We Manufacture Innovation

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March 13, 2025

Dr. Zhongquan Zhou
PHMSA

EWI Project No. 60409GTH

Dear Dr. Zhongquan Zhou:

Enclosed is EWI's report for the above referenced project. Please feel free to contact me at jellis@ewi.org if you have any questions or comments regarding this project.

Sincerely,

Jeff Ellis

Jeff Ellis, PhD
Senior Technology Leader
Polymers

Enclosure

Investigating the Integrity Impacts of Hydrogen Gas on Polymer Composite/Multi-Layered Pipe

Contract No. / PO NO. DOT PHMSA Agreement #**693JK32310009POTA**

EWI Project No. **60409GTH**

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Submitted to:

U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA)

Report

Project No. 60409GTH

on

Investigating the Integrity Impacts of Hydrogen Gas on Polymer Composite/Multi-Layered Pipe

to

PHMSA

March 13, 2025

Jeff Ellis, PhD
EWI
1250 Arthur E. Adams Drive
Columbus, OH 43221

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Executive Summary

Polymer-based composite pipes are increasingly being used or considered as an alternative for metallic pipe in numerous conventional and low carbon oil and gas applications, such as hydrogen transmission. The use of composite pipes can be in stand-alone pipelines, or as an internal liner to retrofit existing steel pipeline networks. The growth in the use of composites in recent years is being driven by lower material and installation costs as compared to conventional welded steel pipelines, and reduced corrosion concerns. Many types of composite pipe can be manufactured in long continuous lengths and spooled on reels for transport. These features can significantly reduce material and transport cost, labor and numerous logistics concerns related to pipe procurement and pipeline construction. While interest in using and deploying composites is growing, there may still be unknowns about safety using them for hydrogen transmission. This report intends to inform the reader of the pipes' long-term durability, inspection and condition monitoring methods, and safety when used in pressured hydrogen applications.

In this report, the materials, design, and construction of composite pipes is described. The subtleties of different types of composite pipes, such as spoolable, thermoplastic composite pipe (TCP), and reinforced thermosetting resin (RTR) pipe, is explained. Safety hazards related to hydrogen transmission are identified. These include hazards related to the pipeline facilities, people, and the surrounding environment. A summary of an extensive literature review of private and public efforts, a broad canvassing and surveying of material suppliers, composite pipe manufacturers, pipeline operators, and regulatory agencies are included. Information from technical journal articles, industry publications, manufacturing marketing materials, conference proceedings, media and news sources, and U.S. national labs reports are all included as well. Standards and codes that address the hazards are named and remaining gaps in them are also discussed. This paper includes demonstration projects of using polymer pipes for hydrogen distribution or transmission.

The findings of this paper include gaps in codes and standards, potential safety risks including structural health monitoring, gas contaminates, and permeation concerns, as well as the differences in failure modes for a variety of materials and construction for composite multilayer pipes.

Many standards exist for composite pipes, since they have been used for multiple decades, but the references to hydrogen transmission are lacking. ASME B31.12 Case 200 is the most complete document for hydrogen piping and pipelines using composites. API 15S (onshore) and DNV-ST-F119 (offshore) are the most complete documents for composite pipes but have yet to mention using them for hydrogen. There are working groups discussing what is needed to update the documents to include hydrogen transmission. Over the next several years new documents will be released.

Some of the potential safety risks are associated with structural health inspection and real-time hydrogen leak monitoring. Embedded fiber optic sensors, annulus concentration monitoring, smart pipeline integrity gauge (PIGs), and other technologies are all being developed to address these safety concerns. Another potential risk is the introduction of mixed or contaminated gas streams. The sources of hydrogen may vary widely and contaminates from the production of blue and gray hydrogen could be carbon monoxide, carbon dioxide, nitrogen, water vapor, methane, and oxygen. These molecules may be present in hydrogen streams and interact with the pipelines for transmission. Effects of these molecules, and their mixtures, with composite pipeline materials should be considered and tested before choosing materials and commissioning infrastructure.

Due to the flammability, explosivity, and negative Joule-Thompson coefficient, special attention should be given to purging and venting requirements and protocols due to potential void formation in polymeric materials, hydrogen heating during depressurization, and the related explosion hazards when mixed with air. This also extends to permeated hydrogen that could collect in spaces like casings under roads, train tracks, and other throughways. Standards may need to include venting or purging requirements for these spaces to ensure they never reach the lower flammability limit. Additional regulations for permeation testing and limits could be enacted to ensure the safety of the people and environment near the pipelines.

Finally, there are many different materials, constructions, and diameters manufactured in the polymer composite pipe industry. Their failure mechanisms vary, most significantly different from thermoplastic to thermoset pipes. Due to these differences, the standards for short-term testing to predict long-term performance may need to be delineated to ensure safety for each type of pipe.

Abbreviated Terms

aHC	amorphous hydrogenous carbon
ACM	polyacrylate
AI	artificial intelligence
AMI	Applied Market Information
API	American Petroleum Institute
API	American Petroleum Institute
ARCH2	Appalachian Hydrogen Hub
ARCHES	California Hydrogen Hub
ARIA	Analysis, Research and Information on Accidents
AU	urethane
BR	butadiene
CLT	constant load testing
CRA	corrosion resistant alloy
CRLP	Composite Reinforced Linepipe
CSA	Canadiean Standards Association
CSM	chlorosulfonated polyethylene
CT	computed tomography
CTL	continuous tensile load
DAS	Distributed acoustic sensing
DGEBA	diglycidyl ether of bisphenol A
DNV	Det Norske Veritas
DOE	Department of Energy
DSC	differential scanning calorimeter
EIGA	European Industrial Gases Association
EMAT	electromagnetic acoustic technology
EPDM	ethylene propylene diene monomer
EPM	ethylene propylene
EU	urethane
EVOH	ethylene vinyl alcohol
FBE	fusion bonded epoxy
FBG	fiber with a Bragg grating
FCP	flexible composite pipe
FEPM	tetrafluoroethylene/propylene rubber
FET	Field Effect Transistor
FFKM	perfluoroelastomer
FKM	fluorine rubber/ fluoroelastomer
FRP	Fiber-Reinforced Plastics
FSI	Fluorosilicone
GERG	European Gas Research Group

GFEP	glass fiber with epoxy cross-plies/glass filled epoxy plies
GFRP	glass fiber-reinforced polymer
GH_2	Gaseous Hydrogen
GO	graphene oxide
GPU	Gas Permeance Units
GRE	Glass-Fiber Reinforced Epoxy
GRP	Glass Reinforced Plastics
GRV	Glass-Fiber Reinforced Vinyl Ester
H2T	H_2 Offshore Transport
HDPE	high density polyethylene
HDPE-RT	high density polyethylene raised temperature
HFTO	Hydrogen and Fuel Cell Technology Office
HIAD	The Hydrogen Incident and Accident Database
HIC	hydrogen induced cracking
HNBR	hydrogenated nitrile butadiene rubber
HPHP	high-pressure hydrogen gas permeation test
IFPN	IFP Energies Nouvelles
IIR	Butyl
IMCI	Integrity Management Continuous Improvement
INGAA	Interstate Natural Gas Association of America
IR	Infrared
JIP	joint industry project
LCP	liquid crystal polymer
LDPE	low density polyethylene
LTS	Local Transmission System
MDA	methylene-dianiline
MDPE	medium density polyethylene
MFL	magnetic flux leakage
MPPT	magnetic permeability perturbation testing
MPR	Maximum Pressure Rating
NAPSR	National Association of Pipeline Safety Representatives
NBR	Nitrile Butadiene/nitrile rubber
NDE	nondestructive evaluation
NDT	nondestructive testing
NIC	non-metallic innovation center
NOV	National Oilwell Varco
NTS	National Transmission System
OIT	oxidation induction test/oxidative induction time
PA	polyamide
PA11	polyamide 11
PAHM	poly(6-aminohexyl methacrylate)

Pd	palladium
PE	polyethylene
PEEK	polyetheretherketone
PEI	polyethyleneimine
PE-RT	Polyethylene-raised temperature
PET	polyester terephthalate
PFR	Product Family Representative
PIG	pipeline integrity gauge
PMMA	polymethylmethacrylate
PNWH2	Pacific Northwest Hydrogen Hub
Ppb	parts per billion
PPI	Plastic Pipe Institute
PPS	polyphenylene sulfide
PS	polystyrene
Pt	platinum
PTFE	polytetrafluoroethylene
PVA	poly(vinyl alcohol)
PVA-co-PE	polyvinyl alcohol-co-ethylene
PVDF	polyvinylidene fluoride
QRA	quantitative risk assessment
RGD	rapid gas decompression
ROW	right of way
RTP	Reinforced Thermoplastic Pipe
RTR	reinforced thermosetting resin
SBR	butadiene styrene
SCG	slow crack growth
SCP	Spoolable composite pipe
S-GRE	Spoolable glass-fiber reinforced epoxy
Si	silicone
SSC	sulfide stress cracking
SSRT	slow strain rate testing
STBP	short-term burst pressure
STP	standard temperature and pressure
T	Polysulfide
TCP	thermoplastic composite pipe
TDA	thermal desorption analysis
THz	terahertz
TPU	thermoplastic polyurethane
UEWS	ultimate elastic wall stress
UV	ultraviolet

1. Introduction

1.1 Hydrogen Economy

Hydrogen is the only fuel, except electricity, that is a secondary energy carrier that can be derived from any primary energy source, thus allowing for long-term renewable energy production.(Erdener et al., 2023) The reasons that the hydrogen economy continues to gain interest are the global push to reduce CO_2 emissions with the intent to mitigate global warming, the Nationally Determined Contributions to reach carbon neutrality, the introduction of carbon trading, and the green investment needs of oil and gas companies. (Hunt et al., 2022) As far as sustainable technologies, hydrogen saw the largest investment increase in 2019 and 2020. And in 2022, President Biden announced a decarbonization goal to reduce levels to 50% of what they were in 2005 by 2030.(Shandross et al., 2021) Some of this is due to hydrogen similarities to natural gas for storage and transmission, so existing infrastructure could potentially be used. In 2022, companies such as Shell, BP, ExxonMobil, and Chevron all had plans to expand their hydrogen production or distribution, as of 2024 Shell and BP both withdrew from these activities.

The production method of hydrogen is an important consideration for decarbonization efforts. Blue or green hydrogen are environmentally friendly alternatives to existing natural gas. Cost effective options for producing green hydrogen include using photovoltaic solar, concentrating solar, onshore wind, and offshore wind energy sources. Gray hydrogen is produced from fossil fuel feedstocks without carbon capture is not considered environmentally friendly. (Shandross et al., 2021)

In May 2023, researchers completed an extensive model of the European energy economy to evaluate the financial appeal of a hydrogen economy, with the intention of stimulating more environmentally friendly energy production to achieve the goal of producing ten megatons of renewable hydrogen in the European Union and import six megatons of renewable hydrogen. They used a model based on 24-bus IEEE Reliability Test System, considering the following costs:(Klatzer et al., 2024)

- Cost for supplying natural gas to the system
- Operation and maintenance (OM) costs of gas-fired thermal units
- Cost for startup, commitment, and generation of thermal units (except gas-fired thermal units)

- OM cost of renewable units
- OM cost of storage units (power system)
- Cost of electricity non-supplied
- Cost of hydrogen and natural gas non-supplied
- CO_2 costs of thermal units (except gas-fired thermal units)
- CO_2 costs of gas-fired thermal units
- Cost of CO_2 emissions in the industry sector
- Investment costs for power generation units
- Investment costs for transmission lines
- Investment costs for hydrogen units
- OM costs for hydrogen units
- Investment costs for natural gas units
- OM costs for natural gas units
- Investment costs for hydrogen pipelines

The model showed that by using current natural gas pipelines to transport approximately 27.7% of hydrogen used, a hydrogen blend of 10% is sufficient to justify investments in hydrogen infrastructure when hydrogen is used as a storage technology. In this case, a key development is the use of salt caverns for long term hydrogen storage. The total energy cost of the modeled system decreased by 5 M€ (0.3%). Figure 1 shows the modeled total system cost and hydrogen deployment under various conditions: E-0 BC, E-100 Excl. Industry, E-20 Incl. Industry, E-0 NG+35%, and E-100 Inc. Industry. The E-# refers to the potential cost of CO_2 in Euros, for example E-100 refers to a cost of 100€ per ton of CO_2. BC is the base case where 154 MSm^3 of hydrogen is deployed and the industry indicated is the iron, steel, and chemical industries which are either included or excluded from the pricing model. In general, the researchers estimate a 35% tax on natural gas in the European Union would make hydrogen transition financially appealing to industry, shown in the NG+35% case. (Klatzer et al., 2024)

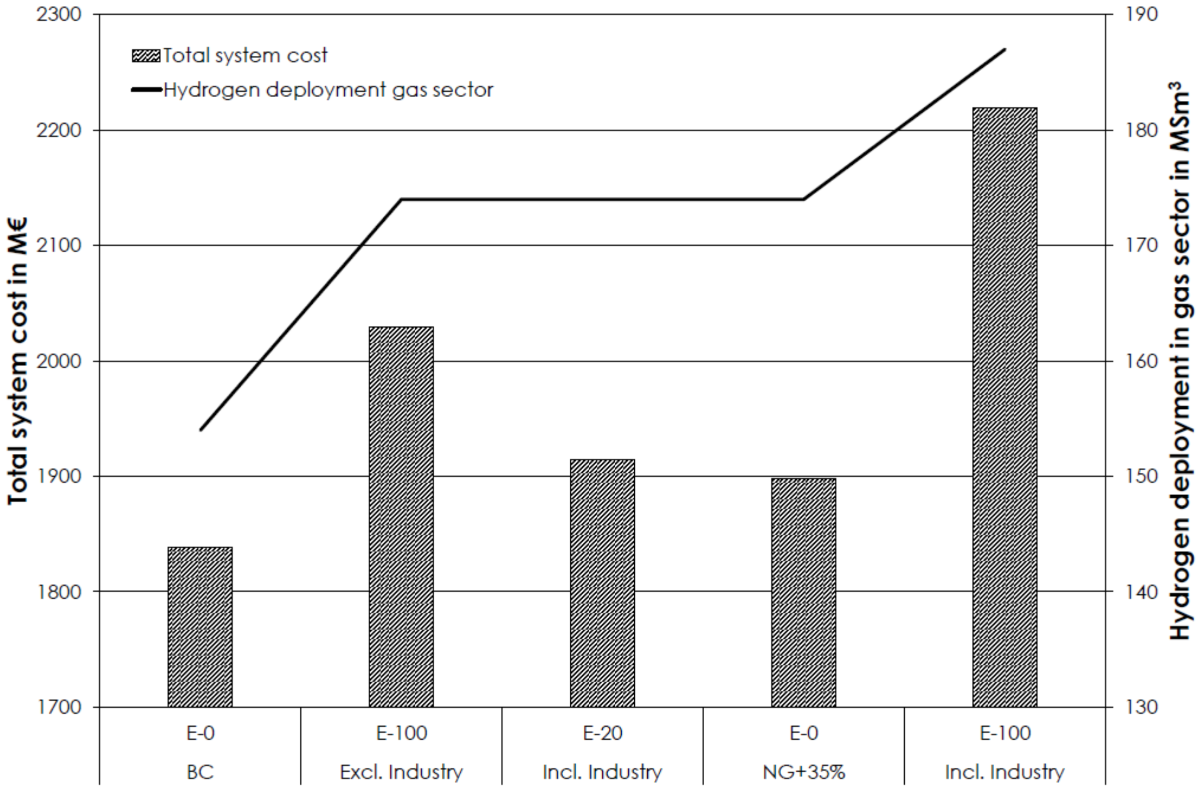


Figure 1: Modeled Total System Cost with Hydrogen Deployment under Various Conditions (Klatzer et al., 2024)

So, in some energy scenarios, there is both an economic and environmental driver to implement hydrogen as an alternative energy. Transporting it through transmission pipelines must be considered and is the focus of this report.

1.2 Hydrogen Properties

Hydrogen is diatomic in its gaseous and liquid forms, and has a low molecular weight of 2 g/mol. It also has low viscosity and flows more than two times faster than natural gas in a pipeline under the same conditions of pipe diameter and pressure. This increased velocity could cause the inner liner of a transmission pipe to wear more quickly. Hydrogen also has a lower heating value than natural gas; it carries 30% less energy. To make up for the lower heating rate, hydrogen pipelines would need to operate at higher pressures or have larger diameters to achieve parity with natural gas energy transfer. An advantage of its low density is that elevation changes in a pipeline do not result in significant pressure changes. Liquefied hydrogen is over six times more efficient than compressed gas delivery, but it must be cooled below -423°F and insulated, making it difficult for transmission service. (Weber & Perrin, 2008) During depressurization hydrogen heats because it has a negative Joule-Thompson coefficient. (Bainier & Kurz, 2019) Bainier and Kurz published details of pumping hydrogen including the energy it takes at range of temperatures and pressures. Hydrogen may become a non-ideal gas at high pressure (e.g., 10,000 psi). These non-idealities need to be considered for accurately determining density, energy storage, and velocities, among other important properties.

1.2.1 Hydrogen Blends and Impurities

In the European Union, hydrogen blends are increasingly unpopular. Concerns include the difficulty and cost of integrating blends into existing pipelines, inconsistent concentrations of hydrogen, and the difficulty of pricing by volume. (Shandross et al., 2021)

The most likely gas to blend with hydrogen is natural gas, as hydrogen can be mixed with it and used as a fuel. Blend limits can vary, but most are up to 30% in deployments as recent as 2022.(U.S. Department of Energy - Office of Energy Efficiency & Renewable Energy, 2022) However, natural gas/hydrogen blends have operational challenges of pressure fluctuations in pipelines and infrastructural flexibility. These blends also increase safety risks of metal embrittlement for reciprocating compressors (up to 1750 m^3/h) or centrifugal compressors (greater than 1750 m^3/h), increased leaking, low Wobbe Index affection combustion efficiency, fire management, environmental impacts, measurement accuracy, and electrical equipment compatibility. (Erdener et al., 2023)

Hydrogen blending projects with natural gas are ongoing. The U.S.-based projects include Dominion to test blends up to 5% hydrogen at an isolated facility, SoCalGas/San Diego Gas & Electric to test blends at 1% and moving up to as much as 20%, HyBlend initiative to study materials compatibility of blending and to develop new risk assessment tools, Entergy to test blends up to 30% at the point of combustion, and CenterPoint pilot of blends up to 5% on low-pressure distribution systems. Studies outside of the U.S. include Canadian Utilities to test blends up to 5% in residential gas distribution network, HyDeploy (Europe) testing up to 20% on a network of 650 homes, H2sarea (Europe) to explore blends up to 20%, ENGIE/GRHYD (Europe) of blends up to 20% on distribution network of 200 homes, Falkenhagen (Europe) testing blends up to 2% since 2013, Snam (Europe) to increase blending from 5% to 10%, Chiyoda Corp. (Japan) to test blending at point of combustion for 80 MW to 1 GW turbines, Tsinghua-Sichuan University (China) conducting laboratory studies of blends up to 17%, and Hydrogen Park SA (Australia) to test blends at 5% to 10% to supply 710 homes. A list of regulatory limits on hydrogen blending by country is also available in the work performed by Erdener et al.; the U.S. is not listed because no applicable regulations could be found. (Erdener et al., 2023)

Contaminates from the production of blue and gray hydrogen could be carbon monoxide, carbon dioxide, nitrogen, water, water vapor, methane, and oxygen.(Arcangeletti et al., 2021) These molecules may be present in hydrogen streams and interact with the pipelines for transmission. Effects of these molecules with materials should be considered before choosing materials and commissioning infrastructure.

Transporting hydrogen as ammonia may be more advantageous than diatomic gas due to lower pressures and high energy density. Kass et al. have a table of materials that are compatible for ammonia transport, but it is outside the scope of this report, so it is not reproduced herein.(Kass et al., 2023)

1.3 Issues with Metallic Pipes

As of 2008, steel pipes transporting hydrogen were between 0.5 to 12 inches and were operated at pressures typically from 580 to 1015 psi.(Weber & Perrin, 2008) Metallic pipeline may not be suitable for hydrogen blends with greater than 12% (Kass et al., 2023) due to embrittlement of the steel structure and ultimately its mechanical failure. The HyBlend project, sponsored by the U.S. Department of Energy, is ongoing and plans to answer many of the unknowns of using blends with hydrogen with metallic transmission pipes and polymer distribution line pipe.

Hydrogen embrittlement occurs during long-term contact of metal with hydrogen during which the concentration of hydrogen dissolved into the metal gradually increases. When the concentration of hydrogen atoms trapped in the metal reaches a threshold, cracks initiate. Hydrogen embrittlement failure is sudden, catastrophic, and not easily predictable. Thus, the use of metal materials in hydrogen transport represents significant risk. (Yang et al., 2023)

Crack growth resistance of steel pipes is 90% reduced in hydrogen environment vs an inert environment. Additionally, the fatigue crack growth rate is up to two orders of magnitude greater in hydrogen than in air for steel pipes. (Laureys et al., 2022)

Other metallic components will also be installed to compress and pump hydrogen through transmission pipes. These components may have the same embrittlement issues as metallic pipes. In a centrifugal hydrogen compressor, the impeller blades tips operate at up to three times the speed required for other gases, (Applied Market Information (AMI), 2023) thus possibly causing other issues like dynamic vibration and erosion. Hydrogen is being produced at a smaller scale today, and the pumping, compressing, and valving components have been engineered to not fail when in contact with hydrogen, so there is a president set for the materials as the pipe volumes are scaled up.

1.4 Overview of Polymers in the Hydrogen Economy

In 2019, global reinforced thermoplastic pipe market was US$5.86 billion and had with a total install of 2900 miles. (HIVE Composites Ltd., 2022). It is predicted that 18% of the total energy needed in 2050 will be provided as hydrogen gas. It will be delivered to transportation refueling networks, for industrial energy use, and for heat and power in buildings. (Cornelissen et al., 2019)

Recently, flexible composite pipe technologies have gained industry attention for their lower environmental impact, ease of installation, corrosion resistance, lower weight, uncomplicated end-fitting design, and ability to act as stand-alone structural line pipe to be pulled through existing steel pipelines. When pulled through steel pipes, their focus can be repurposing or rehabilitation. These pipes are also able to be spooled on reels, smaller drums, or subsea pallets. (Okolie et al., 2023) The weight advantage allows for use of smaller vessels for conveying and installing long lengths and ease of installation both onshore and offshore. End fittings can be installed onsite without welding. Furthermore, the design requirements are held to a higher combined safety standard than steel, API has a confirmed product life and outlined extensive testing. (Nemeth et al., 2022) The applicability of the API standards continues to be discussed for composite pipes of a variety of materials. Some pipes have embedded sensors for continuous monitoring, and they have minimal post-installation maintenance requirements.

Many polymers are used commonly in components used for hydrogen service. These include high density polyethylene (HDPE) for use as liners for hydrogen storage tanks and pipelines, polyphenylene sulfide (PPS) as pipeline liners in high pressure hydrogen distribution, polytetrafluoroethylene (PTFE) is used for seals in mechanical compressors, and the elastomers Type-1 FKM and Nitrile Butadiene (NBR) rubbers as seals and gaskets in valves. (Menon et al., 2016) Polymer composite pipes, either thermoplastic or epoxy thermoset, with continuous fiberglass reinforcement have been used as in-plant hydrogen piping at moderate temperatures and less than 1000 psi with a good safety record as of 2004.(Mohitpour et al., 2004) Polyamides (PA11 and PA12) and polyvinylidene fluoride (PVDF) are also commonly used as a liner material for composite pipes. (Khalid et al., 2020)

Hydrogen gas storage and containment is difficult due to its small molecular size and high diffusivity. The preferred tank materials for pressure above 4,340 psi are fiberglass or carbon fiber reinforced plastics with polymer liners, which are known as Type IV and Type V tanks. These tanks are lighter than their metal-based analogs. (Kass et al., 2023)

Polymer materials are also used in the transmission of gas. Compressor stations, that require polymeric seals and gaskets, are located approximately every 40 to 70 miles of transmission pipeline. They are used to purify, compress, and cool the gas before its reentry back into the pipeline. (Kass et al., 2023) Other similar applications include diaphragms, O-rings, boots, flanges, gaskets, seals, valve seats, hoses, piston rings. For example, compressor valve plates and poppets valves are commonly made of PTFE or polyetheretherketone (PEEK), sometimes filled with glass or carbon.(Applied Market Information (AMI), 2023)

As seen here, rigid and elastomeric thermoplastic and thermoset materials all have a place in the transmission of hydrogen. They are most often used as pipeline materials and seals.

2. Objectives and Scope

2.1 Objectives

The objectives of this project are to identify gaps and needs that impact the safety and integrity of polymer composite/multi-layer pipeline systems when used to transport pressurized hydrogen gas, and to develop guidance for pipe manufacturers and pipeline owner/operators to help ensure safe and economic manufacture and operation of future hydrogen transmission pipelines constructed using composite pipe materials.

2.2 Scope

The objectives of the project were accomplished by EWI through an extensive literature review of relevant private and public efforts, and broad industry canvassing and surveying, which included raw material suppliers, composite pipe manufacturers, and pipeline operators. Additionally, industry standards, codifying bodies, and regulators such as Plastic Pipe Institute (PPI), American Petroleum Institute (API), Det Norske Veritas (DNV), Canadian Standards Association (CSA), federal agencies, state and federal regulators were surveyed or interviewed. The literature gathering effort included relevant peer-reviewed journals, industry publications, manufacturing marketing materials, conference proceedings, other technical materials property databases, media and news sources, and public U.S. national labs reports. The information from these sources was compiled, collated, and analyzed to identify known or assumed technical needs or gaps based on:

- Composite pipe material combinations to be used in hydrogen service.
- Potential gaps in composite pipe field installation practice.
- Methods to control hydrogen absorption and permeation.
- Leak detection and monitoring requirements.
- Composite pipe operational unknowns (i.e., related to material performance, damage mechanisms, condition assessment and potential repair or rehab requirements based on composite pipe structure, manufacturing method and planned service environment).
- Risks specific to connectors, including cathodic protection considerations.
- Prior failure history of composite pipe and associated root cause analyses.
- Failure prediction or damage tolerance assessment methods for hydrogen gas service.
- Current composite manufacturing inspection and quality control requirements and their relevance to hydrogen service.
- Requirements for revising existing pipeline codes and standards.
- State of industry preparedness for use of composite pipe in hydrogen applications.
- Potential societal/public needs and concerns associated with an expanded hydrogen gas pipeline network, particularly using composite pipe materials.

3. Composite Pipe Material Combinations to be Used in Hydrogen Service

There are many different variations of composite/multi-layer pipes. One way to categorize them is displayed in Table 1. This categorization includes the documents which are used to regulate them.

Table 1. Categorization of composite/multi-layer pipes.

Spoolable Reinforced Plastic Pipe – API 15S	Thermoplastic Composite Pipe (TCP) – DNV ST F119	Reinforced Thermosetting Resin (RTR) - API 15HR
•Spoolable Composite Pipe (SCP) •Flexible Composite Pipe (FCP) •Spoolable Glass-Fiber Reinforced Epoxy (S-GRE) •Reinforced Thermoplastic Pipe (RTP) – Unbonded or Bonded	•Offshore only •Flexible Composite Pipe (FCP)	•Glass Reinforced Plastics (GRP) •Glass-Fiber Reinforced Polyester (GRP) •Glass-Fiber Reinforced Vinyl Ester (GRV) •Glass-Fiber Reinforced Epoxy (GRE) •Fiber-Reinforced Plastics (FRP) Pipe – Spoolable and Stick •Fiberglass Pipe

3.1 Spoolable Reinforced Plastic Pipe Regulated by API 15S

Composite polymers are less prone to hydrogen embrittlement fractures than metal, making them an attractive alternative material for pipes. (Yang et al., 2023) Additionally, reinforced thermoplastic pipes (RTP) can be installed for 15% of the cost of steel pipes under ideal conditions with an expected life span of 25 years(J. R. Wright et al., 2014). Additionally, RTPs are easier to transport and install than their rigid steel pipe counterparts, and in 2019 was demonstrated to be installable at a rate of 2 km/day. (Cornelissen et al., 2019)

Zhang, et al. modeled the stress and strain of an RTP with the following dimensions: 0.275-in. thick thermoplastic liner, 0.039-in. thick impermeable (metal) layer, 0.137-in. thick reinforcement layer and 0.137-in. thick thermoplastic cover. At five times the expected use pressure, the stress is greatest in the metal layer at about 712.5 MPa and the strain is greatest in the inner thermoplastic liner layer at about 0.7402%. These values are still within the expected strength limit of the part.(J. X. Zhang et al., 2023)

RTP is a type of pipe that can be spooled, which means it can be provided as a coil or on a structural reel for transportation. It consists of a thermoplastic liner where the structural layer typically contains an even number of balanced helical windings or reinforcement members. Continuous reinforcement can either be metallic or non-metallic fibers and are unbonded. Sometimes RTP and other types of composite pipes are called flexible composite pipe (FCP). Typical thermoplastics used for the liner of RTPs are polyethylene (PE), polyamide 11 (PA11), or polyvinylidene fluoride (PVDF). (H. Li et al., 2022; Okolie et al., 2023) Additionally, PA12 has been commercialized in RTPs in Baker Hughes products.

Smartpipe® is an example of a field manufacturable pipe that consists of an internal thermoplastic liner, a reinforcement layer, and an outer thermoplastic cover. The internal layer acts as a chemical barrier between the fluid and the reinforcement layer. The reinforcement layer is a wound metallic or non-metallic continuous fiber that acts as the structural member and gives it flexibility. It may be made of strips, wires, glass fiber epoxy laminate tapes, liquid crystal polymer, aramid fibers, or other materials. The outer cover protects the reinforcement layer from abrasion, damage, and exposure to the elements. (Nemeth et al., 2022)

Aluminum foil has been shown to thwart hydrogen permeation and can be used to protect the reinforcement layer. (Leighty et al., 2022) In some cases, the aluminum foil may strengthen the reinforcement layer. For the best load strength, the RTP layers should have minimal or no gap between them (Cornelissen et al., 2019)

Since certain RTP pipes have unbonded layers, the hydrogen that permeates through the inner liner then travels down the annulus between the reinforcement layer and inner liner. Cracks in the inner layer can be discovered by detecting excess hydrogen using technology like FlexSteel's Shieldsure®, which monitors the annulus gas. It may also be possible to capture and reinject the permeated gas into the transmission stream. This would lower the explosion risk of accumulated hydrogen and decrease energy loss.

3.2 Thermoplastic Composite Pipe (TCP) as regulated by DNV ST F119

TCP is also a type of pipe that may be spooled ("spoolable"). All layers of a TCP are melt fused together and typically have the same base polymer, unlike that of an RTP. Typically, the carrier for the fiber reinforcement is made of the same polymer as the liner so that they can be melted together. TCP has some advantages over other types of flexible pipes. They have high fracture toughness, great fatigue strength, low storage cost, long shelf life, good corrosion and chemical resistance, higher temperature and pressure ratings, and high damage tolerance. The drawbacks of TCPs are that the fully fused system requires more heat which reduces manufacturing rate, increases production floor space, increases energy use, and increases manufacturing costs.(HIVE Composites Ltd., 2022) Some pipes currently produced use PVDF, PA12, HDPE, HDPE-RT (RT= raised temperature, a.k.a. PERT) or PEEK as thermoplastic liner and either carbon or glass fiber as reinforcement. DNV GL-RP-F119 recommends fully bonded TCP pipe for offshore applications. (Okolie et al., 2023) Like RTPs, another nomenclature for this pipe is flexible composite pipe (FCP). (Khalid et al., 2020)

3.3 Reinforced Thermosetting Resin (RTR)

Fiber-reinforced plastic pipes have many names and acronyms, each defining a subset of the larger group. These include glass reinforced plastics (GRP), glass-fiber reinforced polyester (GRP), glass-fiber reinforced vinyl ester (GRV), glass-fiber reinforced epoxy (GRE). (Rafiee, 2016) The resins used for the inner and outer liner usually are polyester, vinyl ester, epoxy vinyl ester, or epoxy.

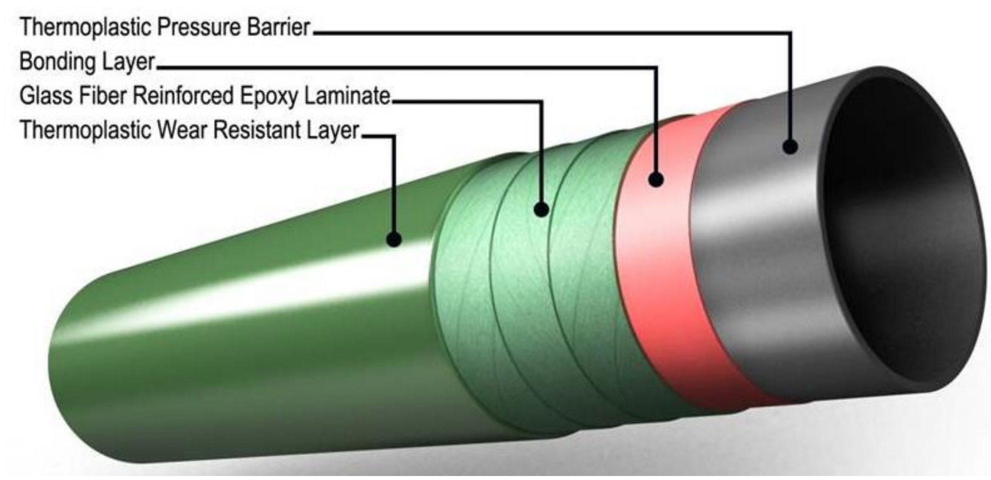


Figure 2. NOV Fiberspar's GRE pipe that includes thermoplastic layers.(Amaechi et al., 2023)

Non-spoolable FRP is termed stick pipe. It is a fiberglass filament-wound, rigid pipe with an epoxy matrix binder commonly available in 2 to 24-inch diameters and operated at pressures up to 3000 psig. (Nemeth et al., 2022) Typical glass types are E-glass, which is inexpensive and offers excellent insulator properties and resists attack from water, and S-glass, which is optimized for strength.

Spoolable FRP pipes are also available. FRP provides excellent strength-to-weight and stiffness-to-weight ratios, which enable new applications and designs. Suitable fiber lay-ups for pipes have been derived and validated up to 5,000 psi through simulation in accordance with ISO 14692.(Grigat et al., 2022) Glass fiber reinforced composites are known to exhibit strong loadbearing capacity, superior toughness and low density. (Cao et al., 2021) These pipes can be used for miles of seamless hydrogen transmission. (Khalid et al., 2020)

S-GRE is a type of spoolable pipe with a structural layer that typically consists of an even number of balanced helical glass fiber windings in an epoxy thermoset matrix.
An additional nomenclature for this type of pipe is reinforced thermosetting resin (RTR) pipe. (Khalid et al., 2020) The angle at which these filaments are wound affects the type of pressure that the pipes are most suited for. 55-deg should be used for biaxial pressure, while 75-deg is best for hoop pressure and 85-deg works for biaxial pressure with axial compression. Notably, for this style of pipe, the impact strength and fatigue life can be increased by applying a pre-stress load.(Sebaey, 2019)

Polymeric composite materials have been used for critical structural repair purposes on metal pipelines since the 1960s for services including petroleum, liquid petroleum products, natural gas, water or ammonia. The thermosetting resins use adhesives/binders, including polyester, vinylester, epoxide, and phenol formaldehyde (Sergienko et al., 2018) Some of these same materials are now used in composite pipes.

