Impacts of Hydrogen Blending on Gas Piping Materials

A Publication for AGA Members

Prepared by the AGA Operations Piping Materials Committee

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Executive Summary

Hydrogen blending into natural gas piping systems provides natural gas pipeline operators with the opportunity to improve energy resilience, maintain a high level of system reliability, and expedite the reduction of emissions. Natural gas, natural gas utilities, and the natural gas delivery infrastructure are essential to meeting the world's greenhouse gas emissions reduction goals for a cleaner energy future.[1] This paper aims to compile and present technical information related to the effects of blending hydrogen into natural gas piping systems on piping materials.

Hydrogen blending with natural gas is being researched for its use in the natural gas pipeline system. However, the presence of hydrogen in the gas stream is not new. Historically, hydrogen has been a significant part of the gas stream in systems where the original gas source was a “manufactured” or “town gas” source. These gas sources, which were based on the gasification of coal, petroleum byproducts, or other materials, often contained hydrogen gas as 10% or more of the product stream. Several utilities have operated for decades with hydrogen blends in their pipelines, such as Hawaii Gas (12% Hydrogen[2]) and Singapore Gas Company (City Gas) (41 to 65% Hydrogen[3]).[4,5]

The properties of natural gas and gaseous hydrogen differ significantly. Hydrogen has a lower energy density than natural gas. A cubic foot of hydrogen has one-third the energy of an equivalent amount of natural gas.[6] Hydrogen has approximately 1/8th the density of methane (the main component of natural gas)[7]. Table 1, below, compares some of the properties of hydrogen and methane (natural gas’ main component).

Property	Hydrogen	Methane
Molecular Formula	H_2	CH_4
Molecular Weight (g/mol) [9]	2.016	16.043
Buoyancy (ratio to air)	0.07	0.54
Density (kg/m^3) [10] [11]	0.0899 ~14 times lighter than air	0.668 ~1.8 times lighter than air
Dynamic Viscosity (10^{-5} Pa-s) [12]	1.10	0.88
Flammability Limits (vol. %) [11]	4-74	5.3-15
Stoichiometric Concentration in Air (vol. %) [11]	29	9
Maximum laminar burning velocity (m/s) [11]	3.25	0.44
Relative radiative heat transfer (%) [11]	5-10	10-33

Natural gas properties will generally be similar to that of pure methane; however, these properties will vary based on the specific composition. As higher order hydrocarbons increase by volume, the molecular weight, density, and combustion properties are affected.

Table 1: Hydrogen and Natural Gas Properties at Ambient Conditions from Glover et al. [8]

System designers and installers must comply with a variety of federal, state, local and other jurisdictional entities' codes for safety and permitting when installing blended hydrogen and natural gas systems.[9]

The American Society of Mechanical Engineers (ASME) B31.8-2018 Gas Transmission and Distribution Piping Systems standard serves as a guideline for safe pressure piping installation and prohibits designs and practices that are known to be unsafe. Although this code is intended for natural gas pipelines without significant quantities of hydrogen, B31.8-2018 accepts some variation in the composition of natural gas since the constituents of natural gas naturally vary. "The code does not specifically call out hydrogen as a constituent of concern, and small quantities of hydrogen may be allowable in not yet defined quantities".[10]

According to the codes and standards assessment prepared by Sandia National Laboratories the ASME B31.12-19, Hydrogen Piping and Pipelines,

> "...is designed to address pipeline codes and standards of hydrogen infrastructure applications…. Pipeline guidance within the code is applicable for systems that contain 10% or more hydrogen by volume with pressures below 3,000 psig. This code addresses hydrogen pipeline service and specifically excludes blends where the hydrogen percentage is less than 10% by volume. …This code also included information on material performance and pressure derating to accommodate

hydrogen embrittlement. Additional rules have been added for the conversion or retrofit of existing pipeline and distribution systems for natural gas or petroleum to H2 service”.[11]

Polyethylene and Polyamide Piping Materials

A review of existing research did not identify any material compatibility issues using existing PE, PA or PVC materials with hydrogen blends up to 20%. The ability of hydrogen molecules to migrate through the PE or PA pipe walls is understood.[12] The larger surface area of pipes means most gas losses will likely occur through pipe walls rather than seals and connections.[13] While hydrogen has a higher permeation rate through polymers than methane, hydrogen blend rates up to 20% show that losses are negligible when considering the overall economics, safety, and environmental concerns. There is considerable ongoing research that is expected to provide additional data concerning the performance of PE and PA pipes in hydrogen blended systems. [14]

Natural Gas Steel Systems

There is no clear industry consensus regarding the maximum allowable hydrogen content in existing steel natural gas transmission pipelines. Most guidelines refer to maximum levels of ~10-20% volume.[15] However, some guidelines allow up to 100% hydrogen, while others show an effect with under 2% hydrogen. The existing ASME B31.12 codes allows pipelines to be built and operated with up to 100% hydrogen, but the code does not apply to hydrogen concentrations less than 10% hydrogen. The principal limits to introducing hydrogen into steel natural gas pipelines appear to be: fatigue loading and the possibility of low toughness material or pre-existing flaws in natural gas pipelines.

Valves, Connections, and Fitting Materials

In general, hydrogen has been found to be non-reactive with most polymers used for seal materials.[16] This means that the introduction of hydrogen into a natural gas pipeline system is not likely to result in the chemical alteration of most seal materials commonly used in the natural gas distribution system. Hawaii Gas has transported synthetic natural gas (SNG) containing hydrogen (12%) in their distribution network since the early 1970s, with no negative interactions with sealing materials reported. Hawaii Gas uses gas distribution products common to other LDCs.

With the variety of different fittings, elastomers, and materials manufactured and installed for the gas industry, each operator should evaluate their materials records. Additionally, operators considering introducing hydrogen into their natural gas system should take appropriate steps to evaluate potential hydrogen compatibility for fittings and elastomers used within their system. Ongoing studies from industry groups such as NYSEARCH will help inform operators about the strengths and vulnerabilities of fittings and sealing materials, but operators should consider introducing hydrogen blends into their own gas systems on a small scale pilot basis in to understand effects before beginning large scale, system wide blending.

Meter and Regulator Components

Various research documents[17] show the ranges of hydrogen levels at which no significant material issues will occur in metering components. The acceptable ranges vary by document, but most sites have an upper limit of 10-20% hydrogen. Higher blends may be acceptable, but research data is unavailable for the effects on the material at these higher blends. Some meter and regulator manufacturers provide their customers with acceptable hydrogen blend levels.[18] Other manufacturers simply state that regulators are acceptable for any non-corrosive gas, indicating they are acceptable for blended hydrogen service. For example, Marcogaz indicates a 30% blend of hydrogen in pressure regulators is possible without significant issues.[19]

Meter cases, typically made from aluminum or carbon steel material, are compatible with hydrogen.[20] Other meter case materials, including cast iron and tin, should be used with caution as compatibility varies by source and by operating conditions. For example, ASME B31.12, which covers hydrogen blends at or above 10% and pressures up to 3,000 psig, prohibits the use of cast or ductile iron in valves and flanges.[21] `Other sources, like The National Renewable Energy Laboratory, (NREL), indicate little to no concern of iron (including ductile and cast) materials for gas distribution.[22]

Following research and testing performed on a regulator station, KIWA Laboratory, a Netherlands-based consultancy focused on Testing, Inspection, and Certification (TIC) stated "Based on the measurements, as presented in this report, the main conclusion is: The tested gas pressure regulating station designed for natural gas can be used for hydrogen without modification."[23]

While this white paper focuses on material compatibility and safety, operators should consider hydrogen's other potential effects on meters and regulators, such as capacity, metrology, leakage, and gas ignition protection.

Pipeline Liners and Rehabilitation Products

Based on our limited research, there are no apparent material incompatibilities preventing the use of lined[24] pipelines for transportation of a natural gas blend with up to 20% hydrogen. While the permeation of hydrogen would be higher than that of methane, it is expected to be acceptable compared to methane. However, additional study is needed to fully understand the compatibility of pipe lining systems with hydrogen. In particular, the performance of the adhesive when permeated by hydrogen and subjected to changes in line pressure and temperature should be evaluated.

Conclusion

Overall, natural gas piping materials appear compatible with hydrogen blended natural gas, and the sources cited in the paper indicate a blend up to 20% hydrogen may be acceptable. No compatibility issues were found in the compilation of this white paper that would impede the continued efforts of researching or trials of hydrogen blended natural gas. Piping components may differ in their acceptable blend levels and should be assessed individually.

1. Purpose and Scope

The ability of natural gas infrastructure to store and transport large amounts of energy to meet seasonal and peak day energy use represents an important and valuable resource that needs to be considered when building pathways to achieve net-zero greenhouse gas emissions goals. Pathways that utilize natural gas and the vast utility delivery infrastructure offer opportunities to incorporate renewable and low-carbon gases, provide optionality for stakeholders, help minimize customer impacts, maintain high reliability, improve overall energy system resilience, and accelerate emissions reductions.[25]

This white paper aims to compile and present technical information related to the effects of blending hydrogen into natural gas piping systems on piping materials. Blending improves energy resilience, maintains a high level of system reliability, and expedites the reduction of emissions. Research sources, information, and technical reports were reviewed by the task group to help assess the compatibility of blending hydrogen with new and existing natural gas piping materials. Safety, system integrity, and reliability are paramount for all AGA member companies. The intent of this white paper is to help operators better assess the potential effects of introducing varying levels of hydrogen into a natural gas piping system.

The white paper does not seek to provide a comprehensive technical analysis of all the potential issues related to blending hydrogen into a natural gas system. Rather, the intent of this white paper is to provide an overview of some of the most common issues and considerations that operators should consider when evaluating whether to blend hydrogen into their systems. This white paper does not include a detailed discussion of certain operational and maintenance topics that may be impacted by the introduction of hydrogen blending, including system flow and capacity analysis, inspection procedures, gas detection recommendations, purging procedures or evaluations of end-use and related equipment. While meter and regulator materials are evaluated in detail, meter accuracy and regulator capacity are not within this white paper's scope.

Natural gas utility systems typically employ a variety of piping materials used in differing applications and pressures. This white paper focuses on material-specific piping systems for modern and existing (vintage, legacy, etc.) polyethylene, polyamide, steel materials, elastomers, and pipe lining materials. Pipe joining methods, fittings, valves, and associated material components are reviewed as part of the piping systems. Meters, regulators, and other natural gas-associated equipment should also be evaluated for material compatibility with hydrogen blending.

The need to adopt or comply with every finding described in this white paper will vary with each natural gas utility and the specific environment in which they operate. The information presented in this white paper should be evaluated in light of each operator's unique system, geographic variables, independent integrity assessment, risk analysis, mitigation strategy, and what has been deemed reasonable and prudent by their state regulators. Therefore, not all of the findings described in this white paper will apply to all natural gas utilities, but the intent is that each utility will better understand the impact which hydrogen blending may have on its unique operating system. Each natural gas utility should thoroughly examine all factors, criteria, and applicable laws and regulations prior to injecting hydrogen into their natural gas system.

2. Polyethylene and Polyamide Systems

Plastic piping is a major and growing component of gas distribution systems. According to the DOT 2021 Gas Distribution Annual Report, plastic now represents 60% of all main piping material installed. More than 98% of newly installed gas distribution piping four inches and under is polyethylene (PE).[26] According to the same report, there are more than 802,000 miles of plastic main and more than 730,000 miles of plastic service piping (representing > 53 million services).[27] In addition, polyamide, notably PA11 and PA12,[28] has recently been approved for use in gas distribution systems up to 6 inches in diameter[29].

This section of the white paper provides a summary of available literature related to the use of plastic piping in natural gas systems with hydrogen blends. This is not intended to be an exhaustive literature review and additional research is ongoing in all areas of hydrogen blending. While there has been work on systems with 100% hydrogen, this section will focus on hydrogen blends with natural gas (with up to 20% hydrogen). This section will also cover the possible short and long-term effects on plastic material properties, including permeability.

2.1 Plastic Materials Background

Plastic piping is a general term referring to materials used in gas distribution systems, including polyethylene, polyamides, and polyvinyl chloride (PVC). Research and pilot projects that inform this white paper have been conducted worldwide. Differing nomenclature has been used to describe the various piping materials. For example, “high density polyethylene (HDPE)” may refer to PE3608, PE4710, PE100, or PE100 RC. "Medium density polyethylene (MDPE)" may refer to PE2708, PE2710, PE63 or PE80, and polyamides may include PA11 or PA12 designations.

Polymer rheological properties[30], such as molecular weight and molecular weight distribution, have changed along with manufacturing technology over the years. For the purposes of this white paper, all HDPE, MDPE, and polyamide designations can be treated as equivalent within their class. DuPont Aldyl A and Driscopipe 7000/8000 piping materials are not treated as equivalent and specific references to these materials will be noted where applicable. Additional research on these piping materials in a hydrogen environment is currently being conducted by GTI Energy.

This section will provide an overview of some of the leading research involving polyethylene (MDPE and HDPE), polyamides (PA11 and PA12), and PVC plastic gas distribution piping with blends of hydrogen and natural gas. A wide range of research and practical experience has shown that plastics, to varying degrees, are well suited to hydrogen and hydrogen/natural gas blends.

