Gazifère Hydrogen Blending

Engineering Report

24 October 2022

Verified By: **Ahmed Nossair** P.Eng, CEng IMechE, PMP, MBA, M.Sc.
Director, New Energy Technologies - Technical

Approved By: **Tracey Teed Martin** P.Eng, MBA
Director, Engineering

Prepared By: *Stations & Low Carbon Transition Engineering*
Prepared For: *Gazifère Inc.*

Executive Summary

Gazifère Inc. intends to establish North America's first gas distribution network that is made up of 100% green and renewable energies. [redacted] As the hydrogen will be produced from clean hydroelectric power, blending of hydrogen into Gazifère's existing natural gas system is proposed to support its goal of decarbonization and fulfil provincial mandates to incorporate renewable gas.

This report was completed to evaluate system suitability for hydrogen blending and encompasses the entirety of Gazifère's gas distribution network in addition to its customers' natural gas piping, appliances and equipment. This engineering assessment broadly follows the methodology prescribed by *CSA Z662 Oil and Gas Pipeline Systems* when determining suitability of a change in service fluid. [redacted]

In light of the rapidly evolving state of affairs when it comes to hydrogen blending, it is imperative that the latest research, emerging codes and standards, and novel developments in materials, equipment and technologies be considered during detailed design and implementation of the proposed project.

This report is broadly divided into four interdependent areas of focus:

1. Gas Distribution Network and Customer Piping,
2. End-user Appliances and Equipment,
3. System Capacity and Operations, and
4. Pipeline System Integrity, Asset Health and Risk Review.

Gas Distribution Network and Customer Piping

Materials in the existing distribution system, stations and customer piping were reviewed for their compatibility with hydrogen blending. Some metals such as cast and black malleable iron, non-austenitic stainless steels and high-alloy steels are more susceptible to increased brittle failure under hydrogen exposure than other metals present in the system. Soft goods in elastomeric seals such as Buna-N may swell under hydrogen exposure and lead to increased wear or leak rates. Mechanical connections may experience increased leak rates due to the smaller size of hydrogen compared to methane. Overall, assuming the absence of existing material flaws, most of the existing materials in Gazifère are compatible with hydrogen, potentially up to 100 vol%.

End-use Appliances and Equipment

[redacted] A natural gas versus blended hydrogen-natural gas comparison ('interchangeability analysis') was performed to determine the maximum amount of hydrogen that can be blended into the existing natural gas stream without violating Gazifère's contractual requirements for gas quality, while simultaneously ensuring no adverse effects on combustion performance and emissions for end-use equipment. [redacted]

[redacted]

System Capacity and Operations

Due to the lower volumetric energy density of hydrogen compared to natural gas, hydrogen blending will result in an increase in total gas volumes to meet current customer energy demand. [redacted]

Pipeline System Integrity, Asset Health and Risk Review

[redacted] The embrittling effects of hydrogen on steel manifest primarily through a reduction in material toughness and a resulting increase in fatigue crack growth rates. The extent of this degradation is highly dependent on material microstructure, effective hydrogen partial pressure and material stresses (gas pressure, thermal, mechanical damage, geohazards, construction, etc.). [redacted] Current knowledge indicates that hydrogen is inert to plastic; however, there is limited validation of the long-term effects of hydrogen on plastic. Material testing and probabilistic studies will be required to ensure the deleterious effects of hydrogen on materials and existing flaws will not pose an unacceptable risk. Partial system replacement and upgrades may be required to mitigate these effects.

[redacted] Further risk assessments and testing will be required for the proposed pure hydrogen assets, in addition to understanding cross-sensitivity and suitability of existing stopping and tapping, leak detection and station equipment.

Recommendations

[redacted] **Any concentration of hydrogen in the HP and XHP gas networks will require studies, validation and testing to rule out concerns with hydrogen-induced failure and to identify the required mitigation.** [redacted]

[redacted] As such, although many portions of the existing network may be suitable for pure hydrogen service, the extent of required system changes exceed the scope for this report.

Table of Contents

[redacted]

Acronyms

The following is a list of acronyms found in this document and their definitions.

Acronym	Description
AGA	American Gas Association
AIGA	Asia Industrial Gases Association
ANSI	American National Standards Institute
API	American Petroleum Institute
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BMI	Black Malleable Iron
BNQ	Bureau de normalisation du Québec (*Quebec Bureau for Standardization*)
C&M	Construction and Maintenance (*Manual*)
CEPA	Canadian Energy Pipeline Association (*defunct*)
CER	Canada Energy Regulator (*formerly known as the National Energy Board*)
CGA	Canadian Gas Association
CNG	Compressed Natural Gas
CP	Cathodic Protection
CSA	Canadian Standards Association
CW	Continuous Welded (*Pipe*)
DBTT	Ductile-brittle transition temperature
DD	(*Heating*) Degree Day
DIMP	Distribution Integrity Management Program
DIN	Deutsches Institut fur Normung E.V. (*German Institute for Standardization*)
EFV	Excess Flow Valve
EGI	Enbridge Gas Inc.
EIGA	European Industrial Gases Association
ERW	Electric Resistance Welded (*Pipe*)
FCGR	Fatigue Crack Growth Rate
FIMP	Facilities Integrity Management Program
GHG	Greenhouse Gas
GWP	Global Warming Potential
HAZ	Heat-Affected Zone
HAZID	Hazard Identification
HF-ERW	High-Frequency Electric Resistance Welded (*Pipe*)
[redacted]	[redacted]
[redacted]	[redacted]
ISO	International Organization for Standardization
JIP	Joint Industry Project
LEGD	Legacy Enbridge Gas Distribution
LEL	Lower Explosive Limit
LF-ERW	Low-Frequency Electric Resistance Welded (*Pipe*)