The failure pressure of carbon fiber reinforced thermoplastic (HDPE) and thermosetting (epoxy) composite pipes, with and without a HDPE liner, has been measured, as reported in Figure 3. Notably, the leakage pressure is similar among the different types of pipes, with or without liner, and whether the polymer is thermosetting or thermoplastic. The resin and fiber fracture pressures of the thermoplastic composite pipes were less than that of the thermosetting composite pipes. The thermoplastic composite is much faster to produce, however, with a processing time of 5.8 min versus a processing time of 301.6 min for the thermosetting pipe. There thermoplastic pipes are preferred at lower pressures. (Yang et al., 2023)

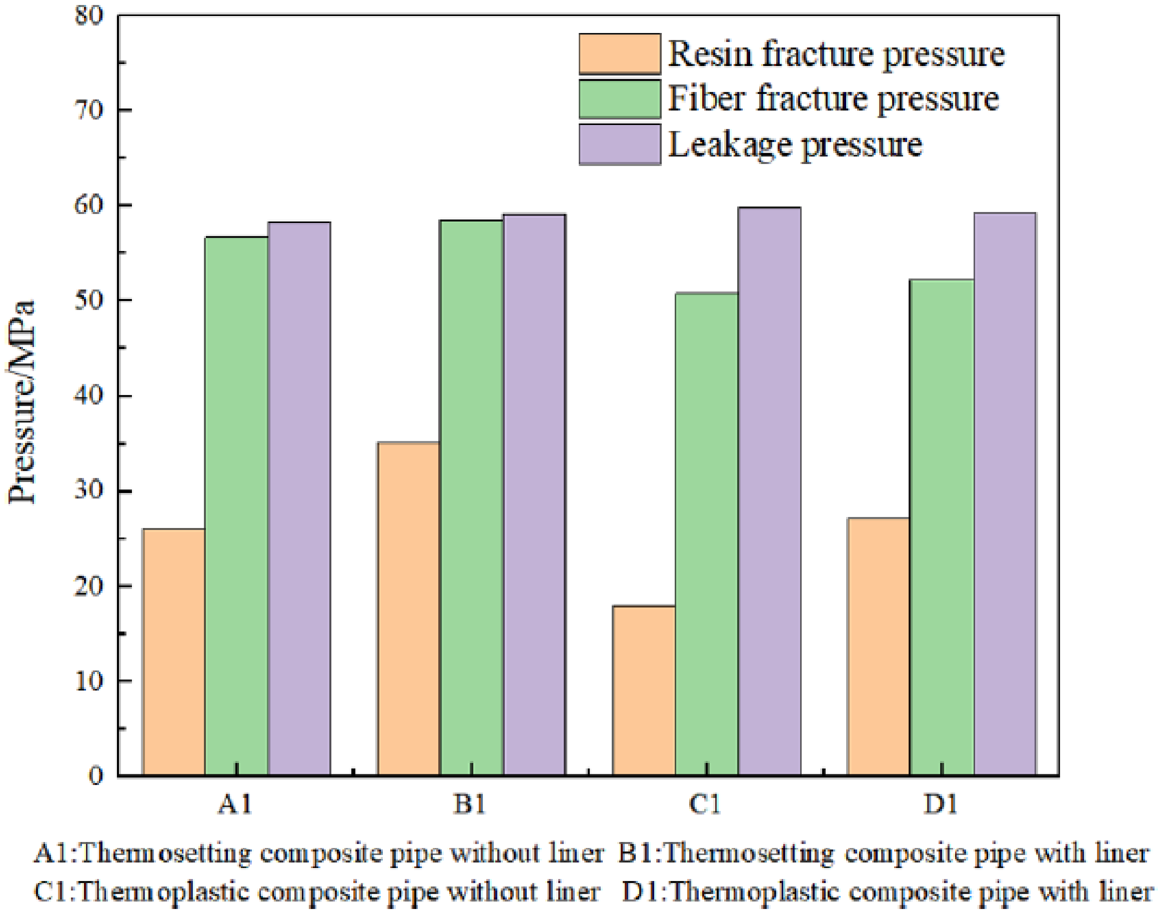


Figure 3. Failure pressure of thermosetting and thermoplastic composite pipe with and without an HDPE liner (Yang et al., 2023)

The number of different materials in composite multilayer pipe is vast. This makes it difficult to regulate all of them using the same standards.

3.4 Suggested Testing Protocols for Design Improvement

For thermoplastic composite pipe and hybrid flexible pipe, the inner liner may be considered the weakest link. Therefore, testing end-of-life aging conditions of the liner for the composite pipes is a conservative approach approved by the DNV. A pyramid approach to qualification has been proposed as shown in Figure 4.(Schuett & Paternoster, 2021)

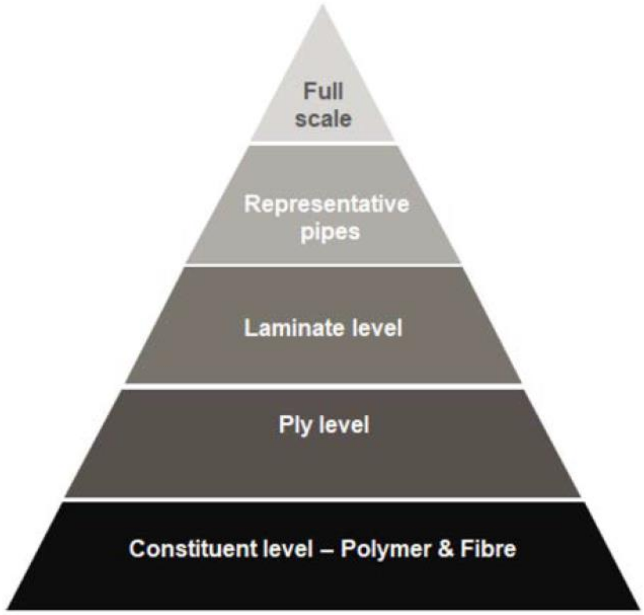


Figure 4: Qualification pyramid for thermoplastic composite pipes (Schuett & Paternoster, 2021)

Topolski et al. recommends the following composite properties additional testing, which the results could influence the materials and design of the composite pipes.(Topolski et al., 2022). They recommend: 1) testing more stress levels along with notched specimens should be studied to better evaluate the material property changes from typical operating conditions, 2) testing of multi-axial stress states in fatigue, quasistatic, and creep loading conditions, 3) long-term testing with hydrogen is needed for accurate lifetime assessment estimates, 4) a better understanding of the changes in crystalline morphology may help to elucidate measured physical property changes, and 5) additional oxidative induction testing by differential scanning calorimetry is needed to better understand pipeline operating conditions for rate of depletion of stabilizers. The authors of this report believe that many of Topolski's suggested tests have already been completed but may remain proprietary information by the pipe manufacturers. Publishing their data or reproducing it by a third party and then making those data public may alleviate reliability concerns of these pipes to withstand the rigors of hydrogen transmission.

4. Potential Gaps in Composite Pipe Field Installation Practices

4.1 Current Practices

API Recommended Practice 15SIH covers unspooling, handling, layout planning, and installation by direct bury (trench and backfill), surface lay, directional drilling, plowing, pull-though methods, and hydrostatic testing for spoolable reinforced line pipe. Other parts of the document cover connectors and corrosion thereof (Section 8 of this report), inspection and field testing (Section 6.4 of this report) and pull-through liners (Section 15 of this report).

Baker Hughes has a comprehensive Installation and Handling Manual for Oilfield Equipment – Flexible Pipe Systems – Onshore / Houston / Services / USA (FDS-HOU-2-08, rev: 7.0). The document is proprietary, so no part of it can be disseminated, reproduced, quoted, or reported on in any manner. Likewise, NOV Fiber Glass Systems also has an Installation Manual that covers the best practices for installing and handling Fiberspar LinePipe, and FlexSteel has an analogous document for their pipe.

4.2 Potential Gaps

API RP 15SIH allows the pipe manufacturer to specify many of the criteria throughout the document. It is a helpful document for regulators to understand what questions to ask manufacturers as they install pipes but does not set boundaries for acceptable limits. Also, the document encourages installation records to be maintained for the full life of the pipeline if relevant to integrity management but does not require it.(Installation and Handling of Spoolable Reinforced Line Pipe (API Recommended Practice 15SIH First Edition, 2021) A regulatory document could solidify this sentiment and could specify documents must be maintained for the life of the pipeline.

5. Methods to Control Hydrogen Absorption and Permeation

5.1 Materials, Permeation, and Testing

This section starts with general permeation information and then is separated into thermoplastics, rigid thermosets, polymeric elastomers, fillers, and coatings as each has a different response to hydrogen permeation.

It has been estimated that the emissions rate (by mass) for transmission pipeline for hydrogen are between 0.02% and 5%.(Esquivel-Elizondo et al., 2023) which is approximately 0.0005%–0.001% of the total volume transported lost.(Haeseldonckx & D'Haeseleer, 2007) Another way to state this is that at 1,500 psi the permeation loss is less than 10 SCF/day/mile of pipe. These estimates depend on factors such as pipe materials, diameter, length, hydrogen pressure, and temperature. Some of this loss can be attributed to the permeation of hydrogen through polymer composite pipes. The permeability coefficient is a product of the solubility coefficient and the diffusion coefficient. The solubility coefficient describes the concentration of the solute in the polymer at steady state and the diffusion coefficient describes the solute transported through the polymer. (Lefebvre et al., 2022) The diffusion of hydrogen through polyethylene pipe walls is up to five times higher than that of natural gas. (Haeseldonckx & D'haeseleer, 2007)

Hydrogen has the second smallest kinetic diameter for permeant molecules. For comparison, helium is 0.26 nm, hydrogen is 0.289 nm, carbon dioxide is 0.33 nm, and methane is 0.38 nm.(Applied Market Information (AMI), 2023) Although the diameter for methane is only 46% larger than that of hydrogen the diffusion coefficient is 10 times slower in certain grades of elastomeric polymers, like fluoroelastomer (FKM). The smaller the molecular diameter, typically the faster the diffusion, unless chemical effects dictate the transport. For example, chemical effects dictate the high solubility of oxygen in polyethylene and PA-6. Molecular simulations have shown more favorable energetic interactions for oxygen over hydrogen in different polymers.(Voyiatzis & Stroeks, 2022) For a sense of scale, the model prediction for the solubility of hydrogen in HDPE and PA-6 at 10,000 psi and room temperature are 286 and 177 ppm by weight, respectively. Also, an important note is that at higher temperatures, the solubility is higher.

The mechanism of hydrogen permeation in polymers is via solution diffusion. Hydrogen condenses on the polymer surface, then dissolves and diffuses as a liquid, passing through the material driven by the chemical potential. Once it reaches the other surface, the hydrogen evaporates as gas. (Sun et al., 2020) A measurement of chemical potential is fugacity, a thermodynamic property describing the preference of a particular phase over another in a substance. (Vieira & de Sousa, 2022)

Hydrogen permeation has been shown to only take place in the amorphous regions,(Voyiatzis & Stroeks, 2022) which act like an amorphous liquid above the polymer's glass transition temperature (T_g). Crystalline regions act as a barrier and restrict permeation completely.(Kane, 2008) Other factors that affect the permeability of polymers to hydrogen include free volume, side chain complexity, density, chain orientation, crosslinking, T_g, plasticizers, humidity, and fillers. In general, the lower the free volume, the lower the permeation rate. So, unfilled elastomers have the highest rate followed by amorphous polymers and then semi-crystalline polymers. Bulky side chain groups can hinder polymer chain movement and decrease permeability. Higher density polymers inherently have higher crystallinity, lower free volume, and lower permeation. When polymer chains are aligned, like an extruded pipe, then the permeation is decreased over that of random chain orientation. Crosslinking induces less mobility for the polymer chains and lower permeability, assuming crystallinity stays constant. The permeation changes significantly at the T_g, so if the service temperature is below the T_g, permeation will be lower. Plasticizers make polymers more durable, but also increase their permeation due to reducing the density and increasing chain mobility. Humidity increases the permeation in hydrophilic polymers like PA6, but does not change it in hydrophobic polymers, such as HDPE. Fillers act as a physical barrier to hydrogen permeation, but their size, shape, and loading will dictate the effect. A paper by Li et al. included a detailed explanation of gas permeation through polymers complete with theoretical equations.(H. Li et al., 2022)

Measurement of hydrogen permeability is very important to qualify materials for pipeline transport. Ideally, the permeation is measured under pressure, to simulate the use environment. A schematic demonstrating this approach is shown in Figure 5.(Liu et al., 2022)

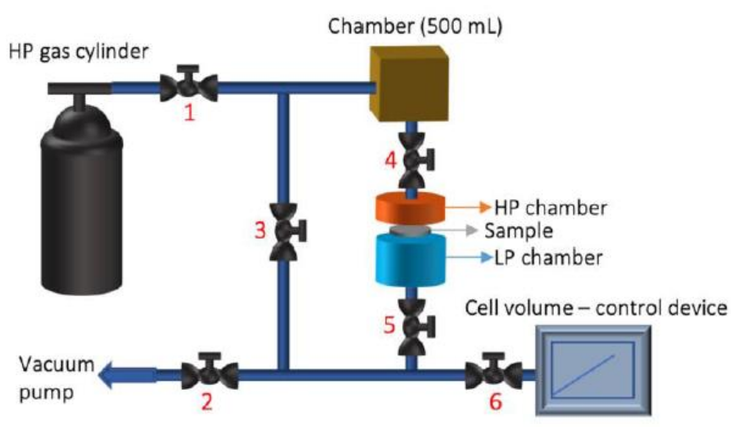


Figure 5. Schematic of Hydrogen permeability testing approach where HP is high-pressure and LP is low-pressure (Liu et al., 2022)

A schematic of a typical permeation test chamber according to CSA/ANSI CHMC2:19 is shown in Figure 6. (Condé-Wolter et al., 2023)

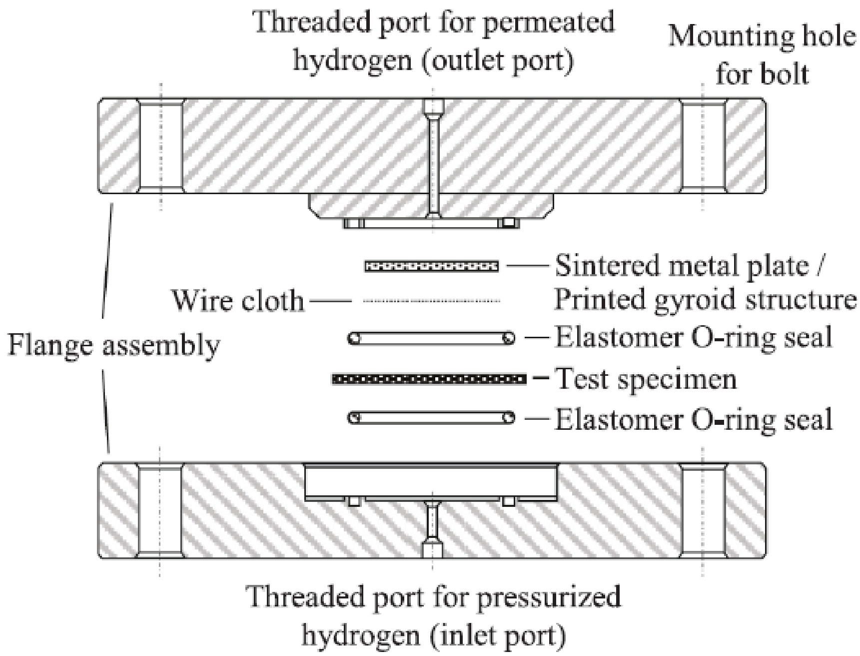


Figure 6. Components and assembly of hydrogen permeation testing fixture (Condé-Wolter et al., 2023)

Equation 1 is used to calculate the permeability, P, from this approach:

$$P = \frac{V_{LP}}{R \cdot T_K \cdot \rho_{HP} \cdot A} \cdot \frac{d\rho_{LP}}{dt} \cdot h$$ **Equation 1**

Where V_{LP} is the volume of the low pressure chamber, R is the gas constant (8.31×10^3 J/K·mol), T_k is the thermodynamic temperature, ρ_{HP} is the pressure of the high-pressure chamber, A is the transmission area of the specimen, $d\rho_{LP}/dt$ is the pressure change of the low-pressure chamber, and h is the thickness of the specimen. (Liu et al., 2022) The non-ideality of hydrogen at high pressure can be modeled using fugacity instead of partial pressure.

It's important to note that the pressure applied during testing affects the measured permeability. Figure 7 shows the permeability of hydrogen through low density polyethylene (LDPE) (UR951 Japanese), HDPE (HB111R Japanese), and PA11 (BESN OTL Arkema) as a function of pressure. PA11 has about 10 times lower hydrogen permeability than either polyethylene, this reduction may depend on the presence of plasticizers in their formulation. The hydrogen permeability coefficient was found to be 0.3-0.4 times lower at 90 MPa than at 0.6 MPa for all three polymers. It is believed that the free volume in the polymer is compressed at high pressure which leads to lower permeability at high pressures. (Kanesugi et al., 2023)

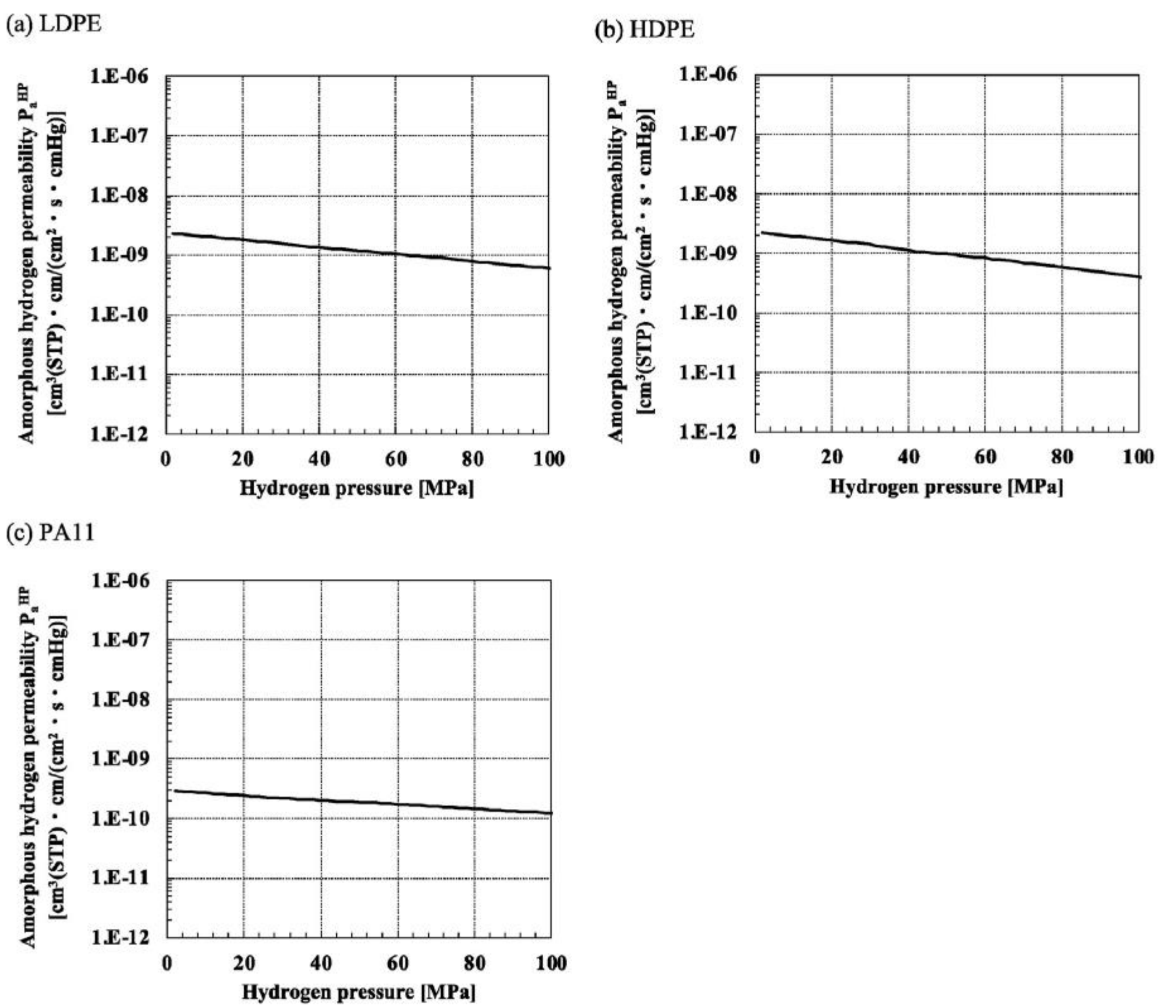


Figure 7. Relationship between hydrogen permeability and pressure (Kanesugi et al., 2023)

5.1.1 Thermoplastics

Zhang et al. studied the molecular simulation of hydrogen permeation behavior in HDPE and ethylene vinyl alcohol (EVOH). They looked at the permeation from room temperature up to 176°F and from 363 to 1450 psi. The solubility, diffusion, and permeability coefficients of hydrogen in HDPE and EVOH both increase a similar amount with increased temperature. They also found that an increase in pressure had a negligible effect on the same variables. EVOH has lower permeability than HDPE because of the hydrogen bonds between its hydroxyl groups impede diffusion. Hydrogen moves more actively through HDPE because it has higher molecular hole amplitude and more holes between polymer chains. (X. Zhang et al., 2024) Another view on variables which determine permeation through polymers was published in an AMI report.(Applied Market Information (AMI), 2023) It included the environmental conditions such as temperature and pressure, permeant molecule properties of size, polarity, and shape, polymer properties such as crystallinity, backbone structure, polarity, molecular weight, chain entanglement, induced stress, and inter/intra molecular interactions. The paper discusses the effects of each of these variables on the permeation rate and agrees with the other papers summarized in more detail in this report.

A review article for mechanisms and evaluation of hydrogen permeation barriers concluded by stating the following arguments.(Y. Li et al., 2023) Hydrogen is a nonpolar molecule and prefers to be dissolved in nonpolar polymers. Alkanes, such as HDPE are nonpolar, while amides and alcohols are polar. Polymers with a compact structure, such as poly vinylidene fluoride (PVDF), polyamide, ethylene vinyl alcohol (EVOH), poly(vinyl alcohol) (PVA) have been shown to have good hydrogen resistance. Even though these polymers may have low hydrogen permeation rates, not all of them may be ideal for pipelines. PVDF is expensive, and EVOH would need to be used as coextruded layer rather than the entire inner layer. EVOH has a hydrogen permeability of 600 to 4000 cm^2-μm/(m^2-day-atm) (equivalent to 0.91 to 6.09 x 10^{-6} Gas Permeance Units - GPUs) when the ethylene content is between 32 and 44 wt.%. HDPE and PA11 have hydrogen permeabilities of 2 x 10^{-8} and 8 x 10^{-9} cm^3/(cm-s-bar), respectively (equivalent to 266 x 10^{-6} and 106 x 10^{-6} GPUs, respectively). An experimental setup for hydrogen permeation testing is shown and described in Evans and Mogan's paper for measurements at elevated temperatures and at differential pressures below 15 psi.

Klopffer et al. also measured the permeation coefficient of hydrogen in PE and PA11. They found that at 68°F and up to 290 psi PE and PA11 had permeation coefficients of 2.10^{-17} and 8.10^{-18} $Nm^3m^{-1}s^{-1}Pa^{-1}$, respectively. They also concluded that the permeability coefficient of either polymer did not change after 13 months of soaking in hydrogen at temperatures up to 176°F and pressure up to 290 psi. (M.-H. Klopffer et al., 2010)

An article focused on Type IV pressure vessels mentioned that HDPE and PA6 are very good hydrogen permeation barriers when compared to other polymers.(Condé-Wolter et al., 2022)

Semi-crystalline PA12 is also a good hydrogen barrier. Polyamide is preferred for Type IV hydrogen storage tanks due to its strong molecular polarity and hydrogen bond interaction where as polyethylene exhibits high permeability.(Sun et al., 2020).

A study of polyamide for use in Type IV storage tanks conducted by Sun, et al.found that hydrogen diffusion increases with higher temperature, due to increased motion. Type IV pressure vessels are constructed with a polymer liner wrapped by a composite material like carbon fiber. Additionally, hydrogen diffusion decreases with increased pressure, which creates microstructure compression. These effects are illustrated by the data show in Figure 8. In this experiment, the materials were tested from 104-185°F and up to 9500 psi. The materials were dried for 15 days before testing.

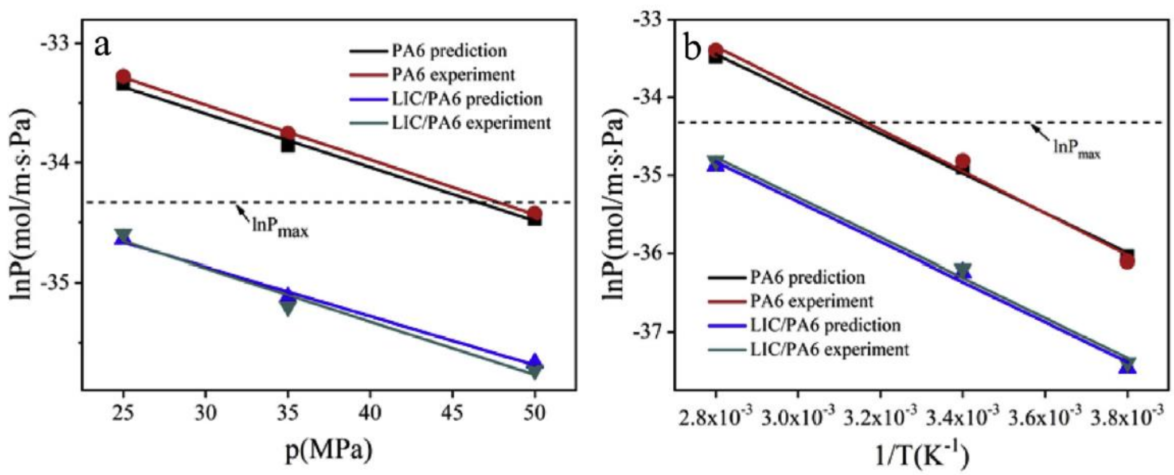


Figure 8: Relationship of hydrogen permeation to pressure (left) and temperature (right)(Sun et al., 2020)

The experimental results were compared to an analytical model to predict hydrogen concentration proposed by Crank, described by Equation 2**.** In this model, it is assumed that the initial concentration of hydrogen is zero.(Sun et al., 2020)

$$C(t) = P_{ext} S_g \left(1 - \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)} \exp\left(-(2n-1)^2 \pi^2 \frac{Dt}{e^2}\right)\right) \qquad \textbf{Equation 2}$$

where P_{ext} is the partial pressure of the surrounding gas, S_g is the hydrogen solubility concentration, D is the diffusion coefficient of hydrogen, and e is the material thickness.

Polymers with high crystallinity and impermeable lamellar structured nanofillers are an effective choice to increase tortuosity of the leak path and decrease permeation due to reduced free volume. (Yuan et al., 2023) A layered composite film of modified graphene oxide reacted with polyethyleneimine (PEI) showed 78.8% reduced hydrogen gas transmission rate versus the substrate. (P. Li et al., 2019) Another research group crosslinked polyvinyl alcohol-co-ethylene (PVA-co-PE) and graphene oxide (GO) using Boric acid, creating a composite with a gas transmission rate 6.9 times lower than Nylon. (X. Li et al., 2018) These materials are interesting and show a great understanding of how to make engineered polymers for hydrogen transmission but are far from being produced at the scale needed for pipes.

EVOH is a promising liner material due to the higher polyvinyl alcohol (PVA) content which increases its polarity. Increased polarity decreases permeability of non-polar gases like hydrogen. However, EVOH tends to swell with water absorption, which may negate that advantage unless it is constrained by other polymer layers or reinforcement materials. Subsequently, EVOH is typically used in a multi-layer assembly. (Condé-Wolter et al., 2023) Kuraray has data to show that their EVAL™ EVOH materials have low hydrogen permeability even at high relative humidity.

For a multi-layer assembly, permeation can be estimated by treating the system as a series connection of multiple permeation resistances.

Equation 3 can be used to calculate the permeability of a single layer from a multi-layer system if all other single layer permeation rates are known, an example of which is given in Table 2. (Condé-Wolter et al., 2023)

$$P_N = \frac{t_N}{\frac{t_{tot}}{P_{tot}} - \sum_1^{N-1} \frac{t_N - 1}{P_N - 1}} \quad \textbf{Equation 3}$$

Where P_N is the permeability of a single layer, t_N is the thickness of that layer, t_{tot} is the total multi-layer thickness and P_{tot} is the permeability of the total system.(Condé-Wolter et al., 2023)

Table 2. Permeability of liner materials using Equation 3. (Condé-Wolter et al., 2023)

Sample name	Mean leakage rate Q [ml/h]	Total sample thickness t [mm]	Layer 1	Thickness Layer 1 [mm]	Layer 2 Liner material	Thickness Layer 2 [mm]	Layer 3	Thickness Layer 3 [mm]	Permeability P of liner material [m^2/s]
#12-PA6-CF-L171	0.123	0,19	PA6-CF	1.54	EVOH-L171	0.3	PA6	0.1	$1{,}619 \times 10^{-13}$
#13-PA6-CF-M100	0.065	0,188	PA6-CF	1.55	EVOH-M100	0.29	PA6	0.1	0.347×10^{-13}

Yuan, et al. investigated gas transmission rates of various polymer composite coatings on steel. The hydrogen gas transmission rate of the samples was tested at 14.5 psi and 77°F. The coatings tested were a composite of a polyester terephthalate (PET) substrate, thermoplastic polyurethane (TPU), epoxy, and graphene flakes, which were arranged perpendicular to the permeation direction, as shown in Figure 9. The results of various configurations of this coating on the hydrogen gas transmission rate are shown in Figure 10. Notably, the gas permeation rate was reduced from 548 $cm^3/(m^2 \cdot 24\ h \cdot 0.1\ MPa)$ to 521 when an epoxy layer was added, and further reduced to 472 when the TPU and graphene composite layer was added, which was even further lowered to 383.80 when the graphene was in the form of an impermeable lamellar sheet, a total reduction in gas transmission rate of 30%. While these were coatings on steel, the same learnings may be applied to thermoplastic composite pipe to reduce hydrogen permeability.(Yuan et al., 2023)

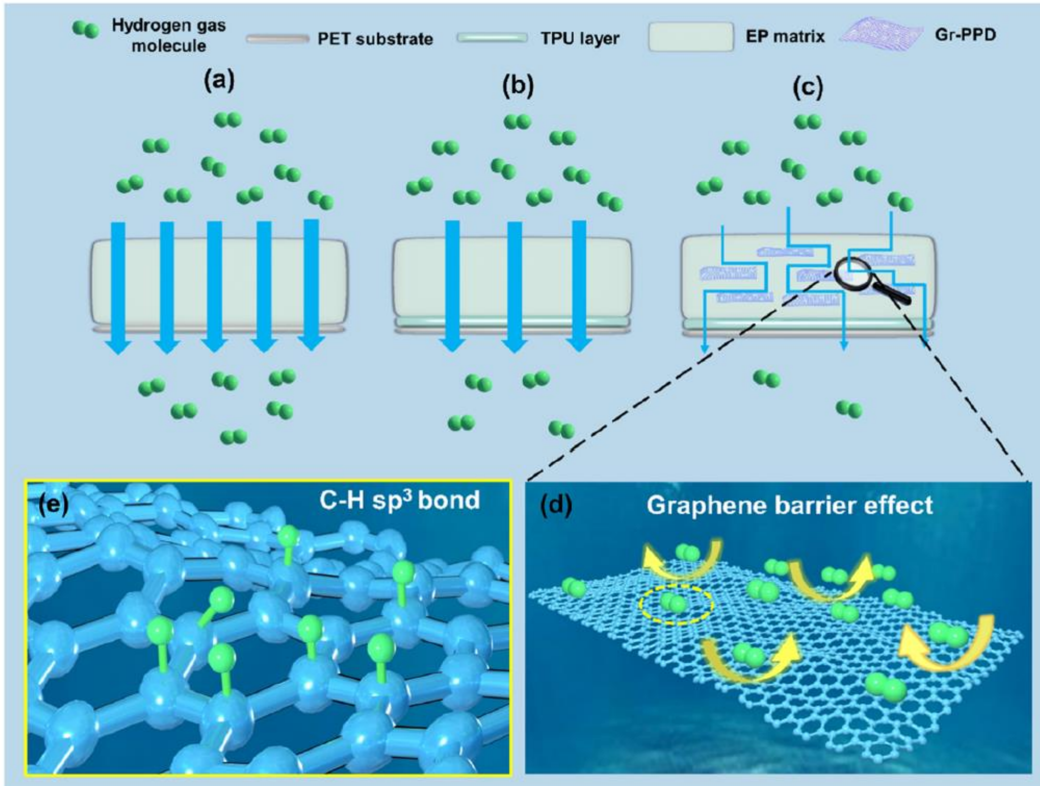


Figure 9. (Above) Schematic diagram of hydrogen gas molecule permeation process for EP coated PET (a), EP/TPU coated PET (b), and 0.5Gr-PPD-EP/TPU coated PET (c), (Below) barrier effect of graphene layer (d), formation of C-H sp^3 bond on the surface of the graphene (e) (Yuan et al., 2023)

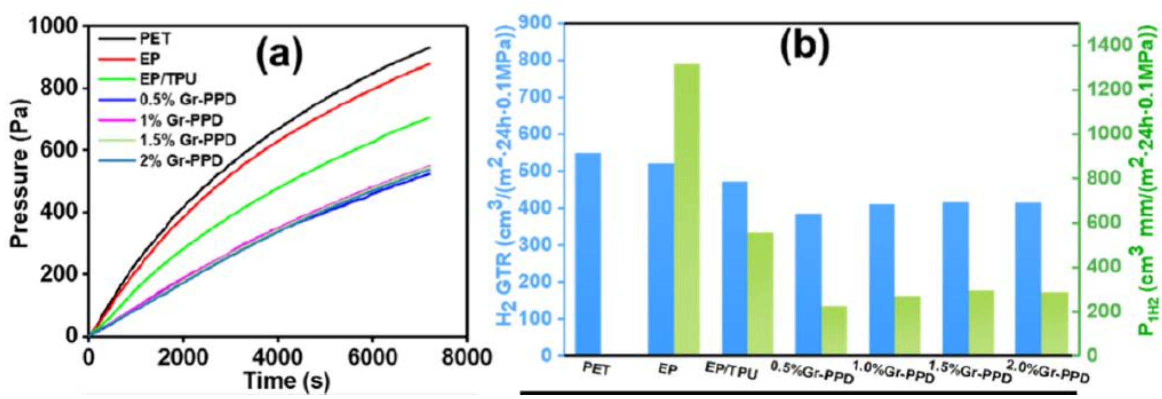
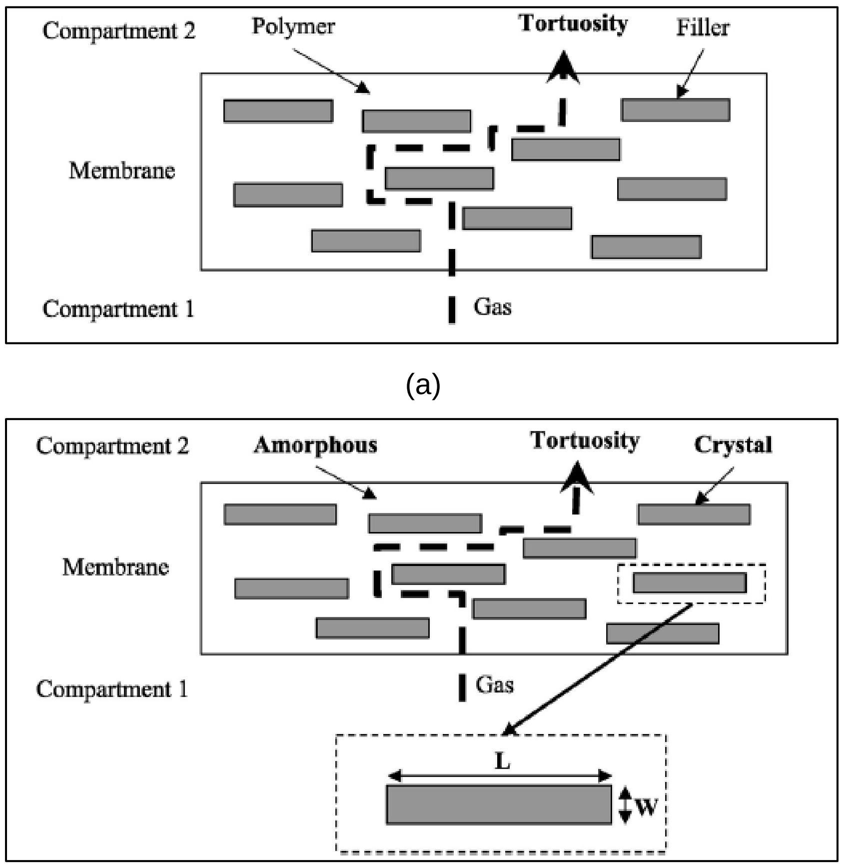


Figure 10. (a) Chamber pressure vs gas permeation time, (b) gas transmission rate (blue bars) and calculated permeability coefficient (green bars) for different coatings(Yuan et al., 2023)

Kanesugi et al. proposed to model the effect of crystallinity on gas permeation using a modified Neilson model to predict tortuosity of the semi-crystalline polymer, as shown in Figure 11. Tortuosity is the idea that after the gas penetrates the surface layer of the polymer, it passes through the material through bypassing internal barriers such as fillers, or in the modified approach, crystalline regions. (Kanesugi et al., 2023)



(b)

Figure 11. Nielson tortuosity model for filled polymer composites (a) vs. proposed model of tortuosity for semi-crystalline polymers (b).(Kanesugi et al., 2023)

When measuring a film, thickness does not have an effect on the permeability, diffusion, or solubility coefficient, however it does directly affect the permeation flux. The flux is an important factor for determining how much hydrogen is lost through a pipe wall per time. Kane presented a model for calculating hydrogen permeability based on volume fraction of the amorphous region, it can be seen in his publication.(Kane, 2008)

The permeation of hydrogen through a 0.04-inch thick PE100 (HDPE) specimen was measured at temperatures ranging from 104 to 176°F and pressures ranging from 87 to 304 psig. The permeation coefficient was found to be faster at higher temperature and lower pressure and the activation energy found from an Arrhenius fit was 33 kJ/mol.(M. Klopffer & Flaconnèche, 2008) An older study also found that the rate of permeation with increasing temperature was exponential in all cases.(Sager, 1940) A similar method was used for measuring the permeability coefficient of hydrogen through PE80 at temperatures ranging from 104 to 176°F. They ranged from 4.8×10^{-8} to 24.1×10^{-8} cm^3/cm^{2}-s-bar.(Foulc et al., 2006)

At low pressures, under 10 MPa, there is not a significant effect of pressure on permeability. (Zheng et al., 2022) (Jung et al., 2021) A detailed study to elucidate physical property changes on five types of PE after hydrogen exposure was performed on disc-shaped specimen.(Fujiwara et al., 2021) Hydrogen pressures reached 13,000 psi at 86°F during the testing. The permeability coefficient decreased with the decrease of diffusion coefficient at higher pressures. The shrinkage in free volume caused by the pressure of the applied hydrogen gas decreased the diffusion coefficient, resulting in a decrease of permeability coefficient. The data showed that the hydrogen diffusion coefficient and permeability coefficient decreased with pressures increasing to 13,000 psi, as shown in Figure 13. Interestingly, permeated hydrogen and penetrated hydrogen continued to increase at higher pressure, but at a slower rate, in other words, the derivative with respect to pressure was decreasing. The compressive strength of HDPE is around 2,900 psi (20 MPa), so at pressures exceeding this, we may expect to see a decrease in free volume.

