

STANDARDS RESEARCH

Assessment of Natural Gas Pipeline Components and Equipment for Hydrogen Service

March 2024

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Acknowledgments

This research report is made possible by a financial contribution from Natural Resources Canada.

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Executive Summary

The increasing interest in utilizing hydrogen as a low carbon fuel to help decarbonize the energy system has led to considerations of transporting hydrogen through existing natural gas pipelines, either as natural gas-hydrogen blends or pure hydrogen. However, the potential impacts of hydrogen on pipeline materials and components necessitate an evaluation of material integrity and risk for safe and reliable operations. Knowledge and data gaps can hinder the development of appropriate Canadian standards for repurposing infrastructure for hydrogen service. This study discusses current practices to identify and recommend for consideration paths forward to address gaps within Canadian standards and codes specific to hydrogen or hydrogen blend service.

The materials and components of natural gas transmission pipeline systems covered in this study include steel line pipes, fittings, flanges, valves, station piping, compressors, and meters, which are governed by standards such as CSA Z662, CSA Z245.1, CSA Z245.11, CSA Z245.12, CSA Z245.15, API Std 617, and API Std 618. Canadian natural gas pipeline systems typically adhere to the requirements of CSA Z662, which also provides provisions specific to hydrogen or hydrogen blend service through guided engineering assessments. The standard also references other hydrogen standards, such as ASME B31.12, for further guidance. Differences in requirements between natural gas and hydrogen service stem primarily from potential adverse effects of hydrogen on materials, such as hydrogen embrittlement in steels. Hydrogen embrittlement can reduce the material's resistance to failure and shorten the component's fatigue life and can be influenced by several factors, including hydrogen partial pressures and pipe grade, based on the material's specified minimum yield strength. This phenomenon is observed in materials used in the pipeline system, such as high-strength carbon steels commonly employed for natural gas transmission pipelines. Other materials that lack ductility, such as cast iron, can be found in components within natural gas pipeline systems, such as certain parts of meters and compressors, and may be unsuitable for hydrogen service. Additionally, concerns arise about hydrogen leaks for some components utilizing mechanical joints (e.g., flanges) due to smaller hydrogen gas molecules compared to natural gas.

Nevertheless, transporting hydrogen through pipelines is not a new concept, and some materials and components used for natural gas services have been used for hydrogen service in both purpose-built and repurposed infrastructures. However, differences in requirements between natural gas and hydrogen service should be extensively evaluated. This study provides a non-exhaustive list of gaps that need to be addressed, including implementing generally more stringent requirements for hydrogen service, which infrastructures built for natural gas service may not meet. It is also essential to determine the hydrogen blend level and conditions (e.g., system pressure) at which these requirements become applicable. Examples of relevant requirements to be evaluated include Charpy V-notch impact properties, material hardness, material specified minimum yield strength, and material ultimate tensile strength. Further, the availability of data on material properties for existing natural gas infrastructure could be an issue, since hydrogen standards such as ASME B31.12 require an evaluation of parameters not typically mandated for natural gas service such as girth weld Charpy V-notch values.

The discussions on the identified gaps in this report can serve as the starting point for interested parties, such as CSA committees, researchers, operators, regulators, and manufacturers, to further assess the applicability of existing requirements for hydrogen service, develop additional technical basis as required, and provide clear guidelines, including potential alternative provisions to facilitate the conversion of existing Canadian natural gas infrastructure into hydrogen or hydrogen blend service.



"In decarbonizing the energy system, there has been a significant interest in pursuing hydrogen as a low carbon fuel."

1 Introduction

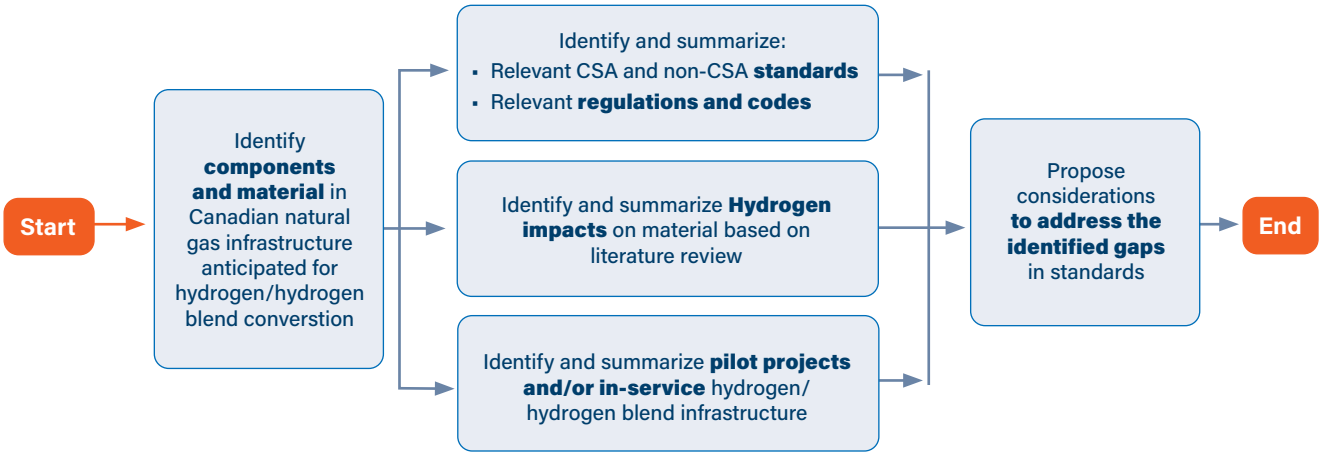
In decarbonizing the energy system, there has been a significant interest in pursuing hydrogen as a low carbon fuel. Hydrogen transportation via repurposed existing natural gas pipelines is being evaluated as a means to transport large volumes of hydrogen, in a form of natural gas—either hydrogen blend or hydrogen gas. The natural gas pipeline systems, in addition to line pipe, also consist of components such as fittings, flanges, valves, compressors, and meters that can be impacted by hydrogen. The standards to which the pipeline systems were originally designed and built generally have less stringent requirements compared with the applicable standards for hydrogen pipelines (discussed in Section 3.3). Additionally, hydrogen detrimental effects on commonly used pipeline steel materials such as reducing fracture toughness [1] and accelerating fatigue crack growth rate (FCGR) [2] have been reported in a hydrogen environment. Therefore, the integrity and reliability considerations associated with hydrogen transport must be thoroughly evaluated to ensure safe, reliable, and efficient pipeline operations.

Knowledge and data gaps pertaining to hydrogen impacts on pipeline components and materials are the subject of ongoing research. Furthermore, these gaps potentially prevent the development of enhanced guidance for repurposing infrastructure for hydrogen service for current Canadian standards. This study was intended to be used for assisting with the development of practical guidance within Canadian standards, codes and regulations (SCR) by identifying the gaps, current practices, relative prioritization, and recommended pathways. First, an overview of relevant materials and components as well as potential impacts of hydrogen are provided. Second, a list of standards, codes, and regulations as of June 2023 is summarized. Third, recommendations to address the identified gaps in standards supporting the Canadian pipeline framework is proposed. This study focuses on steels and excludes discussions on non-metallic materials such as polyethylene (PE) and elastomers.

2 Methods

This study follows a structured approach shown in Figure 1 to provide insights into the conversion of Canadian natural gas infrastructure for hydrogen/hydrogen blend service. The first step involves identifying the components and materials commonly found in Canadian natural gas infrastructure anticipated to be adapted for hydrogen/hydrogen blend service. In the second step, relevant SCRs related to natural gas, hydrogen, and hydrogen blend services are identified and summarized. The study then summarizes a thorough literature review to investigate the impacts of hydrogen on the aforementioned components and materials. While some areas, such as the effects of hydrogen on carbon steels, have a substantial amount of available data, other areas, such as the impacts on titanium alloys, may lack sufficient data. Whenever feasible and applicable, the

Figure 1: Flowchart of research methods implemented in this study



study incorporates important findings on hydrogen impacts on components and materials. The fourth step involves identifying and summarizing pilot projects or operational hydrogen/hydrogen blend infrastructures, or both, based on publicly available data, which serves as a benchmark for hydrogen service. Finally, by synthesizing the gathered information, gaps in standards and applications are identified and necessary requirements to address these identified gaps are proposed for consideration. The aim is to facilitate the safe and efficient integration of hydrogen or hydrogen blend infrastructure within the Canadian natural gas network.

3 Results and Discussion

3.1 Overview of Materials and Components and Hydrogen Impacts

This section provides a general summary of the materials and components used, or planned to be used, in equipment, piping, and pipeline systems to transport and distribute hydrogen or hydrogen blends. The overview includes a summary of research and practices in pilot projects and in-service hydrogen and hydrogen blend infrastructures as well as hydrogen impacts on the utilized materials.

3.1.1 Line Pipe, Fittings, Flanges, and Valves

3.1.1.1 Line Pipe

Line pipe, specifically steel line pipe, is defined as seamless or welded steel pipe for use in pipeline transportation in the petroleum and natural gas industries [3]. Steel line pipes for use in Canadian existing natural gas pipelines typically meet the requirements of CSA Z662 [4] and CSA Z245.1 [5]. CSA Z662 [4], through Clause 17, also provides additional provisions specific to hydrogen gas service, both for new pipelines designed for hydrogen or hydrogen blend service.

As detailed in a report on hydrogen impacts on pipelines [6], hydrogen transmission pipelines in the United States are made of carbon steels and are typically smaller in diameter (508 mm or less) compared to natural gas transmission pipelines (up to 1,220 mm) [7]. Most hydrogen pipelines were installed after 1970 and operate at pressures resulting in hoop stress less than 50% of pipe specified minimum yield strength (SMYS) and maximum operating pressure (MOP) in the order of 6,700 kPa, although some can operate as high as 10,000 kPa [8]. Not all of these pipelines were originally designed for hydrogen service; some have been successfully converted

from other services, such as crude oil gathering pipeline by Air Liquide, with extensive due diligence efforts implemented [9].

Steel grade can be a starting point for assessing hydrogen service compatibility. The carbon steel grades of hydrogen pipelines are typically low- to medium-strength steels with pipe SMYS equivalent to CSA Z245.1 grades 241, 290, and 359 [5]. ASME Standard B31.12 [10] specifies requirements for pipelines in gaseous hydrogen service and recommends X52 (Grade 359) or lower grade line pipes but allows for higher grade with SMYS up to 80 ksi (551 MPa) with additional considerations. Lower grade steels are generally less affected by HE than higher-strength steels [11]. A general trend has been reported showing decreased fracture resistance of steel in a hydrogen environment with increasing yield strength [12]. Chatzidouros *et al.* [1] observed higher fracture toughness reduction in tested X70 (Grade 483) than in X52 (Grade 359). When introduced to hydrogen, both tested X52 (Grade 359) and X70 (Grade 483) grade steels show comparable accelerated FCGR up to 1 to 1.5 order of magnitude over the FCGR in air [2]. Both tested steel grades show an increase in FCGR as hydrogen pressure increases. However, the relationship between HE susceptibility, steel grades, and fracture toughness remains unclear: other studies indicate higher grade X70 (Grade 483) steel could have comparable fracture toughness [1] and FCGR performance [2], [13] in hydrogen environments relative to X52 (Grade 359) or lower steels. Note that steel grades are assigned based on minimum property requirements of the base metal, therefore, steels with the same grade can have large differences in metallurgical properties. Due to this variability, pipe grade alone will not be sufficient criteria to assess whether a given pipe is susceptible to HE.

From the pipe hoop stress relative to material SMYS and steel grade perspectives, the specifications of the hydrogen transmission pipelines in the United States are in line with pipeline standards for hydrogen service such as ASME B31.12 [10]. The maximum pipe hoop stresses contribute to pipe crack initiation and propagation. Improved pipe fracture properties and limiting maximum hoop stress can both aid in fracture control and arrest design of a pipeline. In general, low pipe hoop stresses can reduce the likelihood of a pipeline rupture. The specifications for hydrogen transmission pipelines in the United States along with the vintage/modern aspect of the infrastructure are similar to those of existing Canadian intraprovincial, specifically Alberta, natural gas transmission pipelines [6], which reflect the potential feasibility of converting these existing pipelines into hydrogen service. In contrast, Canadian interprovincial natural gas transmission pipelines (i.e., pipelines crossing provincial borders) that would typically need higher pipe hoop stress and higher-strength steels would likely not meet the requirements for hydrogen service based on hydrogen pipeline standards such as ASME B31.12 [10]. High-carbon, high-strength steels can be susceptible to HE under high pressure applications [10],[6].