[redacted]	[redacted]
MOC	**Management of Change**
MOP	**Maximum Operating Pressure**
MPET	**Materials, Parts, Equipment and Tools (*Catalogue*)**
MSS	**Manufacturers Standardization Society of the Valve and Fittings Industry**
NDE	**Non-Destructive Examination**
NG	**Natural Gas**
NPS	**Nominal Pipe Size**
NTS	**Nominal Tube Size**
NWT	**Nominal Wall Thickness**
O&M	**Operations and Maintenance**
PDR	**Planning, Design and Records (*Manual*)**
PEM	**Proton Exchange Membrane**
PIR	**Potential Impact Radius**
QRA	**Quantitative Risk Assessment**
R&D	**Research and Development**
RBQ	**Régie du bâtiment du Québec (*Québec Building Regulator*)**
Régie	**Régie de l'énergie du Québec (*Québec Energy Regulator*)**
ROW	**Right-of-Way**
SAE	**Society of Automotive Engineers**
SCADA	**Supervisory Control and Data Acquisition**
SCC	**Stress Corrosion Cracking**
SMYS	**Specified Minimum Yield Strength**
ST	**Steel**
TIMP	**Transmission Integrity Management Program**
UEL	**Upper Explosive Limit**
UNECE	**United Nations Economic Commission for Europe**
WIGA	**Working in a Gas Atmosphere**
WMZ	**Weld-Metal Zone**
[redacted]	[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Report Limitations

In light of the current gaps in hydrogen blending regulations and equipment certification standards within Québec and Canada, this report should be understood as a reflection of the latest knowledge and information available at the time of data extraction, review and publication. While some of the findings from this assessment may be applicable to other areas of the Enbridge Gas network, it is imperative that general extrapolations be avoided and that a case-by-case engineering assessment be conducted for hydrogen blending in other systems. Moreover, as hydrogen blending is a rapidly evolving field of research, the findings and recommendations of this report will need to be re-evaluated to ensure validity and application of the latest best practices during the detailed design of the proposed hydrogen blending assets and implementation process.

1. Background

In support of Gazifère's goal of becoming the first natural gas distributor in North America to offer a gas distribution network made up of 100% green and renewable energies, Gazifère is actively pursuing low or zero-carbon energy sources including renewable natural gas and hydrogen.

The Gazifère natural gas system is regulated by the *Régie du bâtiment du Québec* (RBQ) who has adopted the CSA Z662 *Oil and Gas Pipeline Systems* standard. In accordance with CSA Z662, a change in service fluid from natural gas to blended hydrogen-natural gas requires an engineering assessment to ensure fitness for service and continued safety and reliability. The injection and blending of hydrogen gas into the existing natural gas stream is intended to both reduce overall carbon emissions for Gazifère and its customers as well as diversify energy sources beyond conventional fossil fuel gas.

This engineering assessment is being completed to verify whether the system can withstand the proposed change in service fluid and to identify any required changes to the existing system design, construction, operations and maintenance.

[redacted]

This report contains the methodology that was followed and the results of an engineering assessment meeting the requirements of Clause 3.4 in accordance with the provisions of Clauses 10.3.2, 10.3.8, and 12.10.12 of CSA Z662-19. Additional references to the proposed draft edition of CSA Z662-23 (Version WD5 2021-12-14, herein referred to as the CSA Z662-23 draft) as well as non-mandatory global best practices are made where applicable.

2. Introduction

[redacted]

[redacted] Gazifère's natural gas distribution network and customers are regulated by the RBQ. Under Québec's Safety Code (code de sécurité, ch. 3) and Construction Code (code de construction, ch. 2), the RBQ has adopted, at the time of this report, the use of CSA Z662-2019 (*Oil and Gas Pipeline Systems*), and CSA B149.1-2020 (*Natural Gas and Propane Installation Code*) and B149.3 (*Code for the field approval of fuel-burning appliance and equipment*) as the governing standards for the pipeline network and end-use installation respectively (RBQ, 2022).

[redacted]

2.1 Gazifère Hydrogen Blending

In conjunction with the findings and methodology developed for the Markham hydrogen blending project, the engineering assessment for hydrogen blending in the Gazifère system is based on the latest code requirements for natural gas pipeline systems in Québec and updated R&D findings.

2.1.1. Hydrogen Percentage and Partial Pressure

Unless noted otherwise, throughout this report, hydrogen concentrations are presented as a volumetric percentage in natural gas from 0% (pure natural gas) to 100% (pure hydrogen gas). All stated pressures are given as gauge values (i.e. 0 kPa_g = ~101 kPa_a), 440 kPa_g = 541 kPa_a, etc.).

The impact of hydrogen is largely driven by its partial pressure in a blended natural gas-hydrogen mixture. The partial pressure of hydrogen is the pressure exerted by the hydrogen component and can be determined by Dalton's Law of Partial Pressures as follows:

$$P_{partial,H_2} = (vol\%\ H_2)(P_{total,mixture})$$

[redacted]

[redacted]

[redacted]

2.1.2. Engineering Assessment Methodology

[redacted]

[redacted]

[redacted]

Information reviewed as part of the engineering assessment process includes consideration of the following elements in **Table 2.3** which derive from Clause 10.1.1 of CSA Z662-19 and elements of CSA B149.1-20:

Table 2.3: *Considered elements for the Gazifère engineering assessment*

Element	Key Considerations	Report Section
Gas Network Design, Materials, Manufacturing, Construction and Testing	▪ Design basis ▪ Hydrogen compatibility of materials and design ▪ Manufacturing processes ▪ Construction and testing	4
End-User Equipment	▪ Applicable regulations for end-use equipment ▪ Types of end-use equipment ▪ Interchangeability of natural gas and blended hydrogen ▪ Limiting end-use factors and considerations	5
Physical Configuration and Constraints of the Pipeline System	▪ Flow and network capacity ▪ Potential hydrogen production and consumption ▪ Hydrogen uniformity ▪ Metering and billing considerations ▪ Potential reductions in carbon emissions	6
Pipeline Condition and Failure Mechanism or Mode; Historical and Expected Service, Operations and Maintenance	▪ Mechanism or mode of imperfection formation, growth & failure ▪ Pipeline condition and repair history ▪ Integrity reports and records ▪ Hydrogen-related safety considerations ▪ Hazards and consequences of failure	7