Perez et al. built an instrument for measuring permeability and flux of hydrogen, carbon dioxide, and nitrogen through flat polymer samples at pressure up to 435 psi and temperature up to 300°C. (Perez et al., 2013) They found that higher temperatures induced greater changes in the gas flux than higher pressures. These pressures are only in the lower range of what is capable for transmission in composite pipes.

Wedgner and Konig measured the permeation coefficient of hydrogen through polyethylene distribution pipes. They used a gas chromatograph to measure the amount of permeated hydrogen. They pressurized the pipes with 91 psi hydrogen and made measurements at 46, 57, and 68°F. They found that permeation was an exponential function of temperature. Their data is in Figure 12.(König & PE100+ Association, 2022)

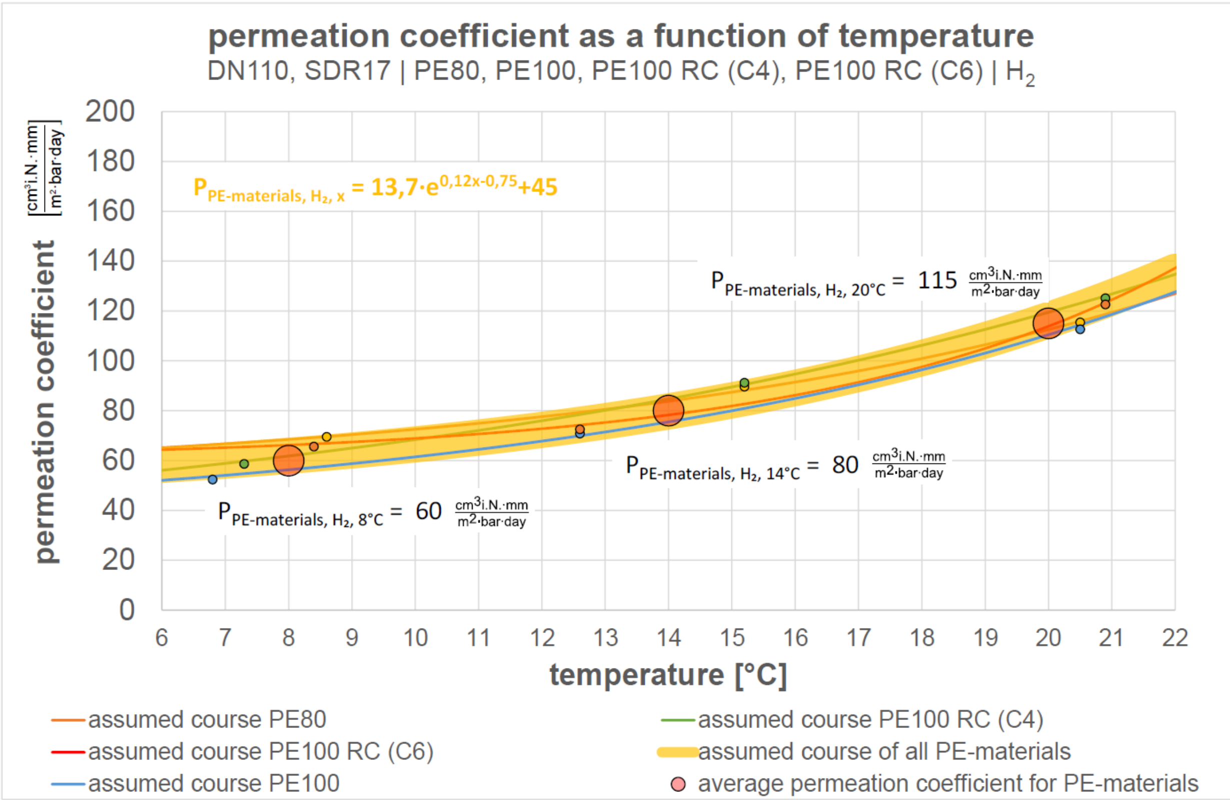


Figure 12. Permeation through PE Distribution Pipes (König & PE100+ Association, 2022)

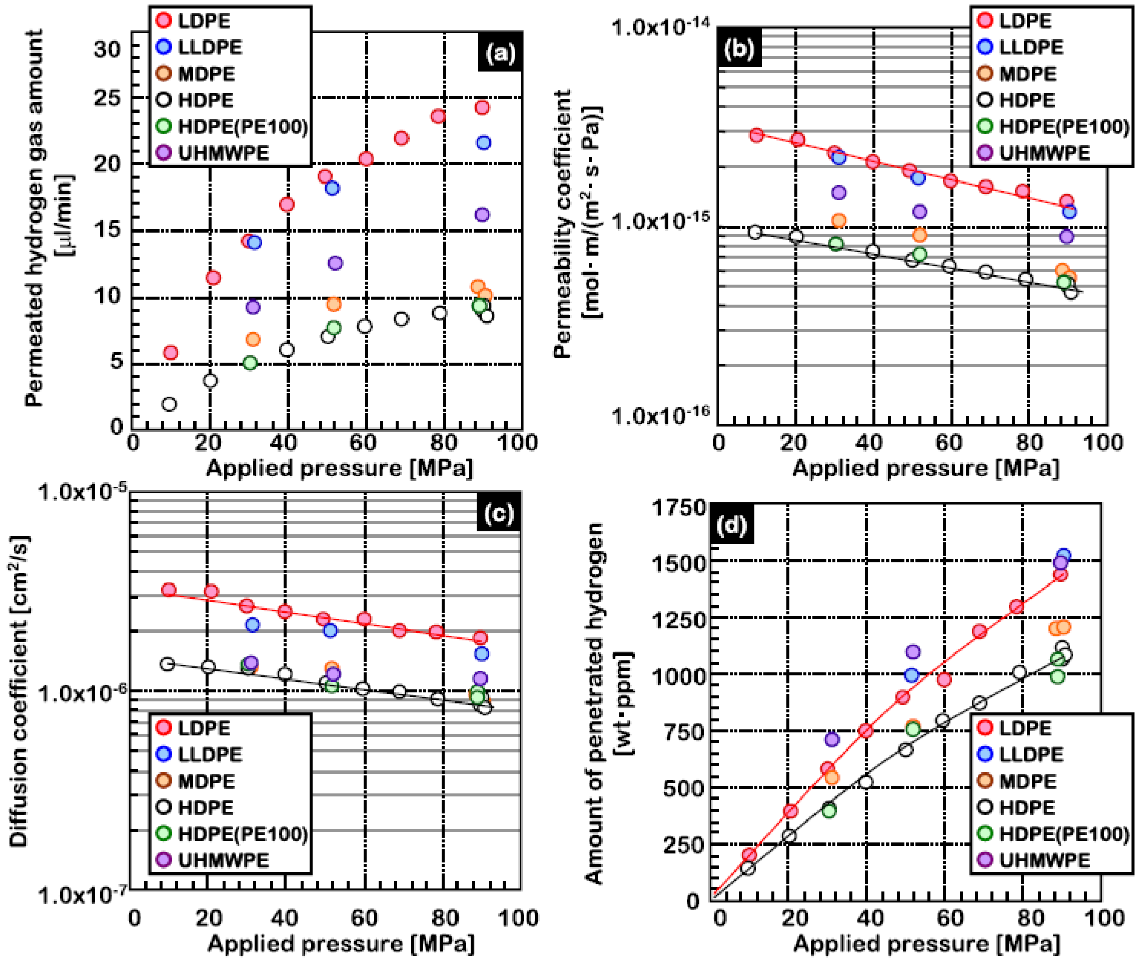


Figure 13. Hydrogen gas permeation test results at 30°C. (Fujiwara et al., 2021)

Fujiwara et al. measured permeation using two methods. One method was thermal desorption analysis (TDA), which included a gas chromatograph for measuring evolved hydrogen, and the second method was high-pressure hydrogen gas permeation test (HPHP). The former was standardized by ISO 15105e1 (JIS-K7126). TDA is only an accurate test method if there is no damage in the specimen during depressurization and only represents hydrogen through an unpressurized polymer. The HPHP gives lower penetrated hydrogen results than TDA due to the hydrostatic pressure on the specimen and is more suited to represent the conditions of a pipeline. Average values for HDPE (PE100) were found to be 7 x 10^{-16} mol-m/(m^2-s-Pa) for permeability coefficient, 1 x 10^{-6} cm^2/s for the diffusion coefficient, and 6 x 10^{-6} mol/(m^3-Pa) for the solubility coefficient. The permeability was dominantly controlled by diffusion, which is based on free volume of the amorphous sections (not crystalline), because the volume shrinkage of the crystal is less than 1% at 14,500 psi. The data show that the permeated and penetrated hydrogen increase with increasing pressure, while the diffusion and permeability coefficient decrease over the same pressure range. Li et al. corroborated this when they concluded increased pressure led to a decrease in the gas permeability coefficient in PE100 pipes at pressure up to 72 psi. (X. Li et al., 2024)

Kanesugi et al. found that the permeation coefficient increases with pressure using the TDA testing method but decreases with pressure using the HPHP method, especially for LDPE as compared to HDPE and PA11. This is due to the way pressure is measured and introduced in each approach. Via HPHP the polymer is under pressure, thus compressing the internal microstructure of the material, while TDA measures the release of hydrogen form a saturated sample during decompression at atmospheric pressure. Based on these results the researchers were able to describe a relationship between the permeation coefficient in the amorphous region of the polymer and the inverse of the free volume fraction as shown in Figure 14 based on EPDM, LDPE, HDPE, PA12, PA11, and PA6 data.(Kanesugi et al., 2023)

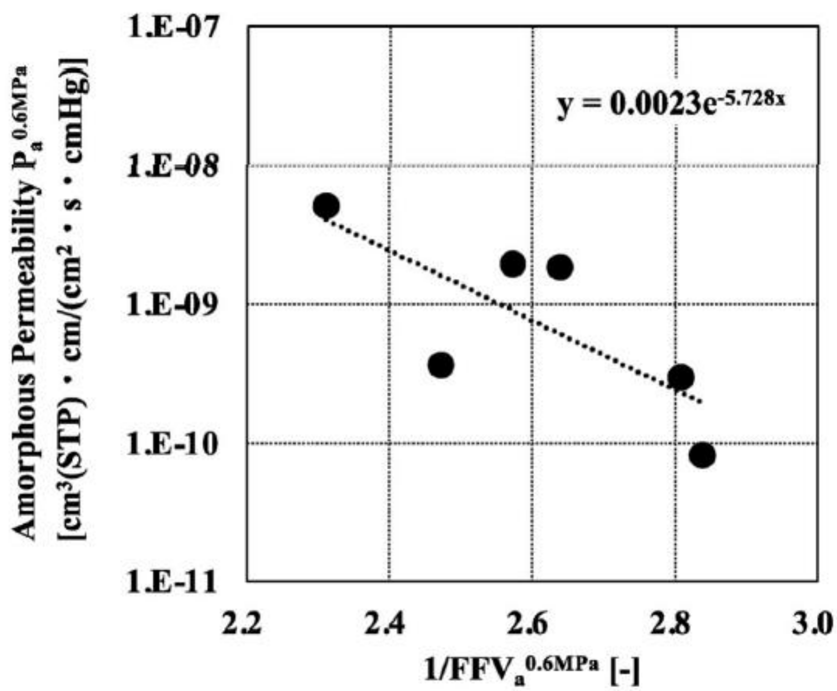


Figure 14: Relationship between reciprocal of free volume fraction and permeation coefficient in the amorphous region at 0.6 MPa.(Kanesugi et al., 2023)

Klopffer et al. measured the hydrogen permeability of a variety of thermoplastic polymers and found the Arrhenius relationship, as shown in Figure 15. The materials tested were polyethylene (PE), poly(6-aminohexyl methacrylate) (PAHM), and polyamide (PA), where the multilayer material had an added 50-100-micrometers thick ethylene vinyl alcohol EVOH layer. They also found that aging of the polymers doesn't affect permeability. (M. H. Klopffer et al., 2015)

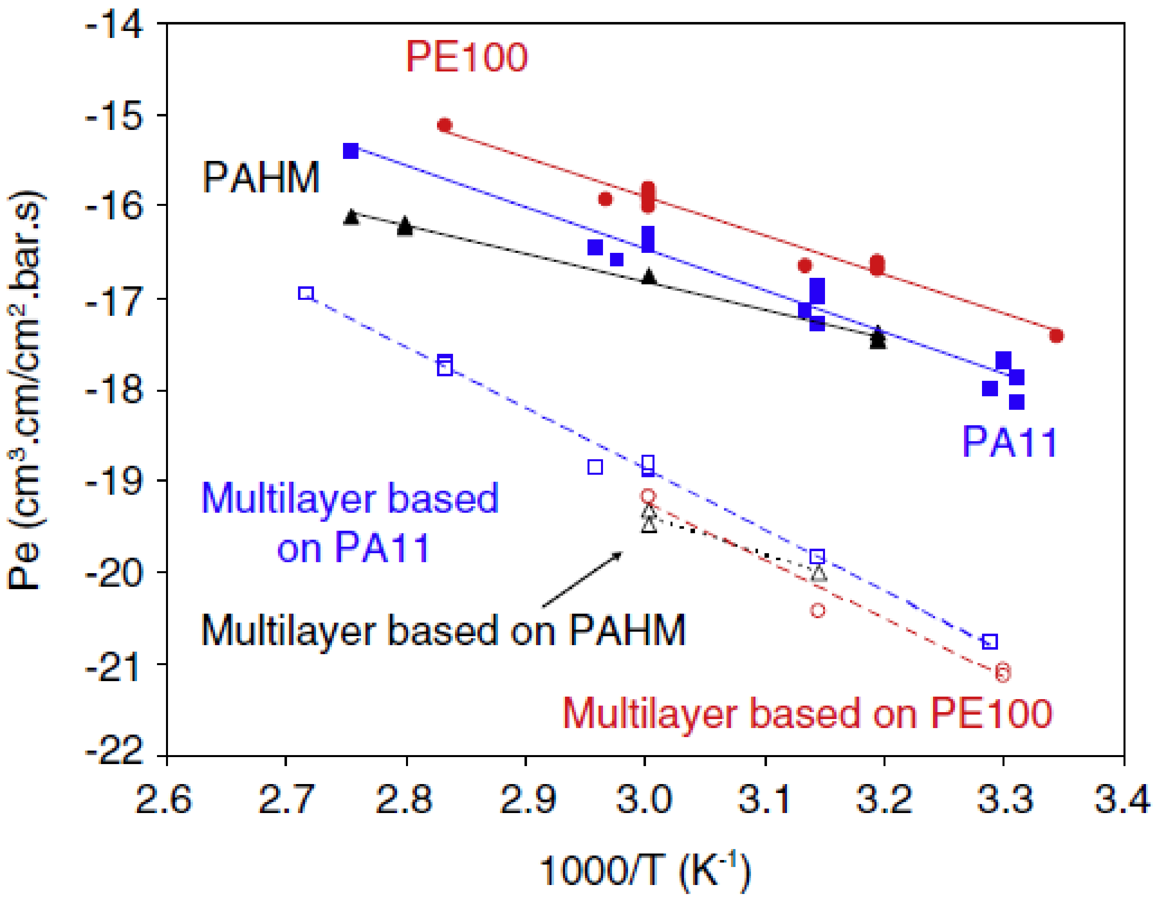


Figure 15: Hydrogen permeability coefficients as a function of temperature. (M. H. Klopffer et al., 2015)

Compiled data shows that HDPE has a hydrogen permeation coefficient between 100 and 1200 cm^3-mm / (m^2-day-bar) when between the temperatures of 10 to 60°C, with the largest values corresponding to the highest temperature.(Janssen, 2023)

Understanding the relationship between permeation coefficient and volume of permeated hydrogen per day is important for scaling up data taken on small disc specimen to full pipe estimates. Hermkens et al. has presented the relationship mathematically in Equation 4. (Hermkens et al., 2018)

$$PC = \frac{Q_P e}{A\Delta p} \qquad \textbf{Equation 4}$$

Where PC is permeation coefficient (ml mm m^{-2} $bara^{-1}$ day^{-1}), Qp is permeated volume (ml day^{-1}), e is the pipe thickness (mm), and Δp is the difference in partial pressure (bara).

The permeation coefficient can then be used to calculate the volume loss of the total pipe using Equation 5.

$$Q_P = \frac{\mathbf{PC\pi(SDR-1)L\Delta p}}{\mathbf{1000}} \qquad \textbf{Equation 5}$$

Where QP is the permeated volume (ml day^{-1}), SDR is the ratio of the pipe wall thickness to the diameter of the pipe, L is the length of the pipe (m).

Hydrogen permeability through thermoplastic materials often used in pipeline applications are shown, along with other relevant material properties, in Table 3. (Kanesugi et al., 2023)

Table 3. Hydrogen permeability and other material properties for common pipeline polymers at normal pressure.(Kanesugi et al., 2023)

Parameter	Hydrogen Permeability (0.6 MPa)	Heat fusion	Heat fusion 100% Crystal	Degree of crystalinity	Crystallite thickness	Crystallite length	Density
Symbol	$P^{0.6MPa}$	ΔH	ΔH_0	χ_c	W_c	L_c	$\rho_{specimen}$
Unit	$cm^3(STP) \cdot cm / (cm^2 \cdot s \cdot cmHg)$	J/g	J/g	–	nm	nm	g/cm^3
EPDM	5.00E-09						0.8570
LDPE	9.12E-10	140.6	288.0	0.4882	8.30	4.60	0.9180
HDPE	4.34E-10	197.7	288.0	0.6865	8.30	14.96	0.9429
PA12	2.60E-10	55.9	209.0	0.2673	4.30	2.80	0.9878
PA11	2.10E-10	40.9	189.0	0.2164	1.70	2.68	1.0186
PA6	4.36E-11	77.1	188.0	0.4101	2.60	2.46	1.1329

Condé-Wolter, et al. measured the permeability of a wide variety of thermoplastic polymers according to the CSA/ANSI CHMC 2:19 standard. The results are given in Figure 16 (leak rate) and Figure 17 (permeability). The PA12 mentioned throughout the paper is a high temperature grade that is amorphous; semi-crystalline PA12 has lower leakage rate and permeability. The PPS was a clear amorphous grade.(Condé-Wolter et al., 2023)

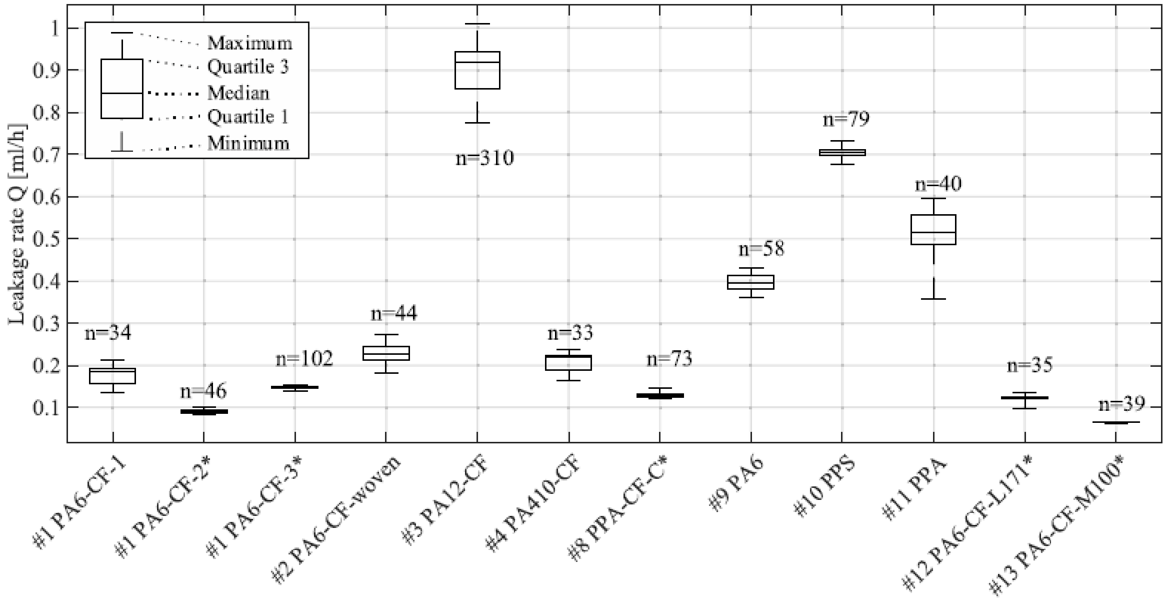


Figure 16. Measured hydrogen leakage rate. The PA12 grade is amorphous. (Condé-Wolter et al., 2023)

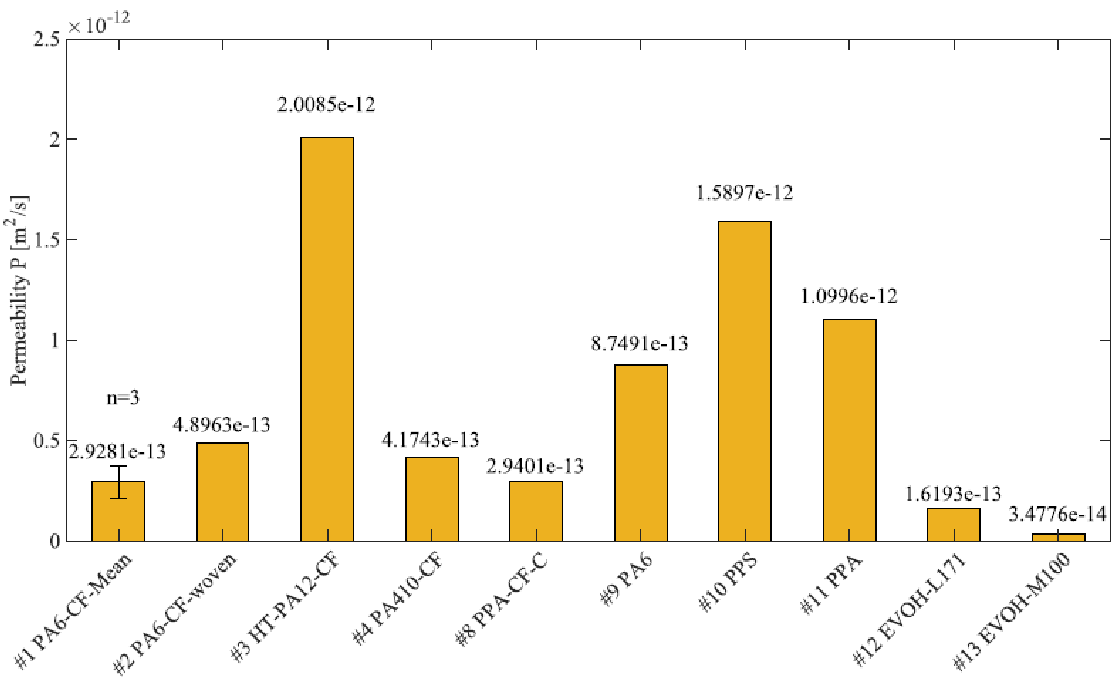


Figure 17. Permeability of various polymers and polymer composites. The PA12 grade is amorphous. (Condé-Wolter et al., 2023)

Klopffer et al. cited that IFP Energies Nouvelles (IFPEN) in France have multiple experimental set ups for measuring hydrogen and natural gas permeation through films and pipes, but are limited to 290 psi. (M.-H. Klopffer et al., 2015) This range is useful for distribution pipes, but cannot reach typical transmission pressures.

Castagnet et al. performed mechanical testing of PE and PA11 exposed to hydrogen pressurized to 0.5-2MPa at temperatures of 68°F, 122°F or 178°F for 9-13 months and observed no changes in the young's modulus, yield stress, or the stress-strain curves.(Castagnet et al., 2012) Klopffer et al. performed a similar study and found no noticeable effect of aging in hydrogen after a year for HDPE, PA11, and PAHM, as shown in Figure 18. (M.-H. Klopffer et al., 2012)

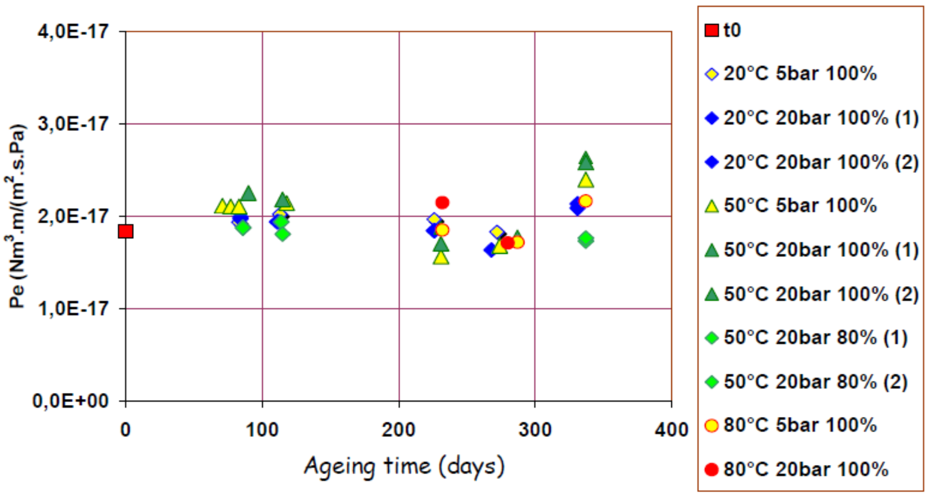


Figure 18: Hydrogen permeability coefficient in PE aged under various conditions of temperature, pressure, and gas composition. (M.-H. Klopffer et al., 2012)

Strohm has presented its own hydrogen permeation coefficient data of HDPE alongside that of others in Figure 19. The temperature dependency of the permeation coefficients correlates well with the Arrhenius equation. Permeation coefficients obtained in experiments performed at very high pressures are somewhat lower than those obtained in experiments at lower pressures. However, in the papers from which these coefficients were obtained a proper explanation for this difference is provided.

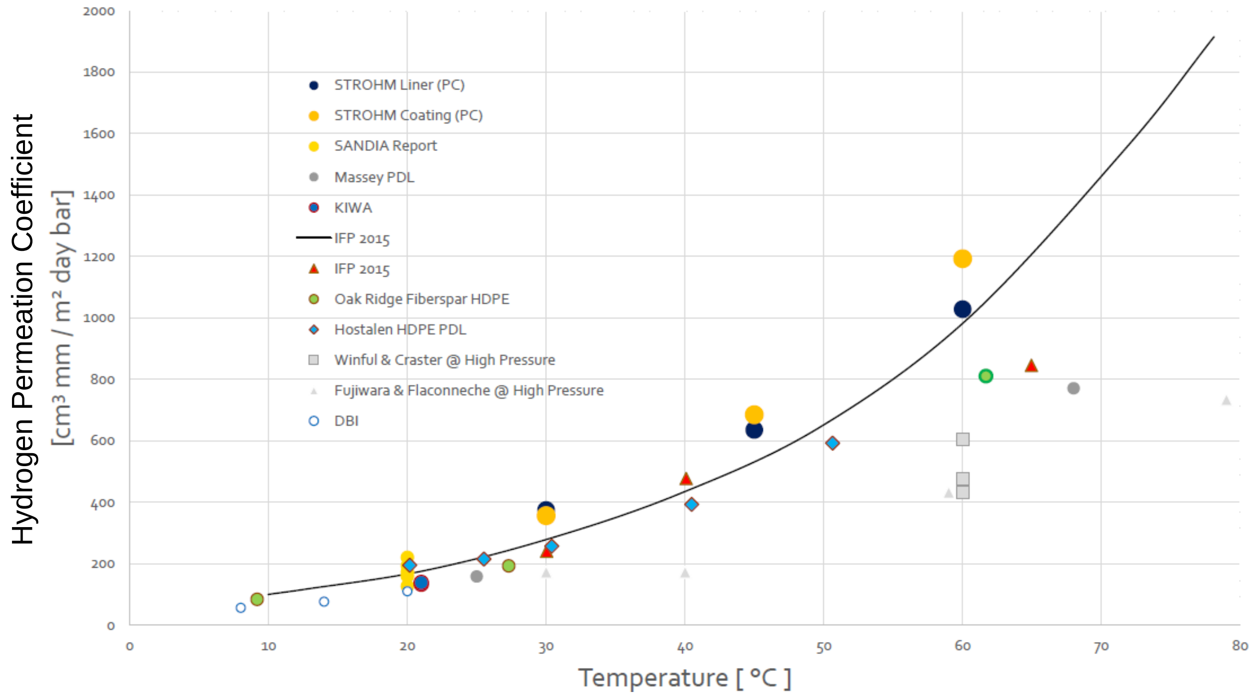


Figure 19. Hydrogen Permeation Coefficient of HDPE.(Frans Janssen, 2023)

As shown in this section, the hydrogen permeation of many thermoplastics used in pipeline construction have been measured. Different set-ups and techniques have been used and a range of temperature and pressures have been applied during testing. There are many data for hydrogen permeation through coupon materials. As new materials are developed for pipelines, they will also need to be tested for permeation.

5.1.2 Rigid Thermosets

NOV Fiberglass Systems had a third party measure the hydrogen permeation through their FGS amine cured GRE pipe and found that its permeation rate at 100°F is 94.7 times lower than that of the same thickness of HDPE at 50°F. The GRE was measured to have a hydrogen permeation of 0.95 x 10^{-10} cm³.cm/(cm².s.bar) at 100°F. Additionally, hydrogen permeation through amine cured GRE was measured independently from two separate manufacturers, and showed permeation to be between 0.84 x 10^{-10} and 1.2 x 10^{-10} cm³.cm/(cm².s.bar) (NOV Fiberglass Systems, 2024)

Humpenoder researched the helium, hydrogen, and methane permeation through fiber reinforced plastics between -328 to 122°F at an unspecified pressure differential. (Humpenöder, 1998) Most notably, they measured glass fiber with epoxy cross-plies (GFEP) with a LY556/HY917 Ciba Geigy resin system and 56 to 67 vol% E-glass content. They concluded that at room temperature the permeation of helium and hydrogen were similar, while methane was significantly lower. They also concluded that the permeation through the GFEP was an order of magnitude lower than through HDPE.