3.1.1.2 Fittings

Pipe fittings are components welded or mechanically joined in the pipeline system and utilized for changing direction, branching, or transitioning to a different pipe diameter. Within the existing Canadian gas pipeline systems, pipe fittings typically meet the requirements of CSA Z245.1 [5] and CSA Z662 [4]. CSA Z245.11 [14] covers wrought steel buttwelding fittings, including extruded headers commonly intended for use in oil and gas pipeline systems. This includes geometrical types consisting of extruded headers and factory-produced bends, with sizes spanning from the nominal pipe size (NPS) ½ to NPS 60, as per CSA Z245.11 [14], where the number refers to the pipe's diameter in inches. A steel's "grade" is a classification based on the material's SMYS, and similar to pipelines, the available steel grades for fittings range from CSA Z245.11 Grade 207 to Grade 690 for typical oil and gas systems [14]. The performance of fittings materials under hydrogen service (e.g., influence of steel grades on HE for fittings) is expected to be similar to line pipe discussed in Section 3.1.1.1 [15].

CSA Z245.11 [14] does not include provisions specific for hydrogen service, however, CSA Z662 [4], through Clause 17, provides additional provisions specific to

hydrogen gas service, both for new pipelines designed for hydrogen or hydrogen blend service. In accordance with the standard, operators shall perform engineering assessments that include various topics, such as material selection and pipeline design, to address the potential adverse effects of hydrogen on pipeline materials. CSA Z662 [4] also cites ASME B31.12 [10] as additional guidance for hydrogen service (e.g., specific for threaded fittings). Therefore, provisions set by hydrogen standards such as ASME B31.12 [10] are considerations in this section.

ASME B31.12 [10] is an existing standard document for hydrogen piping and pipelines commonly referenced for guidance. Additional provisions regarding the design and installation of fittings involved with gaseous hydrogen transportation and storage can be found in sections 704.1.2.1 through 704.1.2.5.1 and Chapter 7 of the International Fuel Gas Code (IFGC) [16]; Section 704.1.2 specifically does not allow cast iron fittings, pipe, and valves for hydrogen service.

Pertaining to fittings for hydrogen service, ASME B31.12 [10] refers to three other standards: ASME B16.5 [10]; ASME B16.9 [18]; and ASME B16.11 [19]. These standards cover pressure and temperature ratings, dimensions, tolerances, marking, material requirements, testing, and methods of designating openings for pipe flanges and flanged fittings. The above listed standards cover fittings composed of cast iron, cast bronze, wrought copper, and steel; wrought buttwelding fittings; and socket-welding and threaded forged fittings, respectively, which are typically employed for oil and gas applications.

In the case of both sets of standards, CSA Z245.11 [14] and ASME B16.5 [17], ASME B16.9 [18], and ASME B16.11 [19], the specifications related to the oil and gas industry are not specifically tailored to hydrogen applications. Although similar, some differences amongst these documents are in how they approach certain subjects. In addition to the range of pipe sizes covered in each document that have already been listed, CSA Z245.11 [14] provides a list of nominal steel grades acceptable for use in fittings, whereas the ASME standards provide a table listing the recommended compositional designations specific to the grades. CSA Z245.11 [14] separates fittings into two distinct categories based on whether fittings have requirements for proven notch-toughness properties or not, whereas the ASME documents do not specify this distinction. Since hydrogen service can reduce the toughness properties of a material discussed in Section 3.1.1.1, the assessment of fittings without proven notch-toughness properties can be challenging, as the notch-toughness of the material is unknown.

Fittings can also be made out of copper, aluminum, cast iron, and carbon steels. Pure copper can be unaffected by high pressure hydrogen, but the inclusion of copper with oxygen can make the material susceptible to HE [20], [21]. However, most copper alloys used in oil and gas systems are deoxidized and thus should not be affected by HE [22]. Hydrogen effects on aluminum alloys are not fully understood, though it has been shown that aluminum exhibits both low hydrogen solubility and diffusivity, and the presence of a stable surface oxide further inhibits hydrogen uptake into the metal [23]. Additionally, in dry hydrogen gas environment, experiments have shown that aluminum alloys appear to have good resistance to hydrogen-assisted fracture [23]. Carbon steels can be classified by the percent concentration of carbon, where low carbon steel consists of less than 0.30% carbon, medium-carbon steel consists of around 0.30 to 0.60% carbon, and high-carbon steel contains more than 0.60% carbon [24]. With increasing carbon concentration comes increased strength and brittle behaviour. Consequently, high-carbon steels are susceptible to HE [16]. Similarly, cast iron, which contains more than 2% carbon, should not be used due to the high susceptibility of HE [16]. Hence, fittings made from cast iron and high-strength carbon steels can be susceptible to HE.

Common joining techniques between fittings and pipe system are welded connections or mechanical connections such as threaded, brazed, or other compression-type connections. As defined by CSA Z662 [4], a weld is a localized coalescence of metals produced by heating the materials to the welding temperature with or without filler metal. A mechanical joint is defined as a pipe joint installed for the purpose of mechanical strength, leak resistance, or a combination of the two. The mechanical strength



"For joints in industrial hydrogen piping systems, welding is preferred over mechanical fittings as it provides higher integrity and less potential for leaks."

is developed by threaded, grooved, rolled, flared, or flanged pipe ends or by bolts, pins, toggles, or rings. The leak resistance is developed by threads and compounds, gaskets, rolled ends, or machined and mated surfaces [10].

For joints in industrial hydrogen piping systems, welding is preferred over mechanical fittings as it provides higher integrity and less potential for leaks [26]. Fitting welds may be socket welds, branch welds, or butt welds and are commonly performed using gas metal arc welding, shielded metal arc welding (SMAW) or submerged arc welding (SAW) by qualified welders following qualified procedures in accordance with CSA Z662 [4]. Before a fitting's selection and application, adverse effects due to operating conditions such as high pressure, cycle loading, vibration, shock, and thermal expansion must be considered by designers and operators [26],[14].

In addition to material consideration, fitting installation can play a role in joint integrity. For in-service hydrogen transportation, fittings must be leak free and able to maintain their integrity. Improperly designed or installed fittings, such as an improperly designed mechanical joint [27], application of flow rates in excess of material or dimensional specifications [28], or fittings identified as containing cutting burrs or exhibiting defects in the structure or threading [29], can result in brittle-like cracking, a type of line failure characterized by rapid crack propagation upon initiation. This type of cracking is especially problematic due to the potential difficulty in detecting it before enough gas has escaped and accumulated to trigger gas sensor alarms [30].

Pipe joints should contain material that is mechanically and chemically compatible with the nominal pipe. Weld strength is required to meet the minimum strength of the base material. Material selection may include testing according to CSA/ANSI CHMC-1 [31].

An example of utilized fittings on current or planned in-service hydrogen blending pipeline design at relatively lower pressure (1,207 kPag) can be found in Enbridge's Low Carbon Energy Project (LCEP) in Markham, Ontario, injecting up to 2% hydrogen by volume into an existing gas distribution system [53]. Enbridge has detailed the standards they met for using fittings in hydrogen service encompassing a variety of different operating conditions [53]. For a piping system carrying up to 2 vol% hydrogen with a design pressure of 1,200 kPag, the facility used NPS 6, Grade 359 carbon steel fittings that met the requirements of CSA Z245.11-17 [32], [53]. For a piping system carrying 100% hydrogen with a design pressure of 3,447 kPag, the facility used NPS 1, Grade TP304 stainless steel fittings that adhered to the specifications in ASME B16.11 [33] or ASTM A182 [34]. Enbridge did not specify the two standards' editions (it was presumed that the editions in use were those circa the year of publication of [53]).

3.1.1.3 Flanges

Pipe flanges are piping components that use bolted connections and gaskets to connect piping and components in a piping system [35]. Flanges in Canadian natural gas infrastructure typically meet the requirements of CSA Z662 [4] and CSA Z245.12 [36], which cover wrought steel welding neck and blind flanges primarily intended for pipeline systems. Pipe flange size requirements span from NPS ½ to NPS 60, with the number relating to the pipe's diameter in inches and are typically composed of steel grades for oil and gas applications ranging from Grade 248 to Grade 690, where the term "grade" classifies the steel by the material's SMYS [36]. This standard also covers flanges having cold working pressure ratings designated by nominal pressure classes ranging from pressure nominal (PN) 20 to 420 (maximum cold working pressure rating from 1,900 to 41,370 kPa). Flanges are also broken into two separate categories, one without requiring proven notch-toughness properties (Category I) and the other requiring them (Category II) [36].

Impacts of hydrogen on the flange materials are expected to be similar to the line pipe material discussed in Section 3.1.1.1 [15]. However, hydrogen leakage is one of the main concerns, and the gaskets connecting the flanges can be considered the most sensitive for hydrogen service and should be carefully evaluated for suitability [15]. A gasket that is unsuitable or damaged can result in leakage through the flange due to the smaller size of the hydrogen molecule compared to natural gas [15]. As such, risks associated with hydrogen leakage need to be reduced as much as possible through proper safety and integrity guidelines set forth during design and maintenance of hydrogen transportation systems. This includes robust ventilation tied into highly sensitive leak detection systems that can identify the smallest of leaks [37]. And given the higher risk of autoignition, many common leakage sources in natural gas systems, such as venting or relief valves, are avoided by design in hydrogen systems.

Flanges in hydrogen transportation systems must be leak resistant types such as raised face, tongue and groove, or ring joint flanges [20]. They must also be hydrogen compatible and adhere to appropriate design pressures and temperatures [20] according to the suitable standards for hydrogen service such as ASME B31.12 [10]. Further, they must exhibit fire resistance due to hydrogen's high flammability. Therefore, materials such as Teflon™ or graphite filled spiral wound gaskets with a raised face flange, or a copper ring with a joint flange are common choices as they adhere to these standards and are difficult to ignite [26].

Pertaining to applicable standards for flanges, CSA Z245.12 [36] does not provide specific provisions for hydrogen service, but CSA Z662 [4] Clause 17 provides additional provisions specific to hydrogen or hydrogen blend service, although no specific provisions for flanges are provided. CSA Z662 [4] cites ASME B31.12 [10] as an additional guidance for hydrogen service. Therefore, provisions set by hydrogen standards such as ASME B31.12 [10] are considerations in this section. ASME B31.12 [10] is specific to hydrogen systems but does reference other standards focusing on flanges. Line and end flanges must conform with the requirements of ASME B16 series. Threaded flanges and slip-on welding flanges are permitted if they comply with ASME B16.5, welding neck flanges if based on ASME B16.5, and large flanges if based on ASME B16.47. Specific material requirements related to bolting can be found in ASME B31.12 [10] Section PL-2.2.3 Flanges. Flanges may also be used in hydrogen service if they meet the requirements of ASME BPVC VIII.1 [38] using the allowable stresses and temperature limits of ASME B31.12 Code [10]. Flanges can be found in a variety of styles and encompass several pressure classes, as classified in ASME B16.5 from 150# to 2500# rating [35]. For hydrogen service, flanges typically follow a 300# minimum rating, as specified in ASME B16.5 [17]. Flange assemblies must also withstand the maximum operational pressure of a pipeline (i.e., cannot be the weakest link) and maintain their physical and chemical properties for any temperature range the pipe is anticipated to be subjected to during service [39]. And due to the high leak susceptibility associated with flanges, the use of flanged connections in hydrogen service should be limited to hydrogen cutoff rooms and outdoors [16].

An example of flange application in hydrogen service is discussed by Chevron [39]. According to Chevron's publication, where flanges are required, gasket reliability is a major focus and continues to evolve; spiral wound gaskets are preferred for lower pressure classes. Further, 1500# classes and above are reviewed case-by-case with temperature becoming one of the major factors [39]. For pipe connections of 2 inches or larger that cannot be welded into a permanent joint, flanged connections are used with the gasket material preference being spiral wound stainless steel sandwiched between layers of elastomer. Within this set-up, the stainless steel protects against complete failure of the gasket in case of a fire and the elastomeric layers provide a complete seal when flange bolts are tightened [40].