Plastic Pipe Institute (PPI) TR-19 2020 "Chemical Resistance of Plastic Piping Materials"[31] provides a starting point for understanding the possible effects of various chemicals and gases on thermoplastic materials, including PE, PA11/PA12, and PVC. Note that the data presented in PPI TR-19 is for non-pressure applications generally gathered through sample immersion in a particular media to understand potential chemical attacks including permeation, swelling, solvation and environmental stress cracking (ESCR). Additional considerations are necessary when assessing pressure rated materials. It should be noted that PPI TR-19 2020 indicates that all materials discussed in this section are resistant to hydrogen.[32]

2.2 Polyethylene (PE) Compatibility with Hydrogen Blends

Polyethylene gas piping is designed and produced to meet the standards found in ASTM D2513.[33] PE piping has been successfully used in gas distribution systems in North America and around the world for over 60 years. It has outstanding chemical resistance to a wide range of chemicals and gases. In a 2010 literature review, the Gas Technology Institute (GTI) noted that "little or no interaction between hydrogen gas and PE should be expected...hydrogen alone does not provide radicals that can cause polymer breakdown".[34] PPI TR 19-2020 indicates that all grades of PE are resistant to hydrogen gas up to 140°F.[35] In fact, none of the studies reviewed for this white paper presented any concerns related to PE compatibility with hydrogen.[36]

Hermkens et.al (2018) assessed the use of PE100-RC pipes to transport hydrogen at the Groningen Seaport.[37] This study concluded that PE100-RC pipes are fit for transporting 100% hydrogen at pressure up to 2 bar (29 psi), and more generally concluded that PE pipes permit the transport and distribution of hydrogen in a safe and reliable way.[38] The delivery of hydrogen using PE piping is not new to the gas industry. Some utilities have had a hydrogen component in their system for decades. For example, Hawaii Gas has been using PE pipes to transport synthetic natural gas (SNG) containing hydrogen (10-12%) in their distribution network since the early 1970s with no deleterious effects on system piping or components.[39] Additionally, Hong Kong Gas Company has been using PE piping in their network since 1987 with a 46 – 52% hydrogen component [40] . Singapore Gas Company (City Gas) has used a blend of (42-65%) hydrogen in their low pressure pipe town gas since 1861.[41]

The following sections highlight research demonstrating the compatibility between hydrogen and PE piping. It is divided into the effects of hydrogen on the short and long-term properties of polyethylene pipe. Studies assessing the compatibility of PE piping with hydrogen and hydrogen blends generally identify the impact to both short and long-term material properties. As such, both short and long-term properties that are important to the performance of the material in natural gas distribution systems will be assessed in this paper.

2.3 Impact on Short-term PE properties

Short-term testing provides a quick assessment of the potential impact of hydrogen on mechanical properties and often includes tensile testing and/or burst testing to assess a loss in strength or ductility. A study by Klopffer et.al. (2010), notes that it can be "reasonably concluded that tensile properties are not affected by hydrogen diffusion into PE, even up to 100 bars [1450 psig]. The same result stands for PA11 materials".[42] Additionally, a "hydrogen environment was shown to have no noticeable effect on the ductile fracture on PE and PA11, as estimated from a limited series of tensile tests in double-notched samples".[43]

Hermkens et.al. (2018) exposed PE100-RC[44] to 100% hydrogen for 1000 hours at low pressure (2 bars or 29 psi) along with changes in weight and yield strength. Experiments for the "chemical interaction showed no significant differences between pipes exposed to air and those exposed to hydrogen".[45] The experiments found no negative effects to material integrity.[46]

2.4 Impact on long-term PE properties

Due to improvements in PE compounds over time, the manufacturing year of the PE pipe may be important to consider due to differences in properties such as molecular weight or molecular weight distribution (MWD) and slow crack growth resistance (SCGR). A study by Iskov & Kneck (2017) found no indication of changes in rheology from hydrogen exposure.[47] Rheological properties may include viscoelastic, temperature-dependent, and aging behaviors. Furthermore, the study found no adverse effects from the transportation of hydrogen on PE100 pipes for 1, 2, 3, 4 and 10 years, or from a combined exposure effect of 4 years of natural gas transport and 2 years of hydrogen transport.[48] Iskov & Kneck also noted that after 4-10 years of continuous hydrogen exposure there was no influence on PE80 or PE100 gas pipe durability as measured by rheology, OIT (oxygen induction time), elongation at break or SCGR.[49] SCGR and thermal stability are two important long-term properties that ensure a long design life.

Another study of 80% hydrogen and 20% natural gas in the PolHYtube [50] [51] project showed no significant changes in tested chemical or mechanical properties including: OIT, modulus, elongation at break, and SCGR for PE100 or PA11 after more than 3 years of exposure to hydrogen at 10 bar (145 psi). In another study, tests on PE80 and PE100 from different production years (new and used) showed no change in OIT, modulus, elongation at break, and SCGR.[52]

Several studies have looked at the possible effects of aging on the material's ability to resist degradation. For example, in research by THyGA, "PE was found to have no corrosion issues and no deterioration or aging was observed after long-term testing in hydrogen gas".[53] Additionally, Klopffer et.al. (2010) concluded that after long-term aging (up to 13 months), at a range of pressures and temperatures, no deleterious effects on the mechanical properties of PE were indicated.[54]

2.5 Polyamides (PA) Compatibility with Hydrogen Blends

Polyamide piping materials used in gas distribution include PA11 and PA12. PA11 gas piping is designed and produced to meet the standards of ASTM F2945.[55] PA12 gas piping is designed and produced to meet the standards of ASTM F2785.[56] PA11 and PA12 produced after January 22, 2019, are permitted by 49 CFR Part 192.121 for use in gas distribution systems up to 6 inches in diameter and operating pressure up to 250 psig. PPI TR 19-2020 indicates that PA11 and PA12 are resistant to hydrogen gas up to 194°F.[57]

Klopffer et.al. (2010) concluded that tensile properties are not affected by hydrogen diffusion into PE or PA, even up to 100 bars (1,450 psig), and "the same conclusion stands for the aspects of the mechanical behavior investigated here, *i.e.*, tension, creep and ductile fracture, in both as received and aged materials."[58]

While no specific studies referenced include PA12, it is anticipated that PA12 will perform similarly to PA11 pipe. In a presentation on PA12 titled "Gas Pressure Piping Systems – Transport of Hydrogen in Natural Gas Infrastructure", Evonik[59] notes that PA-U12 resistance to hydrogen is demonstrated by PA-U11.[60]

2.6 Effects of Hydrogen Blends on PVC

PVC is no longer widely used in gas distribution. According to PHMSA data, less than 10,000 miles of mains remain in service.[61] However, it is still important to address all system components and materials to the extent possible. PPI TR 19-2020 indicates that PVC is resistant to hydrogen gas up to 140°F.[62]

Table 2, below, provides a summary of the effects of various gas components on the plastic materials in Dutch distribution grid(s). This study of a variety of materials, including PVC and PE, showed no effect from integration of hydrogen blends of up to 20%.

	Components containing sulphur	H_2S	Mercaptans	Odorant	Ammonia	Components containing chlorine	Components containing fluorine	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
PVC	none (up to 160 ppm)		probably none		None			probably none		unknown	none	none, unless liquid		none	none (up to 20 mol%)
PE	none (up to 160 ppm)		probably none		None			probably none		unknown	none	none, unless liquid		none	none (up to 20 mol%)
POM	none (up to 160 ppm)		probably none		None			water	unknown		none	probably none			none
N BR	none (up to 160 ppm)		probably none		None			probably none		none		none, unless liquid		none	
SBR	none (up to 160 ppm)		probably none		None			probably none		none		none, unless liquid		none	

legend

	=	The effect is not known, but is expected to be very small or non-existent.
	=	This component in wide-band gas has no effect on materials.
	=	The effect is not known.
	=	Deleterious effects are to be expected in some conditions.

Table 2: Results of Experiments from Hermkens et al. [63]

2.7 Permeability of Natural Gas - Hydrogen Blends

Corrosionpedia (www.corrosionpedia.com) defines permeation as "the rate of molecular diffusion of gases, vapors, and fluids through a solid material membrane." Permeation is often raised as a concern with respect to transporting hydrogen through plastic pipes. As hydrogen is a much smaller molecule than methane, it is logical to assume the permeation rate will be higher. Although permeation is also expected to occur through elastomer seals and joint connections, the larger surface area of pipes means the majority of gas losses will likely occur through pipe walls rather than seals and connections.

Permeability is the product of diffusivity and solubility. "There are several factors that affect the permeability of polymers to hydrogen including crystallinity, chain orientation, fillers, and side chain complexity".[64]

These properties impact the free volume space available for molecular diffusion. PE is a semicrystalline polymer made up of highly ordered crystalline regions and loosely entangled amorphous regions. Crystallinity is strongly related to the density of the PE. The higher the crystallinity, the higher the density. It has been shown that as crystallinity (or density) increases, the permeability to hydrogen and other gases decreases.[65] Klopffer et.al (2007) found that the permeation products of sorption and diffusion took place exclusively in the amorphous regions. No permeation occurs through the crystalline regions.[66]

The transport of a gas molecule through a polymer is a complex process. See Appendix A-1 for a more detailed discussion on this process in PE, PA, and PVC pipes.

Testing has shown that with new plastic piping, hydrogen concentrations of up to 20% through polyethylene pipe can result in a 1.5 to 2.0 times increase in permeation versus methane alone. Hermkens et.al. (2018) calculated a permeation coefficient of 126.8 $ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$ for hydrogen, compared to 56 $ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$ for methane in PE pipes.[67] As Hermkens et. al. relates, "opinion is that the risks are comparable, due to the limited difference in the permeation coefficient and the differences in physical behavior of hydrogen in air compared to methane".[68] It should be noted that permeation, unlike a point source such as a leak, is the result of a slow loss of product through the wall of the pipe over a large surface area. Therefore, the safety risk of permeated hydrogen-methane gas blends, a flammable mixture, should be similar to that of methane alone. The potential risk associated with the accumulation of gas in a confined space should always be assessed. At concentrations above

20% hydrogen, the losses increased. GTI in their 2010 report to NREL calculated permeation with a 20% hydrogen blend and noted the following:[69]

- 20% hydrogen blend within the approximately 415,000 miles of PE pipe would result in the loss of ~43 million ft^3/ year (loss consisting of 60% hydrogen and 40% natural gas).
- This estimate is almost twice the total gas loss for systems delivering natural gas only; however, it is still considered to be economically insignificant (approximately 0.0002% of the natural gas consumed).

A recent Columbia University report noted that according to Mejia, A.H., et.al. (2020), "hydrogen was thought to leak from plastic pipelines more readily than natural gas through permeation. However, recent research has shown those leak rates may be similar to natural gas".[70]

Due to the differing energy properties of hydrogen and methane, the actual energy loss is reduced although emissions increase. In an April 2021 white paper "HDPE Pipe is Hydrogen Ready" [71], Dr. Jeroen Wassenaar and Dr. Predrag Micic noted that "energy losses through hydrogen permeation are 30% lower for hydrogen compared to natural gas at equivalent network pressure" (see Figure 1 below).

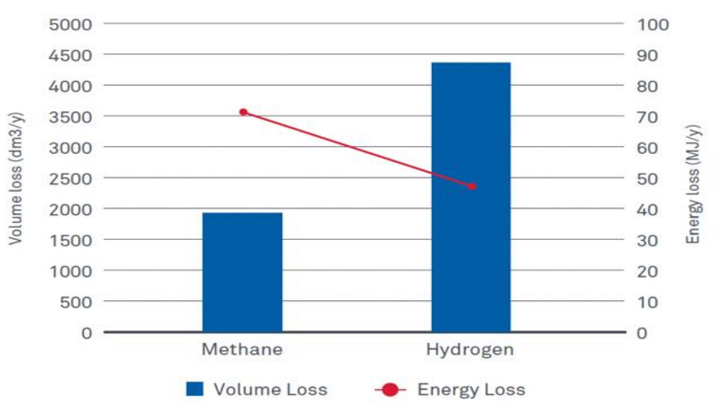

Figure 1: Volume and Energy Loss Per Year Through Permeation for a 1km Long DN90mm SDR11 Pipeline Operated at 2 bar (29 psig) Transporting Either Methane (Natural Gas) or Hydrogen at Room Temperature. [72]

The following tables from the GTI 2010 report to NREL[73] are included to provide additional background on material permeation and potential gas losses.[74] Table 3, below, provides the permeation coefficient and calculated gas loss through a PE80 pipe at a range of pressures for pure methane and methane plus 10% hydrogen blend. It should be noted that the total methane loss for pure methane compared to the total methane loss with a 10% hydrogen blend was nearly double at the 58 psig test pressure indicating that hydrogen may suppress some methane losses. Other findings from Table 3 include:

- The hydrogen permeation coefficient is four or five times higher than that of methane.[75]
- The permeation rate of methane and hydrogen increases with pressure.
- The aging of pipelines has no apparent significant effect on permeation coefficients

Gas	Pressure (psig)	Time-Lag (day)		Permeation Coefficient ($\times 10^{-3}$ ft^3-mil/ft^2/day/psig)		Gas Loss (ft^3/mile/year)		
		CH_4	H_2	CH_4	H_2	CH_4	H_2	Total
Pure CH_4	58	6.46	NA	0.18	0	54.07	NA	54.07
90% CH_4 + 10% H_2	58	4.31	0	0.09	0.34	25.90	10.59	36.49
	116	6.39	0	0.12	0.50	67.03	31.04	98.07
	174	5.69	0	0.12	0.52	101.91	48.54	150.45

Note:
*: The original data in this table are from the experimental test results in the paper of "Evaluation of the Permeability to CH_4 and H_2 of PE Currently Used in Gas Distribution Networks" [18], and are converted to the English unit.

Table 3: The Permeation Coefficient and the Calculated Gas Loss from a 32 mm (1.26") PE80 Pipe Under the Pressure of (58 psig (4 bar), 116 psig (8 Bar) and 174 psig (12 Bar).* [76]

Table 4 provides the experimental and literature permeation coefficients for a range of materials.

Material	Hydrogen	Methane
MDPE (PE2708) [a]	1.43	0.29
HDPE (PE3608) [a]	1.09	0.16
HDPE (PE4710) [a]	1.09	0.16
PVC [a]	0.95	NA
Natural Rubber [b]	28.39	NA
Butyl Rubber [b]	4.27	NA
Buna S (SBR) [b]	23.02	NA
Neoprene (CR) [b]	7.67	NA
Buna N (NBR) [b]	9.12	NA

Note:
a: Data are from "AGA Handbook: Plastic Pipe Manual for Gas Service" [29]
b: Data are from EIA report "Hydrogen Transportation Pipeline" [13]

Table 4: Permeation Coefficient (10^3xft^3-mil/ft/day/psig) of Hydrogen in Plastic Pipe and Elastomer Materials. [77]

Table 5, below, shows the calculated gas loss rate through HDPE pipe at a range of pressures and hydrogen contents. The 100% hydrogen gas loss rate in U.S.-grade plastic pipes is five or six times higher than that of 100% methane.[78]

Hydrogen Content	At 60 psig			At 3 psig			At 0.25 psig		
	H_2	CH_4	Total	H_2	CH_4	Total	H_2	CH_4	Total
0%	0.0	49.4	49.4	0.0	2.5	2.5	0.0	0.2	0.2
10%	32.9	44.5	77.4	1.6	2.2	3.9	0.1	0.2	0.3
20%	65.9	39.5	105.4	3.3	2.0	5.3	0.3	0.2	0.4
50%	164.7	24.7	189.4	8.2	1.2	9.5	0.7	0.1	0.8
100%	329.3	0.0	329.3	16.5	0.0	16.5	1.4	0.0	1.4

Note: The calculation was performed by GTI.