The permeabilities of various thermoset composites were measured and are given in Table 4, along with selected other materials. The epoxy measured is a 2,2-Bis (4-hydroxyphenyl) propane with epichlorohydrin resin-hardener ratio 11:12. The amorphous graphite was less than 0.002-inch particles and the fly ash and halloysite were less than 0.005-inch particles. Interestingly, the permeability for the epoxy with fly ash is the same for both 5% and 30% fill. The permeability of the composite is dependent on the permeability coefficient of the pure polymer, the type of filler, the volume percent of fill, the size of the filler, and the dispersion of the filler. (Gajda & Lutyński, 2022)

Table 4. Hydrogen permeability of various materials. (Gajda & Lutyński, 2022)

Sample	Permeability Coefficient P_{H2}	
	(cm^3 STP $*$ cm $*$ cm^{-2} $*$ s^{-1} $*$ $cmHg^{-1}$)	Barrer
Concrete	7.804×10^{-5}	7.804×10^{5} ($\pm 2.497 \times 10^{4}$)
Polymer–concrete	3.414×10^{-5}	3.414×10^{5} ($\pm 1.092 \times 10^{4}$)
Mudstone (Carbon)	2.330×10^{-7}	2.330×10^{3} ($\pm 8.250 \times 10^{1}$)
Salt rock (Permian) (before creep)	4.815×10^{-7}	4.815×10^{3} ($\pm 1.823 \times 10^{2}$)
Salt rock (Permian) (after creep)	1.95×10^{-11}	0.195 ($\pm$0.024)
Epoxy resin	1.820×10^{-11}	0.182 ($\pm$0.023)
Epoxy resin + graphite (5% vol.)	2.350×10^{-11}	0.235 ($\pm$0.029)
Epoxy resin + halloysite (5% vol.)	3.220×10^{-11}	0.322 ($\pm$0.040)
Epoxy resin + fly ash (5% vol.)	1.770×10^{-11}	0,177 ($\pm$0.022)
Epoxy resin + fly ash (30% vol.)	1.774×10^{-11}	0.177 ($\pm$0.022)
Polyester resin	4.357×10^{-11}	0.436 ($\pm$0.054)
Polyurethane	2.611×10^{-11}	0.261 ($\pm$0.033)
Stainless steel [33]	4.640×10^{-17}	4.640×10^{-7}

The hydrogen leak rate through 0.4-inch (1 cm) thickness, over 10,000 ft^2 (1,000 m^2) surface area, at 145 psi (1 MPa) and 68°F (20°C) for thermoset composites compared to each other is shown in Figure 20. It is also compared to stainless steel, porous rocks, and concrete as shown in Figure 21. While the permeability of the polymer composites is greater than that of stainless steel, it is still considered low enough to prevent hydrogen loss by permeation. During 60 days of hydrogen storage, only about 35 ft^3 at standard temperature and pressure (STP) of hydrogen will diffuse from the thermoset composites. (Gajda & Lutyński, 2022)

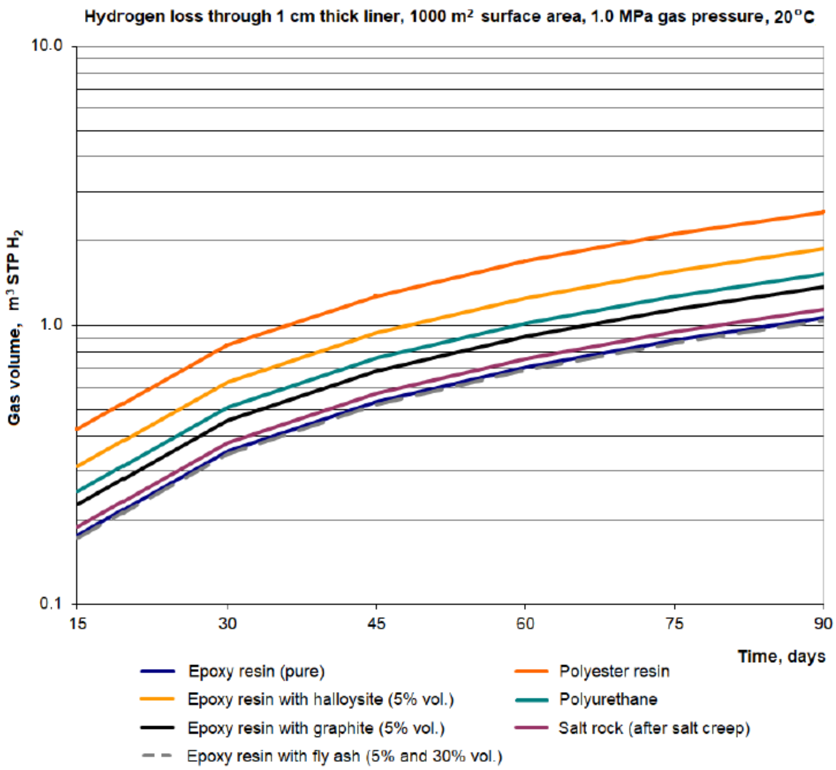


Figure 20. Calculated hydrogen leak through different polymers. (Gajda & Lutyński, 2022)

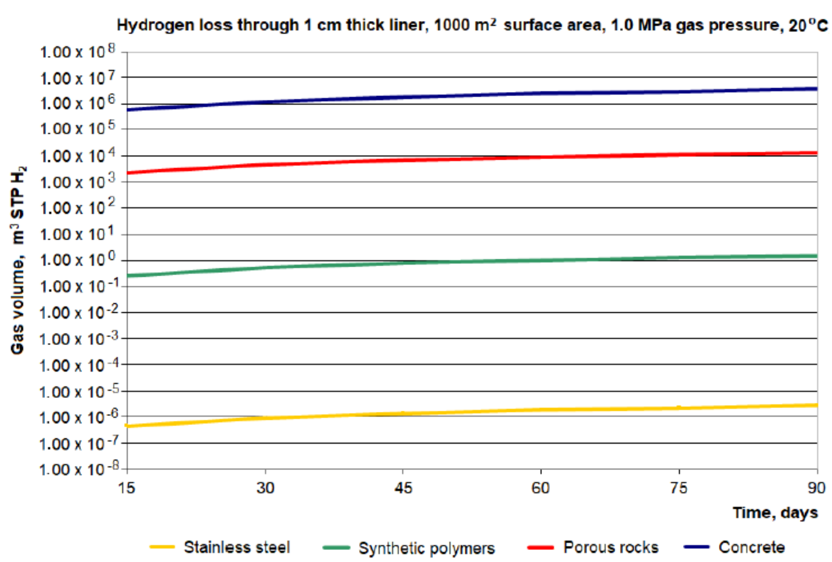


Figure 21. Calculated hydrogen leak through different materials (Gajda & Lutyński, 2022)

Smith, et al. measured the Hydrogen leak rate under a pressure of 1,500 psi in glass-fiber-reinforced plastic GFRP pipe with a 0.22-in. thick HDPE liner at room temperature. The

decrease in hydrogen gas over time is shown in Figure 22. The measured leak rate indicates that less than 0.02% of the stored hydrogen is lost per day. Additionally, the liner did not show any visible or measurable damage
during a blow down test. (Smith et al., 2016)

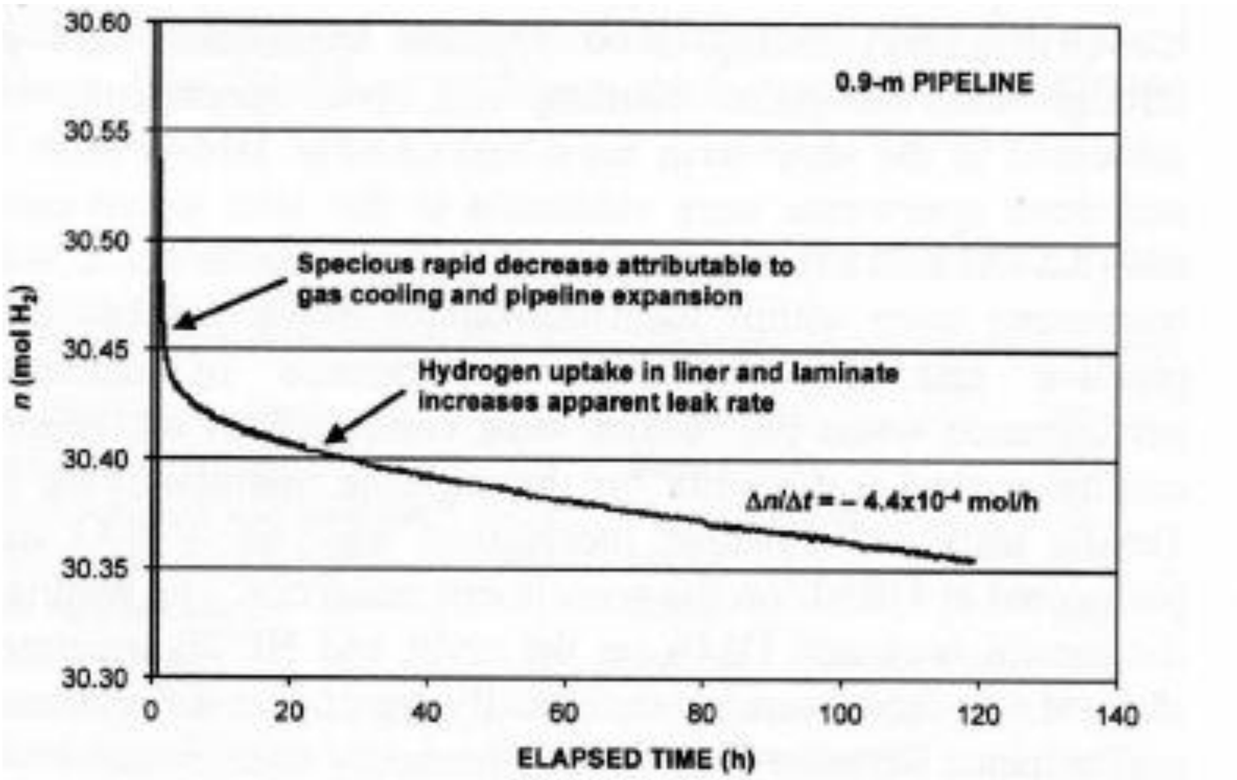


Figure 22: Mols of hydrogen gas leaked over time.(Smith et al., 2016)

Since hydrogen permeation rates are lower in rigid thermosets than thermoplastics, the potential for damage during rapid gas decompression (RGD) could be higher. This is the case for thermosets with voids from manufacturing, or interfaces between the thermoset and reinforcement material that attract hydrogen due to adsorption. During long-term service the hydrogen would permeate through the thermoset and to the voids or interfaces until saturated. During RGD the hydrogen in the voids and at the interface would have a longer time for bubble nucleation, growth, and damage to the pipe because they are trapped and can only escape slowly from these areas due to the low permeation rate of hydrogen through the thermoset. In thermoplastics the hydrogen permeation rate is higher and the hydrogen can permeate through the material during RGD thus mitigating the volume expansion of the trapped gas and also the damage to the pipe.

5.1.3 Polymeric Elastomers

O-rings in pipe field fittings, like end connectors, are one place where polymeric elastomers are used. They are typically designed as a back-up seal, not the main barrier between high pressure hydrogen and ambient, but elastomers may be in direct contact with hydrogen over the decades-long service life of the pipe.

There are many studies on the transport properties of polymeric elastomers. They have shown that hydrogen diffusivity in semi-crystalline polymers appears to be an order of magnitude lower than elastomers. However, the solubility of these materials is not very different. Following the math of permeability being the product of solubility times diffusivity, this would lead to the general trend that the permeability is also an order of magnitude lower for thermoplastics when compared to elastomers. Relaxation effects in elastomers are much faster compared to semi-crystalline polymers, this can cause gas molecules, such as hydrogen, to more quickly establish equilibrium in elastomers. (Menon et al., 2016) Values published by Jang and Chung are in Table 5, which contains two thermoplastics and two elastomers. Transport properties from Barth et al. have been published for polymers and elastomers used with hydrogen also in Table 5. (Barth, 2013)

Table 5. Transport Properties of Polymers Measured at Room Temperature (Barth, 2013; Jang & Chung, 2020)

Polymer	Permeability Coefficient x 10^{-9} (mol.H_2/(m.s.MPa))	Diffusion Coefficient x 10^{-10} (m^2/s)	Solubility Coefficient (mol.H^2/(m^3.MPa))
HDPE	0.82	1.9	4.3
PTFE	3.2	-	-
Buna N	5.0	4.3	11.4
Viton A	3.5	1.9	19
EPDM	9.4	3.7	25.5
NBR	2.9	0.7	41.5
FKM	1.2	0.3	40.0
PET	3.1	1.1	28.2

Researchers at Clemson University compared the permeation properties of self-healing copolymers, which are lower molecular weight than polymers used in composite pipes, to elastomers and found similar results, per Table 6. They found that for the self-healing copolymers, the hydrogen permeation is proportional to the source pressure and inversely proportional to the molecular weight of the polymer. Also, as shown in Figure 23, the permeation increases with temperature. (Hitchcock et al., 2022)

Table 6. Hydrogen permeability of self-healing copolymers compared to common elastomers(Hitchcock et al., 2022)

Sample	Permeability (mol H_2/m*s*Mpa)
50:50 p(TFEMA,nBA)	1.4E-08
50:50 p(MMA/nBA)	4.3E-09
Poly(butadiene) (BR) Ref [6]	1.4E-08
NBR-shore 60 Ref [6]	1.67E-09
EPDM-shore 68 Ref [6]	6.96E-09

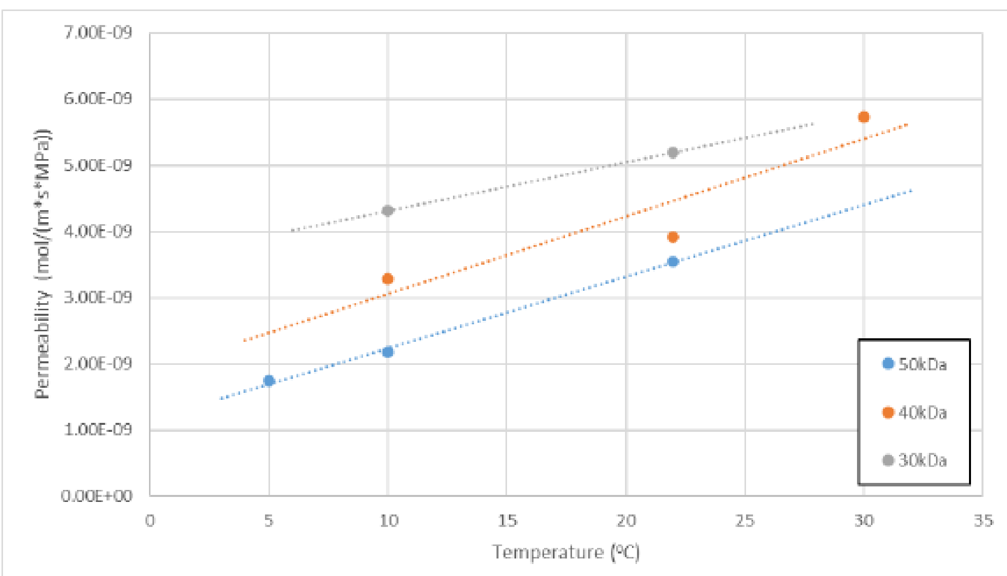


Figure 23. Hydrogen permeability of self-healing copolymer, p(TFEMA.nBA) with molecular weight of 30, 40, and 50 kDa, versus temperature. (Hitchcock et al., 2022)

Elastomeric O-rings can be the source of hydrogen loss not only by permeation, but also by leakage around the seal, or mechanical damage applied to it. Examples of these mechanisms are shown in Figure 24.

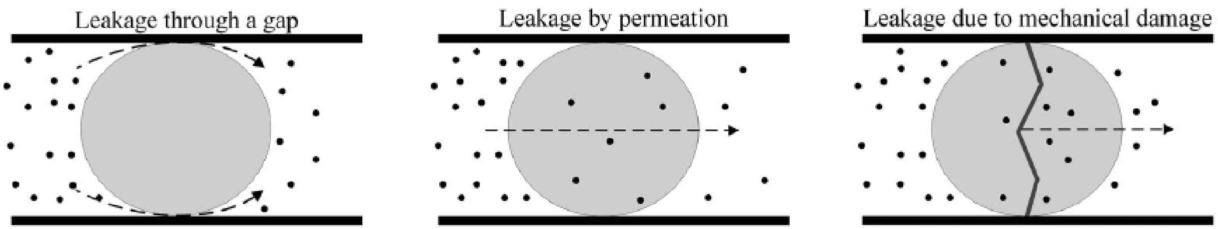


Figure 24. Schematic representation of an O-ring and the ways in which hydrogen can pass it. (Balasooriya et al., 2022a)

The hydrogen permeability of three types of elastomers, nitrile rubber (NBR), ethylene propylene diene monomer rubber (EPDM), and fluorine rubber (FKM) are given in Table 7. A diagram of the two techniques used to make these measurements is shown in Figure 25 (Jung et al., 2021)

Table 7: Hydrogen permeability measured via two techniques for three kinds of rubber (Jung et al., 2021)

Specimen	Permeability (mol/m·s·MPa, $\times 10^{-10}$)	
	TDA-GC	VC
NBR	28.4 ± 4.3	14.7 ± 2.9
EPDM	79.2 ± 11.9	59.1 ± 11.8
FKM	13.2 ± 2.0	6.1 ± 1.2

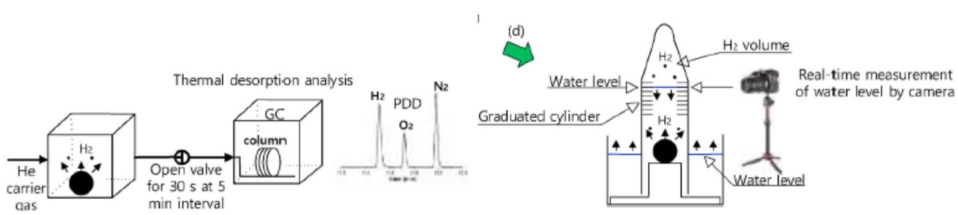


Figure 25: Hydrogen permeation measurement methods. (Jung et al., 2021)

5.2 Fillers

Fillers are used in the outer layer, but not typically the liner. They are used to decrease the hydrogen permeation and increase oxidation resistance, which can be tested using the oxidation induction test (OIT) using a differential scanning calorimeter (DSC). They are typically compounded at loadings low enough to not significantly affect the polymer's mechanical properties. Fillers are not typically used in rigid pipeline materials, but they are used in elastomers. This section shows the advantages and disadvantages to different types of filler and how they affect hydrogen permeation.

Several studies have shown that the addition of impermeable fillers to polymers limit hydrogen diffusion by creating tortuous paths which increase the diffusion path length. However, this effect is mitigated by there being less material to permeate. Samples with a 67% by volume glass fiber reinforcement show a reduction in permeability from 1 x 10^{-12} to 1 x 10^{-13} m^2/s (Condé-Wolter et al., 2023)

It has been shown in polystyrene (PS) and polymethylmethacrylate (PMMA) that adding graphene oxide nanoparticles increases the free volume of the polymer and thus also increases the hydrogen permeability.(Patel & Acharya, 2023) Depending on their geometry, spherical versus planer, these types of fillers should be avoided for transmission pipelines.

Two types of graphene fillers were tested in PP which showed reduced permeability with the added filler. The tested fillers were a reduced graphene oxide with a surface area of 137.2 m^2/g and aspect ratio of ~170 (AVA 0312), and graphene nanoplatelets with a surface area of 6.5 m^2/g and aspect ratio of ~18 (BeD). Interestingly this work also showed that the form factor of the filler has a significant effect on the permeability reduction, as shown in Figure 26 which compares the two types of fillers tested. Surface area and degree of dispersion of the filler are considered the important properties to permeation.(Liu et al., 2022)

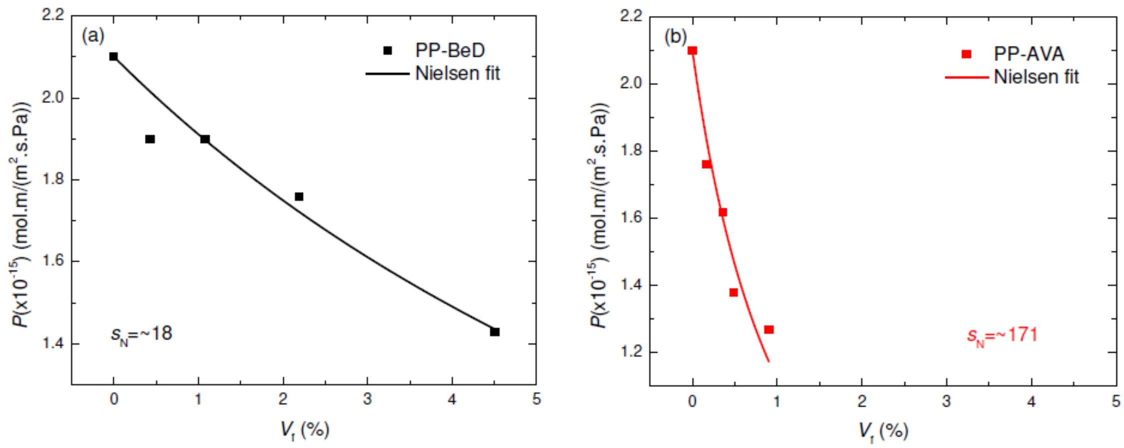


Figure 26. Hydrogen permeability of PP filled with two types of graphene: graphene nanoplatelets (left) and reduced graphene oxide (right) vs volume fraction of filler. (Liu et al., 2022)

BeD filler has microscale dispersion with an aspect ratio of 18 while the AVA filler is more homogenous with nanoscale dispersion and an aspect ratio of 170. The effect on permeability was modeled using Nielson's model, which has been incorporated into Equation 6.

$$P_c = P_m \frac{1 - V_f}{1 + \frac{S}{2} V_f}$$ **Equation 6**

Where P_c is the permeability of the filled polymer, P_m is the permeability of the unfilled polymer, s is the aspect ratio of the filler, and V_f is the volume fraction of the filler. (Liu et al., 2022)

The hydrogen permeability of carbon fiber in thermoplastic composites was found to be dependent on the quality of the fiber-to-matrix interface, especially with regard to void content. This factor was shown to be much more critical than the bulk crystallinity or the fiber-to-matrix adhesion. The quality of the fiber-to-matrix interface was improved when the wettability of the matrix to fiber was increased by surface activation treatment of the carbon fiber as well as when the fiber favors matrix nucleation. This was demonstrated using grafted polymer with an activated reinforcement (carbon fiber). The carbon fiber was shown to have no or slightly negative effect on crystallization of PVDF, but a positive effect on crystallization of PPS. The result is that the filler reduced permeability of PVDF much more than for PPS, as shown in

Figure 27. The solid blue bars in the figure are the neat polymer, whereas the hatched and patterned bars contain carbon fiber.(Allusse et al., 2022)

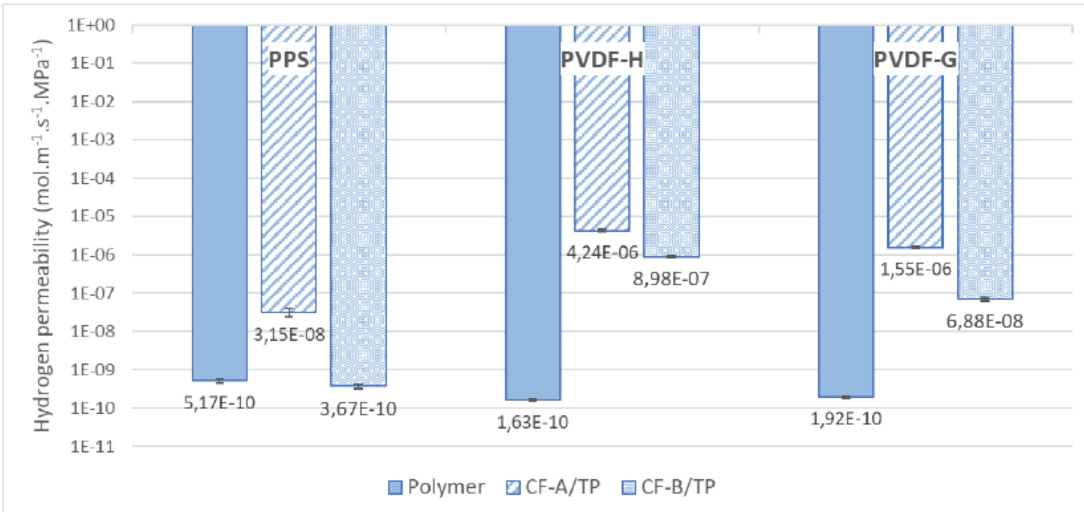


Figure 27. Hydrogen permeability of 0.002-inch thick PPS, 0.004-inch thick PVDF-H (homopolymer) and 0.004-inch thick PVDF-G (grafted). Each polymer type has two types of carbon fiber filler: untreated (CF-A) and with surface treatment (CF-B).(Allusse et al., 2022)

The effect of carbon black and silica filler on hydrogen uptake of NBR was studied by Fujiwara et al.. They found that while silica filler reduced uptake, carbon black increased it. This is because there of a phenomenon called bound rubber where rubber is chemically absorbed on the carbon black surface. While the bulk matrix hydrogen uptake was found to be constant regardless of the filler (thus reducing uptake as filler increases), the hydrogen uptake of the bound rubber was increased enough to remove the benefit of the carbon black filler. (Fujiwara et al., 2022)

On a related note, reinforcement materials, such as steel strips, that cover much of the area surrounding the inner liner act as a permeation barrier. As much as a 90% decrease in hydrogen permeation has been observed for these unbonded RTP pipes. Also, the hydrogen travels down the annulus between the reinforcement layer and the inner liner, where it can be captured and reinjected into the transmission stream. (FlexSteel patent US11680685B2)

5.3 Coatings

The authors of this document found very little literature on coatings being developed specifically for composite pipes and hydrogen transport because multi-layer extrusion is used more often for composite pipe manufacturing. The most relevant research is regarding a nanocomposite of poly(vinyl alcohol) (PVA) and high aspect ratio (~20,000) silicate nanosheets composed of synthetic clay sodium fluorohectorite (NaHec) that was spray coated on a polyester terephthalate substrate (PET). The 1.5 micrometer thick coating has a hydrogen permeability as low as 0.6 $cm^3/\mu m\text{-}m^2 atm$ per day at 0% relative humidity and increased to just 0.8 at 75% relative humidity. To achieve comparable hydrogen permeability performance to this 1-µm thick coating, an EVOH liner would need to be 0.4-cm thick. The spray coating main appeal is therefore in light weighting applications. (Habel et al., 2020)

Fundamental testing was completed by Humpenoder on glass filled epoxy plies (GFEP). These materials are chemically similar to some FRP pipes. He applied a coating and then measured the permeation. (Humpenöder, 1998) The coatings included polyimide, amorphous hydrogenous carbon (aHC), titanium nitride, copper, gold, and silver. They found that thick surface coatings on polymer walls were mechanically unstable and that thin surface coatings had low or no effect on decreasing permeability. However, they found that adding aluminum or tin foil with thicknesses from 0.004 to 0.010 inches dropped the permeation below detectable levels for their mass spectrometer. So, starting with a solid foil of metal decreased permeation better than adding metal as a coating. These can be added as an internal layer but may change the overall pipe mechanical properties.

Alternatively, polymer coatings have been developed for steel pipes and they can be effective at adding permeation barriers to a system, but their quality is affected by their crystalline structure, surface density (ratio of the weight of a coating's active material to the area of the coated region), cross-linking density, molecular mass, chain orientation, plasticizers, cracking due to difference in thermal expansion coefficients, thickness, and coating manufacturing and application process and method. Li et al. state that polymer composite pipes with graphene for permeation reduction were more competitive due to the cost and potential for mass production.(Y. Li et al., 2023)

Lei et al. tested hydrogen permeability, solubility, and diffusivity of 16 potential steel pipeline coatings that were developed to be applied to the inner wall. A film of crosslinked PVA film was tested and modeled and showed the lowest permeation rate of the 16 formulations tested, where a 0.08-inch thick coating could reduce the permeated hydrogen concentration by 44%. (Lei et al., 2022)

Although there are examples of coatings for composite pipelines, they would be difficult to implement on the interior of a pipe and may not have sufficient adhesion for the lifetime of the pipe. Co-extruded layers during pipe manufacturing are a more likely technology to be implemented.

6. Leak Detection and Monitoring Requirements

6.1 Leak Detection Methods

Approaches to leak detection generally fall into two categories, hydrogen gas detection or leak detection, both are discussed in more detail herein. Leak detection is addressed in API RP SA Integrity Management.

Dräger's X-am 5600 Personal Monitor employs a pair of detectors to alert the presence of hydrogen gas and is one of many examples of small portable devices designed to survey process equipment, monitor pipelines, and maintain personnel safety. (www.draeger.com) Other hydrogen gas detectors include the Gas Dog GD200-H2 portable hydrogen gas detector (www.gasdog.com) and the RKI Instruments SP-220 Gas Leak Checker. (www.rkiinstruments.com) Each device requires a manual scanning of the area around the pipeline to detect hydrogen gas.

Odorants may be added to enhance the detection process and provide an olfactory irritant detectable by personnel without using instruments. Research on odorants as a leak detection method has been conducted as part of the Hy4Heat project. They found that 78% 2-methyl-propanethiol, 22% dimethyl sulfide is a suitable chemical to add as an odorant to pure hydrogen.(Topolski et al., 2022) Dimethyl sulfide, an often naturally formed compound during cooking certain foods or generated by bacteria during food spoilage, can be detected with devices such as Dräger's X-am 5000-series of portable gas detectors and sensors.

Most manufacturers of portable instruments also offer permanently installed monitors. Typically, these are applied where the presence of gas is somewhat confined, like a storage or processing facility. They can be applied to pipelines but most likely to manifolds, pumps or other areas most prone to developing leaks.

The second category entails monitoring characteristics of the leak. Gas leaks through a crack or other defect in the pipeline, especially when under high pressure, often produce high frequency acoustic signatures. These emissions can be detected with contact transducers applied to the pipeline or with portable microphones associated with detection instruments. The challenge is separating the leak signature from other noises, such as that produced by the moving gas over various surfaces or the pumps inducing the flow. Niu et al. investigated an approach to characterizing crack length in HDPE using ultrasonic nondestructive testing (NDT) with a convolutional neural network to enable fast processing of data acquired from a single side. Their method resulted in an average error of 3.2% for crack lengths and 3.8% for crack positions, which is promising as a crack evaluation method for hydrogen pipes. (Niu et al., 2023)

As high-pressure gas escapes from the pipeline through a pipeline fault to the area surrounding the pipe, a refrigeration effect occurs for gases like CO_2 and methane and a heating effect occurs for hydrogen.(Zhou et al., 2019) This notable temperature difference is readily detected by suitable temperature sensors.

FlexSteel has a patented system (Patent US11680685B2) for continuously monitoring the annulus space in real time for gas being transported. If an anomaly in concentration in the annulus is recorded, then it is likely that the inner liner has been damaged.

6.2 Sensors

The previous section discussed leak detection methods, and there are several sensing technologies that support the location of leaks by detecting the presence of hydrogen or by measuring changes to process or environmental parameters induced by the leak.

Regarding the former, the National Energy Technology Laboratory published a summary entitled “Real-time Sensor Technologies for H_2 Transportation and Subsurface Storage Monitoring” (R. F. Wright et al., 2023) that cites several hydrogen detection approaches, including their advantages and disadvantages to implementation, shown in Figure 28 below.

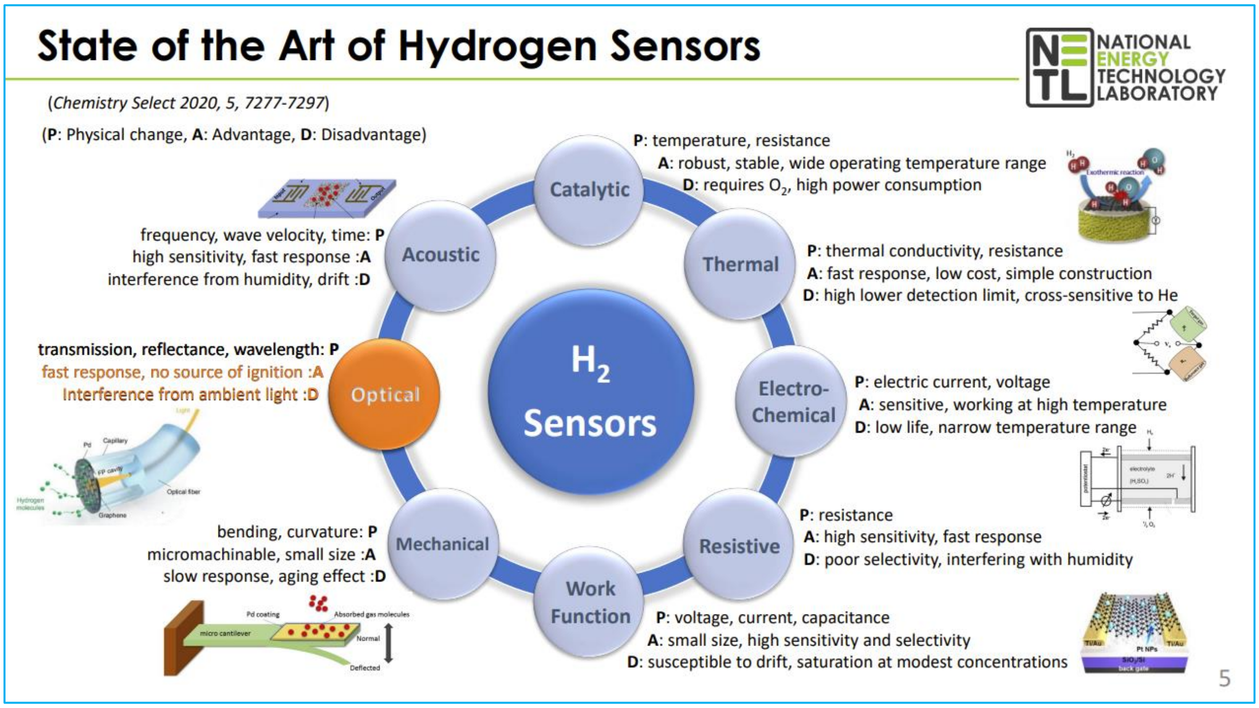


Figure 28. Various Methods of Sensing Hydrogen, Their Advantages and Disadvantages

(R. F. Wright et al., n.d.)