Another example of flanges utilized on current or planned in-service hydrogen blending pipeline design at relatively lower pressure (1,207 kPag) can be found in Enbridge's LCEP. Enbridge has detailed the standards they met for using flanges in hydrogen service encompassing a variety of different operating conditions. For a piping system carrying up to 2% hydrogen, with a design pressure of 1,200 kPag, the facility used NPS 6, Grade 359 carbon steel line pipe with flanges that met the requirements of CSA Z245.12-17 [41].

3.1.1.4 Valves

Valves are devices used in pipeline systems that help regulate, direct, or control the flow or pressure of the transporting material within a pipeline system [42]. Canadian natural gas infrastructure adheres to provisions set forth in CSA Z662 [4] and CSA Z245.15 [43] for valves made out of steels, which cover gate valves, plug valves, ball valves, and check valves for pipe sizes ranging from NPS 2 to 60, with the ensuing number representative of the pipe's diameter in inches. Further, the standard covers valves exhibiting pressure ratings designated by nominal pressure classes from PN 20 to PN 420, with valves bifurcated into two separate categories: those requiring proven notch-toughness properties (Category I) and those that do not require proven notch-toughness properties (Category II) [43].

Similar to fittings discussed in Section 3.1.1.2, various metal alloys are employed throughout the natural gas infrastructure in valves, including carbon steels, stainless steels, copper, aluminum, brass, and cast and ductile irons [21]. High-strength steel, most commonly found in the stems of values, can be susceptible to HE [10].

Due to the hazardous nature of hydrogen (i.e., higher likelihood of ignition upon component failure due to lower ignition energy and wider flammability range compared to natural gas), above ground pressure containing parts including valves should only be made of metallic parts, and all use of non-metallic parts should be limited to services that do not provide primary mechanical strength, such as valve internals [20]. Plastics and elastomers may be used for internal valve seats and seals in hydrogen service, or in fixed joints, such as elastomer O-rings [44]. Plastics, elastomers, and other non-metallic materials that maintain their integrity at elevated temperatures, which are not susceptible to premature degradation in the presence of hydrogen and can withstand friction and wear in high pressure environments, may be used for flange and valve packing or gaskets, or both [26], [45]. Several of the elastomer materials used in natural gas pipeline systems that are also hydrogen compatible include fluoroelastomers, acrylonitrile-butadiene rubber (NBR), and ethylene propylene diene monomer (EPDM) [21].

Concerning the applicable standards for valves, CSA Z245.15 [43] does not provide provisions specific for hydrogen service, but CSA Z662 [4] Clause 17 provides additional provisions specific to hydrogen or hydrogen blend service although no specific provisions for valve materials are provided. CSA Z662 [4] cites ASME B31.12 [10] as additional guidance for hydrogen service. Therefore, provisions set by hydrogen standards such as ASME B31.12 [10] are considerations in this section.

ASME B31.12 [10] includes rules for the use of valves in hydrogen pipeline systems through reference to ASME B16.34 [46] and ASME B16.38 [47], the standard encompassing flanged, threaded, and welded end valves and the code for large metallic valves for gas distribution, respectively. Valves can be critical safety

devices when utilized to shut down a portion of the system in the case of emergency or if leakage has been detected [48]. Thus, they are critical components in pipeline systems, with increased importance when hydrogen is involved, due to the smaller size of hydrogen molecules in comparison to methane molecules, which results in a greater risk of leakage at valves and corresponding connections that must be considered in the transportation of hydrogen [49]. Valve design must therefore accommodate the extreme operational conditions that pipelines can encounter, such as high pressure, extremely low temperatures, or excessive vibrations [50].

Several examples of the repurposing of oil and gas pipeline systems to hydrogen transportation currently employed or studied in North America and worldwide include information relating to valve usage in hydrogen service:

- Air Liquide converted a 54.7 km pipeline, originally built in 1979 for crude oil transportation and consisting of various pipeline grades and wall thicknesses, to hydrogen [9]. The pipeline has been operating at 5,102 kPag (740 psig) since 1996 with the original pipeline ball valves remaining in use with hydrogen service [9].
- BP converted a 34.9 km long NPS 8 grade X52 (Gr. 359) pipeline to hydrogen service in 1977 to 1978, approximately three years after installation. The transition to hydrogen was reported to be relatively simple with no special efforts required, but some of the packing used for sealing valves was dried out due to the previous ethylene service, which had allowed molecular hydrogen to escape. Therefore, the frequency in which valves were checked was increased from the US DOT recommended conservatism interval of 7.5 months to 6 months, concluding that valve rebuilds would be necessary in this particular line [51]. Note that some guidance in industry [20] recommends that all valves shall be refurbished when requalifying existing pipelines for hydrogen pipelines.
- In 2005, Air Products had 563 km of operating hydrogen pipelines in North America, with most systems located in Texas, Louisiana, and California and in operation since 1970 [52]. The pipe sizes range from NPS 4 to 12 and operate at pressures between 2,413 and 13,100 kPag. At least 30 excess flow valves (EFV) are devices that can automatically close and restrict the flow of hydrogen if the set pressure is exceeded [52]. Some segments of these pipelines were converted to hydrogen service from liquid service built in the 1940s [52]. Metallurgical analysis revealed concerns with the pipe quality due to the composition and manufacturing process. Ultimately, pipe in sensitive areas was replaced and additional precautions were set in place, like more extensive hydrotesting, and the installation of numerous EFVs and pipeline safety valves with a required reduction in the allowable pressure [52].
- Enbridge's LCEP [53] has also detailed their valve usage and the standards adhered to when implementing valves in specific design specifications involving hydrogen transportation. For piping systems carrying up to 2 vol% hydrogen with a design pressure of 1,200 kPag, the facility used NPS 6, Grade 359 carbon steel line pipe with valves that met the requirements of CSA Z245.15–17 [54]. For piping system carrying 100% hydrogen with a design pressure of 3,447 kPag, the facility used NPS 1, Grade TP304 stainless steel fittings that adhered to the specifications in ASTM A351 [55]. The project distributes up to 2% hydrogen to the existing gas distribution system, which also comprises non-metallic materials, such as medium density polyethylene line pipe with valves, that meet the requirements of ASME B16.40-19 [56].
- In Europe, N.V. Nederlandse Gasunie converted a pipeline built in 1996 to a mixture of gaseous 70% to 100% hydrogen and methane [49]. Because of the increased risk of leakage for hydrogen with respect to methane, they decided to replace the existing valves of the two existing valve stations with "H_2 compliant" valves at an early stage of the transition. This was done not only to avoid issues related to unforeseen leakages but also any potential incompatibility issues associated with the existing valves such as poor material compatibility with hydrogen. However, upon further review, they realized that the "H_2 compliant" valves were almost identical

to the original valves apart from the thickness of the body, which was increased to reduce the peak body stresses. In 2019, they performed a test on one of the replaced valve stations at 6,619 kPag hydrogen that included leak tests, seat tests, and over 20 blowdown operations at the valve station, the latter of which involves relieving pressure in the pipe through venting of the transported material (blended gas and hydrogen in this case) into the atmosphere during well operations or during pipeline operations or maintenance. They noted that during blowdown operations, there was no ignition of the released hydrogen, and in the process concluded that there was no need to replace the original valve stations in the first place, even for 100% hydrogen usage [49].

3.1.2 Station Piping

Gas pipeline systems include piping within stations (commonly referred as station piping) along the pipeline such as piping at compressor stations, metering stations, and pressure-regulating stations. The station piping within natural gas infrastructure will be exposed to the hydrogen environment when converting the infrastructure into hydrogen or hydrogen blend service. Similar to line pipes described in Section 3.1.1.1, station piping designed for natural gas can be made out of materials potentially susceptible to hydrogen adverse effects such as carbon steels.

Station piping, for the purposes of the discussion here, can be divided into five subcategories: natural gas station piping, process station piping, hydrogen-specific process station piping, pure hydrogen station piping for natural gas-hydrogen blending use, and blended natural gas-hydrogen station piping. The first three subcategories are broadly governed by CSA Z662 [4], ASME B31.3 [57], and ASME B31.12 [10], respectively. Note that ASME B31.12 [10] provides standard provisions for hydrogen service, though it is not currently mandated in Canada or worldwide [6]. Pure hydrogen station piping for natural gas-hydrogen blending use and blended natural gas-hydrogen station piping does not explicitly fall under the purview of existing standards; therefore, it is important to understand the existing related standards when considering blending hydrogen into existing natural gas station piping or constructing new natural gas-hydrogen blending stations. Similar to other components discussed previously (line pipe, fittings, flanges, and valves), piping materials can be made of a number of various metal alloys, such as carbon steels and stainless steels, with similar concerns pertaining to hydrogen adverse effects.

3.1.2.1 Natural Gas Station Piping

CSA Z662 [4] defines four types of stations: compressor station, measuring station, pressure-regulating station, and pump station. This distinction is important because, in accordance with CSA Z662 [4] Clause 5.1.1, compressor and pump station piping for natural gas service in Canada is designed to ASME B31.3 [57].

Examples of specifications for station piping meeting the requirements of ASME B31.3 in a natural gas compressor station project include the use of either ASTM A106 [58] Grade B or ASTM A333 [58] Grade 6 piping for applications such as fuel gas piping [59]. Fuel gas piping is noteworthy since it will also be exposed to hydrogen where the fuel for the compressor is typically drawn off the pipeline transporting hydrogen-natural gas blend during the conversion of existing natural gas pipeline to natural gas-hydrogen blend service.

3.1.2.2 Process Station Piping

ASME B31.3 [57] broadly governs process station piping. In ASME B31.3 Section 300.1, the scope is defined as “piping typically found in petroleum refineries; chemical, pharmaceutical, textile, paper, semiconductor, and cryogenic plants; and related processing plants and terminals” [57]. ASME B31.3 [57] covers a broad range of fluid mediums and applications, including but not limited to natural gas and hydrogen. As stated earlier, ASME B31.3 [57] is referenced by CSA Z662 [4] for design considerations for pump and compressor stations. ASME B31.3 [57] was also used for the design of hydrogen-containing services prior to the release of ASME B31.12 in 2008 [60].

The design of piping systems for hydrogen service in chemical plants, particularly those found in petroleum refineries, can offer valuable insights into the safe operation of hydrogen piping. These insights can serve as a useful benchmark for pipe specifications and practices as well as inform considerations for

converting existing natural gas infrastructure into hydrogen service. Notably, while there may be some overlap in design requirements between natural gas and petroleum refinery piping, in certain situations, such as high pressure, high temperature (HPHT) applications [39], the specifications for hydrogen piping in refineries may not be directly applicable to natural gas applications.

Chevron's expertise in refining aligns with the established understanding that hydrogen can accelerate fatigue crack growth and cause cracking in hard materials [39]. While hydrogen can reduce fracture toughness in a hydrogen environment, it has not been shown to be a significant limitation for the typical piping conditions and thicknesses found in refining [39]. In 2005, Chevron designed hydrogen piping for use in their refinery operations according to the ASME B31.3 [57] standard, predating the release of ASME B31.12 [10]. All welds underwent 100% radiographic examination, threaded connections or exposed threads were avoided, the use of flanges or other potential leak sources was minimized, and bridge welding was considered to prevent fatigue initiation. The piping specifications include ASTM A106 [58] Grade B and ASTM A333 [61] Grade 6, similar to the natural gas station piping discussed in Section 3.1.2.1 and ASTM A672 [62]. ASTM A106 [58] Grade B pipe is equivalent to API Spec 5L [3] Grade B on alloy composition and mechanical properties with SMYS of 250 MPa. ASTM A333 [61] Grade 6 pipe has SMYS of 240 MPa. It is worth noting that these two pipe grades are in line with practices of utilizing low-strength steels for hydrogen service based on ASME B31.2 [10].