*: The data in this table are calculated by Equation (2) using the permeation coefficient data in Table 16 from "AGA Handbook: Plastic Pipe Manual for Gas Service" [29].

Table 5: The Calculated Gas Loss (ft^3/mile/year) Based on Literature Data for HDPE Pipes at the Operating Pressures of 60 psig, 3 psig and 0.25 psig.* [79]

In the 2010 GTI report to NREL, it was noted that aging of pipe does not appear to have an impact on permeation.[80]

Note: Although studies of permeation through PE polymers have not indicated that age of the material is a driving force, pressure or temperature changes can impact permeation rates. It has been found that permeation follows an "Arrhenius"[81] relationship with temperature, meaning that the permeation rate increases exponentially with temperature. [82]

Permeation studies that included polyamide show that PA11 is less permeable to hydrogen than PE. PA11 and PA12 do have lower permeation coefficients than polyethylene. Hermkens et.al. (2018) reports that hydrogen permeation for PE100 is 1.5 times greater than permeation for PA12.[83]

2.8 Impact of Hydrogen/NG Blends on Joining Methods and Squeeze Off

The ability to repair sections of plastic piping is critical to the maintenance of the natural gas distribution network. Isolation techniques such as squeeze off are routinely used to reduce or stop the flow of gas to allow for repairs. Heat fusion or electrofusion joins new sections of pipe to existing piping. These are proven practices used in natural gas distribution but require further examination in hydrogen blended transport.

During the development of this white paper, no studies were identified that reviewed the potential effects of hydrogen on the ability to heat fuse (*i.e.*, butt fusion, saddle fusion, or socket fusion) PE or PA. However, based on a review of available studies analyzing the impacts of hydrogen on electrofusion, it is not expected that hydrogen will impact the ability of a polymer to be effectively joined by heat fusion. For example, a white paper by Dr. Jeroen Wassenaar and Dr. Predrag Micic (Qenos) found no detrimental effect of hydrogen on the ability of HDPE piping to be repaired using electrofusion.[84]

Additionally, Hermkens et.al (2018) noted that permeation testing demonstrated that the pipe wall is almost saturated with hydrogen after 1,000 hours.[85] Despite this, it “did not result in visible voids or mechanical weak spots in the fusion zone. The temperature during jointing was higher than the melting temperature of PE. This may have led to depletion of the dissolved hydrogen during the jointing process".[86]

Finally, in the 2019 UK Hydrogen Deployment Project (HyDeploy), piping samples were soaked in pure hydrogen for 6 weeks and then squeezed off. This was followed by hydrostatic testing one and six weeks after.[87] The pipes passed both hydrostatic tests indicating that exposure to hydrogen did not compromise the pipeline's integrity.

2.9 Mechanical Joining

Please refer to Section 4: Valves, Connections and Fitting Materials.

2.10 PE/PA Valves and Elastomer Sealing Materials

Please refer to Section 4: Valves, Connections and Fitting Materials.

2.11 Summary of PE and PA Piping Materials

A review of existing research has not identified any short or long-term compatibility issues with the use of existing gas distribution system materials including PE, PA, or PVC with hydrogen blends up to 20% or higher. Studies have clearly demonstrated the ability of hydrogen molecules to migrate through PE or PA pipe walls. Although calculated and empirical permeation rates indicate that hydrogen has a higher rate of permeation through polymers than methane, the currently available scientific literature indicates that hydrogen blend rates up to 20% have losses that are negligible in terms of economics, safety[88], and environmental concerns. There is considerable ongoing research that should provide additional data regarding the performance of PE and PA pipes in hydrogen blended systems. See Appendices A.1 and A.2 for further reading and sources on this information.[89]

3. Steel Systems

While distribution steel pipe mileage has decreased[90] from approximately 45% in 2010 to 38% in 2021[91] it is still a major material and component in gas distribution systems. According to the DOT 2021 Gas Distribution Annual Report, there are more than 514,000 miles of steel main and more than 193,000 miles of service piping (representing > 14 million services)[92]. However, steel pipes and components are the primary material used in gas transmission systems. Steel pipe accounted for over 99% of transmission pipe material in 2021. In 2021, the US had over 300,000 miles of steel transmission pipelines. Approximately 70% of the transmission pipelines were installed before 1980.

The steel systems section of this white paper will provide a high-level overview of the possible effects of hydrogen damage and its effect on steel properties.

3.1 Hydrogen and Steel Pipelines, Global Perspective

Hydrogen has been produced, transported, and stored in steel for many hundreds of years. These pipelines have been designed and built following hydrogen-specific codes[93]. These codes are more prescriptive regarding allowable loading (static and dynamic) than their natural gas equivalents. The [hydrogen] pipelines are typically manufactured from lower-strength steel, but their existence proves it can transport gaseous hydrogen through pipelines.[94]

There are over 2,823 miles of hydrogen pipelines in the world. Approximately 1,621 miles, or 57%, of hydrogen pipelines are in the United States (US).[95] The US produces approximately 700 billion cubic feet per year[96]. Approximately 87% of the onshore hydrogen pipelines are operated below 50% Specific Minimum Yield Stress (SMYS). No reported hydrogen pipelines are operated at 70% (SMYS) or greater. Over ninety-nine percent (99%) of all hydrogen pipelines are nominal pipe size (NPS) 20 or smaller, with 324 miles of all hydrogen pipelines being nominal pipe size (NPS) 10. Ninety-four percent (94%) of all hydrogen lines were constructed from 1970 to the current day, with the largest mileage built from 1990-1999 (489 miles) and from 2010-2019 (418 miles).[97]

3.2 Hydrogen Damage [98]

The mechanism(s) and extents of hydrogen damage remain an open question. According to N. Gallon et al., the consensus shows that most damage mechanisms involve hydrogen concentrations in metallic lattice regions of high stress (like crack tips). Additionally, hydrogen concentration is greatest where direct dissociation from gaseous external hydrogen may occur (N. Gallon et al.). As discussed in the sections below, the dissociation of gaseous hydrogen leads to several effects.

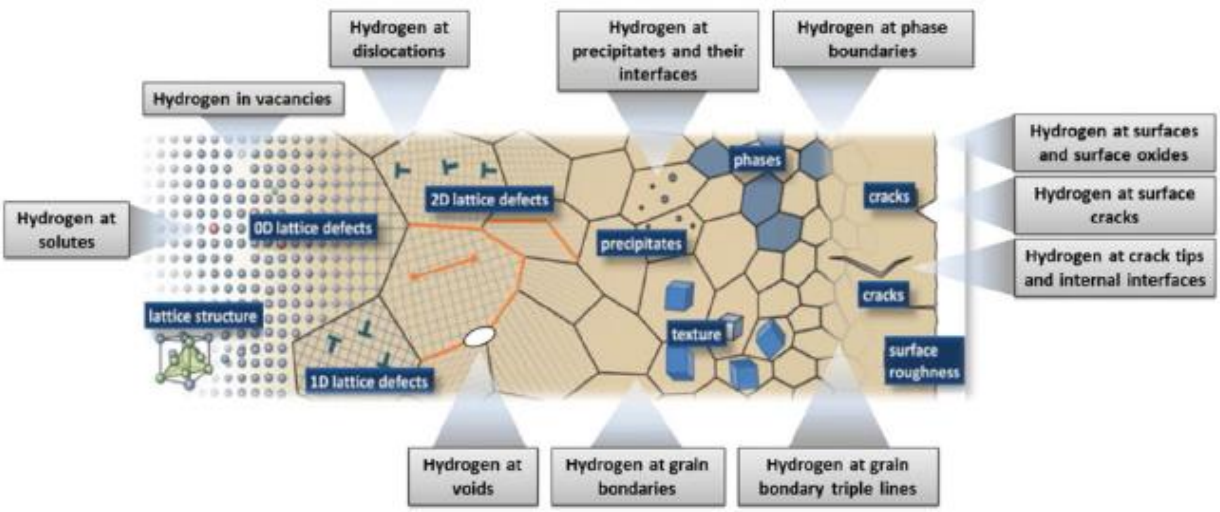

Figure 2: Schematic Showing Possible Hydrogen Traps from Koyama et al.[99]

3.3 Effects on Steel Properties

Gaseous hydrogen appears to have three main effects: an increase in fatigue crack growth rate, a decrease in fracture toughness, and a decrease in ductility (N. Gallon et al.). As stated by N. Gallon et al., the magnitude of these effects appears to differ depending on the material differences, hydrogen purity, or testing methods used, as seen in various reports.[100]

3.4 Fatigue Crack Growth Rate[101]

N. Gallon et al. notes that even at low concentrations of hydrogen, fatigue crack growth rates can increase significantly. Reports also indicate that at low partial pressures of hydrogen, there can be a substantial increase in the rate of crack growth. However, as the concentration of hydrogen increases, the fatigue crack growth rate also increases. The extent of this increase is influenced by various other factors.[102]

ASME B31.12 regulates the impact of hydrogen in steel by recommending lower strength steels in the non-mandatory Annex A. ASME B31.12 PL-3.7.1(b)(2)(-a)(-4) provides a formula for calculating FCGR for higher-grade steels. Fatigue performance is not as predictable and is reduced in both ferritic and austenitic steels and low and high strength steels (N. Gallon et al.). The findings of the N. Gallon et al. report is listed below.[103]

- The rate at which a crack propagates in hydrogen is influenced by the magnitude of the stress intensity factor (ΔK), which represents the driving force for crack growth. In general, crack growth rates in hydrogen are higher than in air for a given ΔK value. However, the acceleration is more pronounced at higher ΔK values, meaning that the effect of hydrogen on crack growth is more significant when the crack is subjected to higher stress levels.
- The presence of hydrogen gas, even at relatively low pressures, can lead to an acceleration of crack growth. As the hydrogen partial pressure increases, the resistance to crack growth decreases, resulting in faster crack propagation. Even at a hydrogen pressure as low as 0.2 MPa (29 psi), crack growth acceleration can be observed.
- The loading frequency refers to how frequently the load is applied and removed during cyclic loading. In hydrogen environments, the acceleration of crack growth rates becomes more prominent as the loading frequency decreases. This means that crack growth in hydrogen is more pronounced under slow cycling or static loading conditions.
- The stress ratio (R) is the ratio of minimum applied stress to the maximum applied stress during cyclic loading. Similar to crack growth in air, crack growth rates in hydrogen also increase with increasing stress ratio. However, the acceleration of crack growth is more noticeable at lower stress ratios, indicating that hydrogen has a more significant effect on crack growth under conditions where the minimum stress is closer to zero.
- The influence of material strength on Fatigue Crack Growth Rate (FCGR) in hydrogen environments is still a topic of ongoing research and study. The relationship between material strength and crack growth rates in hydrogen is not yet conclusively understood and may vary depending on the specific materials and testing conditions.
- The addition of certain inhibitor additives, such as oxygen (O2) and carbon monoxide (CO), has been found to significantly reduce the detrimental effects of hydrogen embrittlement (HE) and

the associated crack growth rates in hydrogen environments. These additives act as protective agents, mitigating the impact of hydrogen on the material's mechanical properties and reducing the likelihood of crack propagation.

The most recent edition of the American Society of Mechanical Engineers, ASME B31.12, includes a formula for calculating FCGR. The formula derived an upper bound FCGR from work looking at X52 and X70 steels in 5.5 MPa (797 psi) gaseous hydrogen.

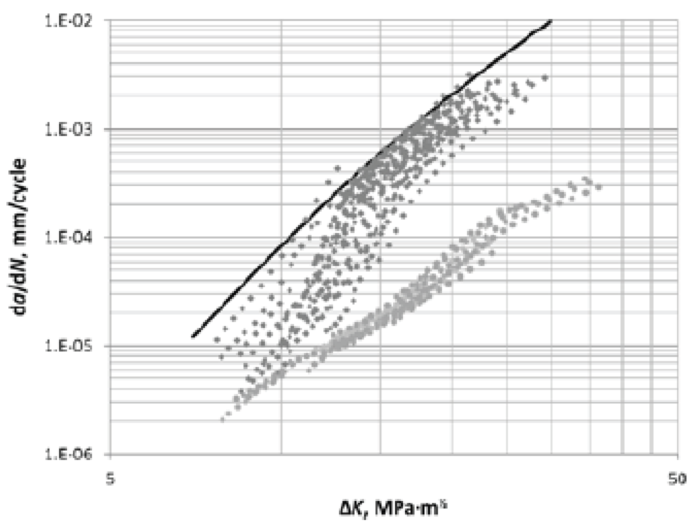

Figure 3: FCGR of API X70 Pipeline Steels in Pressurized Hydrogen Gas Compared with X52 Pipeline in Hydrogen Service.[104]

Note: (Black Solid line being the upper bound limit, the grey circles being data in air and grey diamonds is Hydrogen).

Three low-carbon, micro-alloyed steels chemical compositions are found in Table 6.