Much of the information regarding the state-of-the-art originated from a European publication, Chemistry Select, and specifically from an article reviewing two-dimensional materials used for hydrogen sensing.(Pham & Brown, 2020)

Traditional hydrogen sensing is performed by causing a localized reaction that frees electrons that stimulate electronic circuitry to create a signal. The basis of these sensors is a Field Effect Transistor (FET) with its gate doped to react with the gas. They are fast, low cost and readily incorporated with electronic signal processing hardware. However, early devices suffered from less than desirable sensitivity and selectivity, and they regularly required recalibration. Moreover, the presence of other gases and vapors often interfered with the accurate detection of hydrogen. Research has continued to improve this sensing approach, with palladium (Pd) and platinum (Pt) playing key roles as catalysts to the gas-to-electrical signal transduction. Recent improvements include using nanoparticles of Pd to enhance the performance of these sensors.(Hu et al., 2024)

In many ways, these solid-state devices offer several advantages, but as regulations have gotten stricter, the need for safer and even more sensitive devices has increased. While researchers continue to pursue this class of hydrogen sensors and have made substantial gains in sensitivity (H. Zhang et al., 2023), optical sensors have increasingly found favor among system implementations. The proximity of a potential ignition source (electrical energy source and circuitry) to an explosive gas can be eliminated, and fibers can be customized to measure several pipeline parameters, including hydrogen gas.

While perhaps not as low cost or immediately responsive as solid-state detectors, fiber optic sensors offer advantages that the former have difficulty achieving. Optical sensors are inherently safer than electrical sensors, since the signal processing circuitry and its energy source can be located away from the flammable gases. They are also far less prone to electrical interference and can be extended over long distances with minimal degradation of its signal. This last feature enables sensors to be distributed over several kilometers of pipeline, eliminating the localized limitation of most detectors. Optical fibers may serve as long distance signal carriers between the sensor and the optical source/processing circuitry, or the fiber itself may be modified to transduce the measured parameter to an optical signal.

One of the recent developments in hydrogen sensing entails subjecting hydrogen to a multi-pass cavity that is illuminated with laser light. An optical fiber delivers optical energy to the cavity, which undergoes Raman scattering having frequency characteristics specific to hydrogen. The return signal is filtered and delivered to a spectrometer, and researchers claim high specificity even when the targeted gas is mixed with other compounds. Moreover, they claim that the multi-pass cavity has allowed them to detect an unprecedented concentration of 75 parts per billion (ppb) when sampling and measurements are taken over a 12-minute period.(Singh & Muller, 2023) This concentration monitoring could be useful for detecting degradation in glass-fiber reinforced pipes. It has been shown that weepage and leakage of fluids increase before failure occurs.(Abdul Majid, 2011) This likely increases the flux of hydrogen that transverses the pipe wall before failure. So, a concentration sensor outside of the pipe could be used to detect an increase before a rupture failure.

In most applications of optical fibers, the fiber itself serves as the sensor, yielding a detection capability of the entire length of the fiber. To sense hydrogen directly, the fiber may be overlayed with a palladium or platinum formulation after etching or tapering the fiber cladding.

Tungsten oxide (WO_3) has also been used, but researchers have found that significant performance improvements can be gained when this compound is embellished with platinum. (Pathak et al., 2023) Schematics of these fiber geometries are shown in Figure 29.

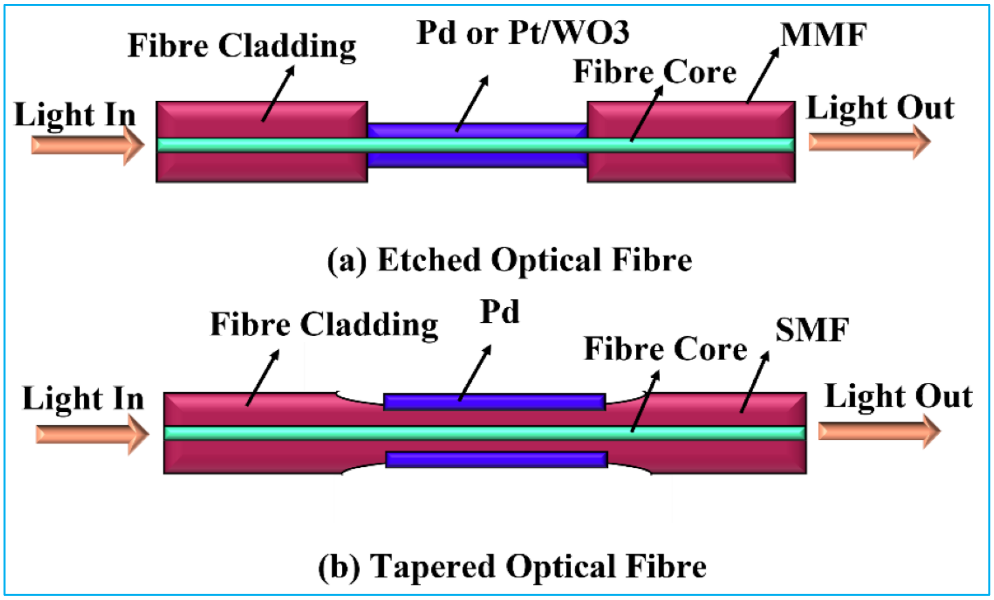


Figure 29. Palladium and Platinum Clad Optical Fiber Hydrogen Sensor (Pathak et al., 2023)

Another technique that has been explored modifies the fiber with a Bragg grating (FBG) that creates a shift in optical wavelength when exposed to hydrogen. The first sensor of this type was created in 1999, but since then, several development teams have made improvements to response time, sensitivity, and operating temperature range. One of these improvements utilizes a palladium coating on the fiber into which a fiber Bragg grating is etched, as seen in Figure 30. (Pathak et al., 2023)

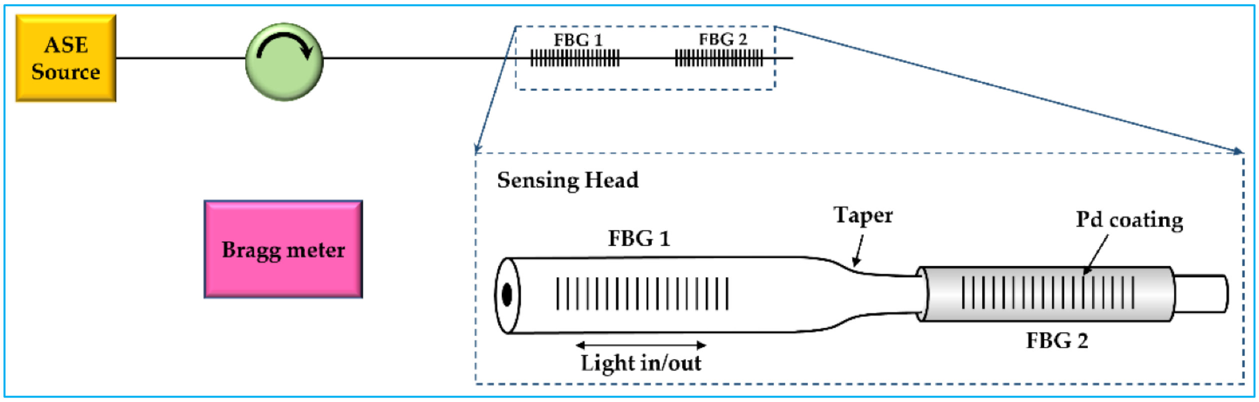


Figure 30. Hydrogen Sensing via Fiber Bragg Grating (Pathak et al., 2023)

Si, et al, expounds on these sensing approaches and how the optical fibers may be configured to yield hydrogen detection. (Si et al., 2024)

Alternative to detecting hydrogen directly, several sensing approaches rely on changes in physical parameters associated with the leak itself. Distributed acoustic sensing (DAS) is a fiber optic-based method of detecting acoustic frequency signatures over the entire length of the fiber. The signatures may be due to induced vibrations from pressurized gas being released through a fissure in the pipe, or it may be due to mechanical strains from the movement of gas through the pipeline. In the latter case, the strains may be due to normal operating conditions, in which case, signal processing software will recognize this condition. But as abnormalities develop, the acoustic signature changes, and these deviations are noted by the processing system.

A principal advantage to this category of fault sensing is that several products are commercially available. One product line is AcoustiSens® fibers and cables manufactured by OFS Optics that relies on Rayleigh backscatter over the entire length of fiber.

Some pipes (e.g., SmartPipe®) implement fiber optic monitoring and communication cables as part of their structures. These are typically placed in contact with the reinforcement layer. They can detect and provide the location of localized temperature change, product leak, excessive strain, or third-party damage along the pipeline length. (Nemeth et al., 2022) However, hydrogen atoms can bind with the SiO_2 to form hydroxyl group that interfere with the passage of light, thus causing hydrogen darkening.(Bonnell, 2015) Some fibers have been chemically modified to resist darkening, but the rate of darkening at the temperature of use should to be modeled to determine if the fiber optic signal will be useful for the life of the pipe. Others propose laying the sensing cable outside of the pipeline, thereby decoupling the maintenance of the sensing fiber to that of the pipe. (Zhou et al., 2019) No matter how the fiber is implemented, it may be configured to detect multiple parameters using the same fiber.

For steel reinforced RTP, eddy current techniques show promising results, since they are capable of detecting cracks or material loss on the steel reinforcement, which provides all of the RTP structural capacity.

Systems, such as tracer wire, markers, or warning tapes, to locate buried pipe should be installed so that its location is known for future excavation. (Installation and Handling of Spoolable Reinforced Line Pipe (API Recommended Practice 15SIH First Edition), 2021)

Gas flow meters have been designed around the speed of sound range of natural gas, but the range is almost three times higher for hydrogen. Therefore, it is necessary to research their long-term stability at these high velocities. (Erdener et al., 2023)

6.3 Monitoring Requirements of Standards

Congressional amendments to the Pipeline Safety Act in the Protecting our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act of 2020 include a provision mandating that PHMSA issue a rulemaking to implement leak detection and repair regulations for natural gas pipelines. PIPES Act of 2020, Section 113 (revising 49 U.S.C. § 60102). Consistent with the Agency's increased focus on renewable resources and leak detection, certain composite pipes expand the network capable of transporting hydrogen and include the requirements in the special permit conditions for fiber optic continuous leak detection monitoring. At the time of writing this document, the authors were unaware of any special permits approving hydrogen transport by pipelines with fiber optic sensors.

API RP 15SA recommends using visual inspection as a significant component of data collection for a spoolable pipeline integrity assessment.(American Petroleum Institute (API), 2022) This includes pipe walking for surface-laid pipes to measure expansion, shifting, third-party interference, external impact, impingement, soil settlement, and pipe deflection angle at the end connections. For buried lines, special attention should be given to riser locations to ensure that settlement or shifting does not lead to end connector damage. API RP 15SA also recommends periodic hydrostatic testing of the installed pipe and periodic removal, testing of pipe spool or coupons in area determined to be higher risk, and monitoring annulus between OD of spoolable pipe and ID of surrounding pipe to test for permeated gases and overall pressure. In some cases, permanent monitoring systems may be installed in the annulus to measure pressure, temperature, or gas composition. The data can be used to infer the health of the pipe in real time. Other methods of inspections include drone imaging instead of walking the pipeline, inserting a camera device/crawler in the pipe to check the condition of the liner and fitting internals, geometry pigs to determine pipe ovality or for instruction, acoustic emission with floating spheres for leak detection, and fiber optic monitoring to assess strain levels, temperature, and third-party encroachment/damage.

6.4 Suggested Testing Protocols for Inspection

A gap exists in the ability to monitor the integrity of polymer pipelines. Most nondestructive evaluation (NDE) techniques have been designed for metallic pipelines, most notably steel. However, methodologies like eddy current testing that rely on substrate conductivity cannot be used on the largely electrically insulating polymer materials. Similarly, magnetic flux leakage (MFL), magnetic permeability perturbation testing (MPPT) and other ferromagnetic-based approaches cannot be used on paramagnetic pipes. Even ultrasonic technologies that rely on electromagnetic stimulation, such electromagnetic acoustic technology (EMAT) cannot be used. Clearly, more inspection technologies must be developed to monitor the long-term structural health of composite pipes. These challenges are being addressed by individual manufacturers, an ADV Integrity joint industry project (JIP), a PHMSA-funded three-year study led by the Gas Technology Institute, and another PHMSA-funded study led by EWI titled, “Assessment of Non-destructive Examination (NDE) and Condition Monitoring Technologies for Defect Detection in Non-Metallic Pipe.”

To this end, several wave-based approaches are proposed, where the waves may be acoustic or microwaves. Recent studies have revealed that terahertz (THz) waves exhibit unique interactions with polyethylene and may be used to create three-dimensional (3D) images of pipelines comprised of this material. (Wang et al., 2024) Though technically wave-based, infrared (IR) thermography has been proposed as a polymer pipeline monitoring technology.

On the horizon are new sensing technologies that have been developed for metallic materials but may be adapted to polymer pipelines. One example is a differential capacitive sensor that significantly reduces the inherent noise associated with previous similar approaches and greatly improves the signal-to-noise ratio. (Peng et al., 2024) While the capacitive sensor has been demonstrated on steel and aluminum substrates, capacitive sensing has more broadly been applied to non-conductive targets.

Develop and test odorants specific to hydrogen for easy differentiation from other gases. Ensure sensors and detectors are stable after long exposure, and that downstream appliances (e.g., fuel cells, stoves, water heaters, furnaces) function properly and there are no detrimental effects to human health using the fuel.

To decrease labor costs of manual inspection for above ground non-metallic pipes by walking along the pipeline right of way (ROW), advances must be made in sensors and artificial intelligence (AI) data analysis from autonomous drones for remote monitoring and leak detection.

Also, to ensure the accuracy of the data collected over decades of service, it requires a better understanding of the impact by hydrogen on gas sensors currently used for natural gas, since these are the most likely to be implemented first.

7. Composite Pipe Operational Unknowns

7.1 Material Performance

Plastic piping has been found to be suitable for hydrogen distribution, but research has shown that hydrogen can impact the density and degree of crystallinity of polyethylene after exposure to very high pressures. More testing may be required to quantify the effect of changes on polymer performance and to composite pipe lifetime as transmission pressures are pushed to new limits. Compressors, valves, storage facilities, and other non-pipe components also contain polymer components that may need more testing as well.(Topolski et al., 2022)

HDPE (PE100) is a material with a controlled molecular weight and polymer chain length distribution, and it’s found most typically in the inner liner of composite pipes. HDPE has resistance to both long-term hydrostatic pressure and stress cracking when the molecular weight is high. It also has impact resistance and flexibility by maintaining a wider polydispersity that contains low molecular weight fraction. As a polyolefin, it has great chemical resistance stability that leads to environmental stress cracking resistance. Slow crack growth of HDPE is limited by the molecular entanglement of the long amorphous chains between the crystalline lamellae. (Fujiwara et al., 2021) Polyamide 12 also has slow crack growth resistance, as shown by cyclic cracked round bar testing.(Messiha et al., 2020)

7.1.1 Hydrogen Effects on Polymer Materials

Russell and Curliss concluded that no plausible mechanism was found for the degradation of polymeric materials in the presence of pure hydrogen. They believe that the absence of degradation is due to lack of interactions between hydrogen and the polymer. The solubility coefficients of hydrogen in polymeric materials are low. Even without this chemical interaction, the hydrostatic pressure has been shown to increase the glass transition temperature (T_g). (Russell & Curliss, 1992) The sorption in ridged polymers is low enough to be accurately described by Henry's Law. This is not the case for rubbery polymers that have higher solubility and require the Flory-Huggins theory of dissolution. If a gas has high solubility, such as carbon dioxide, in glassy polymers, then the sorption can be modeled by the dual mode dissolution theory. If another catalyst is present, such as heat, humidity, or irradiation, in addition to the high-pressure gas, then degradation can occur.(Kane, 2008)

Fujiwara et al. have found that voids can be created in HDPE during depressurization and have quantified the degree of damage using computed tomography (CT) and transmitted light digital image techniques. The higher the degree of crystallinity of the HDPE, the less destruction occurred during depressurization studies. (Fujiwara et al., 2021) These tests were run to saturation at 13,000 psi at 86°F, which is higher than the pressures experienced in a pipeline. In hydrogen storage tanks the high pressures and long times can lead to oversaturation of the polymer when the pressures are decreased, which may lead to gas bubble formation, especially upon fast depressurization.(Voyiatzis & Stroeks, 2022) Likewise, Kim and Lee investigated the hydrogenation of HDPE during decompression of hydrogen gas at 13,000 psi. They observed both physical and chemical changes in the polymer. Physically, a partial hexagonal phase was formed in amorphous regions and the overall crystallinity decreased. The presence of ester groups (-C=O) confirmed that oxidation occurred. They also noted crosslinking and an increase in methyl end termination groups was observed. The spherulite structure of the polymer expanded, which caused the formation of cavities, decreased density, and increased porosity, which could negatively affect the material's mechanical properties. (Kim & Lee, 2023)

Furthermore, HDPE creeps due to force from gas pressure during nominal transmission operational conditions. This phenomenon can be mitigated by the proper design of reinforcement materials as the HDPE liner pushes into them due to the hydrogen pressure. (Yazyev et al., 2020)

According to research conducted by Shrestha and Ronevich, the fatigue life of medium density polyethylene (MDPE) is improved by exposure to hydrogen at pressure up to 3,000 psi, possibly due to the absence of moisture or potentially a change in the polymer microstructure under pressure. (Shrestha et al., 2022)

Because hydrogen gas has a poor energy density by volume, it must be stored under high pressure to be economical (Kulkarni et al., 2023). To avoid the issues associated with pressures above 10,000 psi, API RP 15SA states that rapid gas decompression (RGD), of any transmitted gas, from operation at pressures and/or temperatures outside limits is a potential cause of blistering of the liner material.(American Petroleum Institute (API), 2022) Depressurization rates should be matched with the diffusion of the hydrogen leaving the polymer as to not induce supersaturation, bubble nucleation, and permanent damage.

Rapid gas decompression can cause thermodynamic supersaturation, bubble growth, and blister formation in polymers if the diffusion of the hydrogen through the polymer matrix is too slow to escape. A depiction of this phenomenon in a defect-free, unfilled polymer is shown in Figure 31. Another depiction is shown in Figure 32 which includes a defect or filler in the polymer. Furthermore, an RGD depiction of a polymer liner and reinforcement material system are shown in Figure 33.

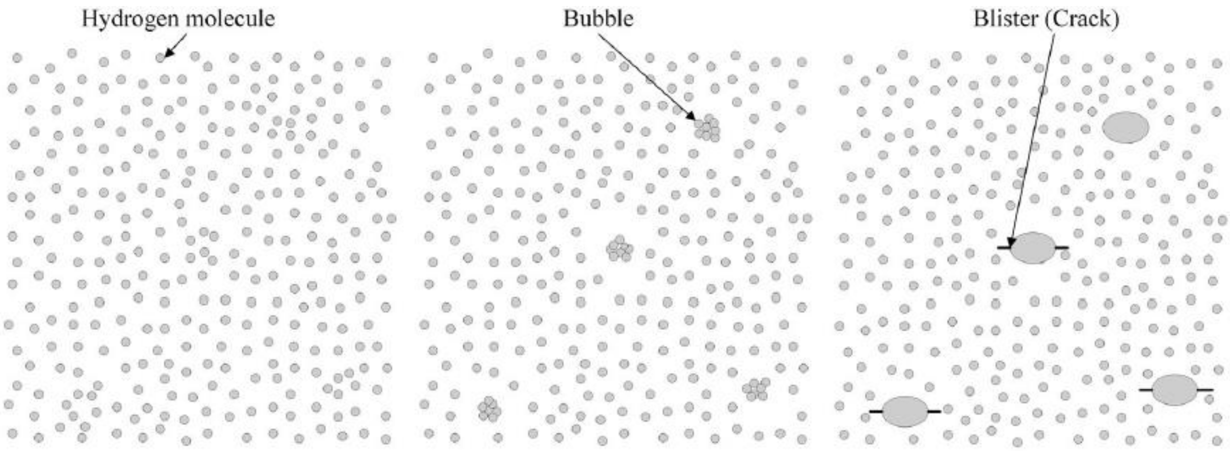


Figure 31. Depiction of blister initiation after rapid gas decompression. (Balasooriya et al., 2022a)

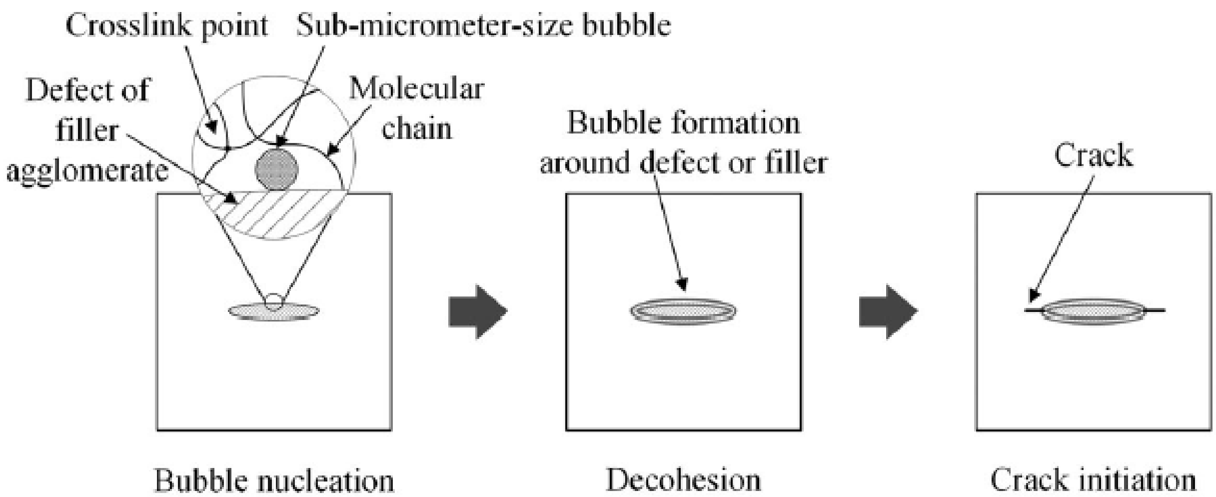


Figure 32. Depiction of crack initiation in a polymer with defects or fillers.(Balasooriya et al., 2022a)

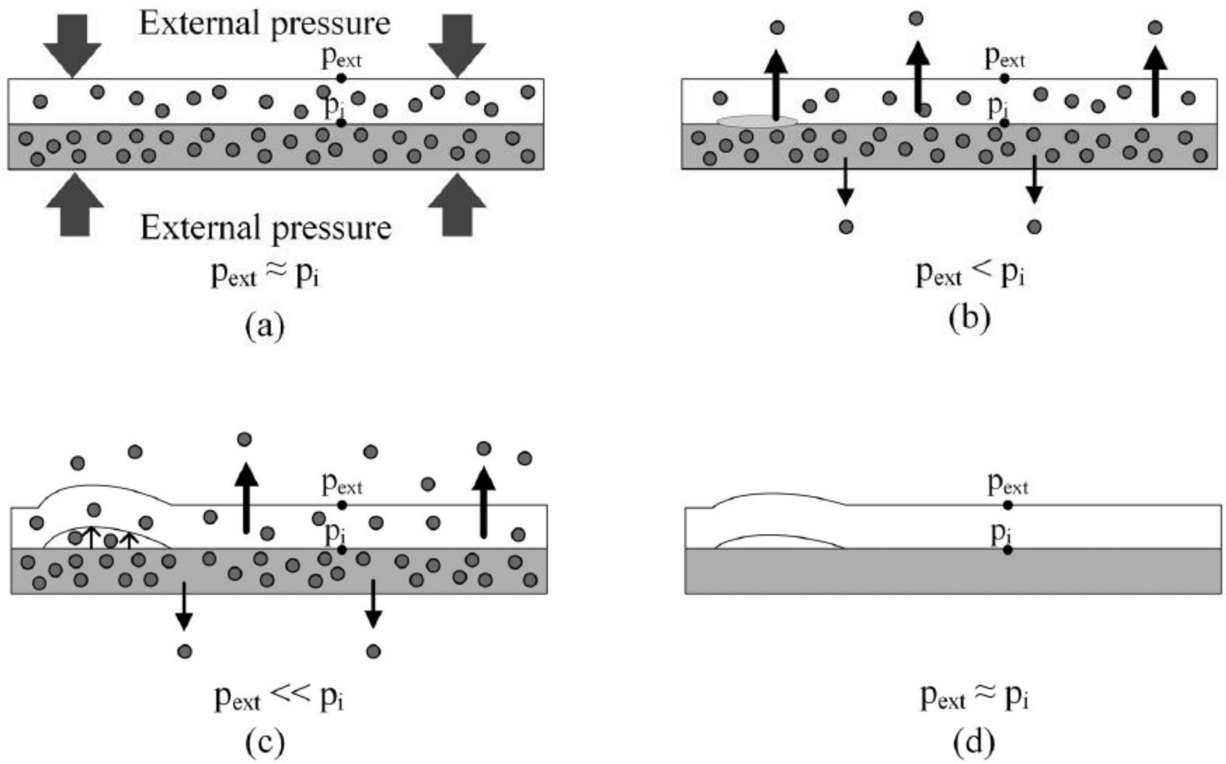


Figure 33. Depiction of the damage between polymer liner (white) and reinforcement material (gray). (a) hydrogen pressurization (b) rapid gas decompression (RGD) (c) end of the RGD, and (d) after hydrogen desorption when a blister remaining in the polymer. (Balasooriya et al., 2022b)

Kulkarni et al. found that damage from rapid decompression from 1,015 psi is reduced with the addition of carbon black and silica filler but increased with the addition of plasticizer. This is because particles mitigate crack formation while plasticizers propagate cracks. The diffusion coefficient is directly related to rapid decompression damage in ethylene propylene diene monomer (EPDM) as shown in Figure 34. Notably, damage was observed inside the materials rather than at the surface as shown in Figure 35. (Kulkarni et al., 2023)

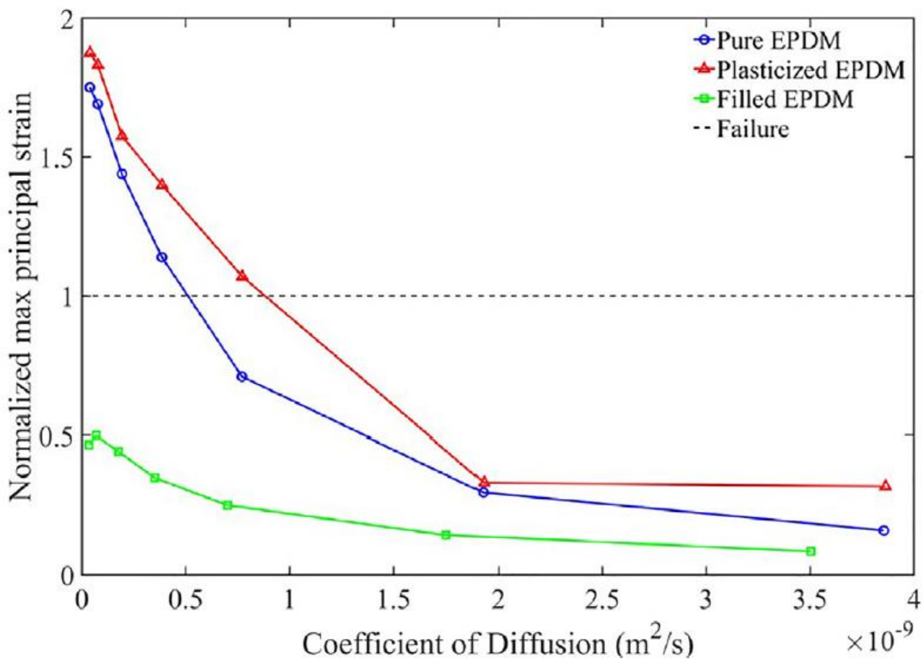


Figure 34: Strain vs coefficient of diffusion for EPDM exposed to hydrogen. (Kulkarni et al., 2023)

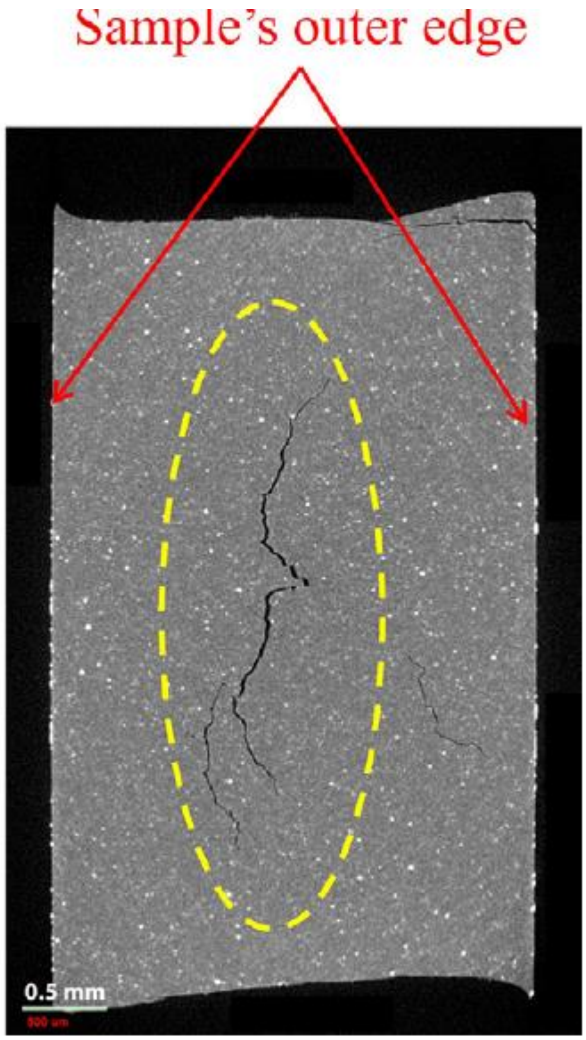


Figure 35: CT scan images of EPDM samples after multiple cycles of rapid decompression in hydrogen.(Kulkarni et al., 2023)

Byrne and Manjarres-Espinosa tested the interactions of hydrogen gas with HDPE pipes (not composite). (Byrne & Manjarres-Espinosa, 2023) They tested bulk material and the butt weld. Samples were exposed to hydrogen at 1,160 psi for 45 days. There was little or no change observed in the Young's modulus and ultimate tensile strength, but a 5% increase in strain at break. The slow crack growth results showed that the butt-welding process had a larger effect on changes in crystallinity than the hydrogen exposure.

In 2023, researchers completed an extensive comparison study of the effects of hydrogen on three polymers for flexible pipe applications. The materials studied were PA11 (grade I), PE (grade II), and TPE (grade III). PA11 has been used as a pressure sheath in flexible pipes since 1972. PE is a less expensive polymer which is considered a potential alternative to PA11. TPE is considered for use as an external protective sheath. For all three materials, there was no visually identifiable change in the material after 20 cycles of RGD from 7,250 psi of hydrogen down to 15 psi at a rate of 1,015 psi / min. However, blistering was observed in the PE material at 7,250 psi and 131°F hydrogen exposure, making PA11 more suited for pipeline transportation. There was no change in mass or volume of the PA11 and PE materials after 5,800 psi hydrogen exposure at 176°F for 6 months, indicating swelling did not occur. The TPE material had a slight reduction in volume (-5% after 6 months), which is likely due to a small loss of plasticizer. Figure 36 and Figure 37 show the change in various material properties for PA11, PE, and TPE after exposure to high pressure, high temperature Hydrogen. (Gabet et al., 2023) Most composite pipes are not rated above 3,000 psi, so this type of damage is not expected within the normal operating conditions for HDPE or PA11.

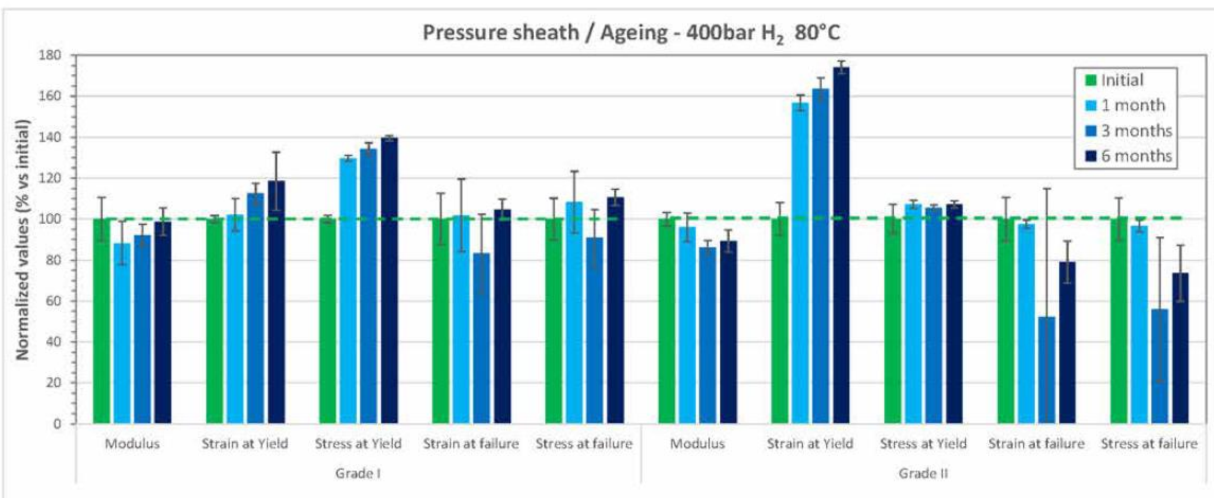


Figure 36: Mechanical Properties of PA11 (Grade I) and PE (Grade II) after long term high temperature, high pressure exposure to Hydrogen (Gabet et al., 2023)

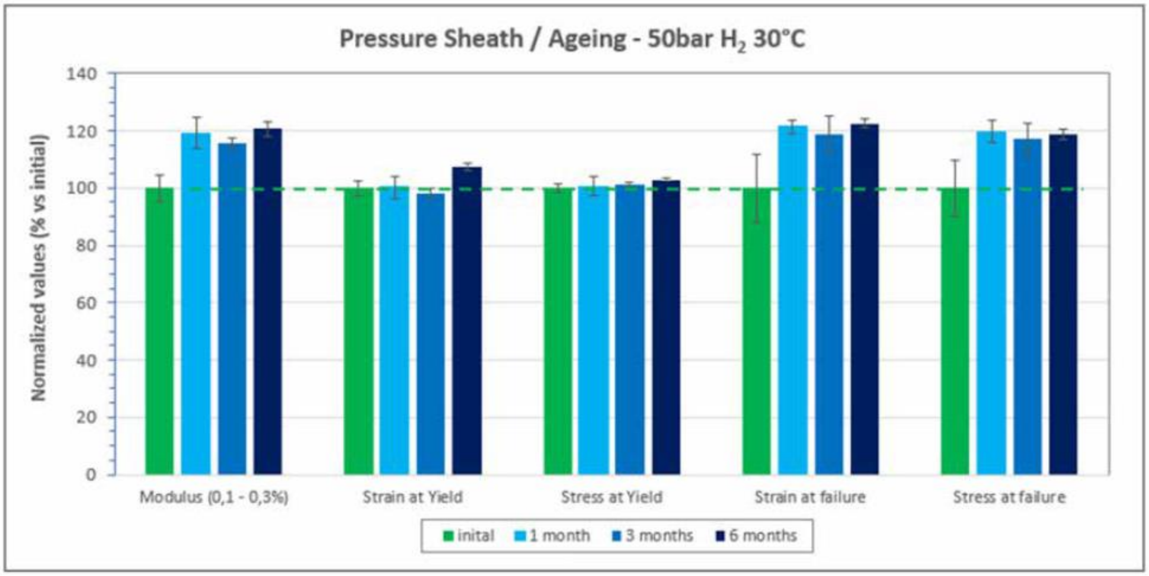


Figure 37: Mechanical Properties of TPE after long term high temperature, high pressure exposure to Hydrogen (Gabet et al., 2023)

Other stressors, such as ultraviolet (UV) irradiation and humidity cause degradation in polymers. UV irradiation leads to photo-oxidation and the formation of free radicals that continue to oxidize the polymer even after it is moved to darkness. Chain scission occurs, as well as an increase in crystallinity due to higher chain mobility, thus leading to a more brittle polymer. The free radicals can be scavenged if the proper additives are added to the outer layer of the pipe. Humidity, another stressor, especially at high temperatures, leads to hydrolysis of polymers after diffusing into amorphous regions. Hydrolysis resistance is addressed in API 17J, and the European Industrial Gases Association (EIGA) published temperatures that polymers are resistant to hydrogen degradation, and noted that higher temperatures may be acceptable, but need further testing. The EIGA published hydrogen degradation temperature for polyamides is 68°F, for PVC it is 140°F, for PTFE it is 482°F, and for PE it is 140°F. (EIGA, 2014)

Gaseous hydrogen contamination can have effects on the polymer inner liner. Each gas contaminant will cause specific chemical interactions that may affect the materials differently. Some contaminates, like sulfur dioxide, decrease the amount of hydrogen permeation through the polymer due to occupying the free volume.(Kane, 2008) The effects of natural gas on the mechanical properties of polymer pipe have been shown to be negligible. HDPE pipe has been used for more than 40 years for natural gas distribution and FRP has been used for downhole and corrosive environments for a similar number of years.(Laney, 2002) Other contaminates may include carbon dioxide, liquid water, water vapor, chloride gas, and oxygen. More testing should be performed on mixed or contaminated gas streams to better understand the rate of degradation under different chemical, heat, and pressure conditions evolved from specific anthropogenic sources.