3.1.2.3 Hydrogen-Specific Process Station Piping

ASME B31.12 [10] is applicable to piping in gaseous and liquid hydrogen service and to pipelines in gaseous hydrogen service. This standard delineates two major categories of hydrogen systems: pipelines and industrial piping. Industrial piping (IP) is defined as "hydrogen service included in petroleum refineries, refuelling stations, chemical plants, power generation plants, semiconductor plants, cryogenic plants, hydrogen fuel appliances, and related facilities." [10].

The definition in ASME B31.12 [10] of IP does not explicitly mention blended natural gas-hydrogen stations or pure hydrogen stations for natural gas-hydrogen blend use; however, it does provide insight into piping compatibility and specifications independent of the end hydrogen use.

3.1.2.4 Pure Hydrogen Piping for Natural Gas-Hydrogen Blending Use

Although natural gas-hydrogen blending applications are not explicitly included in ASME B31.12 [10], operators are designing natural gas-hydrogen blending projects to meet the requirements of the standard for the pure hydrogen piping within the facilities [53]. An example of pure hydrogen station piping for natural gas-hydrogen blend application is the piping within hydrogen generation (e.g., via electrolyzers) facilities and piping connecting these facilities to the existing natural gas pipelines, such us those operated by Enbridge in Markham, Ontario [53]. According to Enbridge, the piping station containing pure hydrogen within Enbridge's hydrogen blending station were anticipated to be designed and installed according to ASME B31.12 [10], CAN/BNQ 1784-000 [63], and CSA B51 [64]. This facility injects up to 2% hydrogen blended gas into a closed distribution system. As part of this system, Enbridge operates a pure hydrogen station, which connects the hydrogen storage tanks to the hydrogen blending station. The pure hydrogen station uses piping with a 33.4 mm external diameter, Grade TP304 stainless steel, that meets the specifications in ASTM A733 [65] or ASTM A312 [66]. The station piping design pressure is 3,447 kPa, which corresponds to 8.3% of pipe SMYS [53]. Austenitic stainless steel grades (e.g., ASTM A312 grade TP304) are considered resistant to HE and generally provide suitable performance among structural metal in hydrogen gas service [6].

3.1.2.5 Blended Natural Gas-Hydrogen Station Piping

Within Enbridge's facility mentioned in Section 3.1.2.4, station piping transporting blended natural gas and hydrogen also exist, specifically on the piping regulating the pressures of the hydrogen-natural



"In the context of converting existing natural gas infrastructure into hydrogen or natural gas-hydrogen blend service, hydrogen impacts on compressors designed for natural gas service must be evaluated."

gas blend [53]. The project installed a new pressure-regulating station for the blended gas using NPS 1 to 6 carbon steel pipe of Grade 290 and meet the specification of CSA Z245.1 [5]. The station piping is designed for 1,207 kPa, which corresponds to a maximum of 5% pipe SMYS [53]. According to the documentation, the pressure-regulating station would be designed in accordance with CSA Z662 [4].

3.1.3 Compressor Equipment

Pipeline systems commonly include compressors. Compressors are needed to move, store, and use gases, such as natural gas, hydrogen, and natural gas-hydrogen blends. Compressors can be found in various applications, such as hydrogen generation plants, and along the pipelines in a facility referred to as compressor stations. In the context of natural gas, compressor stations periodically compress highly pressurized natural gas as it travels through a pipeline, using fuel-driven turbines or engines, or electric motors that drive a connected gas compressor to maintain the pressures and temperatures required for end use [67].

Compressors designed specifically for hydrogen service have existed for many years. However, in the context of converting existing natural gas infrastructure into hydrogen or natural gas-hydrogen blend service, hydrogen impacts on compressors designed for natural gas service must be evaluated. Hydrogen can impact both the performance and construction material of a compressor designed for natural gas service, as discussed in the subsections below. This section will specifically address the hydrogen impacts on materials commonly used in natural gas systems, providing insights for parties considering the conversion of Canadian natural gas infrastructure to hydrogen service.

Gas compressors are typically classified based on the compression principles, and the common types in natural gas service include centrifugal compressors driven by natural gas turbines and reciprocating compressors driven by natural gas engines. Reciprocating compressors are typically used for lower volume, high discharge pressure applications, whereas centrifugal compressors are more commonly used for higher volume, lower discharge pressure applications [68].

3.1.3.1 Centrifugal Compressors

For centrifugal compressors, compressor head or pressure rise is partly dependent on the tip-speed of the impeller [69], governed by its diameter and rotating speed. Introducing hydrogen in natural gas will reduce the gas blend molecular weight and often require higher impeller rotating speed to achieve desired compression-to-pressure ratio [70]. The rotating speed is typically constrained by parameters such as mechanical and material strength limitations [71]. Specific to hydrogen service based on the standard for centrifugal compressors, API Std 617 [72] Clause 6.2.1.12 states that use of materials with a yield strength surpassing 827 MPa (120,000 psi) or higher than 34

of hardness Rockwell C (HRC) is not allowed when subjected to hydrogen gas conditions where the partial pressure of hydrogen goes beyond 689 kPa (100 psig) or the hydrogen concentration exceeds 90 molar percent at any pressure. A 689 kPa hydrogen partial pressure corresponds to 8% hydrogen by volume in natural gas-hydrogen blend at a typical natural gas transmission pipeline pressure (8,275 kPag). Hence, for 8% or higher hydrogen blend, pipeline operators must evaluate material strength and hardness in compressors for hydrogen conversion. Below 8%, material suitability should still be evaluated due to observed HE in materials like carbon steels even at low hydrogen partial pressure [73].

Table 1 lists the materials used in different parts of a centrifugal compressor, including titanium, aluminum, stainless steel (austenitic only), steels, brass, and bronze. In accordance with the ASME B31.12 [10] Non-mandatory Appendix A, these materials are considered acceptable for use with gaseous hydrogen. However, it is important to note that this standard is primarily focused on hydrogen piping and pipelines instead of compressors. The conditions, such as temperatures and stresses, that these materials may be subjected to in a compressor application could be different from those in a pipeline, and hence further assessment is required. For instance, parts of the compressor could be operating at high temperature (as high as 150 °C [68]), while the natural gas pipeline typically operates close to the ground ambient temperature (-5 °C to 25 °C [74]), where HE has been observed to be the most severe [75]. Several publications suggest HE can occur in titanium-based alloys [76].

Considering the wide variation of utilized materials, as shown in Table 1, prior to conversion to hydrogen service, the original equipment manufacturers (OEM) must be consulted to identify the construction material for the compressor unit in question, and a thorough assessment of its suitability for hydrogen service must be conducted. Table 1 also shows that materials deemed not acceptable by the standard, such as cast iron, ductile iron, and nickel alloys (e.g., nickel-copper), could be utilized in various compressor parts. Hence, more thorough assessments for compressors containing the aforementioned materials must be undertaken.

Table 1 also shows non-metallic materials such as polytetrafluoroethylene (PTFE), polyetheretherketone (PEEK), and polyaryletherketone (PAEK) are used for compressor seals. ISO/TR 15916 [77] specifies that PTFE is suitable for gaseous hydrogen service but does not mention the suitability of PEEK and PAEK.

Table 1: Typical materials for components within centrifugal compressors (adapted from [78])

Component	Material
Casing – pressure containing	▪ Cast: cast iron, austenitic cast iron, ductile iron, cast steel, cast stainless steel, cast aluminum, and cast titanium. ▪ Fabricated: steel, stainless steel, and aluminum.
Impeller	▪ Cast: aluminum, stainless steel, and titanium. ▪ Fabricated: aluminum, steel, stainless steel, nickel-copper alloy, and titanium.
Shaft / rotor components	Steel, stainless steel, nickel-copper alloy, and nickel-moly-chrome alloy.
Seals	Aluminum, brass, nickel-copper alloy, bronze, stainless steel, Cr-Ni-Fe-Mo-Cu-Cb alloy, nickel-copper alloy, and non-metallic (e.g., PTFE, PEEK, and PAEK).
Internal mechanisms and structures	Cast iron, ductile iron, cast steel, steel, stainless steel, and aluminum.

3.1.3.2 Reciprocating Compressors

Applicable standards pertaining to reciprocating compressors include API Std 618 [79]. API Std 618 [79] provides some guidance specific to high pressure hydrogen service such as predicted discharge temperatures not exceeding 135 °C, which compressors designed for natural gas may exceed (e.g., maximum allowable discharge temperature of lubricated compressors can be as high as 165 °C [137]). However, no guidance on suitable materials for hydrogen service is provided in API 618 [79].

API Std 618 [79] provides a list of typical materials used in various parts of a reciprocating compressor (Table 2). It should be noted that some of the listed components, such as the frame, crankshafts, and connecting rods, are not normally exposed to the gas during regular operations. However, in the event of a seal failure, or in lubricated compressor application, these components may come into contact with the process gas (i.e., hydrogen in hydrogen service pipeline). As a result, it is still important to evaluate the material suitability of these aforementioned parts with hydrogen.

Table 2 shows that parts normally in contact with the process gas such as cylinders, cylinder liners, pistons, valve seats, and valve plates can be made out of steel, stainless steel, or aluminum. These materials (austenitic only for stainless steels) are deemed acceptable for gaseous hydrogen service according to the ASME B31.12 [10] Non-mandatory Appendix A. However, this standard is primarily focused on hydrogen piping and pipelines and not specific to compressors. Similar to centrifugal compressors described in Section 3.1.3.1,

Table 2: Typical materials for components within reciprocating compressors (adapted from [79])

Component	Material
Frame	Cast iron
Crankshafts	Steel
Connecting rods	Steel
Crossheads	Steel or ductile iron
Crosshead pins	Steel
Distance pieces	Cast iron
Cylinders	Steel, stainless steel, nodular iron, or grey iron
Cylinder liners	Steel, stainless steel, Ni-resist, nodular iron, or grey iron
Cylinder heads	Steel, stainless steel, nodular iron, or grey iron
Pistons	Steel, cast iron, or aluminum alloys
Piston rods and tailrods	Steel or stainless steel
Piston rod nuts	Steel or stainless steel
Valve seats and guards	Steel, stainless steel, nodular iron, or cast iron
Valve plates	Stainless steel or non-metallic
Valve springs	Steel or stainless steel
Packing cases	Steel, stainless steel, or cast iron
Packing case flange	Steel
Piston rings, wear bands, and packing rings	Metallic or non-metallic

conditions such as temperatures and stresses that these materials may be subjected to in a compressor application could be different from those in a pipeline; hence, further assessments should be conducted. Prior to conversion to hydrogen service, the OEMs must be consulted to identify the construction material for the compressor unit in question and a thorough assessment of its suitability for hydrogen service must be conducted. Thorough assessments should be conducted particularly on the compressor wetted parts utilizing materials deemed not acceptable for gaseous hydrogen service based on ASME B31.12 [10] Non-mandatory Appendix A, such as nodular iron, grey iron, cast iron, and Ni-resist (used in compressor parts, such as cylinders, cylinder liners, cylinder heads, pistons, valve seats, and guards, as shown in Table 2).

Reciprocating compressor operators attribute forced outages to valve failures, which could be mitigated by proper design of valve components such as guards, seats, plates, and springs [80]. However, valve design typically caters to a single set of operating conditions, leading to plate or spring failure when operated at off-design conditions such as changing gas molecular weight [80]. Reciprocating compressor suction and discharge valves for natural gas are designed to the gas's molecular weight [80]. Hydrogen blending will decrease the gas mixture molecular weight causing these valves to operate outside the design point. As a result, it is essential to evaluate not only the material compatibility of the valves and their components with hydrogen service but also the mechanical design of these parts before converting to hydrogen service.

3.1.3.3 Compressor Prime Movers

Prime movers for mechanical drives are a common name for machines made for transferring mechanical energy to pumps and compressors. In the context of hydrogen conversion, hydrogen can impact not only the compressors but also their prime movers (e.g., natural gas turbines and natural gas engines), as the fuel for this equipment is typically drawn off the pipeline, which contains hydrogen. Some common natural gas engines parts utilize materials cautioned by ASME B31.12 [10], such as cast iron for engine's cylinders. However, this standard is primarily focused on hydrogen piping and pipelines and is not specific to gas engines [81]. The conditions, such as stresses and temperature, that these materials may be subjected to in a gas engines application could be different from those in a pipeline, and therefore further assessment of cast iron's suitability for fuel containing hydrogen should be performed. Several gas engines OEMs have evaluated the suitability of their equipment for natural gas-hydrogen blend fuels [82]. It is not clear whether retrofitting or replacing parts within existing gas engines with components suitable for hydrogen would be necessary for this application.