Element	C	Mn	P	S	Si	Cu
X52	0.071	1.06	0.012	0.004	0.24	0.016
X70A	0.048	1.43	0.009	0.001	0.17	0.220
X70B	0.053	1.53	0.01	0.001	0.16	0.250

	Ni	Cr	Mo	V	Nb	Ti	Al
X52	0.016	0.033	0.003	0.004	0.026	0.038	0.017
X70A	0.14	0.240	0.005	0.004	0.054	0.027	0.015
X70B	0.14	0.230	0.003	0.004	0.054	0.024	0.012

Table 6: Chemical Composition in Mass Percent of Steels Tested. The Balance is Fe.[105]

3.5 Girth Welds and HAZ

Outside of third party damage, flaws are the most likely source for initiation of cracks in a weld due to large residual stresses. These stresses are usually due to larger surface roughness than the base metal and may have defects such as regions of low cohesive strength (lack-of-fusion), porosity, and inclusions. "For this reason, the fatigue properties of the welds, as well as those of the base metal, must be characterized. There is relatively little known about the FCGR of pipeline weld materials and their associated heat-affected zones (HAZs) in the presence of hydrogen, and even less is known about them in pressurized hydrogen gas".[106]

3.6 Steel Chemistry (ASME) Requirements and Recommendations[107]

Currently, there are two design methods that can be considered in conjunction with steel/piping specifications (i.e., API 5L PSL2[108]) and acceptable manufacturing routes for welded pipes (HFW, SAWL, or SAWH).[109]

> The first ([Figure 4], Option A) is prescriptive and similar to design processes contained in ASME B31.8 Natural Gas Pipeline Code. It considers the use of lower basic design factors, F, and a material performance derating factor, Hf, derived from pressure and tensile strength relationships. The second ([Figure 4], Option B) is performance based, using a fracture mechanics approach (on the basis of ASME Section VIII, Div. 3 – Alternative rules for construction of High Pressure Vessels). The qualification of the pipeline materials is performed by use of fracture mechanics and crack propagation testing that empowers the use of enhanced design factors and withdraws the limitations on pressure due to the use of the Hf derating factor.[110]

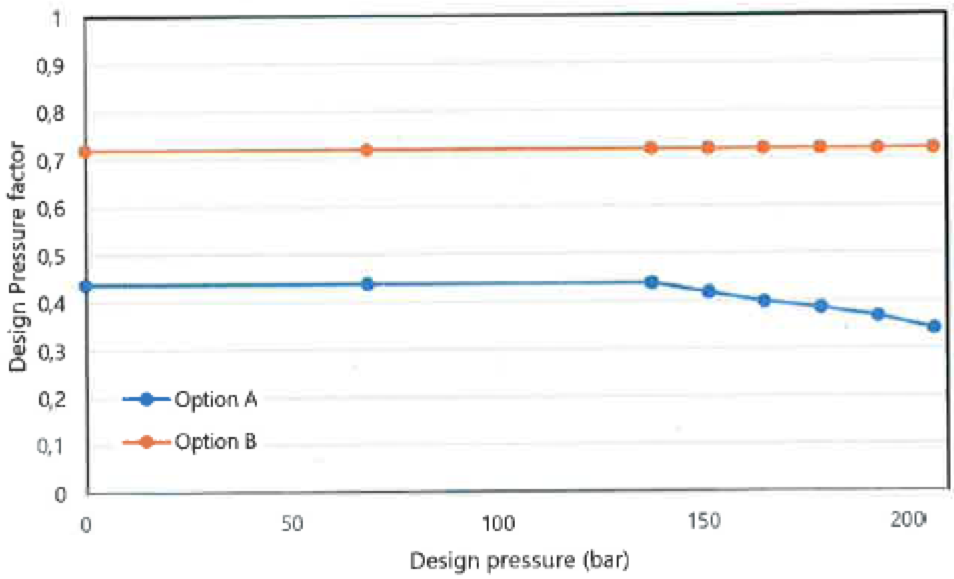

Figure 4: Design Pressure Factors for X60M for Option B vs Option A in Areas Characterized as Class Location 1, Division 2.[111]

In terms of pipeline design for hydrogen transportation, Figure 4 shows why adhering to ASME B31.12 Option B can have a substantial impact. According to A.S. Tazedakis et al., the data in Figure 4 shows that the design factor for Option B for API X60m grade pipe is up to 72% of the specified yield strength for all relevant pressures up to 20.7 MPa (3000 psi). Conversely, Option A's design factor is restricted to a maximum yield strength percentage of 43.7% or less, owing to the material performance (Hf) factor's additional restrictions when the design pressure nears 3000 psi (20.7 MPa).[112] ASME B31.12 Option B & Appendix G; Steel chemistry requirements and recommendations are as listed below:

- Desired microstructure of polygonal and acicular ferrite.
- Thermo-Mechanically Controlled Processed (TMCP) made steel is recommended.
- Phosphorus content ≤ 0.015% wt.
- Recommended carbon content ≤ 0.07% wt.
- Recommended carbon equivalent (Pcm) X52-X60 ≤ 0.15% wt, X65-X80 ≤ 0.17% wt.
- Maximum UTS 110ksi (758 MPa).
- Nb (Niobium) micro alloyed steel is recommended.

3.7 Fracture Toughness[113]

As noted by N. Gallon et al., (although there is some disparity in the reports), it seems widely agreed upon that fracture toughness decreases significantly when measured using stress intensity factor or Crack Tip Opening Displacement (CTOD). However, fracture toughness and Charpy impact energy, which are reasonable in natural gas or air, may not be applicable for service in hydrogen. Several factors, including the hydrogen partial pressure, strain rate, and steel, appear to be related to these variations.

N. Gallon et al. notes fracture toughness values below 50 ksi.in$^{1/2}$ (55 MPa.m1/2) in hydrogen. This value serves as a default minimum threshold in ASME B31.12 for preventing hydrogen-assisted cracking in Option B designs. The resistance of materials to hydrogen-induced cracking varies depending on the pipeline material type and the hydrogen concentration level. This is relevant when converting existing pipelines, but there is reason to believe that the small-scale tests in the laboratory may be overly conservative (N. Gallon et al.). Given the complexity of this subject, some key papers are summarized in Appendix B.

3.8 Strength and Ductility

According to N. Gallon et al., it seems that hydrogen can cause a reduction in ductility, ranging from 20% to 80%, depending on the material and test method employed. The impact on uniform elongation is uncertain; there is no significant effect on the strength, including yield strength and tensile strength.[114]

3.9 Hydrogen Cracking

According to N. Gallon et al., "there does not appear to be any risk of direct hydrogen cracking (HIC) under normal gaseous transportation conditions, although there is a theoretical risk associated with hard spots or welds".[115] Most existing codes have severe restrictions on allowable hardness. The derivation of these limits is unclear. It is probable that these limits are over-conservative. However, work is required to validate this hypothesis. ASME B31.12 and the "AIGA / EIGA guidelines restrict the permissible hardness of welds as shown"[116] in Table 7.

Code	Material	Maximum Permissible Hardness
AIGA / EIGA Hydrogen Pipeline Systems (14)	Steels (Parent and Welds)	22 HRC / 250 HB / 248 HV
	Microalloyed Steels (Parent and Welds)	95 HRB
ASME B31.12:2014 (15)	PWHT Carbon Steel	200 HV
	PWHT Alloy Steels Cr =< 2%	225 HV
	PWHT Alloy Steels 2 ¼ % =< Cr =<10%	241 HV
	Production Testing	237 HB
ASME B31.12:2019	Carbon Steel	235 HV10
	Alloy Steels Cr =< 2%	235 HV10
	Alloy Steels 2 ¼ % < Cr =< 10%	248 HV10

Table 7: Hardness Limitations in Hydrogen Pipeline Codes.[117]

3.10 Maximum Allowable Hydrogen Content

There is much discord about the maximum allowable hydrogen percentages in pipelines. However, there is no clear consensus. According to N. Gallon et al., most guidelines allow for a 10-20% maximum hydrogen blend volume. Other sources note allowable hydrogen concentrations of up to 100%, while others indicate an impact at <2% hydrogen. Current codes permit up to 100% hydrogen but can be restrictive in conversions. Fatigue loading and low toughness in the material are two areas of concern for limitations (N. Gallon et al.). For more information, refer to N. Gallon et al. in the Endnotes. [118]

Publication	Maximum Hydrogen Percentage	Comments
European Commission JRC Final Report (17)	Up to 10% v/v	10% limit based on current consensus, some areas need further investigation
HSE Report (18)	Up to 20% v/v	Vulnerable appliances to be identified and modified for hydrogen levels >10%
NREL Report (19)	Up to 15% v/v	Appears to be feasible with very few modifications to existing pipeline systems or end-use appliances
CEN / ISO Draft Roadmap (20)	Up to 100% v/v	Allowable hydrogen content is dependent on the partial H2 pressure and the fatigue load. If fatigue cycling can be controlled, "*100% hydrogen gas up to the design pressure can be transported in existing natural gas pipelines without affecting the integrity of the pipeline during its lifetime*"
ASME B31.12 (3)	Up to 100% v/v	Guidelines for conversion of pipelines to hydrogen service are included in section PL-3.21 although these are relatively high level and restrictive, and not particularly useable for existing gas pipelines.
AIGA / EIGA Guidelines (14)	Up to 100% v/v	Guidelines for conversion of pipelines to hydrogen service are included in Appendix H. These have similar restrictions to ASME B31.12.

Table 8: Maximum Allowable Hydrogen Content.[119]

4. Valves, Connections and Fitting Materials

Natural gas distribution systems have been built up through the progressive expansion of piping networks over many years. During this time frame, the technology, manufacturing techniques, and materials used in pipeline construction have evolved and improved. Consequently, most gas systems are built from various components that can span the lifetime of each gas system's operations.

Natural gas distribution systems include a wide variety of ancillary components, including mechanical fittings, bolted flanges, threaded connections, valves, and other devices. Many historic valves and fittings are complex assemblies with multiple moving parts and sealing elements made of a variety of different materials. Some primary resources for guidance on hydrogen piping are ASME B31.12 and EIGA (European Industrial Gasses Association) IGC Doc 121. These are design standards for building hydrogen piping infrastructure systems. For example, ASME B31.12 and EIGA IGC Doc121 are written as guidance for the construction of new dedicated, high pressure hydrogen pipe systems rather than a blended methane and hydrogen system. However, the information in these standards is helpful when making decisions about adapting existing pipelines for blended service. Since even an ideal connection may be a potential leak source, both the ASME and EIGA standards recommend minimizing the number of joints as much as possible and welding as many joints as practical.

This section covers the compatibility of non-pipe materials including valves, bolted connections, and fittings including subcomponents and sealing element materials.

4.1 Flanges and Threaded Connections

Pipeline systems consist of different pipes, fittings, and equipment which need to be joined together. Two of the common means of pipe joining are threaded and bolted flange connections.

Flange and threaded pipe joints are means of connecting pipes, valves, and fittings into a piping system. They are used when disassembly for maintenance is desired. A flange joint is made by bolting two flanges together with a gasket in between to provide the seal. A threaded joint typically consists of a pipe segment with external threads connected to a fitting with internal threads.

Pipe connections that are two inches or smaller in nominal pipe size are commonly joined with National Pipe Taper (NPT) threads, typically manufactured with dimensions and tolerances as specified in ASME B1.20.1.[120] Field threading of pipe segments is also a common practice. Thread quality may vary and may affect the ability of threads to form a seal. Threaded connections are a common leak source in the gas distribution system, and the addition of hydrogen, with its smaller molecular size, may increase the potential for leakage. Several hydrogen blending studies and resources, which mention threaded connections in the context of hydrogen compatibility, anecdotally call out a leakage rate of two to four times as much hydrogen as methane through the same joint. In addition, NPT connections used in the gas industry rely on a wide variety of thread sealants. Thread sealants lubricate the mating threads, allowing the surfaces to slide against one another during assembly so that the joint can be fully assembled. Sealants also fill in the small imperfections in the interacting threads, minimizing the leak path. Thread sealants should be tested and assessed for compatibility with hydrogen. Additional investigation may be needed to understand the impact on overall system leak rates that might be anticipated after the introduction of hydrogen.

Two-inch nominal pipe size and larger piping and components found at meter sets, regulator stations, and other facilities are often joined by flanged connections. Flanges are typically made with dimensions and tolerances as specified by ASME B16.5[121] or ASME B16.42.[122] Recommendations for flange designs in hydrogen systems vary. The EIGA IGC Doc 121 is concerned with leaks and resulting fires when flanges are used. EIGA recommends that flanges be of a leak-resistant style (raised face, tongue and groove, or ring joint). The gasket material should be hydrogen compatible, and fire resistance is recommended. Spiral wound steel gaskets are generally preferred, with composite graphite gaskets acceptable at lower pressures. EIGA also recommends adding a flange cover for all installations. ASME B31.12 suggests that full-face gaskets with flat faced flanges might be the better solution.

Gasket design varies by sealing materials. For example, some gaskets are made of compressed fibers with a binder, such as aramid fibers with Buna-N binder. The gaskets are sealed by compressing the entire gasket surface between the flange faces. Other gasket designs have a non-compressible gasket body with a smaller compressible elastomer seal set in a groove within the gasket (for example, fiberglass gasket body with a Viton sealing ring). Another common type uses flexible spiral wound steel sealing elements packed with a secondary material such as graphite or Teflon. The sealing element is constrained within steel inner and outer rings. With the large variety of gasket designs and sealing materials, further testing and research into current and historic gasket materials may help inform which existing pipeline system joints might need to be mitigated to prepare for introducing hydrogen into a natural gas distribution system.

4.2 Elastomer Sealing Materials

Many fittings and gas system components are designed using elastomer sealing elements such as O-rings, gaskets, diaphragms, gasket seal rings, and valve seals or stem packing. For some natural gas equipment, such as meters and regulators, these same elastomeric materials are used for large scale components such as diaphragms, seats, and other elements which depend on the materials to maintain flexibility and other key properties in order to function correctly (refer to Section 5, Meters and Regulators, Table 12, Meter & Regulator Components). For example, in joints where elastomeric sealing elements are used, the integrity of the joint depends on a variety of factors such as the condition and design of the surrounding components (O-ring grooves, mating surfaces, flanges, threads, compression nuts, etc.). However, the joint may still leak due to changes over time in the properties of polymer sealing materials. Issues associated with elastomers may include:

- Permeation – Gasses, when pressurized, tend to diffuse into adjacent elastomer materials.
- Material Breakdown – The most extreme case of seal failure would be a breakdown of the seal material itself.
- Property Changes – Elastomers can exhibit changes in properties based on environment and chemical interaction. Even when the reaction does not deteriorate the sealing material, the effects on the material properties can still compromise the seal.

4.3 Gas Loss through Permeation

Permeation is the absorption of a liquid or gas into a solid material. Elastomers are especially susceptible to this effect because there is significant extra space within the polymer matrix for small gas molecules to occupy. Additionally, since hydrogen is a small molecule, hydrogen is more likely to diffuse into the polymer material than many other gases, including methane.