2.2 Scope of Engineering Assessment

This report is divided into four main areas that may be impacted by the introduction of hydrogen into the existing gas network:

[redacted]

2. Gas Distribution Network & Customer Piping (Section 4)
3. Customer Appliances and Equipment (Section 5)
4. System Capacity & Operations (Section 6)
5. Integrity, Safety, Asset Health and Risk Management (Section 7)

[redacted]

The following items are out of scope for this report:

- Construction planning
- Development/modification and adoption of standards, procedures, processes, etc.
  - If required, this will be completed at later stages based on the recommendations of the Engineering Assessment
- Out to construction (OTC) drawings, including:
  - Blended and pure pipeline design
  - Producer station and injection station designs

  - System retrofit and upgrade designs

2.2.1. Research and Development

[redacted]

A detailed literature review was performed to reflect the latest research findings from around the globe. [redacted]

[redacted]

2.2.2. Gas Distribution Network and Customer Piping

Section 4 covers the pipeline distribution system that is owned and operated by Gazifère as well as downstream customer piping. [redacted] The assessment scope ends at and excludes each customer's gas appliance and equipment. The gas distribution network, as described, is regulated by the RBQ and falls under the requirements of CSA Z662-19. Material compatibility of customer assets (piping installed to CSA B149.1-20 or prior editions) is included within the scope of this section as the materials used in both gas distribution and customer systems are nearly identical. Key considerations prior to introducing hydrogen into the natural gas network include:

- Material compatibility (metals, polymers, soft goods) of gas-carrying assets (pipe, fittings, flanges, valves, meters, regulators, etc.)
- Historical pipeline construction methods (joining, testing, inspection, etc.)
- Potential failure mechanisms or modes
- Material testing, inspection and validation

2.2.3. Customer Appliances and Equipment

Section 5 covers gas equipment and appliances that are owned by Gazifère's customers. Some appliances are owned and maintained by Gazifère as part of its appliance rental program. The assessment scope is limited to end-use equipment and appliances, beginning downstream of CSA B149.1 customer piping. The customer network and equipment are regulated by the RBQ and fall under the Safety Code, which refers to the requirements included in CSA B149.1-20 , for the installation of gas piping systems and appliances, and their associated product certification standard (e.g standards issued by the CSA group), or, in the case of field approved appliances, CSA B149.3 (uncertified appliances must be field approved by the RBQ using CSA B149.3 as the standard that must be met). Key considerations prior to introducing hydrogen into customer equipment include:

- Inventory of the types of residential, commercial and industrial gas equipment
- Gazifère's contractually allowable range for natural gas quality
- Combustion performance (interchangeability of natural gas and blended hydrogen-natural gas mixtures)

- Potential changes to safety, operability or reliability of gas appliances
- Equipment testing, inspection, refurbishment/recalibration and validation

2.2.4. System Capacity and Operations

Section 6 reviews hydraulic capacity and operating history for the Gazifère network. Key considerations prior to introducing hydrogen include historical and anticipated:

- Pressure cycling of pipeline systems
- Identification of optimal hydrogen blending location(s) and implications for hydrogen uniformity
- Metering and regulator capacity and tolerances
- Estimated hydrogen production capacity and seasonal variability in energy demand
- System reliability and redundancy
- Potential reductions in carbon emissions

2.2.5. Integrity, Asset Health and Risk Management

Section 7 addresses risk and integrity implications of blending hydrogen into the existing natural gas system. This portion reviews the following key topics:

- Failure and degradation modes of piping systems and the effects of hydrogen
- Types of pipeline imperfections and the impact of hydrogen on their behaviour and assessment acceptability criteria and repair methods
- System health based on condition records and asset health review
- Physical behaviour of blended hydrogen-natural gas mixtures such as gas release, ignition, fire, explosion and dissipation
- Leak detection and management, including odorization
- Location-specific risks based on material, building type, pressure, blend, etc.
- Risk Assessments
- Integrity and operational procedures

Additionally, high-level considerations for implementation and operational readiness (design, purchase, construction, operations and maintenance standards, processes and procedures) are presented. Formal recommendations for any required changes will be identified as part of the detailed engineering design and implementation phase.

The outcomes from the five report sections collectively feed into the permissible blending limit for the Gazifère system.

2.3 Safety & Financial Regulatory Context

Natural gas for the Gazifère system is imported from *Enbridge Gas Inc* (EGI) in Ontario via two interprovincial pipelines which are owned by *Niagara Gas Transmission Ltd*. (NGTL).

Piping within the EGI system that is located within Ontario is regulated by the *Ontario Energy Board* (OEB) and *Technical Standards and Safety Authority* (TSSA).

The interprovincial crossings and associated custody transfer facilities owned by NGTL are regulated at the federal level by the *Canada Energy Regulator* (CER).

The Gazifère system is entirely located within the province of Québec and regulated by the *Régie de l'énergie du Québec* (Régie) and the *Régie du bâtiment du Québec* (RBQ). [redacted]

[redacted]

[redacted]

In consideration of current regulations for natural gas or hydrogen piping systems in the province of Québec, the hierarchy and combination of some of the key reference standards or documents, as they apply to this engineering assessment, are illustrated in **Figure 2.6**:

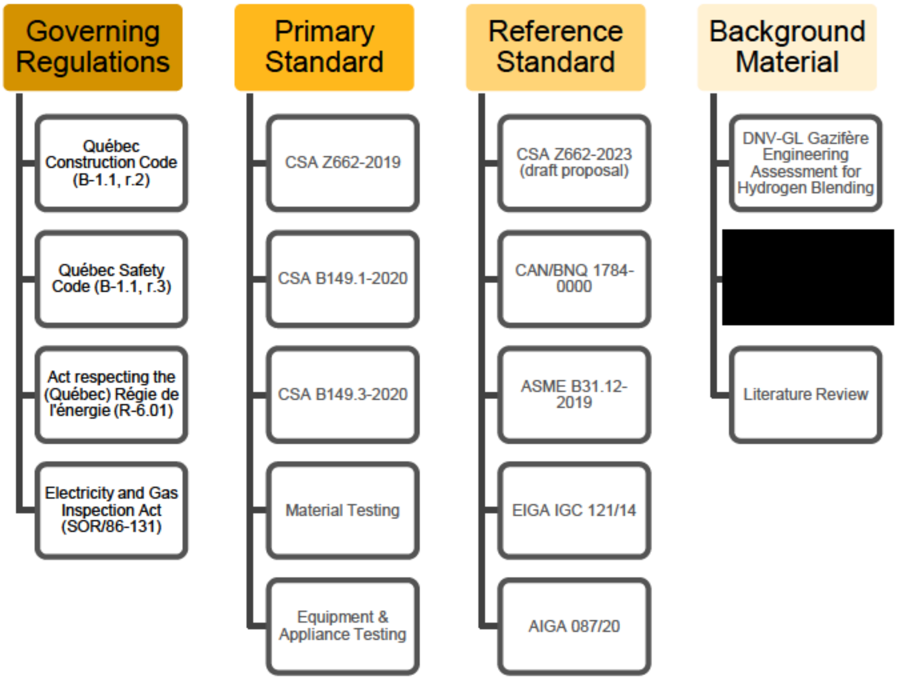

Figure 2.6: *Hierarchy of hydrogen standards, guidelines, research and industry best practices*

Primary Standards comprise codes that have been adopted for use by the RBQ and provide the basis upon which operators may conduct engineering assessments and/or testing to ensure fitness for service of existing pipeline systems.

Reference Standards are existing code documents which do not apply to Gazifère's system but have been adopted by other *Authorities having Jurisdiction* for use in similar contexts as proposed by Gazifère's hydrogen blending project.

Background Material refers to supplementary documents that do not have any regulatory force but can be considered a compendium of industry best practices, guidelines and state-of-the-art research in the rapidly evolving field of hydrogen blending. [redacted]

3. Conceptual Design

Design and operational requirements for the pure hydrogen producer station, pure hydrogen pipeline, hydrogen blending station, system retrofits and storage facilities will be determined as part of the detailed design phase pending decision records for this project. [redacted]

4. Gas Distribution Network & Customer Piping

This section reviews hydrogen compatibility for the existing pipeline distribution system (including mains, services and stations) as covered by CSA Z662. [redacted] Differences between what is allowed for CSA Z662 versus CSA B149.1 installations are identified where appropriate. [redacted]

4.1 Design Basis Review

[redacted]

This section reviews the original design basis for the system, highlights current CSA Z662-19 and CSA B149.1-20 code requirements for natural gas service and compares industry best practices and requirements from non-governing hydrogen reference standards from jurisdictions outside of Québec.

4.1.1. Service Fluid

Gazifère piping was originally designed to service sweet dry natural gas. End-users are similarly designed to accept pipeline-quality gas. Gazifère's contracted gas quality specifications are defined in M13 Schedule 1; this forms the basis for the gas interchangeability and system capacity reviews presented in Sections 5 and 6.

Guidance from CSA Z662-23 draft Clause 17.1.2 for hydrogen indicates that operators should consider the effects of hydrogen sulphide (H_2S), hydrogen service containing free-water, and liquid hydrogen transportation. The proposed hydrogen blending will not introduce hydrogen sulphide into the system such that the requirements of Clause 16 for sour service do not apply. [redacted] Both ASME B31.12 PL-1.3 and IGC 121/14 suggest a maximum moisture content of 1 lb/MMscf (-55°C dewpoint). For blended hydrogen-natural gas mixtures intended for combustion applications only (i.e. no fuel cells), current company limits for moisture may be considered acceptable for up to 50 vol% hydrogen in accordance with the ISO/FDIS 14687 standard. The proposed hydrogen will be transported in gaseous form; liquid hydrogen is not expected within the pipeline distribution system.

Any future hydrogen producer will be subject to pipeline-quality hydrogen gas specifications. [redacted]

While this report assumes SAE J2719 ('fuel-cell quality') hydrogen, lower purity hydrogen may be acceptable for residential combustion applications. Finalized requirements for hydrogen purity will be determined based on an evaluation of potential end-use applications, hydrogen production sources, and upcoming company hydrogen design standards.

4.1.2. Operating and Design Pressure Range and Stress Levels

[redacted]

[redacted]

CSA Z662 permits natural gas pipe design to a maximum of 80% SMYS with varying reduced upper limits depending on the location class. In comparison, ASME B31.12 PL-3.7.1 permits hydrogen pipe design to a prescriptive (Option A) or performance-based (Option B) method. In either case, pipe must not exceed 40% SMYS for a Class 4 location.

For CSA Z662 pipelines, class location requirements do not apply to plastic or steel distribution systems provided the hoop stresses in the piping are not greater than 30% SMYS of the pipe. Hydrogen has not been shown to reduce the minimum yield strength of steel (San Marchi, 2012) nor reduce the pressure-retaining capacity of polyethylene such that the basic hoop stress equation for pressure piping (Barlow's formula) is applicable; however, additional derating factors to account for the effects of hydrogen should be considered using ASME B31.12 PL-3.7.1 as a basis.

[redacted]

[redacted]

4.1.3. Operating and Design Temperature Range

[redacted]

[redacted]

[redacted] While conventional natural gas will drop in temperature in proportion to reductions in pressure, for pure hydrogen, the opposite is true; that is, the temperature of hydrogen will increase proportional to reductions in pressure.

[redacted] For natural gas mixtures containing up to approximately 80 vol% hydrogen, a reduction in pressure will continue to result in a reduction in temperature (Li J, 2021).

[redacted] The requirement for station heating will need to be evaluated on a case-by-case basis depending on the flows, pressure differential and Joule-Thomson coefficient for the blended hydrogen-natural gas mixture.

[redacted]

[redacted]

[redacted] The effect of hydrogen on DBTT is discussed in **Section 7**. The requirements for elevated temperature pipelines in CSA Z662 Clause 14 do not apply. The maximum design temperature of 43°C does not require temperature derating factors in either CSA Z662 Table 4.4 (for NG) or ASME B31.12 Table PL-3.7.1-3 (for H_2). There are no proposed or required changes to the design or operating temperature range in response to the proposed addition of hydrogen.