The common prime mover for centrifugal compressors is a natural gas turbine driving the compressor's rotational shaft. Several gas turbine OEMs suggest the possibility of utilizing a blended hydrogen/natural gas as compressor fuel [83]. However, like for gas engines, it is not clear whether retrofit packages or parts replacement would be required for existing natural gas turbines.

3.1.4 Meters

Meters are devices that measure the volume of natural gas entering and exiting a pipeline and are often designed to also monitor gas properties and composition. These devices are installed along the gas pipelines at meter stations and at the end-user's location. Meters can be found in both gas transmission and distribution systems. Meters are classified based on their measurement principles. Some common types of meters include turbine, ultrasonic, orifice, rotary displacement, vortex, diaphragm, thermal, and Coriolis meters.

Meters are typically chosen based on the anticipated process gas, volumetric flowrate, and pressure and temperature ratings. While purpose-built meters for hydrogen service exist, the suitability of meters designed and installed for natural gas service will have to be evaluated when there is a change of product from natural gas to natural gas/hydrogen blend or pure hydrogen when converting existing natural gas infrastructure into hydrogen or hydrogen blend service [84].

Meters installed for natural gas transmission lines typically have high pressure ratings (in the order of 10,000 kPag [85]) while meters at distribution lines typically operate at much lower pressure (as low as

35 kPag [86] at the customer's site). Therefore, the meters' construction material (shown in Table 3 and Table 4) and consequently their suitability for hydrogen service can vary. Table 3 and Table 4 also show that meters' components can vary with the measurement principles. Table 3 and Table 4 are provided as examples only, however, the materials used to construct meters can vary widely depending on other attributes, such as the meter model, manufacturer, application, operating conditions, temperature, and volumetric capacity [78]. Given this range of attributes, it is not appropriate to generalize about a meter's material suitability for hydrogen service, especially based solely on its measurement principle. Instead, it is important to consult with the meter's OEM and conduct testing and assessment on a case-by-case basis to ensure its suitability for hydrogen service.

Discussions on hydrogen impacts on meters designed for natural gas service have primarily focused on the measurement's accuracy and precision due to the introduction of hydrogen in the transported gas [87]. However, hydrogen can also lead to adverse effects on the meters' construction material. Table 3 shows an example of construction materials for a commercial ultrasonic meter with a typical application for natural gas transmission lines custody transfer [78]. This example shows that the meter's body and flange can be made of either carbon steel, stainless steel, or duplex stainless steel. Carbon steels have been used for hydrogen service, though some carbon steels have been observed to experience material degradation in hydrogen service, with HE being the widely cited phenomenon.

The degree of HE susceptibility is impacted by factors such as microstructures, hydrogen partial pressure, and hardness [6]. Stainless steel, primarily austenitic stainless steel such as TP304L and TP316L (grades based on ASTM A312/A312M [66]) have been cited to be less susceptible to HE [10] and used for meters designed for hydrogen service [10]. Duplex stainless steels, on the other hand, can be susceptible to HE [10], though standards such as EIGA Doc 121/04/E [20] suggest it may be used in hydrogen pipeline components providing they are used at low stress.

Table 3 also shows that a meter's transducer mounts and holders can be made of stainless steels or nickel alloys. Nickel alloys (orifice plate material in Table 4) and material used in Coriolis meter in Table 4 are considered not acceptable for hydrogen service due to potential susceptibility to HE according to the *Non-Mandatory Appendix A – Precautionary Considerations* of ASME B31.12 [10]. ASME B31.12 [10] Non-mandatory Appendix A also suggests cast iron material (found in diaphragm meters in Table 4) is not acceptable for gaseous hydrogen service.

Another metallic material, aluminum alloys, can be found in various parts of meters shown in Table 4 such as in the body and rotor of a turbine meter as well as housing and pistons in a rotary displacement meter. As discussed in [6], there is little information about aluminum alloys' performance in the presence of hydrogen, but the existing data suggests that they are highly resistant to HE when exposed to dry hydrogen gas [10], [77]. However, if the gas contains

Table 3: Examples of a commercial ultrasonic meter of construction material (adapted from [78])

Meter Part	Examples of Construction Material
Body and flange	Carbon steel
	Stainless steel
	Duplex stainless steel
Transducer mounts and holders O-rings	Nitrile butadiene rubber (NBR)
Transducer mounts and holders	Stainless steel
	Nickel alloy

Table 4: Other examples of a meter's construction material, categorized by meter types

Meter Type	Examples of Construction Material	Reference
Orifice meter	Orifice plate: stainless steel, nickel and copper alloys, and carbon steel	[88]
Turbine meter	▪ Body materials – cast aluminum, cast steel, or steels ▪ Rotor – plastic or metal (aluminum)	[89], [90]
Rotary displacement meter	▪ Meter housing: aluminum alloy ▪ Pistons: aluminum alloy ▪ Synchronization wheels: stainless steel	[91]
Vortex meter	▪ Stainless steel ▪ Nickel alloys ▪ Forged carbon steel and cast carbon steel ▪ Duplex stainless steel	[92]
Diaphragm	▪ Housing: steel, aluminum, and cast iron ▪ Diaphragm: elastomers such as NBR	[93]
Thermal	▪ Housing: aluminum alloys ▪ Probe tube: stainless steel	[94]
Coriolis meter	▪ Stainless steel ▪ Nickel alloy ▪ Super duplex	[95]

water vapour, whether in pure hydrogen or a mixture of hydrogen and natural gas, it can lead to conditions that cause HE [10]. Notably, ASME B31.12 [10] does not specify a particular level of moisture content considered safe for the use of aluminum alloys in hydrogen service.

The non-metallic materials such as rubbers and plastics can also be found in meter components, as shown in Table 3 and Table 4. For instance, the O-rings of transducers in an ultrasonic meter and diaphragms of a diaphragm meter can be made out of NBR material, while plastic can be used as the rotor material of a turbine meter. Non-metallic materials are used not only in meters but also in various components of natural gas pipeline infrastructures, including compressors, seals, valves, actuators, and pipe materials. Elastomeric materials, such as NBRs, are also commonly used in components such as seals, gaskets, dispensing hoses. The material permeability, physical stability, frictional wear, rapid cycling effects, and material contamination are some of the concerns associated with exposing non-metallics to hydrogen [96]. There appears to be a lack of extensive information on these issues currently available, however, Melania *et al.* [30] indicates that polymers such as polyethylene, polyvinyl chloride, butyl rubber, polychloroprene, styrene-butadiene rubber, fluorocarbon, and NBR can have a good compatibility in hydrogen service, while other polymers such as natural rubber and silicone rubber may have a fair compatibility with hydrogen.

3.2 Standards, Codes, and Regulations

The discussions pertaining to materials, components, and hydrogen impacts in Section 3.1 mention various applicable standards and codes. These standards and codes include the CSA Z245 series, ASME B31.12 [10], ISO/TR 15916 [77], and CSA Z662 [4], which specify requirements for these materials and components based on the intended services. This section further compiles non-exhaustive lists of standards and codes as well as regulations relevant to hydrogen and hydrogen blending applications to provide material considerations when converting existing natural gas infrastructure into hydrogen or hydrogen blend service.

3.2.1 Relevant Standards for Hydrogen / Hydrogen Blending Applications

CSA Z662 [4], through Clause 17, provides additional provisions specific to hydrogen gas service, both for new and converted pipelines intended for hydrogen or hydrogen blend service. The standard requires operators to perform engineering assessments, which include various topics, such as material selection and pipeline design, addressing the potential adverse effects of hydrogen on pipeline materials. CSA Z662 [4] also cites ASME B31.12 [10] or IGEM/TD/1 Supplement 2 [97] as additional guidance for design, construction, testing, operation, and maintenance of pipelines for hydrogen service. In addition to CSA Z662 [4], other CSA standards are relevant to hydrogen and hydrogen blending applications, with a non-exhaustive list shown in Table 5. Specific to steel pipes, steel fittings, steel flanges, and steel valves, CSA Z662 [4] allows the use of components meeting the requirements of CSA Z245.1 [5], CSA Z245.11 [14], CSA Z245.12 [36], and CSA Z245.15 [43], respectively, with the standard providing additional provisions specific to the application such as natural gas service.

ASME B31.12 [10] is generally used as the standard for high pressure hydrogen pipelines. ASME B31.12 [10] Non-mandatory Appendix A also refers to EIGA Doc 121 [20] as a guideline to tailoring the metallurgy of carbon steels for hydrogen service and good practices for hydrogen gas pipelines. The Non-mandatory Appendix A in ASME B31.12 [10] provides precautionary considerations in the engineering design for hydrogen service, which are not obligatory unless explicitly stated otherwise in specific requirements within the standard. While ASME B31.12 [10] is cited in some country-specific standards worldwide, it does not appear to be mandated in regulations for pipelines containing hydrogen in any jurisdiction in Canada, as discussed in Section 3.2.2. In addition to ASME B31.12 [10], other non-CSA standards and codes relevant for hydrogen / hydrogen blending applications can be found in Table 6.

Some requirements of CSA Z662 [4] and relevant CSA Z245 series specific to natural gas service can differ from hydrogen service standards such as ASME B31.12 [10] further discussed in Section 3.3. The differences between ASME B31.12 [10] and CSA Z662 [4] should be identified and further evaluated to determine if alternatives exist, or engineering assessments can be conducted in lieu of meeting the hydrogen standards' prescriptive requirements. Additionally, other standards and codes such as ISO/TR 15916 [77], EIGA Doc 121 [20], and IFGC [16] provide considerations for hydrogen service such as materials deemed suitable for such service.

In the context of compressor materials, compressors intended for use with natural gas generally comply with the specifications outlined in API Std 617 [72] and API Std 618 [79]. However, the design and materials used in practice can differ among OEMs and specific applications may require additional requirements specified by the users. API Std 617 [72] and API Std 618 [79] include certain provisions concerning hydrogen service discussed in Section 3.1.3, which should be considered when modifying compressors originally designed for natural gas to be used with hydrogen or hydrogen blends. Compressor designs can vary significantly, and as such, operators should seek further evaluation from the compressor OEMs to ensure suitability for the intended application.

Table 5: Relevant CSA standards for hydrogen and hydrogen blending applications adopted in Canadian regulations

Standard	Latest Edition Publication Year
CSA Z662 [4] *Oil and Gas Pipeline Systems*	2023
CSA Z245.1 [5] *Steel pipe*	2022
CSA Z245.6 [105] *Coiled aluminum line pipe and accessories*	2021
CSA Z245.11 [14] *Steel fittings*	2022
CSA Z245.12 [36] *Steel flanges*	2021
CSA Z245.15 [43] *Steel valves*	2022
CSA Z245.20 [98] *Plant-applied external coatings for steel pipe*	2022
CSA Z245.30 [99] *Field-applied external coatings for steel pipeline systems*	2018

Table 6: Relevant non-CSA standards and codes for hydrogen and hydrogen blending pipeline system components

Standard	Publication Year	Country of Adoption	Material Requirements for H_2
ASME B31.12 [10] Hydrogen Piping and Pipelines	2019	International	Yes
EIGA Doc 121 [20] Hydrogen Transportation Pipelines Note: EIGA Doc 121 was prepared and intended for use by all International Harmonization Council members: AIGA, CGA, EIGA, and JIMGA, with regional editions of AIGA 033 [102], and CGA G-5.6 [103]	2014	International	Yes
IGEM/TD/1 Supplement 2 [97] High Pressure Hydrogen Pipelines	2021	UK	Yes Cites ASME B31.12 [10]
IGEM/TD/3 Supplement 1 [104] Repurposing of Natural Gas (NG) pipelines with MOP not exceeding 7 bar for NG/Hydrogen blends	2022	UK	Yes
IGEM/TD/13 Supplement 1 [105] Pressure regulating installations for Natural Gas/Hydrogen blended mixtures at pressures not exceeding 7 bar	2021	UK	Yes
ISO 23555-1 [106] Gas pressure safety and control devices for use in gas transmission, distribution and installations for inlet pressures up to and including 10 MPa — Part 1: General requirements	2022	International	Yes Up to 10% H_2
ISO 23555-2 [107] Gas pressure safety and control devices for use in gas transmission, distribution and installations for inlet pressures up to and including 10 MPa — Part 2: Gas pressure regulator	2021	UK	Yes Up to 10% H
ISO/TR 15916 [77] Basic considerations for the safety of hydrogen systems	2015	International	Yes
International Fuel Gas Code (IFGC) [16]	2021	UK	Yes
API Std 617 [72] Axial and Centrifugal Compressors and Expander-compressors	2022	International	Yes
API Std 618 [79] Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services	2016	International	Yes
ANSI/NACE MR0175/ISO 15156 [108] Petroleum and natural gas industries – Materials for use in H_2S-containing environments in oil and gas production	2021	International	No

Specific to pipe coatings, conversion into hydrogen service may also impact the coatings designed to meet the requirements of CSA Z245.20 [99] and CSA Z245.30 [99]. However, impacts of hydrogen on coatings are beyond the scope of this study but can be found in another CSA research report [100].