Polymer materials are susceptible to the loss of small amounts of the gas mixture through direct diffusion of the molecules of one or more of the component gases. This occurs through the polymer material and out to the surrounding atmosphere. The amount of product loss through diffusion depends on the temperature, the pressure of the product, and the fractional composition of the gas mixture.[123] Since the diffusion process across a polymer membrane or seal happens one molecule at a time, the rate of gas loss is relatively low compared to other failure modes. Thus, there is minimal public safety risk associated with this issue. See Table 9 for coefficients of hydrogen permeation through various elastomer materials.

Material	Permeability coefficient, 10^{-9}, mol H_2/m*s*MPa	Diffusivity coefficient, 10^{-10}, m^2/s	Solubility coefficient, 10^{-9}, mol H_2/m^3*MPa
Buna-N	5.1	4.2	12
Viton® A	3.5	1.9	19
EPDM	17	5	33
Nylon (PA11)	0.4	0.65	6.2
Teflon	3.2	-	-
HDPE (reference)	0.82	1.9	4.3

Table 9: Permeability Coefficients for Hydrogen.[124]

Nylon (PA11) has the lowest permeability to H2 compared to the other elastomers. EPDM is 42 times more permeable to H2 as Nylon, and three times as permeable to H2 as Buna N.

4.4 Swelling and Bubbling from Gas Permeation

Once gases diffuse into a solid material, these molecules can collect in voids within the material and form small pockets of gas within the solid itself. Due to the elements of elastomer sealing interacting with devices, properties may change that could lead to a compromised seal. Changes in volume can cause the sealing element to deform and expand beyond its grooves or interfaces, leading to permanent seal deformation. These effects are exacerbated when the component is moved into a lower pressure environment. The bubbles of gas expand, potentially causing the elastomer components to suffer permanent impairment from small tears.

For larger polymer components such as meter or regulator diaphragms, changes in geometry may keep these flexible elements from being able to move as designed. These changes can thus impede the functionality of the equipment. Gas that has permeated into a complex multi-layered diaphragm type component may gather in large pockets of gas and lead to delamination of the part. On smaller elastomer components (such as O-rings), public safety risk related to swelling or bubbling appears to be low.

Experiments at Sandia National Laboratory exposed common elastomer sealing materials to high-pressure hydrogen combined with helium and argon, which would often be paired with hydrogen as inert purge gasses. After being exposed to pressurized hydrogen and inert gases, the parts were returned to atmospheric pressure and checked for increases in part volume. Note that this testing was on material samples only, without follow up testing on seal function after exposure.

Material	H2/He	H2/Ar
Buna-N	123%	174%
Viton® A	137%	134%
EPDM	Unk	102%
POM, Teflon®, Nylon (PA-11)	Unk	0%

Table 10: Swelling (% Volume Increase) after High-Pressure Gas Exposure and Depressurization.[125]

Buna-N and Viton® A, which are commonly used seal materials in the natural gas pipeline industry, displayed a significant increase in overall volume. When researchers looked at the microstructure of these Buna-N and Viton parts after the experiment, there was evidence of voids from gas pockets and micro-tears in the material, even after swelling had subsided. Other materials tested (ethylene propylene diene monomers (EPDM), polyoxymethylene (POM), Teflon®, Nylon 11) showed little to no swelling effects, indicating that these materials may be less susceptible to damage due to permeation. Note, EPDM is included because it was part of the Sandia study, however EPDM is not recommended for use with natural gas.[126]

4.5 Material Breakdown

If a seal material reacts chemically with one or more of the elements in the gas mixture, then the material can deteriorate until the sealing element breaks, cracks, or is pushed out of the way by the internal pipeline pressure. External operating conditions including temperature can also affect the rates of these chemical reactions. Reactive material breakdown is a progressive process, therefore seals with this failure mode have the possibility of holding pressure after initial installation. Reacting chemically and breaking down can then happen over time, with the potential of a significant gas release after degradation.

Elastomer sealing materials used in the pipeline industry have been chosen because they meet engineering requirements including resistance to reaction with chemicals in the petroleum products realm. Some materials, such as Viton®, are especially resistant to a chemical reaction. Designers may choose these materials to help minimize risk resulting from material breakdown, such as a heavily odorized environment, while maintaining required engineering performance.

In general, hydrogen is non-reactive with most polymers used for seal materials in natural gas distribution systems. This means that chemical alteration of the seal material is not a significant threat. Historically, hydrogen has been a significant part of the gas stream in systems where the original gas source was a "manufactured" or "town gas" source. These gas sources, which derived from gasification of coal, petroleum byproducts, or other materials often contained hydrogen gas as 10% or more of the product stream. Hawaii Gas has transported synthetic natural gas (SNG) containing hydrogen (12%) in their distribution network since the early 1970s with no reported negative interactions with sealing materials. Hawaii Gas uses gas distribution products common to other LDCs.

4.6 Property Changes

Changes in tensile strength, elasticity, and resilience, which do not result in the failure of sealing elements, may still lead to leakage through joints. Most joints that use elastomer seals depend on the seal to compress and fill the space between the rigid elements of the joint. Changes in properties can lead to leakage, especially when the joint's piping is subjected to outside loads.

Research on elastomer properties shows little evidence that the presence of pressurized, gaseous hydrogen leads to a decrease in tensile strength or other mechanical properties at pressures up to 1450 psig.[127] However, further testing at Sandia with high pressure hydrogen (often paired with inert purge gasses) on common elastomer sealing materials Viton® A, Buna N, and EPDM revealed that viscoelastic properties, including Storage Modulus and Loss Modulus, were affected. A practical measurement of the change in viscoelastic properties

is to measure increases in compression set behavior after gas exposure. Compression set is an effect where a material that has been subjected to a compressive load does not return to its uncompressed state – instead, the elastomer elements are permanently deformed. Most joints containing elastomer sealing elements (for example, O-rings) rely on the compressed elastomer to push out against mating parts in the assembly, filling in the space between metallic or hard plastic components. Elastomers experiencing compression set harden into the compressed position, rendering the seal less effective. These compressions set seal effects may be overcome by ensuring sufficient compressive force during manufacture, assembly, or installation.

Material	H2/He	H2/Ar
Buna-N	9%	60%
Viton A	60%	428%
EPDM	Unk	20%

Table 11: Increase in Compression Set Compared to No High-Pressure Gas.[128]

There is evidence that elastomer sealing materials may be subject to degradation in a pressurized hydrogen environment, and more exploration of these effects is needed. Past research does not directly represent the operating environment that pipeline components in the natural gas transmission and distribution system would be subjected to. In 2021, NYSEARCH started a project involving experiments with elastomers in a mixed hydrogen and methane environment (see NYSEARCH Technology Brief "Hydrogen Blend Impact on Elastomer Materials). [129]

4.7 Valves

Valves are a critical component in any natural gas distribution system. Their fitness for service is critical to ensure safety for the infrastructure and the local communities. Due to the higher risk profile of hydrogen, fitness is even more important when hydrogen is blended into natural gas. "The risk analysis for valves used in hydrogen service is based on three primary factors: pressure, temperature, and concentration of hydrogen. In each instance, end users and manufacturers consider the most extreme conditions to which the valve could be subjected".[130]

Generally (in a distribution system with up to 10% hydrogen blended with natural gas), it is expected that existing valves would not need to be modified.[131] However, each facility owner/operator would need to complete a detailed site study to ensure the compatibility of all materials, including valves, with the hydrogen and natural gas blend. In addition, the detailed system study should document the changes required to re-balance the flow within the plant [piping system] to the properties of the new gas specification.[132]

The critical components for valve evaluation include but may not be limited to:

- Type and Design

- Materials Selection
- Sealant
- Test

Valve Type and Design:

- In case of low pressure and low percentage of hydrogen, a welded body with minimal welds may be preferable to a bolted body because it minimizes the potential leak paths.[133] On the other hand, in cases of high pressure and high concentration of hydrogen, weld areas could be affected by hydrogen. Therefore, valve manufacturer testing of body weld processes in hydrogen service may be warranted.

Materials Selection:

- Carbon steel seems acceptable in cases of low hydrogen percentage by volume pressure. However, for higher levels of hydrogen, austenitic stainless steel is preferable.[134] Cast materials should be avoided because of the risk of porosity and voids.
- Some valve designs include elastomer stem packing, polymer seats, and other internal components (see elastomer sealing section for more information). The EIGA report recommends using double seals or packing for hydrogen service valves in order to minimize leak risk.[135] Detailed design review of new and in-service valves and further testing may be needed to assess whether internal valve components may be affected by long-term hydrogen service.

Sealant:

- Further research is needed to assess the compatibility of sealant materials with hydrogen-natural gas blends.

Testing:

- There are limited internationally recognized standards regarding valve testing for hydrogen blended into natural gas. Further investigation may be needed by the gas industry and manufacturers.

- Common industry practice is to test valves per API 6D[136] requirements: hydrotest for shell and seats and supplemental gas test for the seats. This testing is primarily strength testing and not material compatibility.
- Some utilities recommend a design validation test for fugitive emissions[137] to minimize the risk of external leaks from the valve body. Because the helium molecule is very close in size to the hydrogen molecule, this is the media used to safely perform tests to simulate the operating conditions of a pure hydrogen service. An example of the test procedure is included in ISO EN 15484.[138]

Tensile testing showed limited material-related issues have been identified in a gas distribution network at operational pressure for natural gas containing up to 20% hydrogen.[139] The value of 20% for hydrogen concentration is also confirmed specifically for steel valves by a recent state-of-the-art analysis based on document and project reviews, interviews of operators and researchers, and more.[140] THyGa D2.4, which tested metallic materials for evidence of hydrogen embrittlement states that “a gas mixture composed of natural gas and up to 50% hydrogen should not be problematic for any of the metallic materials [including valves] employed in a gas distribution system, unless high mechanical stress/strain and high stress concentrations are applied”.[141] Note that several utilities have operated for decades with hydrogen blends in their pipelines (e.g., Hawaii Gas, 12% Hydrogen[142]; Singapore Gas Company (City Gas), 41 to 65% Hydrogen[143]; Hong Kong Gas, 46-52% Hydrogen[144]).

Like metallic valves, plastic valves are complex assemblies of sub-components. The outer shell and end connections of the valve are usually made of the same material as the piping system that they are designed to be installed with (for example, HDPE or MDPE). But shafts, operators, balls, and seals are often made from different polymer materials than the main body of the valve. See sections 4.2 to 4.5 for discussions of elastomeric sealing components, and section 2 for details of material considerations with PE and PA materials. Because polymer valves are made to both seal internal pressure and move during operation, there may also be grease or other lubricants applied during the assembly of the plastic valve. Unlike many metallic valves, valve designs do not usually allow an operator to disassemble a plastic valve in order to inspect internal components, replace seals, or to lubricate the assembly.

Little specific technical literature exists that addresses extensive tests of valves with hydrogen, and further studies and tests are recommended. Further research should seek to define the limitations in hydrogen concentration, pressure, and temperature for standard natural gas valves. Valve manufacturers have carefully chosen the combination of metallic components and polymers to provide long-term dependable service. But additional testing may be needed to ensure that introducing hydrogen into these complex assemblies does not cause an interaction that limits service life or increases leakage risk. Industry may be able to depend on manufacturers to lead testing their own products, but utilities will need to consider developing their own testing for valves currently in service.

4.8 Mechanical Fittings and Joints

Mechanical fittings have been widely used in natural gas systems as part of steel and plastic pipelines, both in historic pipeline construction and modern piping systems. Various fitting designs have been used, including bolted tapping tees, stab couplings, and nut follower couplings. Most mechanical fittings rely on elastomer seals that are compressed against the pipe wall. The integrity of joints that use compressed elastomer seals depends on the long-term resiliency of the elastomer material, as well as proper installation with adequate gasket compression. The sealing capability of the joint may be compromised by improper installation or by post construction movement of the fitting due to shifting backfill (in certain fitting designs). Elastomers are more permeable to hydrogen and may exhibit swelling or formation of voids after exposure to hydrogen gas, which could compromise seals in mechanical fittings (see the Elastomer Sealing Materials section for more details). It is worth noting that standard polyethylene heat fusion tees and electrofusion tees use elastomer O-rings or gaskets to seal their completion caps. There are mechanical fitting designs that do not use elastomers as part of their seal. Instead, the fittings depend on the deformation of the pipe and fitting materials to complete the connection, resulting in a simpler finished configuration.

The body of a mechanical fitting for steel pipe may be made of carbon steel, stainless steel, or cast iron. As discussed in the steel pipelines section, carbon and austenitic stainless steel perform well in the presence of hydrogen as long as the operating pressures and pipe wall stresses are low. Since mechanical fittings are typically suitable for lower pressure applications, hydrogen effects on metallic fitting components should be minimal.

Fittings for plastic pipe are often made of polymers like polyethylene, polyamide, or PVC. These fittings may contain metallic elements such as internal stiffeners or external completion rings in the assembly. Many of the polymers may be unique to older fitting models which are no longer in production, and some vintage fittings may have been manufactured by companies that no longer make components for the gas industry. Polymer materials used for mechanical fittings may need further study before operators begin introducing hydrogen into the gas stream.

With the vast variety of different fittings that have been manufactured and installed for the gas industry, each operator should evaluate their vintage materials records. It is important to determine the level of testing that is needed to evaluate potential hydrogen compatibility for fittings used within their system.

5. Meter and Regulator Components

Based on a review of existing literature and industry experience, hydrogen blended gas may affect meters and regulators in a natural gas system. This section focuses on material compatibility and safety related to hydrogen blending. While material compatibility and safety are the focus of this section, natural gas utilities should also consider the other effects hydrogen may have on meters and regulators, such as capacity, metrology, leakage, and gas ignition protection. The information on meters and regulators provided in this section is a compilation of research, references, and future projects.

5.1 Meters

Various studies identify ranges of hydrogen levels at which no significant material issues will occur in metering components. The acceptable ranges vary by study, but most indicate an upper limit of 10-20% hydrogen. Higher blends may be acceptable, but research data is currently unavailable for the effects on the material at these higher blends. A summary of the compiled data on metering is provided below. Table 12 lists commonly used meter components and their compatibility with hydrogen. Materials used for meter components were given the greatest consideration when evaluating compatibility with hydrogen blends. Measurement type (displacement, velocity, mass flow, etc.) is the largest factor in the metrology of hydrogen blends.