Some rubbery polymers, such as elastomeric O-rings, seals, or gaskets have a relatively high solubility for hydrogen gas. Therefore, fast depressurization or rapid temperature changes may cause swelling or blistering. This is sometimes known as explosive decompression due to the expansion of gas in polymer’s free volume. The mechanism by which this works is that the solubilized gas expands quickly when the pressure around it is decreased, inducing bubble nucleation and growth causing irreversible damage to the polymer. (J. L. Ellis, 2009; Fujiwara et al., 2021; Menon et al., 2016; San Marchi, 2008) Blister formation to NBR rubber two hours after hydrogen decompression from 13,000 psi at 86°F has been observed.

Menon et al. published data on two thermoplastics and two elastomers and the effect that 14,500 psi hydrogen at ambient temperature had on them.(Menon et al., 2016) The materials were soaked in high pressure hydrogen until saturated, and then depressurized quickly, in less than one minute. They observed that hydrogen can change the molecular orientation and the free volume of an elastomer. They also observed that hydrogen can exhibit weak interactions with elastomer backbones and be trapped within the polymer after depressurization, which can lead to increased compression set. Buna N showed a 41% decrease in storage modulus and Viton A showed a 50% decrease, showing that plasticization occurred in both elastomers. Both elastomers also showed significant swelling immediately after removal from hydrogen, 57% and 69% respectively. Which decreased to 3.9% and 11.5% respectively, after 48 hours. Compression set increased by 1% for Buna N and 9% for Viton A. Conversely, the storage modulus and densities of the thermoplastics, HDPE and PTFE, did not change significantly showing that hydrogen was neither retained nor did it irreversibly damage them. However, PTFE showed a 35% increase in Young’s Modulus after hydrogen exposure and HDPE showed a 15% increase.

Li et al. have concluded that permeation of gases into the thermoplastic liner of RTPs may lead to its blister fracture and damage its safe operation.(H. Li et al., 2022) But this conclusion was not specific to hydrogen, so hydrogen's low solubility and fast transport properties may mitigate the damage risk for hydrogen transmission pipes.

Douglas and Gray were focused on studying elastomer compatibility with hydrogen.(Douglas & Gray, 2023) From a chemical perspective they claim that hydrogen has little to minor effect, 0 to 5% volume swell, on the following elastomers: Kalrez® FFKM, butadiene styrene (SBR), butadiene (BR), butyl (IIR), chlorosulfonated polyethylene (CSM), ethylene propylene (EPM, EPDM), fluoroelastomer (FKM) dipolymer, FKM terpolymer, nitrile (NBR), polychloroprene (neoprene CR), and urethane (AU, EU). While natural rubber (isoprene NR, IR) and polyacrylate (ACM) have a minor to moderate effect, 5 to 10% volume swell, and fluorosilicone (FSI, FVMQ), Polysulfide (T), and silicone (Si, VMQ) have a moderate to severe effect, 10 to 20% volume swell. Testing was performed on FKM elastomers in hydrogen for 450 hours, 212°F, and at least 1,450 psi. The tensile strength change, elongation at break change, and modulus change were all below 7.5%, which shows good stability. Rapid decompression testing was also performed and FKM and hydrogenated nitrile butadiene rubber (HNBR) passed, while EPDM failed. They also concluded that some grades of FKM terpolymer have up to nine times lower permeation coefficient when compared to other FKM grades. This is likely due to the differences in fillers type and loading.

Thatathil studied the stability of four elastomers and two plastics by exposing them to hydrogen at 1,450 to 2,900 psi for 10 months, then depressurized at 10 psi per min.(Thatathil, 2023) The elastomers were HNBR, FKM, tetrafluoroethylene/propylene rubber (FEPM), and perfluoroelastomer (FFKM), and the plastics were PTFE and PEEK. None of the materials showed any bubbles, surface defects, bulk defects, or gas entrapment. The materials also did not have significant changes in mechanical properties, hardness, or swelling. Overall, there was no evidence of thermal or chemical degradation on any of the materials. These pressures are representative of what is expected in a hydrogen transmission line.

Ellis et al. study the effect of fast hydrogen depressurization on NBR, FKM, PTFE, silicone, and EPDM O-rings. Soak pressures were around 2,000 psi, times were up to 72 hours, and depressurization was as fast as 0.2 seconds to get back to ambient. Significant changes were observed in decreased strength for the FKM O-rings and decreased elongation for the NBR O-rings.(J. Ellis et al., n.d.)

The European Industrial Gases Association published elastomers that are compatible with hydrogen. Butyl rubber, Neoprene, Buna S, Hypalon, Viton, and Buna N all have good chemical resistance to hydrogen.(EIGA, 2014) No temperatures or pressures were defined for these ratings.

Kass et al. have a list of compressor station components, sub-components and polymeric materials of construction that list their compatibility with hydrogen/natural gas blend, supercritical carbon dioxide, and ammonia.(Kass et al., 2023) All of the materials were labeled as suitable for the hydrogen/natural gas blend. These included PTFE, NBR (depending on grade), polyurethane, silicone, polyester, nylon, Neoprene, acetal, FKM, HNBR, EPDM, and FFKM perfluorocarbon.

The DOE H-Mat program studied NBR and ethylene propylene diene monomer (EPDM) at 14,000 psi of hydrogen. The data showed a decrease in storage modulus for EPDM with fillers and plasticizers and that NBR showed an increase compression set. (Kass et al., 2023) These tested pressures are much higher than those used for composite pipelines at this time.

Byrne and Manjarres-Espinosa also tested the interactions of hydrogen gas with NBR (durometer 70A). (Byrne & Manjarres-Espinosa, 2023) Samples were exposed to hydrogen at 1,160 psi for 7 days. The NBR samples swelled up to 3% in pure hydrogen but then returned to their original volume 48 hours after removal. The swelling was up to 19% in the 10%H_2:90%CH_4 gas blend but also returned to the original volume. This indicates that natural gas blends with hydrogen may be more deleterious than 100% hydrogen.

Khalid et al. provides a concise review of material properties after hydrogen exposure. (Khalid et al., 2020) HDPE was exposed to temperatures between 68°F and 176°F and hydrogen pressures up to 290 psi for 13 months resulting in no mechanical property differences. Also, HDPE and PTFE were exposed to hydrogen at ambient temperature and 14,500 psi for one week resulted in no significant change in their glass transition temperature or tensile strength.

Tangential to the single material degradation mechanisms listed herein, the polymer matrix to fiber interface can be a source of failure. In a TCP pipe, a microcrack within the interface between the polymer matrix and fiber can lead to a large loss of strength and stiffness.(Okolie et al., 2023).

As evident from the literature reviewed, pure hydrogen at pipe pressures (< 3,000 psi) lead to no notable degradation of the polymers in composite pipes. Rapid gas decompression from high pressures (< 10,000 psi) did induce damage to polymers, but these conditions are easily avoidable for transmission pipelines.

7.1.2 Hydrogen Effects on Reinforcement Materials

Reinforcement materials for composite pipes include fibers made of glass, carbon, aramid, polyesters, steel, and liquid crystal polymer (LCP). They provide hoop strength to the pipe and back up the inner liner when hydrogen pressure is present.

API RP 15SA lists potential threats to spoolable pipe systems.(Integrity Management of Spoolable Reinforced Line Pipe (API Recommended Practice 15SA First Edition), 2022). The most prevalent threat related to exposing the reinforcement layer to hydrogen is that metallic reinforcement could rupture and reduce structural capacity causing leaks or burst due to hydrogen induced cracking (HIC). Non-metallic fibers are not subject to HIC but might require more testing to determine effects of hydrogen when under stress for the lifetime of a pipe. However, FlexSteel tested steel strip material via slow strain rate testing (SSRT), and constant load testing (CLT). CLT was based on common method for sulfide stress cracking (SSC) testing for H_2S service, but extended duration from one month to six months to ensure sufficient test length. The testing showed that no HIC occurred (base metal and welds tested), no loss of yield strength of the material. The only noticeable change in the material was a slight decrease in the area at break, but it was still within the ductile region. This decrease may have been simply a result of a low number of samples tested. Of key importance for steel reinforcement compatibility with hydrogen versus steel pipelines is that the steel strips are only exposed to annulus pressure rather than bore pressure. Annuli are typically fitted with vent valves with less than 5 psig cracking pressure; therefore annulus pressure remains less than 20 psia.

Researchers from Oak Ridge National Laboratory studied glass-reinforced polymer pipe pressurized with hydrogen at pressures up to 1,500 psi. They performed leak testing and observed no damage mechanisms to the fiberglass reinforcement and no loss of mechanical properties.(Smith et al., 2016)

Polymer or glass reinforcement materials are not likely to be damaged by pure hydrogen, but more studies of the rate of HIC should be completed to ensure metallic materials will keep their integrity for the lifetime of the pipe even when hydrogen by-products are present. The by-products of hydrogen production can include carbon dioxide, hydrogen sulfide, liquid water, water vapor, and oxygen. Pipe manufacturers' studies have shown that worse case scenarios cause a corrosion rate negligible for the life of the pipe, but there are ongoing studies to determine the corrosion rate when these, and other, chemicals permeate through the inner liner ,mix, and contact the steel strips in composite pipelines.

7.2 Damage Mechanisms

Many damage mechanisms will be more physical, rather than chemical, and they include dropping, bending, coefficient of thermal expansion, running over by a vehicle, and high tensile stress during pulling through another pipe, among others.

Some failure mechanisms for composite pipe include yielding, fracture, debonding of layers, cracking, effects of rapid gas decompression, swelling, thermal softening or hardening, photodegradation, or morphological changes.(Echtermeyer et al., 2017) Some conditions that can cause failure are fluid or external temperatures being too hot or cold, over pressurization, over loading, variable loading/fatigue, damaging impurities in the fluid, erosion of the inner liner, and wax blockage.

Bending a pipe past the elastic strain limit of the polymer causes stress whitening, microcracking, or yielding, all of which are permanent damage that decrease strength and increase hydrogen permeation. The crystallinity content of the HDPE is a factor for the strain limit. The higher the crystallinity, the greater the strength, but the lower the yield strain and the larger the minimum allowable bend radius.(Okolie et al., 2023).

Damage mechanisms for glass fiber reinforced composites when under low velocity impact include debonding of the fiber from the polymer matrix and delamination of fiber layers, but not fiber breakage.(Cao et al., 2021) Deniz and Karakuzu found that transverse impact loading can cause damage such as matrix crack, delamination, fiber breaking, fiber-matrix debonding, fiber pull-out and can yield a considerable reduction in structural stiffness.(Emin Deniz & Karakuzu, 2012) They also found that the properties of the composites can be compromised after the absorption of seawater, so choosing the right materials for offshore use is critical. Similarly, Nizamuddin has documented the property changes in glass fiber reinforced vinylester and epoxy after 24 months of exposure to elevated temperature and moisture.(Nizamuddin, 2008) Conversely, Majid states that glass fiber reinforced composite pipes have been used to transport highly corrosive fluids, including seawater, aerated water, and hydrocarbons. The most prevalently used epoxy resin in the manufacture of GRE pipes is diglycidyl ether of bisphenol A (DGEBA), and aromatic amines as hardeners, such as 4,4′-methylene-dianiline (MDA). (Abdul Majid, 2011) Although, Majid also states that moisture can cause a reduction of the glass transition temperature, weakening of the matrix, and decrease strength between the fiber and the polymer matrix causing matrix cracks and delamination. Considering the service conditions and the exact chemistry of the pipes is necessary for choosing materials safe for operations.

It is thought that additional research and development on the pipe connectors is necessary, because increased hydrogen permeation or effusion initiation (e.g., passage of a molecule through a crack) could occur due to differences in coefficient of thermal expansion between the plastics and metal reinforcement material.(Grigat et al., 2022) If the pipes are installed properly following API RP 15SIH, these issues should be mitigated, thus negating the need for additional research.

Furthermore, in operation the increased velocity of hydrogen, over that of natural gas, could cause faster erosion on the inner liner and increased or higher frequency pipe vibrations. (Koo, Ha, Kwon, 2023) Erosion would require bends in the pipe and particles, neither of which are likely to be abundant for hydrogen transmission pipes.

A unique concern for hydrogen transport is flow electrification which happens when a dielectric fluid flows along a surface. This phenomenon may lead to spark discharges which are especially dangerous due to the high flammability of hydrogen, although oxygen would have to also be present for ignition. Figure 38 shows flow electrification that occurs. Bowen et al. investigated this phenomenon for hydrogen transportation and found that the electrification intensity of liquid hydrogen flow is in the safe range. However, impurities in the fluid or a two-phase flow of gas and liquid could increase the risk. Flanges, elbows, and valves may increase the accumulation of electrical charge by changing the flow pattern. (Bowen et al., 2023) DNV is running a JIP to better understand this phenomenon. Results on full scale pipes are likely available in 2026.

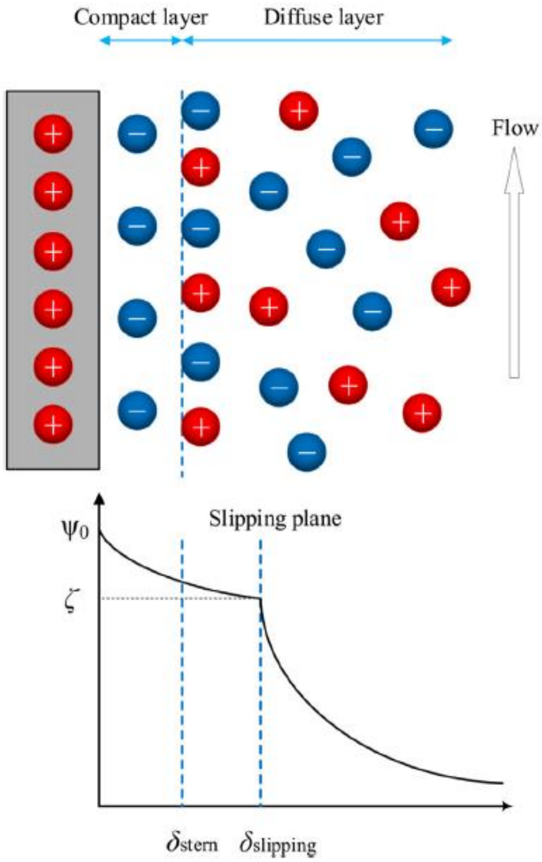


Figure 38: Schematic showing flow electrification (Bowen et al., 2023)

7.3 Condition Assessment

One way to assess obstructions on the inside of the pipe is to send a pipeline integrity gauge (PIG) through the pipe. This will push out obstructions and clean the ID of the pipe. Other, more analytical PIGs are sometimes implemented to learn more about the health of the pipe or the environmental conditions in the wall along the length of the pipe. One example is Smartpipe's SQUIID®, which is an in-line technology, allowing for periodic inspection of the composite pipeline. This technology uses sensors that are embedded in different layers of the pipe. These sensors can be as close as every foot along the length of the pipe. The SQUIID® is sent down the pipe, while still at operating pressure, to gather information such as temperature, humidity, moisture, or presence of hydrocarbons. Changes or anomalies in the values for these variables could indicate issues with the pipe. This technology allows population of a database that can be used for conditions monitoring. SmartBall is another technology that combines acoustic leak detection with 100% coverage capability of in-line inspection.(Fletcher 2008)

7.4 Repair and Rehab Requirements

A significant part of the cost of operating hydrogen stations is maintenance. The National Renewable Energy Laboratory found that 41% of the maintenance hours for hydrogen stations are for dispensers, and 10% of those hours are for failed parts.(Hitchcock et al., 2022).

Non-reinforced polymer pipelines are commonly repaired by cutting out a damaged or failed section and then using electrofusion jointing to add a new piece. One study showed that this joining process works on pipes that have been aged in room temperature, 29 psi hydrogen. (Hermkens et al., 2018). This is a technique that requires cleaning/removing the outer diameter of the pipes, slipping the ends into a coupler with an electrical element in it, and applying current through coupler to melt the coupler to pipes.

API RP 15SA recommends taking remedial actions as soon as damage is identified.(American Petroleum Institute (API), 2022) A team including the pipe manufacturer, installation experts, pipe subject matter experts, and purchaser should assess the damage and identify remedial actions. The team may decide to continue operation, complete repairs, or cut out the damage section and replace it with a new pipe section using two midline connectors. Reinforcement repair is not typical for spoolable pipe, replacement is typical.

Grigat et al. believes that there is need for further research and development into the inspection and repair of FRP composite pipelines to ensure their safety and longevity when used for hydrogen transport.(Grigat et al., 2022)

7.4.1 Suggested Testing Protocols for Repair Maintenance

Pipeline and system purging and venting requirements and protocols need more development to ensure public and environmental safety. Since hydrogen heats as it is depressurized, venting must be performed at a rate not to exceed the ignition temperature of hydrogen. Also, since hydrogen is lighter than air, venting must be accomplished into a space with ceiling containment and no possible ignition sources.

7.5 Manufacturing Methods

Manufacturing methods vary widely between manufacturers of composite pipeline. Some examples of the differences are listed herein. In general, manufacturing that occurs in a central location starts with raw materials, such as polymer pellets, and includes extrusion processes to make the inner liner, and sometimes the outer cover of the pipe. On the other hand, manufacturing that can be relocated to the pipe installation location generally starts with polymer stick pipe or sheets which are welded together to fabricate a continuous pipe during installation. In both cases, winding machines that control tension and angle as the pipe is conveyed past are used to apply the reinforcement material. In RTR pipes, epoxies are used to bond the reinforcement fibers to the thermoplastic liner, others use heat to affix them, and some have no attachment. Okolie et al. provide a lengthy description of different pipe manufacturing techniques. (Okolie et al., 2023) Each manufacturer has proprietary manufacturing methods that differentiate them from their competitors. Several variations of such manufacturing techniques are described in the following reference.(Grigat et al., 2022) They state that laser-assisted thermoplastic tape winding is used to melt the wound tape material to the inner layer, which eliminates the need for oven heating, but may slow down winding speed and induce local residual stresses.

7.5.1 Suggested Testing Protocols for Manufacturing

API 15S suggests that process controls and materials must be monitored and stay in an operating window for the following variables, or manufactured pipe must be cut from the spool and tested to ensure the quality of pipe. All of the following variables should be monitored to manufacture a consistent product.

- Polymer resin: polymer type, melt flow index, contamination level, percent water absorbed in pellets
- Extrusion: temperature in each zone, tolerance on die head, tolerance on extruder screw, speed of screw rotation, tolerance on extruded geometry, maximum void allowance
- Reinforcement material: type of material, tolerance on diameter, strength, winding angle, winding tension
- Welds: free of foreign objects, proper melt and flash, sufficient cooling before force is removed
- Other: barrier layers may have different variables depending on how they are attached

7.6 Planned Service Environment

Service environments could vary significantly for composite piping. Some of its uses for transmission of hydrogen include stand-alone pipe installed in a ditch or installed as surface-laid pipe. It could be pulled through another pipe (steel or polymer) and used as a liner. These pipes may experience pressures up to 3,000 psi and surface ground temperatures in the southwest U.S. can reach 140°F. Although, PHMSA regulates that pipe must be buried 3-feet deep, so maximum soil temperatures are lower. Finally, there are offshore applications with different regulations, such as a riser. In general, the pipe will be rated for a temperature range that matches that of the water, maximum pressure, and chemical compatibility. For risers, they must be able to support their own weight, when factoring in buoyancy, so that it is not damaged by tensile forces. PHSMA regulations only pertain to swallow water installations, not deep water, so long riser are out their regulatory scope.

8. Risks Specific to Connectors

8.1 Types of Connectors

Each pipe manufacturer designs, fabricates, and implements connectors for their pipe. API 15S provides the qualification testing requirements for connectors. Furthermore, API RP 15SIH includes information for connectors, couplings, end fittings, and other field-fittings. It defines a connector as a device used to provide a leak-tight structural connection between the end-fitting and adjacent piping, and includes bolted flanges, clamped hubs, weld necks, and proprietary connectors.(Installation and Handling of Spoolable Reinforced Line Pipe (API Recommended Practice 15SIH First Edition), 2021) The same document defines a coupling as a specific type of fitting developed for joining one section of spoolable composite pipe to another. It then defines an end-fitting as a mechanical device that forms the transition from the spoolable pipe to the connector, and a field-fitting with a connector or coupling designed for permanent installation. FRP pipes are typically joined by threaded connectors machined directly into the fiberglass.(Nemeth et al., 2022) GRE pipe connectors are made of the same material as the pipe, not metal, so the risks to their connectors are the same as the pipe itself. Pipes classified as RTP and TCP typically have metallic connectors that swage or thread onto the internal and external surfaces of the pipe. Some of them include O-rings, while some do not. Additionally, some manufacturers recommend specialized tooling (e.g., swaging machine) and/or fixtures to install the connectors.

More specifically, Baker Hughes provides end fittings with NPT threads, weld ends, or API/ASME flanges. They are available in carbon steel with a zinc chromate finish, carbon steel with fusion bonded epoxy (FBE) coating, 316 stainless steel, or 2205 duplex stainless steel.

Soluforce offers metallic and non-metallic fitting options. Their electrofusion fittings are designed so that the hydrogen does not come in contact with the metal parts, so it mitigates the possibility of embrittlement. (https://www.soluforce.com/renewable-energy.html)

With or without hydrogen, the difference in the coefficient of thermal expansion between the composite pipe and the metallic connector could be an issue. The pipe will expand and contract more than the metal with temperature swings, causing stress at their interface. These stresses must be anticipated so that the pipe does not fail during the pipe's service life.

8.2 Effects of Hydrogen on Connectors

Some connectors use O-rings to seal on the outer diameter of the pipe. O-rings are rubbery polymers that have higher solubility than rigid plastics and require the Flory-Huggins theory of dissolution to model their hydrogen sorption.(Kane, 2008) Metallic connectors that have direct contact with hydrogen could undergo hydrogen embrittlement or hydrogen induced cracking (HIC), thus changing their mechanical properties with time.

API RP 15SA lists potential threats to spoolable pipe systems.(American Petroleum Institute (API), 2022) The most prevalent threat related to exposing the field fittings to hydrogen is that metal could rupture and reduce structural capacity causing leaks or burst due to HIC.

Hydrogen permeation of an E-glass fiber reinforced polyethylene TCP with an internal diameter of 4 inches and its end connectors has been tested by Strohm.(Frans Janssen, 2023) This was done using the test setup shown in Figure 39. The figure shows the TCP test specimen inside a climate chamber used to control the temperature. The small blue hoses are used to purge the measurement chambers and to transport their content to a mass spectrometer. The test was performed at the design pressure of the TCP, 725 psi and four different temperatures, 72, 86, 113 and 140°F to determine the effect of temperature on the permeation rate. The pipe section of the TCP and the two end connectors were encapsulated in individual polycarbonate measurement chambers. These measurement chambers were purged with a constant flow of nitrogen used as carrier gas. The permeated hydrogen was separated from the nitrogen using a membrane and its mass measured using a mass spectrometer. Analytical and model predictions using experimental material data of the polyethylene and its glass fiber reinforced composite correlated well with the obtained results.

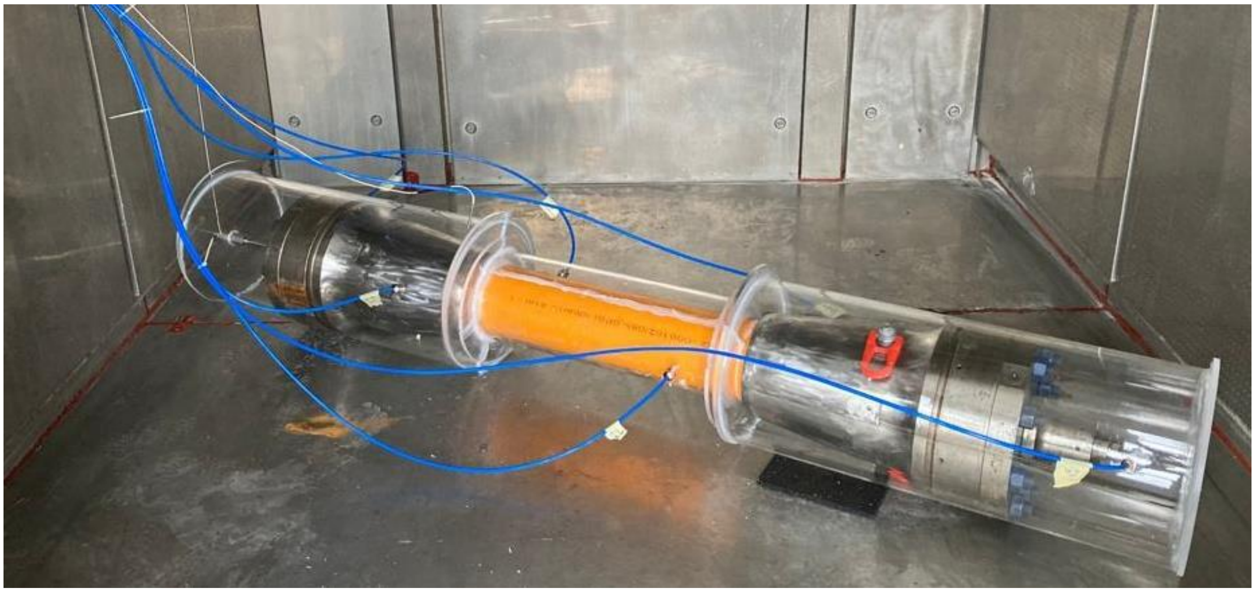


Figure 39. Pipe and End-Fitting Permeation Testing at Full Scale.(Frans Janssen, 2023)

Baker Hughes performed a test to get similar data by submerging a pipe with end connectors in water and measured the volume of hydrogen at set points. They pressurized the pipe and connecters with 580-psi hydrogen at 95°F for 90 days and followed ISO 4080:2009 – Method 1. Finally, the non-metallic innovation center (NIC) developed a permeation rig for simultaneous non-metallic pipe (up to 10-inch diameter) and connector assessment in gas mixtures including CO_2, H_2 and H_2S at up to 2,500 psi and 266°F. (https://www.non-metallic.com/news/2022/new-pipe-scale-permeation-rig-to-assess-pipe-and-connectors)

8.3 Improper Installation

API RP 15SIH states that field-fittings shall not be installed in the pipeline bend zone and that the manufacturer shall provide a minimum distance from the bend to the beginning of the straight section.(Installation and Handling of Spoolable Reinforced Line Pipe (API Recommended Practice 15SIH First Edition), 2021) This is to avoid stress at the composite to metal interface, which is an area that could be damaged if the yield stress of the pipe is exceeded.

Baker Hughes has a comprehensive Installation and Handling Manual for Oilfield Equipment – Flexible Pipe Systems – Onshore / Houston / Services / USA (FDS-HOU-2-08, rev: 7.0). It includes a section on installation of end fittings and couplings. The document is proprietary, so no part of it can be disseminated, reproduced, quoted, or reported on in any manner. Likewise, NOV Fiber Glass Systems also has an Installation Manual that covers the best practices for installing and handling Fiberspar LinePipe, and FlexSteel has an analogous document for their pipe.

For unbonded pipes, an annulus test would allow for testing the integrity of the inner liner. If gas was detected in the annulus after a short time, it could be reasonably assumed that the inner liner was damaged. This could also be the case for integrity management for a longer time if sensors were installed at the connectors and were connected to the annulus.

8.4 Cathodic Protection

It is a responsibility of the pipe and fitting manufacturer to provide guidance for mitigating corrosion of field-fittings. This can be accomplished by installation of cathodic protection, field applied protective coatings, use of corrosion resistant alloy (CRA) field-fittings, or viscoelastic tape. The manufacturer may also be required to verify performance of the cathodic protection system and provide guidelines for proper placement of welded anode lead wires to the fitting.(Installation and Handling of Spoolable Reinforced Line Pipe (API Recommended Practice 15SIH First Edition), 2021) Integrity threats related to the cathodic protection are anode exhaustion, disarrangement, and electrical discontinuity which could lead to excessive corrosion.(American Petroleum Institute (API), 2022)

9. Prior Composite Pipe Projects and Outcomes

9.1 Pipes Currently Manufactured

Distribution pipes are typically 1 to 2 inches in diameter, made of polyethylene, without reinforcement, and operate at pressures up to 300 psi. On the contrary, transmission pipes can be up to 36 inches in diameter, or more recently even larger, and typically operate at pressures up to 3,000 psi.(Topolski et al., 2022) (Berardi et al., 2021) The diameter of long distance hydrogen transportation pipes is typically 3.9 inches.(Yang et al., 2023) Composite pipes that are currently manufactured as listed in Table 8.

Table 8. Commercial Composite Pipes for Potential Hydrogen Transmission

Manufacturer	Product Name	Liner Polymer Type	Reinforcement Type	Nominal Pipe Size (inch)	Pressure Ranges (psig)	Max Temp. (°F)
Baker Hughes	PythonPipe	HDPE, and permeation	Fiberglass Tape	2 to 8	Up to 3,000	180

Manufacturer	Product Name	Liner Polymer Type	Reinforcement Type	Nominal Pipe Size (inch)	Pressure Ranges (psig)	Max Temp. (°F)
		resistant options				
	Thermoflex	HDPE, Nylon, PPS	Aramid Fiber, Glass Fiber, Steel Wire	2.375 and 6	Up to 1,500	N/A
BrainDrip	SG Liner	HDPE with permeation layer	Carbon Fiber	6 to 36	N/A	N/A
Flexpipe	Flexpipe / Flexpipe HT	HDPE	Fiberglass	2 to 6	Up to 1,500	180 for HT
	Flexcord	HDPE	Steel Cord	3 and 4	2,250	140
FlexSteel	FlexSteel Line Pipe	N/A	Helical Steel Strips	2 to 8	Up to 3,000	N/A
Future Pipe Industries	FlexStrong	HDPE	Fiberglass Tape	2 to 6	Up to 1,500	185
NOV Fiberglass Systems	Fiberspar	HDPE	Glass Reinforced Epoxy	2 to 6	Up to 2,500	180
	DuraFlex	HDPE	Fiberglass Tape	3 to 8	Up to 750	180
	Star 8rd EUE	N/A	Glass Reinforced Epoxy	1.5 to 8	Up to 3500	212
	Star Super Seal	N/A	Glass Reinforced Epoxy	2 to 14	Up to 3000	212
	Star SSKL	N/A	Glass Reinforced Epoxy	Up to 40	Up to 3000	210
	Red Thread, Green Thread, Bondstrand	N/A	Glass Reinforced Epoxy	2 to 60	Up to 750	
Primus Line	Primus Line	HDPE, TPU	Aramid Fabric	6, 10, 14, and 20	Up to 1,190 (6 in), 740 (10 in), and 460 (14 in), 232 (18 in)	N/A
Smart Pipe	Smart Pipe Line Pipe	HDPE	Liquid Crysal Polymer	4 to 20	Up to 2,200	N/A

Manufacturer	Product Name	Liner Polymer Type	Reinforcement Type	Nominal Pipe Size (inch)	Pressure Ranges (psig)	Max Temp. (°F)
SoluForce	Hydrogen Tight (H2T)	HDPE with bonded aluminum	Aramid Fiber	4 and 6	Up to 609 psi	150
Strohm	Glass-HDPE	HDPE	Glass Fiber	8	Up to 5,000	150
	Carbon-PA12	PA12	Carbon Fiber	8	Up to 10,000	180
	Carbon-PVDF	PVDF	Carbon Fiber	8	Up to 10,000	250

Byrne et al. tested the effect of hydrogen on legacy grades of polyethylene found in existing natural gas pipelines. They found that key material properties of PE63 and PE80 such as the melting point, crystallinity, and oxidative induction time (OIT) were not affected by exposure to hydrogen. However, the slow crack growth (SCG) resistance was significantly affected by hydrogen at lower stress concentration values. The time to failure was doubled for PE63, but decreased by 22% for PE80. (Byrne et al., 2023)

9.2 Stability for Blends and Impurities

Traidia et al. measured the permeation of gaseous CO_2, H_2S, and CH_4 through a multilayer pipe with PVDF on the inner, then a tie layer, then PE-RT. The tests were run at 1,500 and 3,600 psi at 200°F. They also evaluated the degradation after exposure and rapid gas decompression (RGD) at 1,000 psi per minute. The results of their testing showed that H_2S had the smallest volumetric flow rate, while CO_2 was next, and CH_4 was the highest. H_2S also had the lowest value for diffusion coefficient, while CH_4 was next, followed by CO_2. For permeability coefficient, CH_4 had the lowest, H_2S was in the middle, and CO_2 had the highest. Finally for solubility coefficient, CH_4 was the lowest, CO_2 was in the middle, and H_2S was the highest. Analyzing the polymer separately shows that PVDF has one order of magnitude lower permeability for all three gases when compared to PE-RT. For all samples tested there was no visible damage to the gas-contacting PVDF after 25 days in the permeation experiment followed by RGD. The PE-RT showed material creep/dilatation. Peel testing between the layers showed a change from cohesive to adhesive failure, but yielded similar peel strengths, so chemical bonding and ties at the interface were sufficiently maintained. (Traidia et al., 2024) For this test no significant material degradation issues were noted, and the creep of PE-RT could be mitigated by the presence of reinforcement fibers.