3.2.2 Canadian Regulations

Pipelines in Canada are regulated at the federal or provincial levels. Pipelines that cross provincial or federal borders are regulated at the federal level by the Canada Energy Regulator (CER). Pipelines that do not cross provincial or federal borders are regulated by provincial regulators. While federal and provincial regulations within Canada currently do not make specific reference to hydrogen or hydrogen blended pipelines, each typically incorporates CSA Z662 [4] by reference for design, construction, operation, modification, discontinuation, and abandonment of pipelines. The materials and components discussed in this report are addressed via references in CSA Z662 [4]; any technical gaps can be addressed exclusively by updates to the standards.

3.2.2.1 Federal Regulations

Federally regulated pipelines are required to adhere to the requirements of the Onshore Pipeline Regulations (OPR) SOR/99-294 [109]. While the OPR contains no specific reference to hydrogen or hydrogen blended pipelines, it states that design, construction, operation, or abandonment of pipelines that transport liquid or gaseous hydrocarbons must be in accordance with CSA Z662 [4]. CSA Z662 [4], through Clause 17, provides additional provisions specific to hydrogen gas service, both for new and converted pipelines intended for hydrogen or hydrogen blend service.

3.2.2.2 Provincial Regulations

Provincially regulated pipelines are required to adhere to the requirements of the provincial regulations outlined in Table 7.

3.3 Proposals to Address the Identified Gaps in Standards Supporting the Canadian Pipeline Framework

A list of gaps to be addressed based on the discussions in Section 3.1 and governing RCSs covered in Section 3.2 can be found in Table 8. The priority level assigned to each gap is based on the urgency, significance, and feasibility further discussed in sections 3.3.1 to 3.3.13. Differences in requirements between standards typically used to construct a natural gas pipeline system in Canada and hydrogen standards such as ASME B31.12 [10] exist. An exhaustive list of such differences is outside the scope of this study; however, some important differences are discussed in this section. Where ASME B31.12 [10] imposes more stringent requirements, CSA may consider evaluating whether these requirements are applicable for low hydrogen blend, low pressure pipelines, or both, resulting in low hydrogen partial pressures. This evaluation should specifically determine the threshold at which the hydrogen-specific requirements become relevant. High-priority gaps in Table 8 represent issues that impact a significant portion of Canada's existing natural gas infrastructure and/or can be potential showstoppers in hydrogen service conversion. Medium-priority gaps in Table 8, while important to accelerate the rollout of the hydrogen economy, may not be potential showstoppers and can be addressed through case-by-case engineering assessments.

3.3.1 Hydrogen – Natural Gas Blends at Low Hydrogen Partial Pressure

CSA Z662 [4] defines a hydrogen blend pipeline as a natural gas pipeline system when hydrogen has been added (Clause 17.3.2). The definition encompasses a broad range of hydrogen concentration in the hydrogen-natural gas mixture, from a trace amount of hydrogen to nearly pure hydrogen. Z662 [4] requires an engineering assessment prior to introducing hydrogen into an existing pipeline and also cites ASME B31.12 [10] or IGEM/TD/1 Supplement 2 [97] for additional guidance for hydrogen pipelines.

Table 7: Summary of Canadian provincial pipeline regulations

Province	Regulator	Act/Regulation	Description
British Columbia	British Columbia Energy Regulator (BCER)	Energy Resources Activities Act (SBC 2008, c 36) [110] / Pipeline Regulation (BC Reg 281/2010) [111]	No specific reference to hydrogen or hydrogen blended pipelines. Requires permit holders to design, construct, operate, maintain, deactivate, reactivate, or abandon in accordance with CSA Z662 [4]. Under Bill 37 Energy Statutes Amendment Act, 2022, the definitions of "energy resource" and "natural gas" per the Energy Resources Activities Act (formerly Oil and Gas Act) were added or changed to include hydrogen.
Alberta	Alberta Energy Regulator (AER)	Pipeline Act (Revised Statutes of Alberta 2000 c P-15) [112] / Pipeline Rules (Alberta Regulation 91/2005) [113]	No specific reference to hydrogen or hydrogen blended pipelines. Requires that permit holders design, construct, operate, maintain, deactivate, reactivate, or abandon in accordance with CSA Z662 [4].
Saskatchewan	Ministry of the Economy	The Pipelines Act (Statutes of Saskatchewan c P-12.1) [114] / The Pipelines Administration and Licensing Regulations (Statutes of Saskatchewan c P-12.1 Reg 2) [115] / Saskatchewan Pipelines Code (Directive PNG034) [116]	No specific reference to hydrogen or hydrogen blended pipelines. Requires that permit holders design, construct, operate, maintain, deactivate, reactivate, or abandon in accordance with CSA Z662 [4].
Manitoba	Manitoba Public Utilities Board	The Public Utilities Board Act (C.C.S.M. c. P280) [117], The Gas Pipe Line Act (C.C.S.M. c G50) [118] / The Oil and Gas Act (C.C.S.M. c O34) [119] / Drilling and Production Regulation (M.R. 111/94) [120]	No specific reference to hydrogen or hydrogen blended pipelines. The Public Utilities Board Act and Gas Pipe Line Act require adoption of relevant codes, rules, or standards prepared and published by the Canadian Standards Association. Order No. 178/19 requires that operators comply with CSA Z662:19 [121]. The Oil and Gas Act contains no specific reference to hydrogen or hydrogen blended pipelines and no reference to CSA or other standards. Regulations under the Oil and Gas Act apply to upstream (drilling and production) pipelines and flowlines; no reference was found to transmission or distribution pipelines.
Ontario	Ontario Energy Board / Technical Standards and Safety Authority	Technical Standards and Safety Act (S.O. 2000 c 16) [122] / Oil and Gas Pipeline Systems Code Adoption Document Amendment (FS-253-20) [123] / Oil and Gas Pipeline Systems (Ontario Regulation 210/01) [124]	No specific reference to hydrogen or hydrogen blended pipelines. Oil and Gas Pipeline Systems Code Adoption Document requires that companies comply with CSA Z662:19 [121].

Province	Regulator	Act/Regulation	Description
Quebec	Régie de l'énergie Québec	Regulation respecting petroleum exploration, production and storage licenses, and pipeline construction or use authorization (CQLR c S-34.1, r. 3) [125]	No specific reference to hydrogen or hydrogen blended pipelines. Requires that any authorization holder who designs, constructs, uses, maintains, or temporarily or permanently ceases to use a pipeline must comply with CSA Z662 [4].
New Brunswick	Nova Scotia Utility and Review Board	Pipeline Act [128] (R.S., c. 345, s. 1.) / Pipeline Regulations [129] (Nova Scotia) (N.S. Reg. 199/2004)	No specific reference to hydrogen or hydrogen blended pipelines. Requires that permit holders design, construct, operate, maintain, deactivate, reactivate, or abandon pipelines that transport liquid or gaseous hydrocarbons in accordance with CSA Z662 [4].
Nova Scotia	Ministry of the Economy	The Pipelines Act (Statutes of Saskatchewan c P-12.1) [114] / The Pipelines Administration and Licensing Regulations (Statutes of Saskatchewan c P-12.1 Reg 2) [115] / Saskatchewan Pipelines Code (Directive PNG034) [116]	No specific reference to hydrogen or hydrogen blended pipelines. Requires that permit holders design, construct, operate, maintain, deactivate, reactivate, or abandon in accordance with CSA Z662 [4].
Newfoundland and Labrador	N/A	N/A	There are no natural gas pipelines in this province [130]. The Petroleum and Natural Gas Act does not apply to onshore pipeline distribution [131].
Prince Edward Island	N/A	N/A	This province is not connected to a natural gas distribution system [130]. The Oil and Natural Gas Act does not apply to onshore pipeline distribution [131].
Northwest Territories	Office of the Regulator of Oil and Gas Operations	Oil and Gas Operations Act (SNWT 2014,c.14) [132]	No specific reference to hydrogen or hydrogen blended pipelines or CSA Z662. Several active pipelines in the Northwest Territories are regulated by the CER. A local distribution company is regulated by the Northwest Territories Public Utilities Board [130].
Yukon	N/A	N/A	This territory has no natural gas pipelines currently in operation [130].
Nunavut	N/A	N/A	This territory has no natural gas pipelines [130].

Table 8: List of gaps and recommendations for research and standardization

Gaps and Recommendations Topic	Priority	Addressed in Section
Hydrogen – Natural Gas Blends at Low Hydrogen Partial Pressure	High	3.3.1
Line Pipe, Fittings, Flanges, and Valves		
Charpy V-notch (CVN) Impact Tests	High	3.3.2
Material Hardness	High	3.3.3
Material Grade Based on SMYS	High	3.3.4
Ultimate Tensile Strength (UTS)	High	3.3.5
Station Piping		
Existing standards do not provide detailed guidance or prescriptive rules for blended natural gas-hydrogen station piping	Medium	3.3.6.1
Differences in design pressure calculations between CSA Z662 [4], ASME B31.3 [57], and ASME B31.12 [10]	High	3.3.6.2
Compressor Equipment		
Evaluation of hydrogen impacts on compressor parts materials	High	3.3.7
High yield strength and hardness materials in centrifugal compressors	High	3.3.8
High discharge temperature in reciprocating compressors	Medium	3.3.9
Construction material of compressor prime mover parts	High	3.3.10
Meters		
Evaluation of gas meter material's suitability for hydrogen service in addition to hydrogen impacts on meter measurement performance	High	3.3.11
Low stress gas meter application with materials deemed not acceptable by hydrogen standards	High	3.3.12
ASME B31.12 [10] and AMPP/NACE MR0175 [108] for gas meter applications	High	3.3.13

ASME B31.12 [10] excludes gas with less than 10% hydrogen by volume (PL-1.3), which suggests that the guidance does not apply to a gas mixture with less than 10% hydrogen. Meanwhile, IGEM/TD/1 Supplement 2 [97] suggests that no evidence confirms that blends containing up to 10% hydrogen by volume do not cause material degradation, although the standard considers the risk low [97].

From the material suitability standpoint, system pressure has also been shown to influence the hydrogen effects on pipe materials in addition to hydrogen concentration. Hence, hydrogen concentration by itself may not fully characterize the potential hydrogen effects, and it is the hydrogen partial pressure that should be used for the assessment of material applicability. Hydrogen has been shown to have adverse effects on carbon steel pipe material at low hydrogen partial pressures [73], [133], which could be the result of high system pressures and low hydrogen concentrations. Hence, low hydrogen concentration service can impose material integrity risks, but test data pertaining to hydrogen's adverse effects on pipe material at low hydrogen partial pressures is limited and currently considered a data and knowledge gap in the industry.

Recommendation

To address this gap, as further research is conducted, developing guidance on hydrogen blend service at low hydrogen partial pressure should be considered, including in future CSA Z662 editions. This guidance is crucial for the industry, especially during the initial stages of hydrogen rollout, where projects are likely to transport hydrogen blend at lower hydrogen concentration partly due to emerging hydrogen supply and demand factors.