Energies, a European journal published by MDPI,[145] studied the effect of hydrogen blending on natural gas diaphragm meters. In performing durability tests on diaphragm meters up to 15% hydrogen, they found no damage that would compromise operational safety.[146] Marcogaz and the Pipeline Research Council International (PRCI) researched industry data for metering components and found similar results. Marcogaz indicates no significant issues for diaphragm, rotary, turbine, or ultrasonic meters up to 10% hydrogen. Higher blends did not have significant information or had conflicting references.[147] PRCI also indicates that metering components and materials can handle a 10% hydrogen blend, with higher blends not studied. PRCI also indicated that accuracy was minimally affected up to 5% hydrogen for diaphragm, rotary, turbine, ultrasonic, orifice, and Coriolis meters.[148] However, further study is recommended for fasteners, adhesives, and lubricants as they are expected to be negatively affected by hydrogen.[149] While the above statements generally hold true, manufacturers should be consulted when determining their equipment's feasible hydrogen blend limits. Several meter manufacturers have provided their customers with documents supporting the use of their meters with hydrogen blends up to a given amount.

Meter cases typically made from aluminum or carbon steel material are compatible with hydrogen (see Table 12 and footnotes). Other meter case materials, including cast iron and tin, should be used with caution as compatibility varies by source and by operating conditions. For example, ASME B31.12, which covers hydrogen blends at or above 10% and pressures up to 3,000 psig, recommends against cast iron use in hydrogen service and prohibits the use of cast or ductile iron in valves and flanges at blends of 10% and higher.[150] Other sources, like NREL, indicate little to no concern for using iron (including ductile and cast) materials for gas distribution.[151]

5.2 Regulators

Pressure regulator material compatibility is not widely discussed in the literature researched. As with meters, regulator components were reviewed and listed in Table 12 with their rated hydrogen compatibility.

Like meter manufacturers, some regulator manufacturers provide customers with acceptable hydrogen blend levels. Other manufacturers state that regulators are acceptable for any non-corrosive gas, indicating they are acceptable for blended hydrogen service. For example, Marcogaz indicates a 30% blend of hydrogen in pressure regulators is possible without significant issues.[152] Ductile and cast-iron bodied regulators should be evaluated based on operating conditions and used with caution due to the previous reference to ASME B31.12 for pipelines with 10-100% hydrogen blends and pressures up to 3,000 psig.

KIWA performed research and testing on a regulator station to determine the suitability of gas pressure regulating stations for hydrogen. This project utilized a regulator station with a capacity of 750 m3n/h (28,000 SCFH) natural gas and performed testing with a nominal inlet pressure of 8 bar (116 psi) and nominal outlet pressure of 100 mbar (1.5 psi). KIWA concludes: "[t]The tested gas pressure regulating station designed for natural gas can be used for hydrogen without modification. Note: This study's conclusion only concerns the technical functioning. No definitive statement can be made about long-term behavior."[153]

While hydrogen itself is not typically corrosive, it can cause issues such as embrittlement and hydrogen induced cracking in certain materials. Therefore, it's important to consider the materials and alloy compositions used in hydrogen-related applications.

Manufacturers often specify the testing performed and the materials used to ensure compatibility with hydrogen. They may have conducted extensive research and testing to determine the appropriate materials for their specific application. These specifications help ensure the safety and reliability of the components when exposed to hydrogen.

No significant compatibility issues with hydrogen blends were identified in sources referenced for this paper for the most used meter and regulator materials. However, the long-term effects of hydrogen on meters, regulators, and elastomeric components are not fully understood and need further investigation by the gas industry.[154]

METER & REGULATOR COMPONENTS	Rating	Source Count	Sources****
All Components			
Aluminum Alloys including Anodized Aluminum	A***	5	1,2,4,6,9
Gray Cast Iron	B	3	2,4,12
Carbon Steel	A**	6	1,4,9,6,7,12
Spring Steel	N/A		
Epoxy (adhesive)	A	2	4,11
Cork-neoprene Rubber(neoprene)	A	1	8
Neoprene	A	5	1,2,3,5,9
Buna N (Nitrile) Rubber	A	5	1,2,3,5,9
Natural Rubber	B	4	1,2,3,5
Nylon ®	A (up to 120F)	3	1,2,3
Nylon Fabric (diaphragm material)	N/A		
Polytetrafluoroethylene (PTFE)	A	5	1,2,3,4,9
FKM / Viton ®	A	6	1,2,3,4,5,9
Acetal / POM (gears)	N/A		
Austenitic (300 Series) Stainless Steel	A	4	1,2,6,9
Copper & Copper Alloys (Brass/Bronze)	A	5	1,2,4,6,9
Coatings and Chemical Plating	N/A		
Fiberglass reinforced Polyethylene	A	1	10
Zinc Alloy / Zamak	A	1	9
Phenolic Resin	N/A		
Lubricants / Grease	N/A		
Polypropylene	A	2	1,2
Solder	N/A		
*EPDM**	A	5	1,2,3,4,5
*SBR**	B	2	3,5
*Silicone Rubber**	C	3	1,2,5

A = Excellent, B = Good, C= Fair/Questionable, N/A = Information not Available+

Table 12: Meter & Regulator Components.

Table 12 Notes:

*These components are included in the table for reference but were not readily identified as currently used meter and regulator components in the lists provided for use by manufacturers.

**Carbon steels are generally considered compatible. Higher tensile strength steels can be susceptible to hydrogen embrittlement. Tensile strengths below 115 ksi and hardness below 22 HRC are recommended. Operating conditions of temperatures between –22F and 140F and pressures below 1450 psi are recommended.[1]. At higher pressures, additional safety factors should be considered. See ASME B31.12 for additional information and guidance in calculating this safety factor. See also the Steels Systems section of this paper.

***Aluminum alloys are considered generally safe with hydrogen blends in dry conditions, but not all effects are fully known.

While many elastomeric materials listed in this table are considered compatible with Hydrogen gas, not all long-term effects are fully known. For additional information regarding elastomeric materials in hydrogen blended pipelines, see the Valves, Connections, and Fitting Materials section.

Some sealing components, like pipe thread sealant, were not listed in the table, as only certain brands or formulations of the product are compatible with hydrogen blended natural gas. These components should be reviewed individually to determine compatibility.

AGA has not and is not evaluating meter components for compatibility with hydrogen. The literature is provided review only.

****- See Appendix C.1

There is considerable ongoing research that should provide additional data regarding the performance of meter and regulator components. See Appendix C.2 for further reading and sources on this information.

6. Pipeline Liners and Rehabilitation Products

6.1 Overview of Pipe Lining Systems

Cured-in-place pipe lining systems have been used to rehabilitate or extend the life of aging metallic natural gas pipelines. The liner can prevent leakage and provide reinforcement, though typically, the metallic pipe must still provide structural integrity, so the pipeline must not be excessively deteriorated for lining to be a viable option. The liner is installed by an inversion process, using pressurized air or water to drive the liner into the pipeline.

There are a limited number of manufacturers of lining systems for gas pipelines, most of them located outside the United States. Still, some pipeline operators within the United States have made use of these systems since the 1990s. While liners may be an effective and economical method for pipeline renewal under some conditions, lined pipelines represent a relatively small portion of gas distribution systems in the United States.

6.2 Pipe Lining Materials

A typical lining system consists of an elastomer skin that forms the inner surface of the lined pipeline and is directly exposed to the gas, a fabric jacket that provides mechanical strength, and an adhesive to bond the jacket to the inner wall of the metallic pipe being rehabilitated.

The elastomer skin is typically made of polyurethane or polyester. The fabric jacket is made of synthetic fiber, typically polyester. The adhesive is a two-part system consisting of an epoxy resin and a hardener.

Performance requirements for gas pipe lining systems are specified by ASTM F2207, *Standard Specification for Cured-in-Place Pipe Lining System for Rehabilitation of Metallic Gas Pipe*.[155] The specification addresses peeling strength, design pressure, workmanship, and quality control. It also requires testing for chemical compatibility with liquids that might be found within a gas pipeline (e.g., water, gas condensate, and mercaptans) but does not require any testing for compatibility with hydrogen.

6.3 Hydrogen Impacts

One manufacturer tested the hydrogen permeability of its pipe lining system. It found that the permeation rate for hydrogen, while much higher than for methane, was not excessive and would be acceptable for an 80% methane, 20% hydrogen blend.[156]

As noted above, lining systems are intended for use in only partially deteriorated metallic pipelines, as they rely on the metallic pipe for structural integrity. Before the liner is installed, leak routes through the metallic pipe should be limited to corrosion pits, bell-and-spigot or mechanical joints, cracks, etc., representing only a small fraction of the overall internal surface area of the pipe. Therefore, most of the installed liner is backed by the largely impermeable metallic pipe.

There are no apparent incompatibilities that would prevent the use of lined pipelines for transportation of a natural gas blend with up to 20% hydrogen. While hydrogen permeation would be higher than methane, it is not expected to be excessive. However, additional study is needed to understand the compatibility of pipe lining systems with hydrogen fully. In particular, the performance of the adhesive when permeated by hydrogen and subjected to changes in line pressure and temperature should be evaluated.

7. Conclusion

This white paper provides a literature review on the potential impact of blended hydrogen on the natural gas distribution system. Natural gas distribution systems have been built and expanded over decades. During this time frame, the technology, manufacturing techniques, and materials used in pipeline construction have evolved and improved. Consequently, most gas systems are built from various steel piping, polyethylene piping, and other components that span the lifetime of each natural gas system's operations.

The constituents of natural gas vary based on the source. Pipe materials in a natural gas system are exposed to different mixtures of gases including hydrogen blends when a “manufactured” or “town gas” source is utilized.

Gas Technology Institute (GTI) performed a quantitative risk assessment on US natural gas distribution systems for carrying natural gas containing hydrogen. The risks in natural gas distribution systems increase by adding hydrogen into the system. The assessment results indicate that the risks in distribution mains and service lines are different, especially at higher levels of hydrogen in the system. If less than 20% hydrogen is introduced into a distribution system, the overall risk is not significant for both distribution mains and service lines. However, the service lines are more impacted than mains because they are mostly in confined spaces. If the hydrogen level in natural gas increases beyond 20%, the overall risk in service lines can significantly increase and the potential hazards can become severe.[157] Conversely, the overall risk in distribution mains still can be moderate at up to 50% hydrogen. For hydrogen level above 50% in natural gas, the risks in both distribution mains and service lines significantly increase compared to natural gas, and the overall risk in distribution system becomes severe.[158]

With the variety of different pipes, fittings, elastomers, and materials manufactured and installed for the gas industry, each operator should evaluate their vintage materials records. In addition, operators should determine the level of testing needed to evaluate potential hydrogen compatibility for pipe, material, fittings, and elastomers used within their system.

The research and data discussed in this white paper indicate some level of acceptable blend rate of hydrogen, with many supporting the conclusion that blends of up to 20% hydrogen can safely be integrated into existing natural gas systems. Greater concentrations introduce additional challenges and may require modifications. Individual pipeline components should be identified in each blending scenario to determine their compatibility with hydrogen blending. Each system and set of components are unique such that care, and caution should be exercised when assessing the use and blend rate of hydrogen in the natural gas piping system.

Appendix A.1: Polyethylene and Polyamide Systems

Permeability of Natural Gas- Hydrogen Blends

The following papers provide a more detailed explanation of the process in PE, PA and PVC pipes:

Klopffer, M.H., Flaconneche, B., and Odru, P. (2007). *Transport properties of gas mixtures through polyethylene*. Plastics Rubber and Composites, Volume 36, No. 5.

Flaconneche, B., Martin, J. and Klopffer, M.H. (2001). *Permeability, diffusion and solubility of gases in polyethylene, polyamide 11 and poly(vinylidene fluoride)*. Oil & Gas Science and Technology, Vol. 56, No. 3, pp 261-278.

Barth, R.R., Simmons, K.L., and SanMarchi, C. (2013). Polymers for Hydrogen Infrastructure and Vehicle Fuel Systems: Applications, properties, and gap analysis. SANDIA Report SAN2013-8904, Sandia National Laboratory, Albuquerque, NM.

Summary for PE and PA Materials

Further reading/Other References:

A. H. Mejia, J. Brouwer, and M. M. Kinnon, "Hydrogen Leaks at the Same Rate as Natural Gas in Typical Low-Pressure Gas Infrastructure," *International Journal of Hydrogen Energy*, 45, no. 15 (2020): 8810–26, https://www.sciencedirect.com/science/article/pii/ S0360319919347275.

The EDGaR project (cite "http://www.edgar-program.com/themes/from-monogas-to-multigas," [Online]. [Accessed 21 June 2016].)

Hermkens, R., Bruin, J.D., Stok, E.V.D., and Weller, J. (2016). *Can PE and PVC gas distribution pipes withstand the Impact of sustainable gases?* Proceedings of the 18th Plastic Pipes Conference, Berlin, Germany.

Klopffer, M.H., Berne, P., Castagnet, S., Weber, M., Hochstetter, G., and Espuche, E. (2010). *Polymer Pipes for Distributing Mixtures of Hydrogen and Natural Gas: Evolution of their Transport and Mechanical Properties after an Ageing under a Hydrogen Environment*.

Melaina, M.W., Antonia, O., and Penev, M. (2010). Blending Hydrogen into natural gas pipeline networks: A review of key issues. NREL.

Iskov, H. and Kneck, S. (2017). *Using the natural Gas Network for Transporting Hydrogen – Ten Years Experience*. International Gas Union Research Conference Proceedings, Rio de Janeiro.

Hermkens, R., Colmer, H. and Ophoff, H.A., (2018). *Modern PE Pipe Enables the Transport of Hydrogen*, Proceedings of the 19th Plastic Pipe Conference PPXIX, Las Vegas.

GTI Project Number 21029 Final Report (2010). *Review of Studies of Hydrogen Use in Natural Gas Distribution Systems*. Prepared for National Renewable Energy Laboratory, Golden, CO.

Hydrogen in the Gas Distribution Network – A Kickstart project as an input into the development of a national hydrogen strategy for Australia.

