foster innovation, supporting SMEs and industrial competitiveness in the hydrogen economy, while enhancing reduction of the risk of leaks and failures, thus ensuring safer energy systems for communities with an alignment with environmental regulations and reduction of long-term ecological risks associated with persistent chemicals.

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