9.3 Case Studies and Root Cause Analyses

This section contains a list of completed, ongoing, and planned studies in the areas of hydrogen transmission and composite piping. None of the examples contain a failure with a root cause analysis. The authors of this document are unaware of a study with a root cause failure analysis of a polymer composite pipeline. Some of the studies are on steel pipes but still include the transmission or distribution of hydrogen at different levels in natural gas pipes. These examples are meant to show the scale at which research is continuing for implementing hydrogen as an energy source.

As of 2008, the major players of hydrogen transportation and distribution were Air Liquide, Air Products, Linde, and Praxair. The estimated length of the hydrogen pipeline network was 994 miles in Europe and 559 miles in North America and were a majority steel pipe. The U.S. most pipelines were located along the Gulf Coast in Louisiana and Texas and are used by refineries and in chemical manufacturing.(Weber & Perrin, 2008) The materials of each pipeline are not disclosed, but historically have been stainless steel, high and low grades of carbon steel, ductile cast iron and various alloys of aluminum alloys, copper, nickel, and titanium. (Mohitpour et al., 2004) The U.S. increased its dedicated hydrogen pipeline to 1,600 miles by 2022. (U.S. Department of Energy - Office of Energy Efficiency & Renewable Energy, 2022)

The Interstate Natural Gas Association of America (INGAA) led the Integrity Management Continuous Improvement (IMCI) 2.0 initiative titled “Safely Pivoting to Support a ZeroCarbon Future” which commenced in 2021. This initiative builds off IMCI 1.0, which focused on progressing integrity management in the industry following several large consequence incidents that occurred in 2010. The next initiative, IMCI 2.0, brought the industry members of INGAA together to focus on improving the reliability and safety of existing natural gas transportation and storage infrastructure to support zero carbon fuels, such as hydrogen.(Nemeth et al., 2022) INGAA and its members stay at the forefront of research dealing with the safe transport and storage of hydrogen. They also collaborate with customers, the public, and government officials.

A Danish study flowed hydrogen through PE 80 and PE 100 pipe for 10 years. No degradation associated with long-term exposure to hydrogen was found. Based on these results, they believe that these pipes are suitable for use in environments containing hydrogen.(Nybo Lomholt & Bilgrav Bandsgaard, n.d.)

A second Danish study also performed hydrogen testing on PE pipes over a 10-year period. Iskov and Kneck reported that Danish Gas Technology Centre and Borealis AB exposed PE pipes to 58 psi hydrogen at 46°F for 10 years. They measured polymer viscosity, oxygen induction time (OIT), tensile elongation at break, and continuous tensile load (CTL) slow crack growth before and after exposure, and compared them against pipes in a warehouse for the same duration. They found that hydrogen exposure for 4 years for PE80 and 10 years for PE100 indicate no influence on any of the measured properties. (Iskov & Kneck, 2017)

A study in the northern part of the Netherlands concluded that PE100-RC (crack resistance grade) pipes were suitable for the transport of hydrogen at pressures up to 29 psi through laboratory testing. For one aging test, rings of the pipe were strained to 1.9% and held at 29 psi hydrogen for 1,000 hours. Tensile testing of the aged rings showed no statistically significant difference from the original values. The weight of the rings before and after was similar showing, no remaining hydrogen after depressurization. In another test, permeation was measured by inserting a pressurized pipe with capped ends into a larger pipe, then measuring the concentration of hydrogen in the annulus with a gas chromatograph. This was performed at 29 psi and room temperature and continued until steady-state was reached. The test showed that the hydrogen breakthrough time was one day, but that saturation of the pipe wall took 1,000 hours. The result was that a one kilometer of pipeline operated at 29 psi will emit 1,160 gallons of gaseous hydrogen per year. This is more than double the amount of emitted natural gas from the size pipe. (Hermkens et al., 2018)

DNV ran a JIP in 2021 and 2022 based on assessing cost and reliability of thermoplastic composite pipes (RTP and TCP) entitled, “Non-metallic composite pipes for transportation of H2.” (https://www.dnv.com/article/non-metallic-composite-pipes-for-transportation-of-h2-219692/) It included a cost comparison to steel pipes as well as a risk assessment and industrial guidelines to cover gaps in the standards for design and qualification, such as DNV-ST-F119 and API 15S for hydrogen applications. DNV is running a Phase 2 project adding to this work, and it is focused on permeation, electrostatic discharge, fire exposure, and 3rd party intervention. The goal is to de-risk the implementation of hydrogen infrastructure and the objective is to update the flexible composite pipe (FCP) hydrogen infrastructure guideline by addressing the risks identified in Phase 1. They expect to perform small scale testing in 2025 and full-scale testing in 2026.

In Oahu, Hawaii, U.S., HawaiiGas has been providing synthetic natural gas with 10-12% hydrogen to its customers for the last 50 years in steel pipes.(Kass et al., 2023) According to an October 1, 2010, article titled, ”Feds check state’s gas pipes,” the caption of an accompanying picture states, “The U.S. Office of Pipeline Safety inspects Hawaii natural gas pipelines. Here, Gas Co. Engineers insert a ‘magnetic flux leakage’ inspection tool in a transmission line in Kapolei to check wall thickness and weld integrity.”

One of the ongoing projects is titled HyDeploy. (https://hydeploy.co.uk/) The objective of this UK-based project is to demonstrate that hydrogen can be safely blended into the natural gas grid without end users modifying their appliances. It includes HDPE distribution pipelines, but no composite pipelines.(Isaac, 2019) Before introducing hydrogen into pipelines, laboratory testing was performed at operational temperatures and pressures (22 psig). The HDPE pipes were soaked for six weeks, then evaluated for total elongation at failure, modulus of elasticity, ultimate tensile strength, and proof strength. The data showed that there was no noticeable difference in tensile properties. There was also a squeeze off test completed to show that pipelines could be repaired after hydrogen exposure.

Future Grid (https://www.nationalgrid.com/FutureGrid) is a project led by National Gas, aiming for a full-scale conversion of the existing National Transmission System (NTS) to a hydrogen transmission network. Currently, they operate a test facility with decommissioned assets to investigate the impacts of 2%, 5%, 20%, and 100% hydrogen blends on their infrastructure. Composite pipelines are not utilized for this project.

Hydrogen in the Local Transmission System (LTS) Futures (https://www.sgn.co.uk/about-us/future-of-gas/hydrogen/lts-futures) is run by SGN and is similar to the Future Grid project. It is also part of the National Hydrogen Programme. LTS Futures is tasked with assessing the impact of hydrogen on the existing LTS infrastructure, mainly to research, develop, and test the compatibility of LTS pipelines and ancillary fittings with hydrogen. LTS Futures' live trial is still ongoing but does not appear to utilize composite pipelines. H100Fife (https://www.sgn.co.uk/H100Fife) is a subproject of SGN’s LTS Futures project, which allows residents of Fife, Scotland to opt into a 'decarbonizing home heating project' that utilizes hydrogen instead of natural gas. SGN partnered with HSL to study the impact of Hydrogen on

PE materials used in natural gas distribution systems in up to 300 homes. The study tested PE materials against current UK gas industry standards, results are not yet available.

Hy4Heat's (https://www.hy4heat.info/) goal was to determine the feasibility, safety, and convenience of replacing natural gas with hydrogen in commercial buildings and gas appliances. As the focus of their work was on the compatibility of hydrogen with gas appliances, their report had no mention of composite pipelines.

A report on the European Hydrogen Backbone is a high-level assessment of the benefits of a pan-European hydrogen transmission network and does not address any specifics of a composite hydrogen transmission pipeline. Their models predicted that up to 55% of the developed pan-European H_2 network could consist of repurposed natural gas transmission pipelines. This report calls for more investigation into the suitability and availability of existing pipeline segments and storage assets for repurposing. (Moultak et al., 2023)

Phase 1 of a project called H21 at Leeds City Gate in the North of England showed that polyethylene pipes did not crack after being used with hydrogen.(Topolski et al., 2022)

H2OpZee is a joint project, based in the Netherlands, between RWE and Neptune Energy that aims to develop 300-500 MW electrolyzer capacity in the North Sea to use offshore wind to produce green hydrogen. The project will utilize existing underwater pipelines. EnerSea, an offshore energy engineering firm, has been awarded the task of designing the pipeline network. (https://www.enersea.nl/hydrogen/) The construction of the pipeline network will be outsourced to Gassco, a Norwegian gas company, and is part of the H_2 Offshore Transport (H2T) project. (https://gassco.eu/en/about-us/what-we-do/low-carbon-value-chains/pmi-che-pipeline/) Their report only mentions that onshore and offshore hydrogen transmission pipelines would likely be made of newly constructed or repurposed natural gas pipelines. No further details of the pipeline materials are mentioned. (https://tyndp2022.entsog.eu/executive-summary/a-new-tyndp-2022/)

Another Netherlands-based project, at the Groningen Seaport, will install 2.5 miles of 6-inch diameter SoluForce RTP (a.k.a., FCP) underground that is operating at 600 psi. (https://www.soluforce.com/renewable-energy.html) The pipes will distribute hydrogen produced by wind turbines to companies in the chemical and industrial sectors.

The Angeles Link Q3 2023 report from SoCalGas referenced Project OP6 F which aims to identify specific materials for hydrogen pipeline, fittings, and differences in operational equipment. It also discusses safety considerations, pressures, and maintenance operations associated with design.

The U.S. DOE has a project named H2Hubs, also known as The Regional Clean Hydrogen Hubs Program, and it aims to form the foundation of a national clean hydrogen network across the United States. As part of the H2Hubs project The Leighty Foundation was asked to release a report detailing urgent research, development, and demonstration needs. The Leighty Foundations Clean H2 Mfg+ Electrolysis report briefly mentions a Composite Reinforced Linepipe (CRLP) shown at the ASME International Pipeline Conference in 2002. The 42-inch diameter 3,400 psi 0.75-inch thick X70 steel pipe had a FRP exterior to provide hoop strength. Hydro testing of this pipeline found that applied overpressure permanently deformed the FRP-confined steel. Under normal pressures, the steel line pipe remained under compression as the hydrogen atoms had a lower chance of invading the steel's crystal structure. NCF industries and TransCanada Pipelines concluded that large and frequent pressure excursions in high-purity hydrogen service may inflict less, or negligible, embrittlement and corrosion cracking on the steel core (Leighty, 2022). The Leighty Foundation also showcased a Gaseous Hydrogen (GH_2) transmission pipelines polymer-metal hybrid tubing concept from Smart Pipe a high-pressure reinforced thermoplastic pipeline replacement technology. They said the pipe was likely immune to hydrogen embrittlement but did not provide testing results.

HyBuild LA's Phase Two calls for dedicated transmission pipelines to carry compressed green hydrogen gas to create a new pipeline backbone infrastructure. They estimate that 99% of the materials used in California's transmission natural gas pipelines are composed of cathodically protected externally coated steel. Their long-term goal is to create a transition plan for retrofitting or replacing existing natural gas pipelines for 100% green hydrogen use. In the interim, existing natural gas pipelines would transport blended green hydrogen. However, current regulations do not allow for blended hydrogen. HyBuild LA's Phase Two report did not explore details of materials in their proposed pipeline, instead they called for further research on this topic.

NaturalHy was a project run by the European Gas Research Group (GERG) that ended in 2009. Preparing for the hydrogen economy by using the existing natural gas system as a catalyst.

They concluded that up to 20% hydrogen could be blended with natural gas for safe transport through existing steel pipes and use as fuel in buildings.

The Alberta Energy Regulator maintains a website where all pipeline incidents in Alberta, Canada are categorized. [Workbook: Pipeline Performance Report (2024) (aer.ca)] It does not currently have data specific to hydrogen at this time but may in the future as more transmission pipes are commissioned.

There are ongoing U.S. DOE projects related to hydrogen hubs. These include Appalachian Hydrogen Hub (ARCH2), California Hydrogen Hub (ARCHES), and Pacific Northwest Hydrogen Hub (PNWH2). They are also negotiating awards to add more hubs in Texas, (HyVelocity H2Hub), Minnesota, North Dakota, and South Dakota (Hearland Hub HH2H), Pennsylvania, Delaware, and New Jersey (Mid-Atlantic Clean Hydrogen Hb MACH2), and Illinois, Indiana, and Michigan (Midwest Alliance of Clean Hydrogen MachH2).

Data pulled from Rystad Energy in October 2024 shows that there are 249 future hydrogen piping projects globally planned. Many of these have pipe diameters larger than currently available spoolable pipes. In fact, the average pipe diameter listed is nearly 28 inches. Larger composite pipes and regulations for them need to be matured to bid on these future projects.

Finally, full scale burst testing can be performed on polymer composite pipe sections or hydro testing can be performed on the entire length. An approach was demonstrated on a 144-ft long steel pipe by researchers at the University of Tokyo. A 2.4-ft long initial crack was created by an explosive charge, then the pipe was pressurized with 2,320 psi of hydrogen.

With many hydrogen piping projects ongoing much is learned about safely using pipes for transmission and distribution. The results from some of the projects involving composite pipes should be completed in the next couple of years, thus adding to the knowledge and understanding of the limitations of these types of pipes for hydrogen transmission.

10. Failure Prediction or Damage Tolerance Assessment

10.1 Lifetime Prediction Methods

The most widely used lifetime prediction model is detailed in the 15S specification from API. It delineates composite pipes by their reinforcement material by stating that steel reinforced composite pipe does not have significant regression properties, but that non-metallic reinforced pipe does. The maximum pressure rating (MPR) of product family representative (PFR) for non-metallic reinforced pipe is confirmed by long-term hydrostatic pressure testing as developed by adhering to ASTM D2992-12, Procedure B. There is an API task group (SC 15 TG2) devoted to better defining the ASTM D2992 test protocol and allowable failures, they plan to have a path forward in 2025. Additionally, the elevated temperature test in API 15S is used to ensure sufficient design life. Finally, ASTM D1598 and D1599 define test protocols to find the time-to-failure under constat internal pressure and the resistance to short-time hydraulic pressure, respectively, for reinforced plastic pipe.

In 2004, Hayden and Tverberg believed that accelerated test methods for non-metallic materials exposed to high pressure hydrogen gas needed to be developed. Material properties, such as creep, ultimate strength, impact strength, and fatigue strength should all be included in the modeling as a function of time exposed to hydrogen.(Hayden & Tverberg, 2004)

Yeleswarapu et al. performed accelerated aging and lifetime prediction on glass fiber-reinforced polymer (GFRP) materials that used Araldite LY556 and Hardener HY951 epoxy. (Yeleswarapu et al., 2021) They exposed the materials to a hot, wet environment to induce hydrolysis to the epoxy and degrade the bond efficiency of the fiber-matrix interface. This affects the material's flexural properties and tensile strength and leads to failure. They also exposed the material to UV irradiation to induce photo-oxidation of the epoxy. They found that the tensile strength decreased by 12% after two weeks for UV exposure, but that the same decrease took six weeks in the hot, wet conditions. Through modeling, they related this amount of degradation to be similar to approximately 20 years of real service life use.

Majid et al. has multiple publications that present the experimentation and modelling of a general lifetime performance of glass-fiber reinforced epoxy composite pipes.(Abdul Majid, 2011; Abdul Majid, Afendi, Daud, Amin, Mohamad, Cheng, & Gibson, 2013; Abdul Majid, Afendi, Daud, Amin, Mohamad, Cheng, Gibson, et al., 2013; Abdul Majid, Afendi, Daud, Gibson, et al., 2013; Abdul Majid et al., 2011, 2014; Gibson et al., 2011; Krishnan et al., 2018; Nazirah et al., 2015; Pranesh et al., 2014) They found that the performance was similar to the Tsai-Hill interactive failure criterion, which is based on a modified Von Misses distortional energy criterion. The ultimate elastic wall stress (UEWS) tests were expressed in a single quadratic term of the axial and hoop stress through laminate theory. The modeling of the lifetime is based on the formation of matrix micro cracks within individual plies, delamination between plies, weepage, fiber fracture, and finally, bursting.

Testing of polymers has shown that hydrogen permeability coefficients increase with increased temperature and decrease with longer aging times. Aging behaviors of various polymers in hydrogen are summarized in Table 9. (J. Li et al., 2023)

Table 9. Aging behaviors of selected thermoplastics in a compressed hydrogen environment (J. Li et al., 2023)

Number	Material	Temperature	Pressure	Duration	Testing Items	Phenomenon
1	PTFE (used as seals in compressors)	25 °C	100 MPa	1 week	Mechanical properties (Young's modulus, yield stress, strength)	Improved mechanical properties (Young's modulus, yield stress, and strength values are increased)
2	HDPE (used as tank liners)	25 °C	100 MPa	1 week	Modulus; Tg; compression set properties; density; outgassing characteristics; Tensile strength	Improved mechanical properties (Young's modulus, yield stress, and strength values are increased)

3	PE100 PA11	80 °C	2 MPa	9 months	Crystallinity ratios; mechanical properties	Increased crystallinity ratios; no change in mechanical properties
		20 °C	2 MPa	13 months		
		80 °C	0.5 MPa	13 months		
		80 °C	2 MPa	1 month		
		50 °C	2 MPa	13 months		
		20 °C	0.5 MPa	13 months		
4	HDPE	Not concerned	0 MPa, 28 MPa, 31 MPa, 35 MPa	20 h	Ultimate tensile strength (UTS)	Decreased ultimate tensile strength (UTS) with increasing testing pressure
5	HDPE, PA11, PAHM	20, 50, 80 °C	0.5 MPa, 2 MPa	1 year	Permeation coefficient (in situ method)	Unchanged permeation coefficient; irrespective of the aged pressure and temperature
6	HDPE	Thermal cycling between −40 and 85 °C	43 MPa	1200 h (4000 cycles and 0.3 h/cycle)	Permeation coefficient (periodic measurements); porosity	Progressive changes in the permeation curves; significant structural changes in porosity

10.2 Damage Tolerance Assessment Methods

This section is covered collectively in sections 6.2 Sensors, 7.2 Damage Mechanisms, and 7.3 Condition Assessment.

11. Current Composite Pipe Manufacturing Inspection and Quality Control

11.1 Manufacturing Inspection

To provide a complete, rigorous, and representative inspection, the potential issues with the materials and pipe manufacturing must first be understood. For TCP pipes the defects can be divided into fiber, polymer matrix, and interface categories. The fiber defects include irregular fiber distribution, tow distortions, misalignment, sizing variation, undulations, breakage, and waviness. The matrix defects include hydrolysis during extrusion due to incomplete drying of pellets, voids, polymer degradation, residual stress, inclusions (foreign objects), varied crystallization, and in the case of epoxy layers, incomplete curing. The interface defects include poor bonding and delamination.(Okolie et al., 2023)

To ensure pipe quality, representative portions of the pipe shall be factory pressure tested to actual burst test failure pressures that are consistent with the short term burst tests of the PFR or product variant. As an alternate, the entire length can be hydrotested to 1.3x or 1.5x the design pressure; this can be performed in the spooled orientation. To demonstrate factory acceptance of composite pipe manufactured on-site and prior to installation, burst testing shall be performed on representative samples and recorded for traceability. The only permissible mode of failure shall be the tensile rupture of the reinforcement. Test records shall be traceable to all pipeline installed, or purchased for subsequent pipe repairs or replacement, and shall include: pressure test reports and all pressure testing parameters (time, pressure, procedure and/or standard number, date, and test acceptance parameters) and pressure testing with recorders with in specification calibration records. The pipe manufacturer shall provide certification that the factory acceptance tests were completed and that all pipes were visually checked during the pressure tests for leaks. (Nemeth et al., 2022)

When processing TCP pipes polymer impregnation into the fiber reinforcement is necessary to get a consistent product, but high melt viscosities can make it difficult. Visualization of the fiber impregnation during manufacturing is important to make a consistent product without void defects.(Okolie et al., 2023) Automated techniques to apply the reinforcement layer with the correct winding speed and tension have been successfully implemented into manufacturing lines to improve overall product quality and consistency.

11.2 Quality Control

Quality control includes checks before, during, and after the manufacturing of the pipe. Processes to check FRPs for manufacturing issues may include cure system acceptance, cure system storage, resin mixing, glass fiber wind angle, time, chemical compatibility, temperature and humidity of curing, and traceability of manufactured product. After manufacturing, some defects can be identified by eye, such as air bubbles (voids), blisters, cracks, crazing, scratch, delamination, worm holes, fisheyes, dry spots (no resin), pimple, burn, pit, pinhole, resin pocket, or wrinkle. On the other hand, API Specification 17J for unbonded pipe defines property requirements for extruded materials. These include mechanical, thermal, permeation, chemical compatibility, and aging for the inner liner, anti-wear layer, outer sheath, insulation layer, and reinforcement materials. There are fluid service factors for hydrocarbon liquid, gas, and multiphase fluids, but there has yet to be one established for hydrogen.

Parts of a manufactured pipe can be cut from the larger spool and analyzed for fiber orientation, fiber breakage, voids, and inclusions using micro-computed tomography. Residual stress is difficult to measure but can be assessed by environmental stress cracking testing. Residual stress can be reduced by cooling the polymer more slowly after extrusion, by minimizing the number of layers, decreasing the winding force, and decreasing the difference in coefficient of thermal expansion between the polymer and the fiber. Although, residual stress is typically negligible compared to fiber strength. Void content can be reduced by increasing winding force to get better contact between the fiber and polymer matrix.(Okolie et al., 2023)

11.3 Qualification

Elevated temperature and pressure failure testing for composite pipe for qualification is prescribed by API 15S and ISO 14692 to use ASTM D2992, which is a regression-based procedure that can take two-years to complete. Majid et. al has suggested that an ultimate elastic wall stress (UEWS) testing method for glass-fiber reinforced pipes can expedite the testing qualification procured to be completed in one day, but the pipes would need to be aged first to understand degradation at service conditions.(Abdul Majid, 2011) In addition ASTM 1599 – Procedure A is used to determine short-term burst pressure (STBP) of a pipe.

Other standards that specify accelerated aging test procedures, conditions, and evaluation criteria: ISO 11114.5, SAE 12579, T/CATSI 02007-2020, CSA ANSI CHMC 2-19, UN Regulation Number 134, ISO 16486, and applicable Chinese GB/T standards. A comparison of some of these standards procedures, evaluation criteria, acceptance criteria, and test conditions are shown in Table 10, Table 11, Table 12, and Table 13. (J. Li et al., 2023)

Table 10. Comparison of accelerated aging test procedures from three existing standards (J. Li et al., 2023)

Ageing Test Item / Standard Number	Hydrogen Static Exposure	Hydrogen Initial Cycling	Hydrogen Extended Ageing
ISO/FDIS 11114-5	√	×	×
CSA/ANSI CHMC 2:19	√	√	√
T/CATSI 02 007-2020	√	×	×

Table 11. Comparison of accelerated aging evaluation criteria from three existing standards (J. Li et al., 2023)

Ageing Test Items / Standard Number	Hydrogen Permeability Coefficient	Tensile Strength	Tensile Modulus	Elongation	Flexural Modulus
ISO/FDIS 11114-5	×	√	√	√	√
CSA/ANSI CHMC 2:19	√	√	√	×	√
T/CATSI 02 007-2020	×	√	×	√	×

Table 12. Comparison of accelerated aging acceptance criteria from three existing standards (J. Li et al., 2023)

Standard Number \ Ageing Test Items	Hydrogen Permeability Coefficient	Tensile Strength	Tensile Modulus	Elongation	Flexural Modulus
ISO/FDIS 11114-5	–	√	–	√	–
CSA/ANSI CHMC 2:19	6 NmL/(h·L)	√	–	–	–
T/CATSI 02 007-2020	–	≤20%	–	≤20%	–

Table 13. Comparison of accelerated aging test conditions from three existing standards (J. Li et al., 2023)

Standard Number \ Test Conditions		Test Duration	Test Temperature	Test Pressure	Test Humidity	Depressurization Rate
ISO 11114-5		1000 h	≥Maximum expected temperature in service	Maximum developed pressure of the cylinder	dry	–
CSA/ANSI CHMC 2:19	Hydrogen static exposure	192 h	15 °C	1.25 NWP	dry	12.5 NWP/h
	Hydrogen initial cycling	740 h	55 °C	113% NWP–3% NWP		11 NWP/h
	Hydrogen extended ageing	3.6×10^5 h	55 °C −40 °C 15 °C	113% NWP–3% NWP, 80% NWP–3% NWP, NWP–3% NWP		P_{max} to P_{min} in 2–5 s
T/CATSI 02 007-2020		1000 h	≥85 °C	≥1.25 NWP	–	45 NWP/h

11.4 Suggested Testing Protocols for Inspection

In-plant inspections of pipes with non-metallic reinforcement should include checking fiber orientation, void content, material loss, discoloration, blistering, crazing, cracking, damage, deformation, bending strain, and axial strain. Researchers have shown that acoustic emission monitoring of multiaxial UEWS tests of filament wound glass fiber-reinforced epoxy composite pipes under hydrostatic, pure axial, and pure hoop loading at room temperature can detect matrix cracks and delamination.(Abdul Majid et al., 2015) If this technology could be further developed to check manufactured pipe in-line, it could mitigate sending defected pipes to the field. Pipes with metallic reinforcement should be inspected for cracks, corrosion, and misalignment of the steel as it is manufactured.

Inspection of field fittings is currently performed by checking to see if they have moved. More advanced techniques need to be developed to understand if the seals are still functioning properly.

12. Requirements for Revising Existing Pipeline Codes and Standards

This section contains a general overview of how new and revised codes and standards are developed. Not every step of every process is listed, there is enough detail listed to see differences between the processes.

12.1 Processes for Revisions

The path to implementing new American Petroleum Institute (API) regulations is first identification of integrity and safety risks. Next, the risks are prioritized, of which the top risks are studied through research and development. The data from research and development allows standards to be written by committees/groups of subject matter experts. The standards are voted on and revised, as needed, before they are released. Then finally, regulations are based on the standards.

ASME codes and standards are developed through a voluntary consensus process. A request for a new code or standard can come from individuals, committees, professional organizations, government agencies, industry groups, public interest groups, or from within ASME. The request is assigned to an appropriate committee, and they determine if there is a need to develop it. Developing the code or standards is an open and transparent process with input and appeal rights from the committee and public. A consensus, but not unanimity, must be obtained by voting for the issuance of a new or revised code or standard.

ASTM provides voluntary consensus standards. The development process includes five major steps. 1. Initiation of a new work item must be accepted to move forward as a standard project. 2. A subcommittee with interest in the specific technical topic area is formed and a task group writes a draft. 3. The chairman of the task group leads the development of the draft through rounds of review, voting, and revisions. 4. The draft is voted upon by the subcommittee and may go through more revisions before getting approval. 5. The document must be approved by a subcommittee, main committee, and a society before getting released with an alphanumeric code.

Generally, CSA only incorporates new technology into a standard when that technology has been proven in the field. The Alberta Energy Regulator’s legislation gives the authority to allow trials of new technology, and if successful, allow those for incorporation. Alberta Energy

Regulatory introduced composite products into the marketplace to gain experience, then CSA built them into the Z662 Standard later.

The implementation of DNV standards can involve the output of a JIP, as it did for DNV-ST-F119.

Developing standards for ISO takes many independent technical experts who are nominated by ISO members. The process begins with the development of a draft that meets a market need within a specific area. The draft is shared among the experts for commenting and further discussion. The draft is then voted upon, and if it passes, then the development of the standard continues. If it does not pass, then the document is further modified, and voted on again. The typical time from draft to final publication is three years.

13. State of Industry Preparedness for Use of Composite Pipe for Hydrogen Applications

13.1 Current Projects

Current projects are listed in Section 9.3 of this report. It is titled, “Case Studies and Root Cause Analyses.”

13.2 Gaps

Standards for hydrogen permeation exist for structures other than polymer transmission pipes. For example, GTR 13 international standards require that the hydrogen permeation of Type IV tanks is less than 46 $N\text{-}cm^3\ h^{-1}\ dm^{-3}$ at 10,000 psi and 131°F and ISO19880-5 requires that the permeation of hydrogen from the flexible dispensing hose is less than 500 $N\text{-}cm^3\ h^{-1}\ m^{-1}$ at 12,700 psi.(Fujiwara et al., 2021) As of the time of Kass et al.’s report in 2023, there were no available permeability limits defined for hydrogen and its blend with natural gas, ammonia, or carbon dioxide in pipelines.(Kass et al., 2023) Permeation standards for transmission pipes should be defined.

Safety of operational procedures for detection, ignition, explosion relief, purging, and repairs to pipeline remain a gap in the protocols. These items are partially covered in API 20S but need to be revised/updated for composite pipes. Some ways that flammability and explosion are mitigated are that the ends of an unbonded RTP are purged with nitrogen and either vented to atmosphere or collected for resubmission into the pipe. Furthermore, permeated hydrogen through bonded pipes will diffuse faster through soil than polymer pipe wall, so a buildup will not reach the lower flammability limit. Places that could be an issue would be casings under roads, train tracks, and other structures.

Limited data for testing polymer pipes is available currently, but more stress levels along with notched specimens should be studied to better evaluate the impacts from typical operating conditions. It is also recommended that multi-axial stress states in fatigue, quasistatic, and creep loading conditions be tested. Additionally, accurate lifetime assessments can only be estimated after more long-term testing with hydrogen is performed. Better understanding of the changes in crystalline content or morphology changes may help to elucidate measured physical property changes. Additional oxidative induction testing by DSC is needed to better understand pipeline operating conditions for rate of depletion of stabilizers. (Topolski et al., 2022)

14. Potential Societal/Public Needs and Concerns

14.1 Hydrogen Gas Composite Pipeline Network

If hydrogen permeates through pipelines or leaks at connection points as a diatomic molecule, then the following concerns exist. It is highly flammable when mixed with air between 4 and 75% by volume, explosive between 15 and 59%, it burns a light blue color making it difficult to see in daylight. In the stratosphere, it interacts with hydroxyl radicals to extend the lifetime of methane and it increases the production of ozone.(Lakshmanan & Bhati, 2024) Its high diffusion rate allows it to disperse quickly, which lowers the flammability and explosion risk outdoors, but it collects on ceilings, as it is lighter than air, in indoor spaces if not properly ventilated.(Weber & Perrin, 2008) Furthermore, if hydrogen is quickly depressurized, it heats due to a negative Joule-Thomson Coefficient which could be an ignition source as it mixes with oxygen in the air.(Voyiatzis & Stroeks, 2022) Hydrogen emission rates, as estimated based on what has been reported in literature, are shown in Figure 40. (Esquivel-Elizondo et al., 2023)

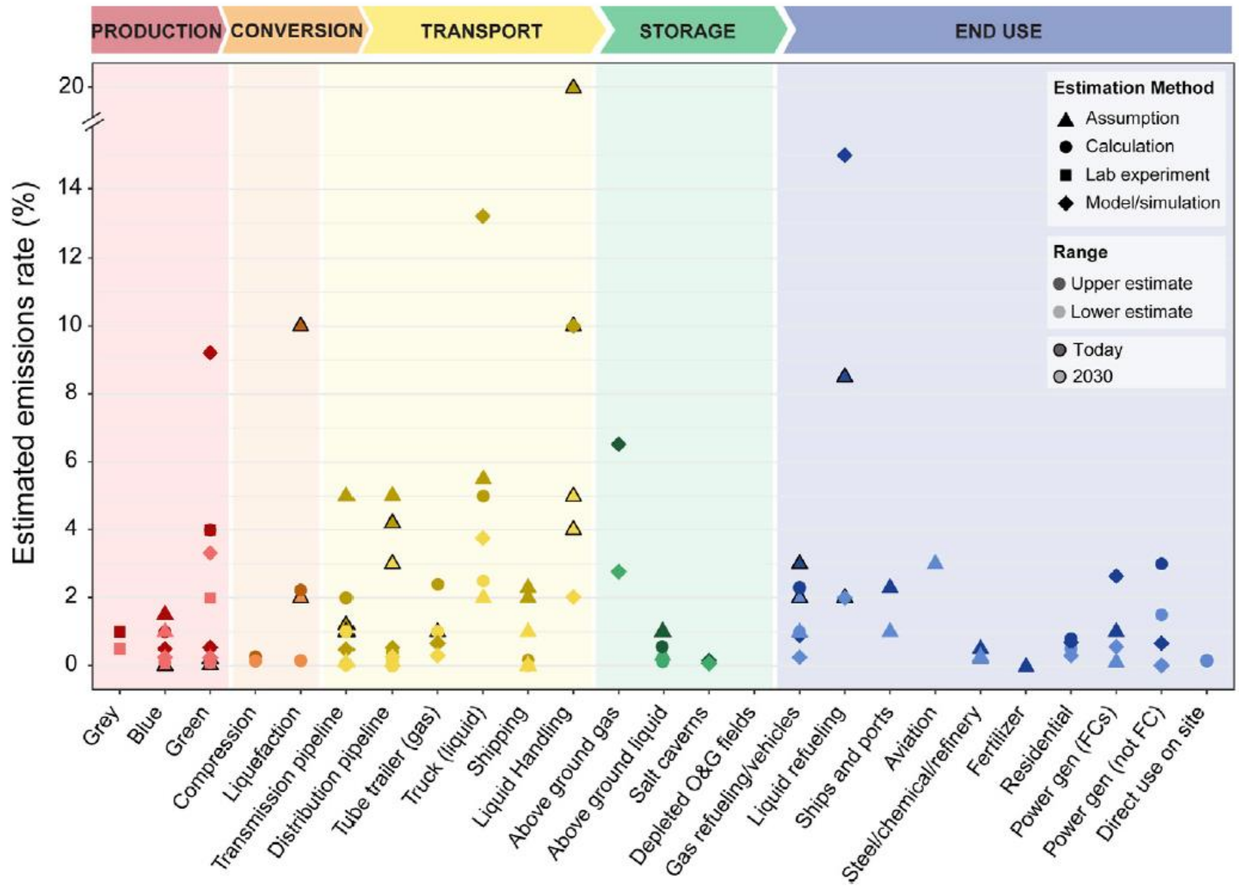


Figure 40: Estimated hydrogen emission rates for each part of the hydrogen supply chain.(Esquivel-Elizondo et al., 2023)

Blending hydrogen with natural gas produces about twice the greenhouse gas emissions of transporting pure hydrogen. However, the transport of blended gases may be necessary as a temporary measure as the infrastructure needed to transport pure hydrogen is established. Table 14 shows the relative carbon emissions of various hydrogen feedstocks. Notably, "black" hydrogen is 20% more carbon intensive than gasoline and 50% more than natural gas while "blue" and "green" hydrogen have 10% of the carbon intensity of gasoline and 13% of the carbon intensity of natural gas. (Ott et al., 2023)

Table 14: Carbon intensities of hydrogen feedstocks and associated contaminants (Ott et al., 2023)

Hydrogen "Color"	Description	Carbon intensity	Potential contaminants
Black	Coal gasification	High	Ash, CO_2, SO_2, NO_x
Gray	Steam methane reforming (SMR)	Moderate	CO, CO_2
Turquoise	Methane pyrolysis	Low	Carbon
Purple	Electrolyzation of nuclear power plant steam	Low	O_2, Cl_2
Blue	SMR with carbon capture and sequestration (CCS)	Low—Negative	CO, CO_2
Green	Electrolysis of water from using renewable energy	Low—Negative	O_2, Cl_2

For additional concerns, the voice of the public through their opinions can be found from Environmental Defense Fund, Pipeline Safety Trust. (https://primis.phmsa.dot.gov/Meetings/MtgHome.mtg?mtg=153)

A more extensive and thorough threat analysis should be performed to mitigate the risk of intentional human destruction. Also, having procedures in place to mitigate and detect damage to the infrastructure containing pressurized hydrogen. A 1,000 mile long 16-inch diameter pipeline can contain up to 1,800 MT of gaseous hydrogen when shut-in and has a flow rate of 500 MT per day.(Leighty et al., 2022) Thorough training of pipeline operators is necessary to understand additional risks that hydrogen transmission bring with it. Also, accurate metering and measuring of hydrogen to fairly charge end users for usage may be difficult due to limited reliable sensors for gaseous hydrogen.