4.1.4. Anticipated Loading Conditions

[redacted] Addition of hydrogen may reduce pipe resistance to fatigue loading from vehicles, particularly in the case of vintage seam welds. [redacted]

High axial or bending stresses may be present because of poor construction practices or in response to historical geophysical conditions such as ground movement or earthquakes. Highly stressed areas of pipe may be more susceptible to hydrogen embrittlement. [redacted] The implications of potential hydrogen embrittlement are discussed in **Section 7**.

[redacted]

4.1.5. Valve Spacing

CSA Z662-23 draft Table 17.1 calls out the need to review sectionalization and valve spacing requirements, as well as minimum separation distances in response to changes in dispersion, flammability and explosion risk from hydrogen.

The behaviour of hydrogen-natural gas mixtures and associated change in dispersion, flammability and explosion are addressed in **Section 7.4.4**. **Table 4.3** compares minimum valve separation for natural gas and hydrogen systems as required by CSA Z662 and ASME B31.12 respectively.

***Table 4.3**: Valve spacing standards for natural gas and hydrogen pipelines*

Location	CSA Z662-19 Table 4.7 (for NG)	ASME B31.12-19 PL-3.15 (for H_2)
Class 1	Not specified	32 km
Class 2	25 km	24 km
Class 3	13 km	16 km
Class 4	8 km	8 km
Distribution	Not specified	Not specified

For distribution systems, current natural gas requirements in CSA Z662-19 Clause 12.4.13 require that valves be located to limit the time required to shut down a section of the line in an emergency, with consideration given to operating pressure, pipe size, local physical conditions, and the number and type of consumers affected.

[redacted]

4.1.6. Pipeline and Equipment Design Service Life

The presence of hydrogen in the pipeline system may result in degradation to piping and equipment, and thereby reduce their associated repair vs. replace lifespan. The exact impact is dependent on material properties, operating conditions and mitigating operational factors as discussed in **Section 7.1**. It is important to note that premature material degradation and failure is likely to manifest in the form of leaks which can generally be repaired. Therefore, while there may be an overall increase in O&M costs to manage leaks, overall service life of the materials themselves may be unchanged.

Enhanced integrity and asset management systems will be needed to properly monitor and mitigate potential reduction in service life of assets due to hydrogen. Requirements for increased leak survey are discussed in **Section 7**.

4.2 Materials and Design Review

Materials within the gas distribution and customer network were originally selected and purchased for natural gas service and therefore may not be compatible with hydrogen. This section reviews historical material specifications, current CSA Z662 and B149.1 code requirements for natural gas, and references hydrogen standards or best practices from other jurisdictions.

4.2.1. Pipe Specifications and Properties

[redacted]

[redacted]

ASME B31.12 is often referenced for the design of hydrogen distribution/transmission pipe, especially in North America where there are not yet other competing standards for hydrogen. CSA Z662-23 is expected to identify requirements for the design of hydrogen systems but has not yet been released. Upcoming revisions to API 5L are also expected to identify requirements for hydrogen service; pipe purchase specifications shall be updated upon the release of these standards.

ASME B31.12 currently allows use of CSA Z245.1, API 5L, ASTM A106, ASTM A179(M), ASTM A53, ASTM B88 and ANSI LC1 (CSA 6.26) pipe for hydrogen service; CSA B137.4 is not listed because the current standard does not include polyethylene pipe. [redacted] Similarly, IGC 121/14 recognizes plastic pipe and copper tubing for use in hydrogen systems but does not identify a requirement to conform to any particular standard.

Stainless steel is commonly included in assemblies of components and used as flexible tubing for sense lines. This tubing is not consistently identified on the drawings or specified by suppliers of component assemblies. A review of any stainless steel used in the system will need to be undertaken and where it cannot be confirmed as compatible with hydrogen, may need to be further evaluated.

Minimum Wall Thickness

[redacted]

[redacted]

ASME B31.12 recommends a minimum wall thickness of 6.4 mm to minimize the likelihood of severe mechanical damage. Considerations regarding mechanical damage are addressed in Section 7.4.5.

[redacted]

[redacted]

The minimum wall thickness requirement of CSA Z662-19 Clause 12.4.3 for polyethylene pipe is 2.3 mm for PE pipe intended for direct burial. [redacted] IGC 121/14 recognizes the use of polyethylene and does not specify a minimum wall thickness.

Minimum Pipe Grade

[redacted]

The prescriptive (Option A) approach in ASME B31.12 and in IGC 121/14 recommends the use of low-strength steels (x52 and below), whereas higher grades of steel must be de-rated to account for degradation in hydrogen service. [redacted]

Minimum Toughness

CSA Z662 Clause 5.22 specifies steel pipe body toughness requirements depending on operating stress and pipe size. [redacted]

[redacted]

[redacted]

Draft CSA Z662-23 Table 17.1 calls for consideration of hydrogen impacts to material properties, capability and changes to material toughness or susceptibility to cracking. [redacted]

[redacted]

[redacted]

4.2.2. Component Specifications and Properties

[redacted] CSA B149.1 for customer piping specifies that fittings shall conform to the applicable requirements of CSA Z662 or ASME B16 series, or alternatively be certified to ANSI LC-4/CSA 6.32 (*Press-connect metallic fittings for use in fuel gas distribution systems)*.

Table 4.6 summarizes potential component specifications based on historical company purchasing practices and approved materials from CSA B149.1, and identifies discrepancies (in red) compared to ASME B31.12.