Appendix A.2: A Summary of Select References and Findings

Document Title/ Reference	Content/ Major Findings
Hermkens, R., Bruin, J.D., Stok, E.V.D., and Weller, J. (2016). *Can PE and PVC gas distribution pipes withstand the Impact of sustainable gases?* Proceedings of the 18th Plastic Pipes Conference, Berlin, Germany.	Literature survey and extensive exposure tests to verify the effects of Environmental Stress Cracking (ESC) caused by renewable gases on rubber, PE, and PVC piping systems: • Tests performed: constant load, U-clamp, marbone clamp, ring over pipe. Conclusion: rubber, PE and PVC pipes can withstand the Impact of sustainable gases, including H_2 (up to 20%).
Hermkens, R., Colmer, H. and Ophoff, H.A., (2018). *Modern PE Pipe Enables the Transport of Hydrogen*, Proceedings of the 19th Plastic Pipe Conference PPXIX, Las Vegas.	Tests on PE100-RC (raised crack resistant PE) exposed to 100% H_2 for 1,000 hours at 2bar (29 psi – note: lower than typical pressure for PE materials in gas distribution, which is 80-125/145psi): • Chemical resistance of PE to H2: no change in weight and no impact on yield strength → from a material integrity perspective no negative effects are found. • Permeation rate of H2 through PE: permeation of H2 is higher than the one of methane, however, risks are comparable. • Electrofusion of PE pipes exposed to H2: electrofusion procedure was followed with no issues. No voids nor mechanical weak spots were found in the fusion zone. Conclusion: PE pipes permit the transport and distribution of H_2 in a safe and reliable way.
Iskov, H. and Kneck, S. (2017). *Using the natural Gas Network for Transporting Hydrogen – Ten Years' Experience*. International Gas Union Research Conference Proceedings, Rio de Janeiro.	• No influence on the basic structure on the pipes measured with rheology according to ASTM 4440-95a. • No influence on additivation/oxidative strength on the pipes was measured with oxygen induction time (OIT) according to EN 728. • No influence on the pipes was measured as elongation at break and tensile modulus according to ISO 527. • No influence on the slow crack growth properties measured as CTL at 5 MPa/60 C according to ISO6252-1992 / ASTM1473 F. • 4 years (PE80) and 10 years (PE100) of continuous hydrogen exposure and subsequent laboratory tests based on international standards indicate no influence on PE80 or PE100 natural gas pipes' durability.

Transport of Hydrogen with Polyethylene Natural Gas Pipes	Test on PE80 and PE100 piping systems of different production years, new and pre-used: • No change in Oxygen Induction Time. • No change in modulus and elongation at break. • No change in slow crack growth resistance. Conclusion: no evidence has been found of any reaction or degradation of the mechanical properties of the PE pipes by coming into contact with 100% H_2.
Isaac, T. (2019). *HyDeploy: The UK's first hydrogen blending deployment project*. Clean Energy, Vol. 3, No. 2, p114-125.	Tests with 20 mol% Hydrogen on piping materials to verify: • No Hydrogen absorption or no impact of absorption. • No noticeable effects on the tensile properties of materials resulting from exposure to H2 blends at operational pressure. • Electrofusion and squeeze-off testing on PE pipes showed that H2 exposure did not compromise the integrity of the pipeline to be isolated and sequentially returned to service.
Blanchard, L. and Briottet, L. (2020). *Non-combustion related Impact of hydrogen admixture – material compatibility*. Prepared for Testing Hydrogen admixture for Gas Applications (THyGA) Project. Grenoble, France.	Literature review: • PE is found to have no corrosion issues and no deterioration or ageing was observed after long-term testing in hydrogen gas. • Hydrogen leaks 2.5x quicker than methane. Helium is often used instead of H2 for tests. Because of this, it is recommended that welding over threaded connections should always be used when applicable. • Permeability of H2 is insignificant in metals but it is more relevant in PE. However, in the operation conditions the Impact can be considered negligible.
GTI Project Number 21029 Final Report (2010). *Review of Studies of Hydrogen Use in Natural Gas Distribution Systems*. Prepared for National Renewable Energy Laboratory, Golden, CO.	GTI Subcontract Report to NREL – Literature Review • In the investigation of PE pipelines used for hydrogen service, no degradation has been reported. Little or no interaction between hydrogen gas and PE should be expected. Hydrogen alone does not provide radicals that can cause polymer breakdown. • Aging of PE pipe materials was tested with laboratory samples, and it was concluded that aging effect of hydrogen on PE pipe materials is not significant. • There is no major concern on hydrogen aging effect on PE or PVC pipe materials • The permeation rates for hydrogen are about 4 to 5 times faster than for methane in typical polymer pipes used in distribution system. • A study completed shows that for new plastic piping with hydrogen concentrations up to 20%,

	the losses are about 1.5-2.0 times that of methane; the report concluded that economically this was insignificant. Hydrogen concentrations of over 20% start to exhibit noticeable losses • The permeation rate of methane and hydrogen increases with internal pressure • The aging of the pipes seems to have no significant influence on the permeation coefficients in experimental conditions ○
Klopffer, M.H., Berne, P., Castagnet, S., Weber, M., Hochstetter, G., and Espuche, E. (2010). *Polymer Pipes for Distributing Mixtures of Hydrogen and Natural Gas: Evolution of their Transport and Mechanical Properties after an Ageing under a Hydrogen Environment*.	• It can be reasonably concluded that tensile properties are not affected by H2 diffusion into PE, even up to 100 bars. The same result stands for PA11 materials, for which the room temperature scatter appears of first importance compared to a possible hydrogen effect. • Static properties (modulus and yield stress) obviously depend on the nature of constitutive materials, but no more hydrogen effect is observed. The same conclusion stands for the creep behavior of as-received PE and PA11. Creep tests performed at different temperatures show that the time-temperature superposition principle can be applied with similar shift factors, both in ambient air and pressurized hydrogen. In the same way, • hydrogen environment was shown to have no noticeable effect on the ductile fracture of as received PE and PA11, as estimated from a short series of tensile tests in double-notched samples. • After long-term aging up to 13 months in hydrogen atmosphere at various pressures (5 or 20bars) and temperatures (20°C, 50°C and 80°C) ranging below and above the glass transition of PA11 and the alpha-c transition for PE, no deleterious effect was observed on the mechanical properties of PE and PA11.

Table A1: Select References

Appendix B: Hydrogen Fracture Toughness Sources[159]

Title	Reference	Summary	Major Findings
Technical Reference on Hydrogen Compatibility of Materials – Plain Carbon Ferritic Steels: C-Mn Alloys (Sandia Report)	(5)	Comprehensive 2012 summary of available fracture toughness data. Compilation of various historic test results with different test protocols, materials, hydrogen concentrations etc.	Text concludes that "At a constant pressure of 6.9 MPa, the fracture toughness is degraded by as much as 50% in hydrogen gas", various data presented in tables reflects degradation of between 13 and 69%, reflecting the difficulties in quantifying different effects.
Integrity Management for Pipelines Transporting Hydrogen – Natural Gas Mixtures (Muller-Syring on behalf of NATURALHY)	(6)	2009 summary of NATURALHY findings. No details given about test protocols or materials (nominal grade only).	Cracks are identified as the most critical defects in the presence of hydrogen. Drop of 49% in fracture toughness for X52 (150 to 76 MPa.m$^{1/2}$) and 63% for X70 (120 to MPa.m$^{1/2}$) when comparing 60 bar hydrogen to nitrogen. The impact of pure hydrogen on critical initial crack depth is significant (up to 62% smaller for the examples presented) but reduced for smaller hydrogen partial pressures.
Hydrogen Effect on Fatigue and Fracture of Pipe Steels (Capelle et al., NATURALHY work)	(7)	Summary of work performed during NATURALHY looking at electrolytically charged X52, X70 and X100 material. Compact Tension (CT) tests performed, actual hydrogen concentration was not reported. Some fatigue tests also reported as part of this paper.	Relatively small effect (<10%) of hydrogen on $K_{I,i}$ but larger (up to ~44%) effect on δ_i. Effect is reported to be higher for X52 than for stronger steels. This is attributed to the fact that the X52 was 1960's construction with presumably lower quality standards than modern steels, but no details are given.
Sensitivity of pipelines with steel	(8)	NATURALHY paper demonstrating the	Time dependence of local hydrogen

Title	Reference	Summary	Major Findings
API X52 to hydrogen embrittlement (Capelle et al., NATURALHY work)		importance of hydrogen concentration (and hence time) on "fracture toughness". "Roman tile" electrolytically charged tests used. Full scale burst tests also reported.	concentration and "fracture toughness" is measured and quantified. Up to ~65% reduction in total work of local fracture emanating from a notch.
Influence of hydrogen and oxygen impurity content in a natural gas / hydrogen blend on the toughness of an API X70 Steel – Briottet et al.	(9)	Toughness measured as CTOD per ISO 12135:2002 (10) on CT specimens of X70 steels. Testing performed in-situ with various different concentrations of hydrogen and oxygen.	Large decreases in δ for small additions of hydrogen (0.85 bar). Significant mitigating effects for small (100 ppm) additions of oxygen. Different fracture morphologies noted under nitrogen, hydrogen and with small oxygen additions.
Effects of purity and pressure on the hydrogen embrittlement of steels and other metallic materials – Barthelemy	(11)	Literature survey reporting various publicly available test data. Test data reported for wedge opening load and compact tension specimens.	Decreases in both threshold stress intensity factor and fracture toughness with increasing hydrogen pressure. Magnitude of the decrease depends on various factors including steel microstructure.
Full-scale burst test of hydrogen gas X65 pipeline – Aihara et al.	(12)	Report into full scale burst test and small scale hydrogen embrittlement / fracture mechanics tests (3PB pre-charged specimens, J-integral resistance curves constructed). Test was performed on modern high-toughness line pipe.	Crack arrest occurred after a short propagation in the burst test. Simulations predicted the arrest distance to be shorter than for methane gas, and no clear influence on the slope of the dynamic J resistance curve of hydrogen.
Durability of Steels for Transmission Pipes with Hydrogen - NATURALHY	(13)	Extensive testing performed on varying materials of different grades and vintages using both gaseous hydrogen and electrolytically charged samples, and investigating the role of oxygen.	Fracture toughness decreases with increasing hydrogen partial pressure, but amount of decrease is relatively small and low levels of oxygen additions counteract this effect. Up to 25% v/v hydrogen the effect is not considered significant.

Appendix C.1: Meter & Regulator Components – Compatibility Sources

1. *Chemical Compatibility Database from Cole-Parmer*. (2019). Coleparmer.com. https://www.coleparmer.com/Chemical-Resistance

2. *Chemical Compatibility Chart*. (n.d.). Retrieved November 10, 2021, from https://marketing.industrialspec.com/acton/attachment/30397/f-0004/1/-/-/-/-/chemical-compatibility-chart-from-ism.pdf

3. *Chemical Guides Introduction*. (n.d.). Retrieved November 10, 2021, from https://promo.parker.com/parkerimages/promosite/Safehose/UNITED%20STATES/downloads/Industria Hose_Chemical_Resistance_Guide.pdf

4. *Chemical Resistance Chart*. (n.d.). Retrieved November 10, 2021, from https://littlegiant.com/media/151566/995516_Chemical-Res-Chart_09-12.pdf

5. *Compatibility Chart Chemical Natural Rubber*. (n.d.). Retrieved November 10, 2021, from https://rubber-group.com/wp-content/uploads/2018/01/Chemical-Compatibility.pdf

6. *Standard for Hydrogen Piping Systems at User Locations*. (n.d.). http://www.asiaiga.org/uploaded_docs/AIGA%20087_14_Standard%20for%20Hydrogen%20Piping%20Systems%20at%20User%20Location.pdf

7. American Gas Association, material committee. (2021, November 10). *7. ASME B31.12 -Hydrogen Piping and Pipelines* [Review of *7. ASME B31.12 -Hydrogen Piping and Pipelines*].

8. American Gas Association, material committee. (2021, November 10). *Itron* [discussion *Itron*].

9. 423, G. (n.d.). *Section G -Technical Data*. Retrieved November 10, 2021, from https://www.ualberta.ca/chemistry/media-library/safety/gasmaterialcompatability.pdf

10. Rawls, G., Ronevich, J., & Slifka, A. (2017). *Lowering Costs of Hydrogen Pipelines through Use of Fiber Reinforced Polymers and Modern Steels Fuel Cell Technologies Office Webinar*. https://www.energy.gov/sites/default/files/2017/09/f37/fcto_webinarslides_lowering_costs_h2_pipelines_097217.pdf

11. Phenolic/Epoxies Chemical Resistance Data (n.d.) Retrieved November 10, 2021, from http://k-mac-plastics.net/data/chemical/phenolic-chemical-.htm

12. Melaina, M.W., Antonia, O., Penev, M. (2013) Blending Hydrogen in Natural Gas Pipeline Networks: A Review of Key Issues. United States. https://doi.org/10.2172/1219920

Appendix C.2: Meter and Regulator Components: Further Reading

Other studies involving meters, regulators, or their components that are in process:

DOE H-Mat Project: https://www.energy.gov/eere/fuelcells/h-mat-hydrogen-materials-consortium

Hydrogen Impacts Study: https://www.cert.ucr.edu/hydrogen-impacts-study

HyBlend Project lead by NREL (all piping materials): https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines

NewGasMet: www.newgasmet.eu (meters only, of all technologies)