The Hydrogen Incident and Accident Database (HIAD) is an online database housed on the Online Data and Information Network for Energy which is hosted by the European Commission Joint Research Centre to track safety concerns (https://odin.jrc.ec.europa.eu/alcor/). Another, less regulated source of data is the Analysis, Research and Information on Accidents (ARIA) database (https://www.aria.developpement-durable.gouv.fr). These databases may be applied to establish a quantitative risk assessment (QRA), which should include information such as is diagrammed in Figure 41. (Moradi & Groth, 2019)

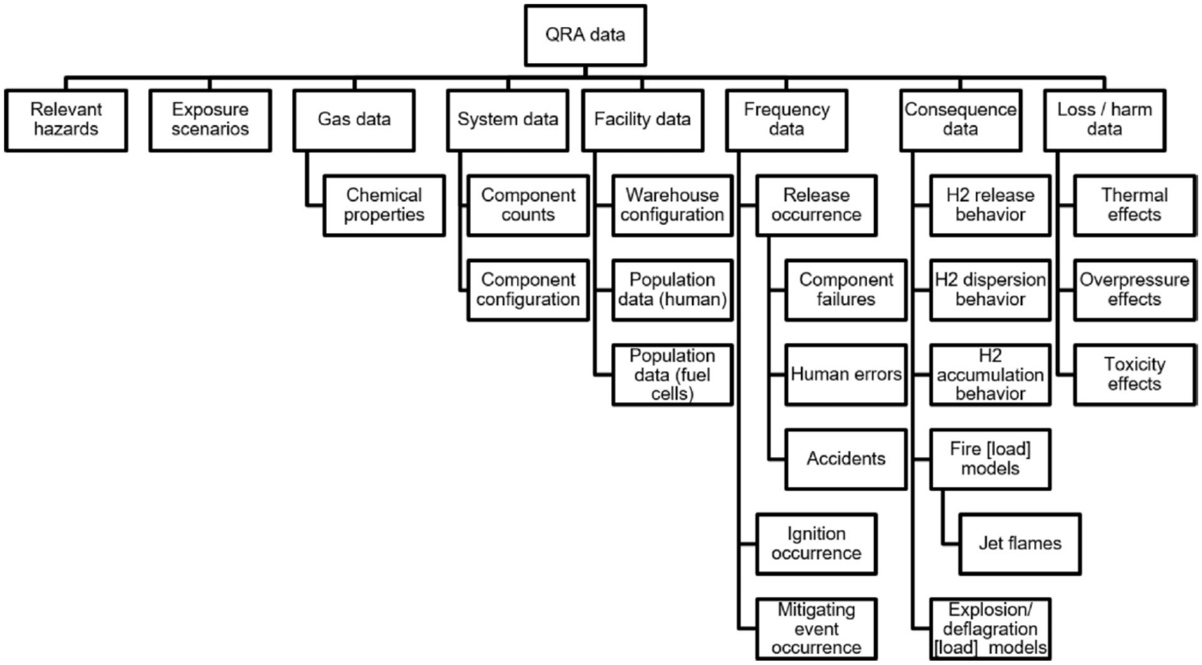


Figure 41: Data needed for Quantitative Risk Assessment for a hydrogen system. (Moradi & Groth, 2019)

15. Differences Between Stand-Alone Pipe and Internal Liner

15.1 High-Level Mechanical Property Requirements

In some cases, composite pipes can be used to line existing steel pipelines. This is sometime called a pull-through liner, and the process is called relining. It results in a loss of cross-sectional area but can rehabilitate a leaky line or allow for new media, like hydrogen. A pull-though liner must have sufficiently high yield strain to be able to get pulled through the bends, corners, and ID restrictions of the existing pipe. FRP stick pipe is not feasible to install as a pull through liner due to its stiffness, but the different types of spoolable and some onsite manufacturable pipes are feasible. Both FRP and spoolable pipe can be used as stand-alone buried or surface lay applications.(Nemeth et al., 2022) In some cases, the liner is folded into a U-shape and wrapped with tape. The tape is to reduce friction and protect the OD during pulling through the host pipe. The tape can then be broken when the liner is pressurized, and it becomes circular. One such product is made by Primus Line. (https://www.primusline.com/en-us/rehabilitation/installation-process)

15.2 Regulatory

One of the largest differences between stand-alone pipe and using it as an internal liner is that the liner requires higher tensile strength. It must not break under its own weight plus the friction of its outer diameter on the inner diameter of the pipe it is being pulled through. Damage during the pull-through process could cause areas for higher hydrogen permeability or nucleation sites for crack growth, however for unbonded pipe they can be tested for by nitrogen in the annulus. API RP 15SIH lists the considerations that need to be satisfied before, during, and after pulling the composite pipe though as a liner.(Installation and Handling of Spoolable Reinforced Line Pipe (API Recommended Practice 15SIH First Edition), 2021) API 15S contains information on how limits are set for pulling liners through pipes. The information needed includes known conditions of the host pipe and friction coefficient measurements to calculate the maximum distance the pipe can be pulled based on the maximum installation tension. For surface lay installations, the installer needs to consider natural obstructions, man-made obstructions, soil conditions, pipe restraints, supports for field-fittings, and actable spans between rack supports.

15.3 Service Conditions

No information has been found to date that allows pull-through pipes to be used in different service conditions than stand-alone pipes.

16. Survey Results from State and Federal Regulators and Standards and Codes Associations

16.1 Survey

The survey sent to regulators is below.

Title of Study: Investigating the Integrity Impacts of Hydrogen Gas on Composite/Multi-Layered Pipe

PHMSA Contract#: 693JK32310009POTA
Project #: 1012

June 2024
EWI
Jeff Ellis
Phone 614.688.5114

Email: jellis@ewi.org

Project Objective: The objective of this project is to investigate the impact to the integrity of composite pipe when used to transport pressurized hydrogen gas. EWI will identify and address safety hazards to the pipeline facilities, people, and the surrounding environment. EWI will identify required design, material and construction specifications, maintenance procedures, and a roadmap for using alternative-steel and non-steel composite systems for composite pipelines. Survey objective: The survey is aimed at eliciting expert input to identify risks for polymer composite pipelines in hydrogen gas pipeline service as well as gaps in current regulations, codes, and standards.

The survey will take approximately 30 minutes to complete. Thank you for your time and dedication to this important project.
Background
For the purposes of this survey polymer composite/multi-layered pipe includes:
- Reinforced Thermoplastic Pipe (RTP)
- Thermoplastic Composite Pipe (TPC)
- Glass Reinforced Epoxy Pipe (GRE), including Spoolable (S-GRE)
- Fiber-Reinforced Plastics (FRP)
- Spoolable Plastic Reinforced Line Pipe
- Composite Line Pipe and Tubulars

The survey questions below are specific to polymer/composite pipe manufactured and used within the defined operational envelopes expected for the types of pipes identified in the bullet list above.

1. How would you describe your familiarity with hydrogen effects on polymers and/or polymer composites.
a. No Knowledge
b. Limited Knowledge
c. Good Understanding
d. High level of Understanding (Expert)
2. What is your role with respect to pipelines? (Check all that apply)
a. Regulator

b. Inspector
c. Certifying Authority
d. Education & Training
e. Testing, Inspection & Certification
f. Engaged in developing/revising/maintaining relevant codes, standards, guidelines or best practice documents
g. None of the above
h. Other (please describe)

3. Are you aware of codes, standards, /guidance or best practice documents, or regulations addressing the design, construction or use of distribution piping (operation at or below 100 psig) operating in hydrogen service (or blended service)?

a. If yes, please list them

4. Are you aware of codes, standards, guidance or best practice documents addressing the design, construction or use of transmission piping (operation at or above 100 psig – including up to 2000 psig or more) operating in hydrogen service (or blended service)?

a. If yes, please list them

5. Are you aware of codes, standards, guidelines, or regulations for hydrogen leak detection from pipes?

a. If yes, please list them

6. Are you aware of codes, standards, guidelines, or regulations for hydrogen permeation through pipes?

a. If yes, please list them

7. Are you aware of codes, standards, guidelines, or regulations for in-service health monitoring (real-time, or near real-time, data collection and assessment of it) of pipes transporting hydrogen?

a. If yes, please list them

8. Are you aware of codes, standards, guidelines, or regulations for manufacturing of composite/multi-layer pipes?

a. If yes, please list them

9. Are you aware of codes, standards, guidelines, or regulations for manufacturer QA/QC testing of composite/multi-layer pipes?

a. If yes, please list them

10. Are you aware of codes, standards, guidelines, or regulations for installation of composite/muti-layer pipe?

a. If yes, please list them

11. Are you aware of codes, standards, guidelines, or regulations for in-service health monitoring of composite/multi-layer pipes?

a. If yes, please list them

12. Are you aware of codes, standards, guidelines, or regulations for repair or rehab of composite/multi-layer pipes?

a. If yes, please list them

13. Are you aware of codes, standards, guidelines, or regulations for connectors related to composite/multi-layer pipes?

a. If yes, please list them

14. Are you aware of codes, standards, guidelines, or regulations for blending hydrogen with natural gas in composite/multi-layer pipes?

a. If yes, please list them

15. Are you aware of codes, standards, guidelines, or regulations for determining the design or service life of composite/multi-layer pipes?

a. If yes, please list them

16. Are you aware of codes, standards, guidelines, or regulations for field inspection of composite/multi-layer pipes?

a. If yes, please list them

17. Where are the knowledge gaps for composite/multi-layer pipes for hydrogen service. (check all that apply)

a. Manufacturing
b. Manufacturer Testing and/or qualification Requirements
c. Installation
d. Health Monitoring
e. Repair or Rehab
f. Connectors
g. Materials performance or compatibility Issues related to Blending Hydrogen with Natural Gas
h. Integrity assessment – life prediction
i. Damage or defect tolerance limits in hydrogen service
j. Characterizing potential damage mechanisms in hydrogen service
k. Leak detection or leak management
l. Long-term performance in hydrogen service
m. Field Inspection
n. Other (blank box to type in)

18. What data needs to be collected before composite/multi-layer pipes can be used for the transmission of hydrogen?

19. Do you have any other concerns for polymer composite/multi-layer pipelines for the transmission of hydrogen?

20. What questions need to be answered before composite/multi-layer pipes can be used for the transmission of hydrogen?

21. What projects are you aware of where hydrogen is being transported in composite/multi-layer pipes?

22. What are the processes for implementing new requirements into standards?

23. Are you interested in participating in the development of codes or standards related to the use of composite/multi-layer pipes for transportation and distribution of hydrogen? If so, please list areas of interest.

16.2 Summary of Results

Responses to the survey were completed by the following people.

- Matthewson Epuna on behalf of the National Association of Pipeline Safety Representatives (NAPSR) Hydrogen Task Group.
- A representative from Alberta Energy Regulator.
- Mark Richards, Technology Manager, Hydrogen and Fuel Cell Technology Office (HFTO) of the U.S. Department of Energy (DOE).
- Stephanie Weidman, Pipeline Safety Director, Railroad Commission of Texas and member of NAPSR Hydrogen Task Group.
- David Granderson, VP – Product Development, Oil & Gas, NOV Completion & Production Solutions, Fiber Glass Systems.

The responses from the five respondents to the survey are summarized below.

Mr. Epuna indicated that he is a regulator and has a good understanding of hydrogen effects on polymers and/or polymer composites. He also indicated that the knowledge gaps for composite/multi-layer pipes for hydrogen service are in the areas of manufacturing, manufacturer testing and/or qualification requirements, installation, repair or rehab, connectors, materials performance or compatibility issues related to blending hydrogen with natural gas, integrity assessment – life prediction, characterization potential damage mechanisms in hydrogen service, leak detection or leak management, long-term performance in hydrogen service, and field inspection.

A representative from Alberta Energy Regulator responded with the following responses in blue.

In Canada we use CSA Z662-23 (Canadian Standards Group National Standard Z662-23 *Oil and Gas Pipeline Systems*) for such composite pipes. The standard recognizes 3 basic types of composite pipe structures: rigid jointed composite pipe, spoolable composite pipe, and reinforced thermoplastic pipe. See the image of Table 13.1 in CSA Z662-23. In my opinion, your list directly above duplicates categories of pipe in more than one category.

The survey questions below are specific to polymer/composite pipe manufactured and used within the defined operational envelopes expected for the types of pipes identified in the bullet list above.

1. How would you describe your familiarity with hydrogen effects specifically on polymers and/or polymer composites.
    a. No Knowledge
    b. Limited Knowledge
    c. Good Understanding
    d. High level of Understanding (Expert)
2. What is your role with respect to pipelines? (Check all that apply)
    a. Regulator
    b. Inspector
    c. Certifying Authority
    d. Education & Training
    e. Testing, Inspection & Certification
    f. Engaged in developing/revising/maintaining relevant codes, standards, guidelines or best practice documents
    g. None of the above
    h. Other (please describe) Performance testing of such pipes (previous career)
3. Are you aware of codes, standards, guidance or best practice documents, or regulations addressing the design, construction or use of distribution piping (operation at or below 100 psig) operating in hydrogen service (or blended service)?
    a. If yes, please list them
    b. No, not specifically in reference to hydrogen.
4. Are you aware of codes, standards, guidance or best practice documents addressing the design, construction or use of transmission piping (operation at or above 100 psig – including up to 2000 psig or more) operating in hydrogen service (or blended service)?
    a. If yes, please list them
    b. No, not specifically in reference to hydrogen.

5. Are you aware of codes, standards, guidelines, or regulations for **hydrogen leak detection** from pipes?
    a. If yes, please list them
    b. No
6. Are you aware of codes, standards, guidelines, or regulations for hydrogen **permeation** through pipes?
    a. If yes, please list them
    b. No
7. Are you aware of codes, standards, guidelines, or regulations for in-service **health monitoring (real-time, or near real-time, data collection and assessment of it)** of pipes transporting hydrogen?
    a. If yes, please list them
    b. Not specifically for hydrogen, but CSA Z662 does include integrity management of composite pipelines
8. Are you aware of codes, standards, guidelines, or regulations for **manufacturing** of **composite/multi-layer pipes**?
    a. If yes, please list them
    b. Yes, as seen in Table 13.1, each type of composite structure has standards or codes for manufacture and quality testing.
9. Are you aware of codes, standards, guidelines, or regulations for **manufacturer QA/QC testing** of **composite/multi-layer pipes**?
    a. If yes, please list them
    b. Yes, see answer to #8.
10. Are you aware of codes, standards, guidelines, or regulations for **installation** of **composite/muti-layer pipe**?
    a. If yes, please list them
    b. Yes, CSA Z662 includes these.
11. Are you aware of codes, standards, guidelines, or regulations for in-service **health monitoring** of **composite/multi-layer pipes**?
    a. If yes, please list them
    b. See answer to #7
12. Are you aware of codes, standards, guidelines, or regulations for **repair or rehab** of **composite/multi-layer pipes**?
    a. If yes, please list them

   b. Yes, CSA Z662 includes direction on repair

13. Are you aware of codes, standards, guidelines, or regulations for **connectors** related to **composite/multi-layer pipes**?
    a. If yes, please list them
    b. Yes, the manufacturing standards include this, and CSA Z662 has requirements
14. Are you aware of codes, standards, guidelines, or regulations for **blending hydrogen with natural gas** in **composite/multi-layer pipes**?
    a. If yes, please list them
    b. Not specifically for hydrogen blending
15. Are you aware of codes, standards, guidelines, or regulations for **determining the design or service life** of **composite/multi-layer pipes**?
    a. If yes, please list them
    b. Yes, the manufacturing standards reference ASTM methods for design qualification
16. Are you aware of codes, standards, guidelines, or regulations for **field inspection** of **composite/multi-layer pipes**?
    a. If yes, please list them
    b. CSA Z662 requires monitoring, leak detection, and integrity management on pipelines, but there are no specific rules for frequency or type of inspection
17. Where are the knowledge gaps for **composite/multi-layer pipes** for **hydrogen** service. (check all that apply)
    a. Manufacturing
    b. Manufacturer Testing and/or qualification Requirements
    c. Installation
    d. Health Monitoring
    e. Repair or Rehab
    f. Connectors
    g. Materials performance or compatibility Issues related to Blending Hydrogen with Natural Gas
    h. Integrity assessment – life prediction
    i. Damage or defect tolerance limits in hydrogen service
    j. Characterizing potential damage mechanisms in hydrogen service
    k. Leak detection or leak management
    l. Long-term performance in hydrogen service

m. Field Inspection

n. Other (blank box to type in)

Defect assessment of composite pipelines is generally impossible. There are no methods for assessment of the composite structure, other than a pressure test. You could take cut-outs for mechanical testing but our experience has shown that these do not provide representative or reliable data for the entire pipeline. A gap is the lack of understanding of how hydrogen might affect the actual polymers. Hydrogen being a small molecule is known to readily permeate polymers. Can this result in plasticization of the pipe body, or voids or microvoids in the structure, or lack of bonding between layers? Also, what might be the effects of hydrogen loss on the outside environment? Could pockets of gas collect? Note that many of these concerns exist also for methane, but the expectation is that hydrogen will permeate to a higher degree.

18. What data needs to be collected before composite/multi-layer pipes can be used for the transmission of hydrogen?
19. Do you have any other concerns for polymer composite/multi-layer pipelines for the transmission of hydrogen? Our experience using polymer composite pipelines in general oilfield services is that these pipelines experience a significantly greater frequency of failure than steel pipeline. (Based on number of failures per km of installed pipeline per an operating year.) Many of these failures cannot be conclusively explained. Some are due to damage, some due to faulty installation, but many occur for seemingly no clear cause.
20. What questions need to be answered before composite/multi-layer pipes can be used for the transmission of hydrogen? My first question is why would we want to use composite pipes for the transmission of hydrogen? Other than avoiding the need to construct proper hydrogen-resistant steel pipelines, which requires some extra effort, or considering options to insert a composite liner inside an existing steel pipeline of unsuitable construction, steel pipelines provide reliable service. Dry hydrogen is not corrosive. My second question is in respect to the risks that may exist due to permeation of hydrogen – what are those risks?
21. What projects are you aware of where hydrogen is being transported in composite/multi-layer pipes? Many of our pipelines will have minor quantities of hydrogen in the produced natural gas, but I know of no projects currently using composites for blended or neat hydrogen.

22. What are the processes for implementing new requirements into standards? Generally, CSA only incorporates new technology into a Standard when that technology has been proven in the field. This is not particularly helpful. In Alberta, the Alberta Energy Regulator's legislation gives us the authority to allow trials of new technology, and if successful, allow those for use. This is how we initially broke some of these new composite products into the marketplace to gain experience. CSA built them into the Z662 Standard later.

Are you interested in participating in the development of codes or standards related to the use of composite / multi-layer pipes for transportation and distribution of hydrogen? If so, please list areas of interest. Not particularly

Mr. Granderson of NOV responded with the following answers, which are in blue font.

1. How would you describe your familiarity with hydrogen effects on polymers and/or polymer composites.
    a. No Knowledge
    b. Limited Knowledge
    c. Good Understanding
    d. High level of Understanding (Expert)
2. What is your role with respect to pipelines? (Check all that apply)
    a. Regulator
    b. Inspector
    c. Certifying Authority
    d. Education & Training
    e. Testing, Inspection & Certification
    f. Engaged in developing/revising/maintaining relevant codes, standards, guidelines or best practice documents
    g. None of the above
    h. Other (VP Product development 32 years as a manufacturer of TCP, RTP, GRE, and SGRE and member of API SC15 and ISO14692)
3. Are you aware of codes, standards, /guidance or best practice documents, or regulations addressing the design, construction or use of distribution piping (operation at or below 100 psig) operating in hydrogen service (or blended service)? NO

    a. If yes, please list them

4. Are you aware of codes, standards, guidance or best practice documents addressing the design, construction or use of transmission piping (operation at or above 100 psig – including up to 2000 psig or more) operating in hydrogen service (or blended service)?
    a. If yes, please list them. ASME B31.12 and code case 200
5. Are you aware of codes, standards, guidelines, or regulations for **hydrogen leak detection** from pipes?
    a. If yes, please list them NO
6. Are you aware of codes, standards, guidelines, or regulations for hydrogen **permeation** through pipes?
    a. If yes, please list them NO
7. Are you aware of codes, standards, guidelines, or regulations for in-service **health monitoring (real-time, or near real-time, data collection and assessment of it)** of pipes transporting hydrogen?
    a. If yes, please list them NO
8. Are you aware of codes, standards, guidelines, or regulations for **manufacturing** of **composite/multi-layer pipes**?
    a. If yes, please list them YES, API 15LR, 15HR, 15S, & API 17J, ISO 14692, DNV F119
9. Are you aware of codes, standards, guidelines, or regulations for **manufacturer QA/QC testing** of **composite/multi-layer pipes**?
    a. If yes, please list them YES ASTM D1599, D2105, D2344, ISO 11357, ASTM D2290
10. Are you aware of codes, standards, guidelines, or regulations for **installation** of **composite/muti-layer pipe**?
    a. If yes, please list them, API 15TL4, AWWA M45, AWWA C950,
11. Are you aware of codes, standards, guidelines, or regulations for in-service **health monitoring** of **composite/multi-layer pipes**?
    a. If yes, please list them NO
12. Are you aware of codes, standards, guidelines, or regulations for **repair or rehab** of **composite/multi-layer pipes**?
    a. If yes, please list them NO

13. Are you aware of codes, standards, guidelines, or regulations for **connectors** related to **composite/multi-layer pipes**?
    a. If yes, please list them NO
14. Are you aware of codes, standards, guidelines, or regulations for **blending hydrogen with natural gas** in **composite/multi-layer pipes**?
    a. If yes, please list them NO
15. Are you aware of codes, standards, guidelines, or regulations for **determining the design or service life** of **composite/multi-layer pipes**?
    a. If yes, please list them YES, ASTM D2992, D1598, DNV F119, C501
16. Are you aware of codes, standards, guidelines, or regulations for **field inspection** of **composite/multi-layer pipes**?
    a. If yes, please list them NO
17. Where are the knowledge gaps for **composite/multi-layer pipes** for **hydrogen** service. (check all that apply)
    a. Manufacturing
    b. Manufacturer Testing and/or qualification Requirements
    c. Installation
    d. Health Monitoring
    e. Repair or Rehab
    f. Connectors
    g. Materials performance or compatibility Issues related to Blending Hydrogen with Natural Gas
    h. Integrity assessment – life prediction
    i. Damage or defect tolerance limits in hydrogen service
    j. Characterizing potential damage mechanisms in hydrogen service
    k. Leak detection or leak management
    l. Long-term performance in hydrogen service
    m. Field Inspection
    n. Other (blank box to type in)
18. What data needs to be collected before composite/multi-layer pipes can be used for the transmission of hydrogen? (1) The Long term strength of the pipe in several R ratios (hoop

stress/axial stress) to develop an operating stress envelope covering the expected R ratios expected in pipeline service. Most standards testing focus only on R=2 (free end pressure only) many times loading the reinforcement in tension and ignoring that the composite pipe is NOT Isotropic (they are anisotropic) and will see loads off the fiber axis in operation. (2) equally important is the potential reduction in strength (change of failure mode) at the termination of composite pipe body to end termination/connectors, near end closure failures many times have no relation to pipe body failures but are aimlessly mixed together to make inaccurate life predictions. (3) confirm no long term corrosion exists and diffusion losses are acceptable and or safely vented/captured.

19. Do you have any other concerns for polymer composite/multi-layer pipelines for the transmission of hydrogen? External damage, or diffused gases in unvented areas. Corrosion of metallic components.
20. What questions need to be answered before composite/multi-layer pipes can be used for the transmission of hydrogen? See 18.
21. What projects are you aware of where hydrogen is being transported in composite/multi-layer pipes? None
22. What are the processes for implementing new requirements into standards? This is quite different depending on the standard body, from DNV mandating, to API allowing commercial and political influences with majority rule.

Are you interested in participating in the development of codes or standards related to the use of composite / multi-layer pipes for transportation and distribution of hydrogen? If so, please list areas of interest. Yes, but depends on the standards rules of development i.e. # 22 above, I would contribute to appropriate technical discussions for appropriate qualification methods which address expected pipeline loads (hoop/axial stress) for composite anisotropic pipe in a committee where science, engineering, and hard peer reviewed data rules over political and commercial interests. We are discussing pipelines thus I would expect pipeline stress engineers (familiar with anisotropic composite pipe) to be an integral part of the standards committee.

Another respondent indicated they had a good understanding of hydrogen effects on polymers and/or polymer composites, and they perform research, development, and demonstration of pipelines carrying hydrogen and hydrogen/natural gas blends. They indicated they were aware of regulations, codes, and standards for polymer distribution piping and polymer transmission pipeline for hydrogen. They also indicated that they did not believe that codes, standards, or guidelines existed for blending hydrogen with natural gas in composite pipes. They indicated that there are knowledge gaps in composite/multi-layer pipes for hydrogen service in materials performance of compatibility issues related to blending hydrogen with natural gas, integrity assessment – life prediction, damage of defect tolerance limits in hydrogen service, characterizing potential damage mechanisms in hydrogen service, and long-term performance in hydrogen service. When asked, “What data needs to be collected before composite/multi-layer pipes can be used for the transmission of hydrogen?” Their response was, “I believe the main concern for multi-layer pipes is the suitability of the inner layer in contact with the hydrogen: strength, fracture toughness, permeability, etc. There is a wide variety of “liner” materials that could be used in multi-layer pipes which makes the data space possibly quite large. These concerns apply to and are being investigated for non-composite polymer pipes. I do not believe there is much concern about the outer composite layer relative to hydrogen.”

Finally, another respondent indicated that they were a regulator but had no knowledge of hydrogen effects on polymers and/or polymer composites. They also indicated that ASME B31.12 was a resource for composite transmission pipes for hydrogen and that ASTM D2517 is possibly a good resource for the manufacturing of composite/multi-layer pipes.

17.Summary

17.1 Applicable Standards

The following standards are applicable to either composite or hydrogen pipelines.

Table 15. Standards to applicable to either composite or hydrogen pipelines

Document Number	Document Title
API 15HR 2016	High-Pressure Fiberglass Line Pipe
API 15LR	Specification for Low Pressure Fiberglass Line Pipe
API 15S 2022	Spoolable Reinforced Plastic Line Pipe
API RP 15SA	Integrity Management of Spoolable Reinforced Line Pipe

API RP 15SIH	Installation and Handling of Spoolable Reinforced Line Pipe, First Edition
API RP 15TL4	Recommended Practice for Care and Use of Fiberglass Tubulars
API 17J	Specification for Unbonded Flexible Pipe
ASME B31.12 2019	Hydrogen Piping and Pipelines (Code Case 200)
ASTM D1598	Time-to-Failure of Plastic Pipe Under Constant Internal Pressure
ASTM D1599	Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings
ASTM D2105	Longitudinal Tensile Properties of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Tube
ASTM D2290	Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe
ASTM D2992-22	Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings
ASTM F2896-23	Standard Specification for Reinforced Polyethylene Composite Pipe for The Transport of Oil And Gas And Hazardous Liquids
AWWA C950	Specifications for Fiberglass Pressure Pipe
AWWA M45	Fiberglass Pipe Design
CSA Z662 2023	Oil and gas pipeline systems
DNV-ST-F119 2019	Thermoplastic composite pipes
ISO/TS 18226 2006	Plastics pipes and fittings — Reinforced thermoplastics pipe systems for the supply of gaseous fuels for pressures up to 4 MPa (40 bar)

A comparison of ASME B31.8 for natural gas piping and ASME B31.12 for hydrogen gas piping is shown in Table 16. (Ott et al., 2023)

Table 16: Comparison of ASME B31.8 and B31.12

	ASME B31.8 Natural gas piping	ASME B31.12 Hydrogen gas piping	Comment
Common carbon steel specifications: ASTM A53, ASTM A106, API 5L	Allowed	Allowed	Carbon steel is generally allowed by both standards
Ductile iron pipe: ANSI A21.52	Allowed	Not Allowed	Ductile iron pipe is not allowed by H_2 standard
Plastic pipe: ASTM D2513, D2517	Allowed	Not listed as a suitable material	Research of H_2 permeability through the plastic to determine which ones are suitable for H_2 service is currently ongoing
Post-weld heat treatment: CS piping	Required for CS with pipe thickness >1¼ in.	Required for CS with pipe thickness >¾ in.	H_2 standard requires PWHT of thinner components due to the loss of material properties associated with H_2
Maximum allowable hardness: CS piping	22 HRC[a] (790 MPa)	13.5 HRC (672.5 MPa)	H_2 standard has more stringent hardness requirements due to hydrogen embrittlement
Maximum allowable hardness: CS weld root	22.3 HRC[a] (792.5 MPa)	13.5 HRC (672.5 MPa)	
Maximum allowable hardness: CS weld cap	26.4 HRC[a] (871 MPa)	13.5 HRC (672.5 MPa)	

Abbreviations: ASME, American Society of Mechanical Engineers; HRC, Hardness Rockwell C; NG, natural gas; PWHT, post-weld heat treatment.
[a]Denotes maximum allowable hardness values for NG pipelines in sour service.

Other standards related to composite materials and/or hydrogen include the following.

Table 17. Standards related to composite materials and/or hydrogen

Document Number	Document Title
AIGA 087/14	Standard for Hydrogen Piping Systems at User Locations
ASME NM.1	Nonmetallic Materials – Part 1 – Thermoplastic Specifications
ASME NM.3	Nonmetallic Materials – Part 2 – Reinforced Thermoset Plastic Material
CSA/ANSI CHMC 2:19	Test methods for evaluating material compatibility in compressed hydrogen applications — Polymers
ISO 11114-5 2022	Gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 5: Test methods for evaluating plastic liners
ISO 14692-1 2017	Petroleum and natural gas industries – Glass reinforced plastics (GRP) piping - Part 1: Vocabulary, symbols, applications and materials
ISO 14692-2 2017	Petroleum and natural gas industries – Glass reinforced plastics (GRP) piping - Part 2: Qualification and Manufacture
ISO 14692-3 2017	Petroleum and natural gas industries – Glass reinforced plastics (GRP) piping - Part 3: System Design

ISO 14692-4 2017	Petroleum and natural gas industries – Glass reinforced plastics (GRP) piping - Part 4: Fabrication, installation and operation
ISO 16486-6 2023	Plastics piping systems for the supply of gaseous fuels- Unplasticized polyamide (PA-U) piping systems with fusion jointing and mechanical jointing — Part 6: Code of practice for design, handling and installation (other dash sections of 16486 may be applicable too)
ISO 19881-2018	Requirements for the material, design, manufacture, marking and testing of serially produced, refillable containers intended only for the storage of compressed hydrogen gas for land vehicle operation
ISO 23936-1	Oil and gas industries including lower carbon energy — Non-metallic materials in contact with media related to oil and gas production – Part 1 Thermoplastic
ISO 23936-4	Oil and gas industries including lower carbon energy — Non-metallic materials in contact with media related to oil and gas production – Part 4 Fiber-Reinforced Composite – To be approved by the end 2024 or beginning 2025
T/CATSI 02007-2020	Fully-wrapped carbon fiber reinforced cylinder with a plastic liner for the on-board storage of compressed hydrogen as a fuel for land vehicles

The following standards are related to seals with hydrogen, many are from automotive.

Table 18. Standards are related to seals with hydrogen

Document Number	Document Title
EC79	Type-approval of hydrogen-powered motor vehicles. Compatibility shall be demonstrated.
ISO 12619-2	Road vehicles — Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel system components. Part 2: Performance and general test methods. 70 hrs exposure then rapid decompressions at room temperature.

ISO 17268	Gaseous hydrogen land vehicle refueling connection devices. 168 hrs exposure, then decompression at room temperature (and -40°C) in less than 1 sec.
ISO 19880-3	Gaseous hydrogen — Fueling stations. Part 3: Valves. 70 hrs exposure then rapid decompression at room temperature.
ISO 23936-2	Petroleum, petrochemical and natural gas industries — Non-metallic materials in contact with media related to oil and gas production. Part 2: Elastomers. 30 days exposure, decompression, 72 hrs at 150 bar, 100°C, then 20 bar/min decompression
SAE J2600	Compressed Hydrogen Surface Vehicle Fueling Connection Devices. 168 hrs exposure, then decompression at room temperature (and -40°C) in less than 1 sec.

17.2 Gaps in Standards (Hazard Analysis)

Many standards exist for composite pipes, since they have been used for multiple decades, but the references to hydrogen transmission are lacking. ASME B31.12 Case 200 is the most complete document for hydrogen piping and pipelines using composites. API 15S (onshore) and DNV-ST-F119 (offshore) are the most complete documents for composite pipes but have yet to mention using them with hydrogen. There are working groups discussing what is needed to update the documents to include hydrogen transmission. Over the next several years new documents will be released.

Some of the potential safety risks are associated with structural health inspection and real-time hydrogen leak monitoring. Embedded fiber optic sensors, annulus concentration monitoring, smart PIGs, and other technologies are all being developed to address these safety concerns. Another potential risk is the introduction of mixed or contaminated gas streams. The sources of hydrogen could vary widely and contaminates from the production of blue and gray hydrogen could be carbon monoxide, carbon dioxide, nitrogen, water, water vapor, methane, and oxygen. These molecules may be present in hydrogen streams and interact with the pipelines for transmission. Effects of these molecules, and their mixtures, with composite pipeline materials should be considered and tested before choosing materials and commissioning infrastructure.

Due to the flammability, explosivity, and negative Joule-Thompson coefficient, special attention should be given to purging and venting requirements and protocols due to potential void formation in polymeric materials, hydrogen heating during depressurization, and the related explosion hazards when mixed with air. This also extends to permeated hydrogen that could collect in spaces like casings under roads, train tracks, and other throughways. Standards may need to include venting or purging requirements for these spaces to ensure they never reach the lower flammability limit. So, additional regulations for permeation testing and limits could be enacted to ensure the safety of the people and environment near the pipelines.

Finally, there are many different materials, constructions, and diameters manufactured in the polymer composite pipe industry. Their failure mechanisms vary, most significantly different from thermoplastic to thermoset pipes. Due to these differences, the standards for short-term testing to predict long-term performance may need to be delineated.

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