[redacted]

***Table 4.6**: Listed component specification standards for natural gas and hydrogen pipelines*

Component	Specification	Approved for NG[7]	Approved for H_2[8]
		(CSA Z662-19 and B149.1-20)	(ASME B31.12 PL-2.2)
Fitting	CSA Z245.11	Y	**N**
	CSA B137.4	Y	**N**
	ASME B16.9	Y	Y
	ASME B16.11	Y	Y
	MSS SP-75	Y	Y
	MSS SP-79	Y	Y
	MSS SP-83	Y	Y
	MSS SP-95	Y	**N**
	MSS SP-97	Y	Y
	ANSI LC-4/CSA 6.32	Y (for customer piping only)	**N**
	ASME B16 series	Y (for customer piping only)	**N**
Flange	CSA Z245.12	Y	**N**
	ASME B16.5	Y	Y
	ASME B16.36	Y	Y
Valve and Pressure-Reducing Device	CSA Z245.15	Y	**N**
	CSA B137.4	Y	**N**
	ASME B16.34	Y	Y
	API 6D	Y	Y

ASME B31.12 does not recognize components manufactured to their equivalent CSA standards; as the requirements between CSA and ASME/MSS are very similar and considered nearly interchangeable under Canadian codes, these discrepancies are deemed acceptable and are expected to be addressed in future versions of CSA Z662. Similarly, ASME B31.12 does not currently recognize plastic components; IGC 121/14, which permits plastic hydrogen systems, does not identify specific specifications which need to be followed. ASME B31.12 precludes the use swage nipples and press-connect fittings manufactured to MSS SP-95 and ANSI LC-4/CSA 6.32 respectively which is believed to be related to leak risks associated with threaded connections. A review of joining methods and associated leak safety considerations is presented in **Section 4.4.2** and **Section 7.4**. Conversely, IGC 121/14 does not forbid the use of either component.

In addition to the aforementioned listed components, both CSA Z662-19 Clause 5.1.3 and ASME B31.12 GR-2.1.1 permit the use of unlisted materials provided they are reviewed by the operating

---

[7] CSA Z662-19 Table 5.3, Clause 12.5, or CSA B149.1-20 Clause 6.2

[8] A more extensive listing of approved materials can be found in ASME B31.12-19 Mandatory Appendix II

company to ensure their suitability for the intended use. [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

4.2.3. Non-Metallic Elements

[redacted]

- [redacted]

The non-metallic materials used in natural gas systems (CSA Z662-19 Clause 5.2.8 and CSA B149.1 Clause 6.9) are largely considered to be compatible for hydrogen service (ASME B31.12 PL-2.2.3). Studies have shown degradation of soft goods in the presence of hydrogen, such as swelling and increased permeation; however, the results vary substantially and are highly dependent on the proprietary resin, production process and manufacturer[redacted]

[redacted] Degradation of non-metallic elements is likely to manifest in the form of leaks. [redacted]

[redacted]

4.2.4. Equipment Specifications and Properties

[redacted] The choice of pressure vessel type depends on the final application, technical performance and cost competitiveness. Many failure modes, such as plastic deformation, buckling, creeping, fatigue, delamination, ruptures, cracks and ageing are considered in pressure vessel design; however, the primary issues for hydrogen pressure vessels from a material compatibility view are as follows (H.Barthélémy, 2011):

- Hydrogen embrittlement of steel
- Compatibility of metals and alloys with low temperature
- The permeation of hydrogen through polymeric liners

[redacted]

4.2.5. Gas Meters

[redacted] Rangeability of meters was not considered to be affected by the addition of hydrogen as volumetric capacity of a meter does not change with hydrogen assuming compatibility of the components. Systemic errors related to the compressibility of hydrogen were noted as the most affected part of measurement. The potential for systematic errors increases with pressure and hydrogen concentration. [redacted]

Measurement Canada released a draft policy (2022-Jul) for meters used in natural gas/hydrogen blending activities which outlined the requirements for adoption of hydrogen blends. It indicates that no additional considerations or changes are needed for up to 5 vol% addition of hydrogen. Beyond 5 vol%, *Measurement Canada* will require, at minimum, a *Certificate of Approval* be provided by an authority recognized by the *Engineering and Laboratory Services Directorate* or objective evidence. This evidence must demonstrate that integrity of the meters is maintained, and overall accuracy remains within tolerances prescribed by the applicable *Measurement Canada* specifications. Above 10 vol%, a revision of the meter's *Notice of Approval,* including calibration, may be required.

[redacted] It was noted that this error increases proportionally with pressure due to the difference in compressibility of hydrogen. Existing meter materials and measurement accuracy are considered compatible for up to 5 vol% hydrogen and no additional action is required. For blends between 5-20 vol%, a *Certificate of Approval* from *Measurement Canada* and updates to the company's meter calibration and maintenance standards and procedures are required. [redacted]

4.2.6. Branch Reinforcement

The requirements for mechanical reinforcement of branch connections are nearly identical between CSA Z662 Table 4.7 for natural gas and ASME B31.12 Table PL-2.3.2-1 for hydrogen. Of note, where operating stresses of a pipeline exceed 50% SMYS, ASME B31.12 specifies additional reinforcement considerations that differ from CSA Z662 but are identical to ASME B31.8 for natural gas systems.

[redacted]

***Table 4.7**: Branch reinforcement standards for natural gas and hydrogen pipelines*

Operating Stress (% SMYS)	Reinforcement per Nominal Branch/Run Size	
	CSA Z662-19 Table 4.7 (NG)	**ASME B31.12-19 Table PL-2.3.2-1 (H_2)**
≤ 20% SMYS	not required; consider if > 700 kPa MOP, thin-wall or severe external loads	not required; consider if > 690 kPa MOP, thin-wall or severe external loads
> 20% and ≤ 50%	< 25% - required, but not if ≤ 50 mm tap hole ≥ 25% to <50% - required ≥ 50% - full-encirclement	≤ 25% - required, but not if ≤ 50 mm tap hole >25% to ≤ 50% - required >50% - full-encirclement
> 50%		<=25% - required, but not if <=50 mm hole >25%, <=50% - required >50% - full-encirclement

Existing company requirements for branch reinforcement as well as minimum separation between adjacent branch connections meet the requirements of both CSA and ASME standards. [redacted]

4.3 Manufacturing Process Review

4.3.1. Classification of Steel Pipe

[redacted]

[redacted]

Differences in manufacturing and the resultant variations in mechanical properties are reflected by a joint (quality) factor which effectively serves to derate the maximum allowable pressure rating of a steel pipe. These factors are provided in **Table 4.8**.