3.3.2 CVN Impact Tests

Charpy absorbed energy, determined through CVN impact tests, is commonly used to approximate the material fracture toughness contributing to the material's resistance to cracking. Various standards, including API Spec 5L [3], ASME B31.12 [10], and CSA Z245 series, utilize CVN as an indicator of material toughness. Additionally, the IGEM/TD/1 Supplement 2 [97] mandates the use of Charpy absorbed energy for estimating fracture toughness in the absence of fracture toughness testing in hydrogen blend service. A gap in existing standards has been identified: despite the use of Charpy tests in these standards, including existing standards for hydrogen service, several studies have shown that the correlations between impact properties and fracture toughness for assessing hydrogen-assisted fracture are not appropriate [134], [135] indicating a gap between state-of-the-art research and existing standards.

Recommendation

To address this gap and to inform future updates of the relevant CSA Z662 [4] and CSA Z245 standards, CSA committees should consider assessing the suitability of using CVN as an approximation for material fracture toughness in hydrogen or hydrogen blend service. If CSA committees determine that using CVN is not appropriate for approximating material fracture toughness in such service conditions, they could consider proposing other methods, such as the crack tip opening displacement (CTOD) or single edge notch tensile (SENT) tests, to assist operators in assessing material compatibility with hydrogen. It is worth noting that both hydrogen standards cited in CSA Z662 [4] Clause 17 for further reference (i.e., ASME B31.12 [10] and IGEM/TD/1 Supplement 2 [97]) currently employ CVN for estimating material fracture toughness. If CSA committees determine that using CVN is appropriate, they should consider conducting a comparative analysis of the CVN requirements across these standards, further discussed in sections 3.3.2.1 to 3.3.2.3.

3.3.2.1 Base Metal

Specific for steel line pipe, CSA Z662 [4] Table 5.1 requirements for pipe body base metal align with CSA Z245.1 [5] clauses 8.4.3 and 8.4.4.2, which allow the use of the two categories (Cat. I and Cat. II) for gas service with the requirements for Charpy absorbed energy shown below:

- Cat. I – No requirements
- Cat. II – 27 J (OD < 457 mm), 40 J (OD ≥ 457 mm)

The minimum required Charpy absorbed energy described in ASME B31.12 [10] is dependent upon hoop stress, pipe wall thickness, and pipe diameter, but the calculated values tend to be lower than 20 J for hoop stress up to 60% of SMYS. Therefore, if Cat. II pipe is used, the requirement of ASME B31.12 [10] for minimum Charpy absorbed energy for the base metal can be lower (i.e., less stringent) than CSA Z662 [4] and Z245.1 requirements. However, if CSA Z245.1 [5] Cat I pipe is used, a comparison of impact properties with ASME B31.12 [10] will not be possible, and therefore material verification will be required.

Specific for fittings, CSA Z245.11 [14] Clause 9.3.4.1 requires a minimum Charpy absorbed energy of 18 J for carbon steel grades lower than Grade 359 and 27 J for Grade 359 or higher, based on full-size test specimens. For flanges, CSA Z245.12 [36] Clause 9.3.4.1 requires the minimum Charpy absorbed energy of 27 J for all sizes. Specific for valves, no minimum values are specified by CSA Z245.15 [43] but CSA Z662 [4] Clause 5.2.3.2 requires a minimum of 18 J for pressure containing valve parts having a grade lower than 359 and 27 J for a grade 359 or higher.

Recommendation

To inform future updates of the relevant CSA Z662 [4] and CSA Z245 standards, specific for the required minimum Charpy absorbed energy, further review of the appropriate minimum Charpy absorbed energy values for line pipe, fittings, flanges, and valves in hydrogen or hydrogen blend service should be conducted. This could be done, for instance, by comparing

- the material's measured Charpy absorbed energy,
- the minimum requirements specified by relevant standards, and
- the material's fitness for service through an engineering assessment (EA), which includes measuring fracture toughness using CTOD or SENT tests in a hydrogen environment.

Anticipatedly, additional data will surface as operators continue gathering information as part of the EA requirement outlined in CSA Z662 [4] Clause 17 when repurposing existing assets for hydrogen or hydrogen blend service. Once this new data becomes available, a prescriptive minimum Charpy absorbed energy requirement might be established.

3.3.2.2 Pipe Seam Weld and Heat Affected Zone

CSA Z245.1 [5] Clause 8.5 specifies the minimum Charpy absorbed energy requirements for pipe seam welds and heat affected zones (HAZ). For submerged arc welded pipe Cat. II, with a test temperature below -5 °C, the requirement is 18 J. For electric-welded pipe Cat. II, the weld zone of the pipe, with a test temperature below -5 °C, should have a minimum absorbed energy of 27 J for OD < 457 mm and 40 J for OD ≥ 457 mm. Additionally, a minimum of 18 J is required for the weld fusion line. In contrast, the ASME B31.12 [10] standard mandates a minimum of 27 J for Charpy absorbed energy for seam welds and HAZ through Cause PL-3.7.1 (-f). Therefore, line pipes manufactured to meet the minimum requirements of CSA Z245.1 [5] would not satisfy the B31.12 [10] requirements for the Charpy minimum absorbed energy (specifically the weld fusion line for electric-welded pipe).

Recommendation

To inform future updates of the relevant CSA Z662 [4] and CSA Z245 standards, specific for the required minimum Charpy absorbed energy, further review of the appropriate minimum Charpy absorbed energy values for welds and HAZ in line pipe, fittings, flanges, and valves in hydrogen or hydrogen blend service should be conducted. This could be done, for instance, by comparing

- the material's measured Charpy absorbed energy,
- the minimum requirements specified by relevant standards, and
- the material's fitness for service through an EA, which includes measuring fracture toughness using CTOD or SENT tests in a hydrogen environment.

Additional data will surface as operators continue gathering information as part of the EA requirement outlined in CSA Z662 [4] Clause 17 when repurposing existing assets for hydrogen or hydrogen blend service. Once this new data becomes available, a prescriptive minimum Charpy absorbed energy requirement might be established.

3.3.2.3 Girth Welds

CSA Z662 [4] for natural gas service, except for hydrogen or hydrogen blend service as outlined in CSA Z662 Clause 17, does not require the collection of Charpy absorbed energy data or the provision of minimum values for girth welds in pipelines. Consequently, the existing natural gas pipelines built according to the minimum requirements of CSA Z662 [4] for natural gas service may lack records of this crucial data and might not comply with provisions for hydrogen or hydrogen blend service in accordance with CSA Z662 [4] Clause 17 and hydrogen standards, such as ASME B31.12 [10]. CSA Z662 [4] Clause 17 Table 17.1 requires the operators to assess the suitability of fracture toughness on welds for the service and potential for HE (e.g., through Charpy testing), but provides no details on the requirements.

Recommendation

To inform future updates of CSA Z662 [4], CSA committees should consider providing details of the requirements for Charpy absorbed energy, including the minimum required values and locations (e.g., weld metal and HAZ). Similar to sections 3.3.2.1 and 3.3.2.2, this could be done, for instance, by comparing

- the material's measured Charpy absorbed energy,
- the minimum requirements specified by relevant standards, and
- the material's fitness for service through an EA, which includes measuring fracture toughness using CTOD or SENT tests in a hydrogen environment.

Additional data will surface as operators continue gathering information as part of the EA requirement outlined in CSA Z662 [4] Clause 17 when repurposing existing assets for hydrogen or hydrogen blend service. Once this new data becomes available, a prescriptive minimum Charpy absorbed energy requirement might be established.

3.3.3 Material Hardness

As discussed in a CSA research report on hydrogen's impact on pipelines [6], high hardness of steel can be indicative of martensitic (a type of crystalline) microstructure, which is the most susceptible steel microstructure to HE. Requirements for maximum hardness vary across standards, as discussed below.

In accordance with CSA Z245.1, the maximum permissible hardness in the pipe seam weld zone is 24 HRC for non-sour service (as stated in Clause 5.4.4.2). However, for grades equal to or greater than 483, the maximum allowed hardness is 30 HRC (as indicated in Clause 5.4.4.3). In the case of electric-welded pipe with an outer diameter (OD) of 323.9 mm or more, the maximum surface hardness in the pipe body is 225 Vickers Hardness (HV), while at the weld seam, it is 300 HV (as per Clause 11.5.7). For sour service applications, the weld metal and HAZ on the weld procedure qualification should have a maximum hardness of 248 HV (as outlined in Clause 16.3). Further, the maximum allowed hardness for the pipe body is 22 HRC (as specified in Clause 16.4), and for the electric-welded pipe weld zone, it is 248 HV (as detailed in Clause 16.5).

For fittings and flanges, there is a maximum hardness limit of 30 HRC (equivalent to approximately 293 HV) at any location, in accordance with CSA Z245.11 [14] (Clause 9.4.1) and CSA Z245.12 [36] (Clause 9.4.1). For valves, CSA Z245.15 [43] does not explicitly specify hardness limits for non-sour service conditions. In cases of sour service, the standard references other relevant standards such as ISO 15156-2 or NACE MR0175/ISO 15156-2 [108]. For procedure qualification welds in sour service, CSA Z245.15 [43] sets a maximum limit of 22 HRC or 250 HV (Clause 10.5), and 248 HV if the specification does not include post-weld heat treatment (Clause 10.6).

In contrast to the CSA standards discussed (CSA Z245.1 [5] , CSA Z245.11[14], CSA Z245.12 [36], and CSA Z245.15 [43]), hydrogen standards such as ASME B31.12 [10] impose more stringent hardness requirements. If the hardness exceeds 225 Brinell Hardness Number (BHN) (equivalent to 20 HRC and 227 HV), hot tapping on the line pipe is not permitted. The ASME B31.12 [10] hardness limit on production welds is 237 BHN (equivalent to 241 HV and 22 HRC).

Recommendation

To address the difference in requirements among these standards, specific for hydrogen service, CSA committees should further consider assessing and determining the steel hardness limits in future updates to CSA standards once the data becomes available through research.

3.3.4 Material Grade Based on SMYS

In non-sour service, CSA Z245.1 [5], CSA Z245.11 [14], and CSA Z245.12 [36] permit the utilization of materials up to specific grades: Grade 825, Grade 690, and Grade 690, respectively. However, hydrogen pipeline standards, such as ASME B31.12 [10], impose restrictions on the use of materials with SMYS exceeding 552 MPa (i.e., materials with a grade higher than Grade 550) due to the increased susceptibility of higher-strength materials to adverse effects caused by hydrogen [10].



"Existing Standards Do Not Provide Detailed Guidance or Prescriptive Rules for Blended Natural Gas-Hydrogen."

Recommendation

Operators, in collaboration with research organizations and standards development organizations like CSA and ASME, should conduct further assessments of the maximum SMYS limits. Additional testing of high-strength line pipe materials, including steels with grades exceeding Grade 550, in a hydrogen environment would be beneficial. This data can serve as a technical foundation for providing additional guidance applicable to the conversion of existing assets that employ high-strength steels, such as interprovincial natural gas transmission pipelines, into hydrogen or hydrogen blend service.

3.3.5 Ultimate Tensile Strength

ASME B31.12 [10] imposes limits on the material ultimate tensile strength (UTS) up to 758.4 MPa. On the other hand, CSA Z245.11 [14] and CSA Z245.12 [36] do not limit the maximum UTS, and CSA Z245.1[5] limits the maximum UTS to 1,145 MPa for steel Grade 825.

Recommendation

Operators, in collaboration with research organizations and standards development organizations like CSA and ASME, should conduct further assessments of the maximum UTS limits for hydrogen or hydrogen blend service. Testing of line pipe materials with UTS higher than 758.4 MPa in a hydrogen environment would be beneficial. This data can serve as a technical foundation for providing additional guidance applicable to the conversion of existing assets that utilize medium- to high-strength steels that may exceed 758.4 MPa UTS limits.

3.3.6 Station Piping

3.3.6.1 Existing Standards Do Not Provide Detailed Guidance or Prescriptive Rules for Blended Natural Gas-Hydrogen

CSA Z662 [4] Clause 17 identifies broad considerations for hydrogen blend pipeline systems, including additional considerations for facilities, but does not provide prescriptive rules in designing and operating hydrogen-natural gas blend station piping (e.g., station piping for fuel gas system transporting hydrogen-natural gas blend fuel within a compressor station).