NYSearch – Elastomer Testing: https://www.nysearch.org/tech-brief_5_05-2021.php

Endnotes

[1] AGA, Net Zero Opportunities for Gas Utilities, https://www.aga.org/wp-content/uploads/2022/02/aga-netzero-emissions-onepager.pdf
[2] Hawai'i Gas website, https://www.hawaiigas.com/clean-energy/decarbonization
[3] GPA Engineering for the Government of South Australian in partnership with Future Fuels CRC on behalf of the COAG Energy Council (2019). Hydrogen in the gas distribution networks.
[4] Percentage (%) in the paper refers to the percent (%) Volume.
[5] Constituents vary in both manufactured and natural gas daily. Each utility's responsibility is to analyze its gas blend for use in the distribution system.
[6] Prepared Direct Testimony of Kevin Woo, David McQuilling, and Kevin Lang on Behalf of Southern California Gas Company, Pacific Gas and Electric, and Southwest Gas Corporation, before the Public Utilities Commission of the State of California
[7] Austin Glover, Jeffrey Mohr, Austin Baird (Sand Report 2021). Code and Standards Assessment for Hydrogen Blends into the Natural Gas Infrastructure
[8] Austin Glover et al., supra
[9] Examples of codes include American Society of Mechanical Engineers, ASME B31.12, Hydrogen Piping and Pipelines, EIGA (European Industrial Gasses Association) Hydrogen Pipeline Systems, IGC Doc 121
[10] Austin Glover et al., supra
[11] Austin Glover et al., supra
[12] See section 2.7 for a detailed discussion on permeation.
[13] GTI, Project Number 21029 Final Report (2010), Review of Studies of Hydrogen Use in Natural Gas Distribution Systems. Prepared for the National Renewable Energy Laboratory (NREL), Golden Co
[14] See Appendix A.1 and A.2
[15] See Table 8- Maximum Allowable Hydrogen Content (Various Sources)
[16] See Tables 9 (Permeability Coefficients for Hydrogen) and Table 12 Meter & Regulator Components,
[17] See Section 5 Meter and Regulator Components
[18] Based on correspondence- Honeywell, Dresser Measurement, Emerson Pressure Management
[19] Muller-Syring, Gert. Marcogaz Technical Association of the European Natural Gas Industry. Hydrogen admission into the existing natural gas infrastructure and end use. Presentation 11-7-2012.
[20] Table 12 and footnotes
[21] ASME B31.12 Hydrogen Piping and Pipelines (2019)
[22] GTI, Project Number 21029 Final Report (2010), supra
[23] Kiwa Technology. Management Summary - Gas pressure regulating station operating on hydrogen. July 2021
[24] Line pipe refers to a lining system consisting of an elastomer skin that forms the inner surface of the lined pipeline and is directly exposed to the gas.
[25] AGA Net-Zero Emissions Opportunities for Gas Utilities
[26] PHMSA, 03/21/2023
[27] ibid
[28] Polyamide 12, PA12 is a specialty type nylon high-performance polymer with outstanding mechanical strength, chemical stability, and durability.
[29] PHMSA 49 CFR Part 192.121
[30] Rheological is a branch of physics, and it is the science that deals with the deformation and flow of materials, both solids, and liquids
[31] PPI TR-19 2020 "Chemical Resistance of Plastic Piping Materials, https://plasticpipe.org/PPI-Home/ALL-PPI-PUB/Technical-Reports.aspx
[32] PPI TR-19 2020, supra
[33] ASTM D2513 -Standard Specification for Polyethylene (PE) Gas Pressure Pipe, Tubing, and Fittings
[34] GTI, Project Number 21029 Final Report (2010), supra
[35] PPI TR-19 2020, supra,

[36] See Appendix A
[37] Hermkens et.al (2018). Modern PE Enables the Transport of Hydrogen, Proceedings of the 19th Plastic Pipe Conference PPIX, Las Vegas
[38] Hermkens et.al (2018), supra
[39] Hawai'i Gas website, supra
[40] Hong Kong Gas website, https://www.towngas.com/en/About-Us/Hong-Kong-Gas-Business/Gas-Production
[41] GPA Engineering for the Government of South Australian in partnership with Future Fuels CRC on behalf of the COAG Energy Council (2019). Hydrogen in the gas distribution networks.) The network is currently being converted to natural gas)
[42] Klopffer, M.H., Berne, P., Castagnet, S., Weber, M., Hochstetter, G., and Espuche, E. (2010). Polymer Pipes for Distributing Mixtures of Hydrogen and Natural Gas: Evolution of their Transport and Mechanical Properties after an Ageing under a Hydrogen Environment
[43] Klopffer, supra
[44] RC stands for resistance to cracks.
[45] Hermkens et.al (2018), supra
[46] Hermkens et.al (2018), supra
[47] Iskov, H. and Kneck, S. (2017). Using the Natural Gas Network for Transporting Hydrogen – Ten Years' Experience. International Gas Union Research Conference Proceedings, Rio de Janeiro.
[48] ibid
[49] ibid
[50] PolHYtube-French National Agency of Research project, Development and study of innovating materials for hydrogen distribution networks
[51] Klopffer, supra
[52] Iskov, H. and Kneck, S. (2017). supra
[53] Lisa Blanchard. Laurent Briolet, June 2020 THyGa, Testing admixture for Gas Applications, Non-combustion related impact of hydrogen admixture- material compatibility
[54] Klopffer, supra
[55] ASTM F2945, Standard Specification for Polyamide 11 Gas Pressure pip, Tubing, and Fittings.
[56] ASTM F2785, Standard Specification for Polyamide 12 Gas Pressure Pipe, Tubing, and Fittings.
[57] PPI TR-19, 2020, supra
[58] Klopffer, supra
[59] Gas Pressure Piping Systems – Transport of Hydrogen in Natural Gas Infrastructure" Evonik
[60] PA11 and PA12 for gas distribution pipe are unplasticized. The use of PA11/PA-U11 and PA12/PA-U12 are equivalent.
[61] PHMSA, 03/21/2023
[62] PPI TR-19 2020, supra
[63] Hermkens, R., Bruin, J.D., Stok, E.V.D., and Weller, J. (2016). Can PE and PVC gas distribution pipes withstand the impact of sustainable gases? Proceedings of the 18th Plastic Pipes Conference, Berlin, Germany
[64] Kane, M.C., 2008. Permeability, Solubility, and interaction of Hydrogen in Polymers- An assessment of materials for hydrogen transport (Rapport technique No. WSRC-STI-2008-00009). Savannah River National Laboratory, Aiken, SC 29808.
[65] Kane, M.C., 2008.supra.
[66] Klopffer, M.H., Flaconneche, B., and Odru, P. (2007). Transport properties of gas mixtures through polyethylene. Plastics Rubber and Composites, Volume 36, No. 5.
[67] Hermkens, supra
[68] Hermkens, supra
[69] GTI, Project Number 21029 Final Report (2010), supra
[70] Columbia, SIPA, Center on Global Energy Policy, "Investing in the US Natural Gas Pipeline System to Support Newt-Zero Targets, Erin M. Blanton, Dr. Melissa C. Lott and Kirsten Nicole Smith"
[71] Dr. Jeroen Wassenaar, and Dr. Predrag Micic, "HDPE Pipe is Hydrogen Ready", White paper, April 2020
[72] Dr. Jeroen Wassenaar, and Dr. Predrag Micic, supra

[73] GTI, Project Number 21029 Final Report (2010), supra
[74] Information is derived from the NaturalHY Project performed by Gaz de France.
[75] There is disagreement concerning the permeation coefficient. Hermkins, 2018 Modern PE Enables the Transport of Hydrogen, Proceedings of the 19th Plastic Pipe Conference PPIX, Las Vegas measured a different permeation coefficient.
[76] GTI, Project Number 21029 Final Report (2010), supra
[77] ibid
[78] ibid
[79] ibid
[80] ibid
[81] The Arrhenius relationship is one of the most satisfactorily and widely used models in accelerated testing when the accelerating variable is temperature
[82] Klopffer, M.H., Berne, P., Castagnet, S., Weber, M., Hochstetter, G., and Espuche, E. (2010). Polymer Pipes for Distributing Mixtures of Hydrogen and Natural Gas: Evolution of their Transport and Mechanical Properties after an Ageing under a Hydrogen Environment
[83] Gas Pressure Piping Systems – Transport of Hydrogen in Natural Gas Infrastructure" Evonik
[84] Dr. Jeroen Wassenaar, supra
[85] Hermkens, supra
[86] ibid
[87] Tommy Isaac (2019). HyDeploy: The UK's first Hydrogen blending deployment project.
[88] Similar to the transport of natural gas (i.e., methane), there are safety concerns related to the transport of hydrogen blends when plastic piping is run through confined, unvented spaces due to elevated explosive risk.
[89] See Appendix A for additional detail.
[90] Percent of type of material compared to all pipe materials. Actual steel main (2010 Steel Main – 556,241 miles; 2021 Steel Main 514,392 miles)
[91] PHMSA website, 3/21/2022
[92] US DOT Pipeline and Hazardous Materials Safety Administration Website 3/21/2022
[93] American Society of Mechanical Engineers, ASME B31.12, Hydrogen Piping and Pipelines
[94] N. Gallon, R.M. Rosen, O.J.C Huising, Pipeline Technology Conference 2021 Berlin, Hydrogen Pipelines – Hydrogen Pipelines, Design and Materials Challenges and Mitigations
[95] API, Technical – API Standards & Hydrogen Infrastructure presentation, February 2022, H2 Hydrogen Tool , N. Gallon, R.M. Rosen, O.J.C Huising, Pipeline Technology Conference 2021 Berlin, Hydrogen Pipelines – Hydrogen Pipelines, Design and Materials Challenges and Mitigations, Home | Hydrogen Tools (h2tools.org); Hydrogen Pipelines | Hydrogen Tools (h2tools.org), 2016 spreadsheet
[96] ibid
[97] ibid
[98] N. Gallon et al., supra
[99] ibid
[100] ibid
[101] ibid
[102] ibid
[103] ibid
[104] Fatigue Crack Growth Rates of API X70 Pipeline Steels in Pressurized Hydrogen Gas Compared with an X52 Pipeline in Hydrogen Service. Drexler, E.S., et al.
[105] ibid
[106] E.S. Drexler, supra
[107]. A.S. Tazedakis, N. Voudouris, E. Dourdounis, G. Mannucci, L.F. Vito, A. Fonzo. World Pipelines April 2021, A Bright Future, A Need for Hydrogen
[108] Product Standards Level (PSL).
[109] High-Frequency Welding (HFW), Longitudinal Submerged Arc-Welding (SAWL)
[110] A.S. Tazedakis, supra

[111] S. Tazedakis, supra
[112] A.S. Tazedakis, supra
[113] N. Gallon et al., supra
[114] ibid
[115] ibid
[116] ibid
[117] ibid
[118] ibid
[119] Various Sources are Noted in Table
[120] American Society of Mechanical Engineers, ASME B1.20.1, Pipe Threads, General Purpose, Inch
[121] American Society of Mechanical Engineers ASME B16.5, Pipe Flanges & Flanged Fittings
[122] American Society of Mechanical Engineers ASME B16.42, Ductile Iron Pipe Flanges and Flanged Fittings, Classes 150 and 300
[123] R. R Barth, K.L. Simmons,C.San Marchi, Sandia Report 2013-8904 (2013). Polymers for Hydrogen Infrastructure and Vehicle Fuel Systems
[124] C. Menon et al., Polymer Behavior in High Pressure Hydrogen, Helium, and Argon Environments as Applicable to the Hydrogen Infrastructure, Abstract Sand 2017-841
[125] C. Menon, supra
[126] Parker O-Ring Handbook, https://www.parker.com/Literature/O-Ring%20Division%20Literature/ORD%205700.pdf
[127] R.R Barth, supra
[128] N.C. Menon, supra
[129] https://www.nysearch.org/tech-brief_9_12-2022.php
[130] AM-12-50 (2012). Recommended Practice for Valves Used in Hydrogen Service, presented at AFPM Annual Meeting.
[131] See Appendix A and Table 8.
[132] GPA Engineering for the Government of South Australian in partnership with Future Fuels CRC on behalf of the COAG Energy Council (2019). Hydrogen in the gas distribution networks.
[133] Summary of Broen Valves, Broen Valve Technologies
[134] Lisa Blanchard and Laurent Briottet (2020). THyGA supra
[135] EIGA IGC Doc 121, supra
[136] American Petroleum Institute (API), Specification for Pipeline and Piping Valves
[137] Fugitive emissions are the unintentional and undesirable leakage, or discharge of gases from such valves, flanges, pipelines, compressors, etc.
[138] International Standards Organization, European Standards 15484, Ethanol as a blending component for petrol.
[139] Tommy Isaac (2019). HyDeploy: The UK's first Hydrogen blending deployment project.
[140] Domptail, Frey, Hildebrandt, Hill, Maunder, Taylor, & Win. Pipeline Research Council International, Inc. Catalog No. PR-720-20603-R01. Emerging fuels – Hydrogen SOTA, Gap Analysis, Future Project Roadmap. 11-9-2020. www.prci.org.
[141] T Lisa Blanchard and Laurent Briottet (2020), THyGA, supra
[142] Hawai'i Gas, supra
[143] GPA Engineering for the Government of South Australian in partnership with Future Fuels CRC on behalf of the COAG Energy Council (2019). Hydrogen in the gas distribution networks.
[144] Hong Kong Gas website, supra
[145] MDPI, Multidisciplinary Digital Publishing, Switzerland
[146] Jaworski, Kulaga, and Blacharski (2020). Study of the Effect of Addition of Hydrogen to Natural Gas on Diaphragm Gas Meters. www.mdpi.com/journal/energies.
[147] Muller-Syring, Gert. Marcogaz, supra.
[148] Domptail, Frey, Hildebrandt, Hill, Maunder, Taylor, & Win (2020). Pipeline Research Council International, Inc. Catalog No. PR-720-20603-R01. Emerging fuels – Hydrogen SOTA, Gap Analysis, Future Project Roadmap. www.prci.org.

[149] ibid.
[150] ASME B31.21-2019
[151] GTI, Project Number 21029 Final Report (2010), supra
[152] ibid
[153] Kiwa Technology. Management Summary, supra
[154] See, for example, KIWA's study of July 2018, concluding that "[a]ll studies published to date have not shown any degradation of plastics and rubber gas distribution materials by hydrogen. The question with regard to the investigations is whether they have been carried out long enough to have sufficient power of expression over long-term behavior." Additionally, see KIWA's study of January 2021 stating that "specific proof that there are no problems remains difficult because there is no systematic and complete overview of the materials used, not even from suppliers and manufacturers."
[155] ASTM F2207, Standard Specification for Cured-in-Place Pipe Lining System for Rehabilitation of Metallic Gas Pipe.
[156] Email fromm Holger Turloff, Karl Weiss to Starline, 03202021
[157] GTI, Project Number 21029 Final Report (2010), supra
[158] GTI, Project Number 21029 Final Report (2010), supra.
[159] N. Gallon, supra.