***Table 4.8**: Joint quality factors for natural gas and hydrogen pipelines*

Seam Type	Joint Factor for NG (CSA Z662-19 Table 4.4)	Joint Quality Factor for H_2 (ASME B31.12-19 Table PL-3.7.1-3)
ERW	1.00	1.00
SMLS	1.00	1.00
CW	0.60	N/A

4.3.2. Vintage and Modern Steel Pipe

[redacted]

[redacted]

North American pipes manufactured and installed prior to the 1970s are generally termed vintage pipes (Leis, 2022); [redacted]

[redacted] All modern pipe which operates below 40% SMYS is compatible with hydrogen per ASME B31.12.

[redacted]

[redacted]

[redacted]

4.3.3. Classification of Polyethylene Pipe

Polyethylene resins are thermoplastic materials that can be re-melted and reformed without losing intrinsic properties. PE resins are classified based on their density. [redacted]

[redacted]

4.3.4. Vintage and Modern Polyethylene Pipe

[redacted] Compared to modern PE, vintage (Aldyl-A) pipe can experience a greater susceptibility to failure (Haine, 2014). MDPE materials are additionally differentiated as either unimodal or bimodal, where the latter type exhibits superior mechanical properties.

[redacted]

[redacted] Long-term effects of hydrogen on reduction in service life for PE is ongoing; the results from this research will be incorporated as applicable. [redacted]

4.3.5. Metallic and Non-Metallic Components

[redacted]

[redacted] As PE is inert to hydrogen, the preferred manufacturing method for plastic components does not change with hydrogen. A detailed review of all company purchase specifications shall be performed to ensure industry best practices for hydrogen service are followed.

4.3.6. Manufacturing Anomalies

It is possible for manufacturing anomalies to exist in new pipe and components. **Table 4.9** summarizes possible pipeline manufacturing anomalies which may be more prevalent in vintage materials:

***Table 4.9**: Typical manufacturing anomalies (Reproduced* from (Battelle, 2005))

Characteristic or Anomaly	Potential Integrity Impact	Comments
Fatigue cracks from cyclic stress created during shipment	Fatigue crack growth from in-service cyclic stress can result in a leak or a rupture	Most common in pipe with D/t ratios >70 produced prior to 1970. Can be detected by pressure test, inline inspection, or during field girth weld radiography.
High levels of impurities and non-metallic inclusions (i.e. dirty steels)	Laminations often near the pipe wall centreline can affect pipe strength depending on alignment	Not suitable for pipe in sour service. Can contribute to pipe production problems. Can produce inline inspection signals that may be confused with critical defects.
Hard spots	Potential in-service cracking if exposed to atomic hydrogen resulting in a leak or rupture	Susceptible to in-service diffusion and embrittlement by atomic hydrogen that occurs in sour service, high cathodic protection potentials and other service environments.
Foreign bodies rolled into the steel or plate/skelp surfaces	Cavity results if foreign body works free during service resulting in wall thickness reduction and possible leak	Foreign bodies can work free early in the life of a pipeline or during a hydrostatic pressure test. May be identified as corrosion metal loss by inline inspection.
Surface breaking anomalies (i.e. slivers, scabs, seams, etc.)	Minimal integrity concern. Possible site for preferential corrosion (uncommon)	Can adversely affect external coating integrity. Can produce inline inspection signals that may be confused with other flaw types.

[redacted]

Gas-carrying piping is generally required to pass initial quality examination or inspections during manufacturing, receipt and installation, and is pressure tested prior to service with the intent of detecting critical initial flaws that could pose a future threat. These types of anomalies and their behaviour in the presence of hydrogen are discussed in **Section 7.1**.

[redacted]

4.4 Construction and Testing Review

4.4.1. Methods of Installation

Hydrogen embrittlement is most apparent at areas with high localized stresses as discussed in **Section 7.1.6**. Such high stresses may be encountered due to:

- Cold bends: overbend/sag bend, trenchless installations, ripples/wrinkles/buckles
- Thermal changes: pipe expansion and contraction due to differences in ground and pipe temperature during installation, backfill and operations
- Ground deformation: geohazards including seismic activity, ground settlement, frost heave
- Water crossings: geohazards due to erosion and loss of restraint
- Restraints: pipe anchors, supports, weights, etc.
- Tie-ins: poor construction practices could result in pipes that are pulled or strained to ensure alignment/fit-up
- Existing flaws: stress concentrators such as arc burns, geometric deformations (dents), mechanical damage (scrapes, gouges) and linear indications (cracks)

Areas of high stress are not expected for customer piping given the stringent installation requirements of CSA B149.1. For distribution systems installed to CSA Z662, it is difficult to identify locations where high stresses may be present. [redacted] Additional considerations and risk assessment in case of hydrogen embrittlement are presented in **Section 7**.

[redacted]

[redacted]

[redacted]

[redacted]

4.4.2. Joining Methods

[redacted]

Current editions of CSA Z662 and CSA B149.1 permit the use of welded, fused or mechanically joined connections. The proposed draft CSA Z662-23 does not preclude the use of these joining methods provided that the potential for leakage is considered for hydrogen applications. It is not expected that the next edition of CSA B149.1 will diverge from CSA Z662-23's requirements for blended hydrogen systems. ASME B31.12 does not recognize fusion as plastic is not within its scope, while IGC 121/14 permits plastic fusion. As hydrogen will leak more readily from mechanical joints compared to natural gas, both ASME B31.12 and IGC 121/14 recommend the use of welded (including seal-welded mechanical) connections whenever practical. [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

In-Service Welding

Both ASME B31.12 PL-3.8 and IGC 121/14 Clause 9.7.2 restrict hot taps on steel pipelines with a wall thickness less than 6.4 mm. [redacted]

[redacted]

[redacted]

4.4.4. Fusion Requirements

As polyethylene is inert to hydrogen, current fusion practices are acceptable for hydrogen service. No changes are recommended for fusion of piping at this time. [redacted]

4.4.5. Mechanical Joining Requirements

Flanged Connections

[redacted] In accordance with ASME B31.12 Non-Mandatory Appendix A, A-9.1.2, above-grade flanged connections at stations should be leak checked periodically and retorqued as required. If leaks continue to persist, the sealing element should be replaced with a hydrogen-compatible material. [redacted]

Threaded Connections

[redacted] Whenever practical, consideration should be given to seal welding threaded connections. This decision should be made in consultation with Engineering to balance ease of maintenance versus leakage risks.