Recommendation

After industry experiences have been established and more testing data are made available, consideration may be given to providing detailed guidance or prescriptive rules for station piping in hydrogen blend service in CSA Z662 [4], both for new built and converted natural gas assets.

3.3.6.2 Differences in Design Pressure Calculations between CSA Z662, ASME B31.3, and ASME B31.12 for Station Piping

One major difference between CSA Z662 [4], ASME B31.3 [57], and ASME B31.12 [10] is the pipe design pressure calculation used to determine the required minimum wall thickness. Each standard incorporates different variables into this calculation resulting in differing design pressure and wall thickness results: CSA Z662 [4] uses the unique variables of design factor *F,* location factor *L*, and joint factor *J;* ASME

B31.3 [57] uses the unique variable of weld joint strength reduction factor *W;* ASME B31.12 [10] uses the unique variable of hydrogen material performance factor M_f, which decreases with increasing pipe grade and pressure and may derate the pressure as much as 32.2%. Not only do the different calculations lead to varying results but also the different factors used for calculations may make it unclear to operators which standard should be applied in the design process of station piping containing hydrogen.

> **Recommendation**
> To address this lack of clarity, consideration should be given to providing explicit guidelines pertaining to the design of station piping containing hydrogen in future updates of CSA Z662 [4].

3.3.7 Evaluation of Hydrogen Impacts on Compressor Parts Materials

In addition to studies discussing the effects of hydrogen on compressor performance [87], it is also important to evaluate the effects of hydrogen on the materials used in compressors. This evaluation is necessary to ensure the integrity of the compressors. Currently, there seems to be a lack of research in this particular area, although OEMs are actively involved in ongoing research and development [136].

As mentioned in Section 3.1.3, the choice of materials for compressor components can vary depending on the specific application, OEMs, and sites. While standards in the industry, such as ASME B31.12 [10], have established guidelines for selecting materials suitable for hydrogen service in pipes, specific guidance for compressor applications in hydrogen/hydrogen blend service is lacking. Compressor operations often involve significantly different operating parameters compared to pipelines, such as higher temperatures (e.g., 165 °C [137]) compared to the typical operating temperature of pipeline system, which is generally close to the ground ambient temperature (e.g., -5 to 25 °C [74] except immediately downstream from the compressor).

> **Recommendation**
> To address the lack of guidance specific for materials of compressor parts subjected to typical compressor operating conditions, operators, OEMs, and research organizations should conduct a study which involves laboratory material testing under hydrogen environment and field pilot testing. This guidance, once established, might be incorporated into specific standards such as API Std 617 [72].

3.3.8 High yield strength and hardness materials in centrifugal compressors

As discussed in Section 3.1.3.1, API Std 617 [72] specifies provisions for materials in hydrogen service: specifically, the use of materials with a yield strength higher than 827 MPa (120,000 psi) or hardness greater than 34 HRC is forbidden when dealing with hydrogen gas applications with a hydrogen partial pressure surpassing 689 kPa (100 psig) or a hydrogen concentration exceeding 90 molar percent under any pressure. A 689 kPa hydrogen partial pressure corresponds to 8% hydrogen by volume in natural gas-hydrogen blend at a typical natural gas transmission pipeline pressure (8,275 kPag). Hence, for 8% or higher hydrogen blend, pipeline operators must evaluate material strength and hardness in compressors for hydrogen conversion. Below 8%, material suitability should still be evaluated due to observed HE in materials even at low hydrogen partial pressure [73].

> **Recommendation**
> Further guidance or alternatives to allow conversion of compressors designed for natural gas into hydrogen service, especially those not meeting these yield strength and hardness requirements, should be developed by standards development organizations such as API and CSA, in collaboration with OEMs and research organizations. This may involve looking at laboratory material testing in hydrogen environment as well as extended field pilot testing.

3.3.9 High Discharge Temperature in Reciprocating Compressors

As discussed in Section 3.1.3.2, API Std 618 [79] provides some guidance specific to high pressure hydrogen service such as predicted discharge temperatures shall not exceed 135 °C, which compressors designed for natural gas may exceed (e.g., maximum allowable discharge temperature of lubricated compressors can be as high as 165 °C [137]). An operator converting an existing compressor designed for natural gas may need to lower the high temperature limit to accommodate this requirement, which consequently reduces the compression ratio and system capacity.

Recommendation

Further guidance from API Std 618 [79] committees on this requirement would be beneficial for the industry to allow safe, reliable, and fit-for-purpose hydrogen conversion. This guidance may include discussion on which materials are less or more susceptible to hydrogen adverse effects specific to high temperature operations associated with compressor applications. Laboratory tests under hydrogen environment at high temperature or extended field pilot testing, or both may be required.

3.3.10 Construction Material of Compressor Prime Mover Parts

As discussed in Section 3.1.3.3, the compressor prime movers (e.g., natural gas engines and natural gas turbines) can be impacted by hydrogen, as the fuel for these prime movers is typically drawn off the pipeline which contains hydrogen in hydrogen or hydrogen blend service.

Most references assess the impact of the prime mover performance with hydrogen such as the emission impacts, power output, and potential operational issues (e.g., gas engine knocking), but do not specifically address the potential hydrogen impacts on the construction material within parts of the prime mover exposed to hydrogen [87].

Some common natural gas engines' parts utilize materials not recommended by ASME B31.12 [10] such as cast iron cylinders [81]. However, the standard focuses on hydrogen piping and pipelines, and it is not specific to gas engines. The conditions such as stresses and temperature that these materials may be subjected to in a gas engine could be different from those in a pipeline, such as significantly higher temperature (e.g., 600 °C [138]) in gas engines compared to pipeline applications that operate at 30 °C [74]).

Recommendation

To address this gap, guidance on materials commonly found in natural gas prime movers and their suitability for hydrogen service in the short and long term should be established by standards organizations such as API and CSA, in collaboration with OEMs and research organizations. Additionally, since current field pilot testing [139],[140] assesses the impacts of hydrogen in a short term (within hours), the long-term impacts of hydrogen on compressor materials are considered knowledge gaps and subject to further research, which may in turn inform the development of relevant provisions for standards. This may involve laboratory testing or extended field pilot testing, or both.

3.3.11 Evaluation of Gas Meter Materials' Suitability for Hydrogen Service in Addition to Hydrogen Impacts on Meter Measurement Performance

The CSA Z662 [4] standard does not include specific guidelines regarding the construction material for gas meters in hydrogen and natural gas-hydrogen blend service. Similarly, the ASME B31.12 [10] and ISO/TR 15916 [77] hydrogen standards do not discuss material specifications for gas meters, but they do provide a list of potentially acceptable and not acceptable materials for use in hydrogen service.

Discussions on the suitability of natural gas meters for hydrogen service in the literature have primarily focused on hydrogen impacts on the measurement performance [87]. As shown in Section 3.1.4, gas meter components can be made of materials susceptible to hydrogen adverse effects, which can impact the meter's integrity.

The body of knowledge in meter component materials' suitability continues to develop and prescriptive recommendations have yet to be established. Therefore, operators contemplating conversion of their existing infrastructure with gas meters that utilize material known to be susceptible for hydrogen adverse effects must evaluate the suitability of these materials on a case-by-case basis or completely replace the gas meters with purpose-built gas meters designed for hydrogen service. Due to the variation of materials in meters, it may be beneficial in some cases to directly replace the meters with H_2-suitable meters if the evaluation and testing are impractical.

Recommendation

Gas meter OEMs and research organizations should conduct a further evaluation concerning the suitability of meter materials for hydrogen service at various operating conditions (e.g., high and low pressure and high and low hydrogen partial pressure) in addition to assessing the hydrogen impacts on meters' measurement accuracy, which could serve as basis for future standardization.

3.3.12 Low Stress Gas Meter Application with Materials Deemed Not Acceptable by Hydrogen Standards

The existing natural gas meters at residential and industrial end-users typically operate at low pressure (as low as 35 kPag), likely exerting low stress on the components containing the gas within the meters. As shown in Section 3.1.4, these meter components can be made of cast iron material, which is deemed non-acceptable by ASME B31.12 [10] due to potential HE. As suggested by ISO/TR 15916 Annex C [77], a material subject to HE, even extremely embrittled, may still be used in hydrogen service if the service conditions allow its use (e.g., low enough stress).

Recommendation

Gas meter OEMs and research organizations should conduct a further evaluation and testing specific for the suitability of gas meters using materials deemed not acceptable by hydrogen pipeline standards for the low-stress applications, such as industrial and residential gas meters, which could serve as basis for future standardization.

3.3.13 ASME B31.12 and AMPP/NACE MR0175 for Gas Meter Applications

As reported by EPRI [141], prior to 2008 and publication of ASME B31.12, first edition [142], some hydrogen pipeline systems were designed to meet requirements for selection and qualification of materials for H_2S service in oil and natural gas production outlined in AMPP/NACE MR0175, which was last edited in 2022 [108]. Gas meters certified for sour service meeting the requirements of AMPP/NACE MR0175 are used in the industry. A study comparing the requirements of AMPP/NACE MR0175 [108] and ASME B31.12 [10], specifically on material hardness as a proxy of susceptibility to HE, shows that the requirements of the two standards are comparable [141].

Recommendation

Gas meter OEMs, in collaboration with research organizations, should conduct a research study assessing the material suitability of sour service gas meters for hydrogen service as well as the necessity of meter replacements when converting natural gas sour service facilities into hydrogen service. This study may be beneficial to help operators and standards development organizations (SDOs) determine if sour service assets should be prioritized for hydrogen conversion. Additionally, this may also provide considerations for operators and SDOs to use readily-available gas meters for sour service for hydrogen service.

4 Conclusions

Converting Canadian natural gas infrastructure into hydrogen or hydrogen-blend service requires assessments and may necessitate modifications. Pipeline components such as line pipe, fittings, flanges, and valves can be susceptible to hydrogen adverse effects. Various parameters, including hydrogen partial pressures, steel grade, hardness, SMYS, UTS, and fracture toughness, may influence the susceptibility to failures associated with a hydrogen environment. Other components within the pipeline system such as compressors, meters, and station piping can also be susceptible to hydrogen adverse effects.

Despite the potential adverse effects of hydrogen, transporting hydrogen through carbon steel pipelines is not a new concept. The use of purpose-built and converted hydrogen pipelines has been prevalent in North America and worldwide for several decades. Additionally, hydrogen blending pilot projects have also successfully deployed.

As of June 2023, Canadian federal and provincial pipeline regulations do not specifically reference hydrogen or hydrogen blended pipelines, but they do reference CSA Z662 for pipelines' design,

construction, operation, modification, discontinuation, and abandonment. The 2023 edition of CSA Z662 [4] includes additional provisions specific to hydrogen gas service through Clause 17 and references ASME B31.12 [10] as an additional guidance document.

Several gaps in standards, body of knowledge, and test data have been identified. To address these gaps, the study proposes the following considerations:

- Development of guidance on hydrogen blend service at low hydrogen partial pressure.
- Evaluation of the suitability of using CVN as an approximation for material fracture toughness in hydrogen or hydrogen blend service, and consideration of proposing alternative methods like CTOD or SENT tests if CVN is found unsuitable. If suitable, minimum CVN requirements in accordance with CSA Z662 [4] and CSA Z245 series for line pipe, flanges, fittings, and valves should be evaluated and compared with existing hydrogen standards such as ASME B31.12 [10].
- Determination of suitable hardness limits, SMYS limits, and UTS limits for hydrogen or hydrogen blend service as the technical basis for future updates to CSA standards.
- Development of detailed guidance or prescriptive rules for station piping in hydrogen blend service for consideration in future updates to CSA Z662 [4].
- Study to address the lack of guidance specific for materials of compressors and prime movers' parts subjected to typical compressor operating conditions. This study may include high yield strength materials and/or at high temperature.
- Further evaluation and development of guidelines pertaining to the suitability of gas meter materials for hydrogen service at various operating conditions, which include low stress, high stress, and/or sour conditions.

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