[redacted]

Interference-Fit Connections

[redacted] The addition of hydrogen is not expected to affect requirements for restraint (welded mechanical rods, soil load, etc.); however, potential swelling of the soft sealing element as discussed in **Section 4.2.3** may result in increased leaks and therefore warrants increased leak survey as discussed in **Section 8**. [redacted]

4.4.6. Minimum Depth of Cover

The minimum cover requirements for buried pipelines vary based on the design operating stress. The proposed draft Table 17.1 of CSA Z662-23 identifies a need to consider flammability, explosion and interference (third party damage) risks associated with blended hydrogen systems. The behaviour of blended hydrogen/natural gas systems and associated risks are discussed in **Section 7.4**.

The minimum cover requirements for new hydrogen pipelines in ASME B31.12 are generally less stringent than what is required by CSA Z662-19 for comparable new transmission pipelines. Conversely, it is important to note that ASME B31.12 was not originally developed for hydrogen distribution in utilities and as such, its cover requirements are greater than what is permitted by CSA Z662 Clause 12.4.7 for new natural gas distribution mains and services:

***Table 4.10**: Minimum cover requirements for new buried piping*

Location	< 30% SMYS NG Piping (CSA Z662-19 Table 12.2)	≥ 30% SMYS NG Piping (CSA Z662-19 Table 4.9)	H_2 Piping (ASME B31.12 Table 3.7.1-6, Class 4)
General	0.30-0.60 m	0.60 m	0.914 m
Agricultural			1.219 m[11]
Road/rail ROW	0.45-0.75 m	1.20 m	0.914 m or as required to resist superimposed loads
Below travelled surface, road	0.45-0.60 m	1.20 m	
Below base of rail, cased	1.20 m	1.20 m	
Below based of rail, uncased	2.00 m	2.00 m	
Water crossing	1.20 m	0.60-1.20 m	0.914 m
Drainage or irrigation ditch	0.75 m	0.60-0.75 m	0.914 m

IGC 121/14 recommends adequate cover to protect against agricultural operations, erosion and other surface activities. In both CSA Z662 and ASME B31.12, reduced cover may be possible subject to an engineering analysis of the relevant external loads such as would be encountered under a roadway or railway crossing (discussed in Section 4.1.4).

[redacted]

[redacted]

4.4.7. Crossings and Proximity to Other Facilities

[redacted]

The proposed draft Table 17.1 of CSA Z662-23 recommends consideration of the flammability, explosion and interference risks, as well as static discharge risk for powerlines in the vicinity of a

---

[11] For conversion of existing natural gas pipelines in agricultural areas, ASME B31.12 suggests a reduced cover of 914 mm (36 in.) may be considered

blended hydrogen pipeline. For new installations, ASME B31.12 specifies a minimum clearance of 457 mm; reduced clearance is possible where precautions are made to protect the pipe such as through casing, bridging or insulating material.

The behaviour of blended hydrogen/natural gas is discussed in **Section 7.4.4**. Research on these topics is ongoing. Static discharge risk and impacts to nearby vapour clouds need to be considered.

[redacted]

4.4.8. Visual Examination, Inspection and Non-Destructive Testing

The draft version of CSA Z662-23 is not expected to require additional non-destructive examination or inspection (NDE) of welds or fused joints for blended hydrogen systems. In comparison, ASME B31.12 requires a minimum of 75% of daily production welds to be inspected in class 4 locations.

[redacted]

[redacted]

[redacted]

4.4.9. Pressure Testing

Natural gas pipelines designed to CSA Z662 are required to be tested to a minimum of 1.25xMOP in class 1 and 2 locations, or a minimum of 1.4xMOP in class 3 and 4 locations. Distribution piping is generally required to be tested to at least 1.4xMOP; however, CSA Z662-19 Clause 12.8 makes allowances to omit strength tests and only perform leak testing in some cases. CSA B149.1-20 Clause 6.22 for customer piping generally requires leak testing only for working pressures below 230 kPa, or 1.5xMOP for higher working pressures.

The draft version of CSA Z662-23 is not expected to impose higher strength or leak testing requirements for hydrogen pipelines. In contrast, ASME B31.12 specifies a minimum test pressure of 1.5xMOP while IGC 121/14 defers to local code requirements (i.e. CSA Z662 for Gazifère). In addition, Table PL-3.6.1-1 of ASME B31.12 specifies MOP deratings in the case of changes in location class. The greatest limitation for Class 4 locations translates to a strength test pressure factor of 1.8x in order to preserve the current MOP of a system.

As noted in **Section 4.1.2**, class location does not apply to distribution systems. [redacted]

[redacted]

[redacted]

[redacted]

5. End-User Appliances and Equipment

This section reviews equipment suitability in blended hydrogen systems with a focus on the effects of hydrogen on combustion performance. Potential changes to material properties in the presence of hydrogen are addressed in the previous Section 4 and Section 7. This section also addresses the potential adverse effects of increased burner temperature on material properties and combustion performance.

5.1 Regulations

As indicated in **Section 2.3**, current Canadian and North American regulations do not cover requirements for end-use appliance and equipment in blended hydrogen-natural gas systems. As a result, Canadian regulations and relevant codes and standards committees for end-use equipment have thus far worked in collaboration with industry to lead recommendations to changes in the code for the adoption of hydrogen-blended fuels. As a result, there is currently no limitation or acceptance criteria for end-use equipment to be designed, operated or installed using pre-developed codes and standards aside from use in refineries in Canada. Committees and working groups have been developed within the Canadian Standards Association (CSA) and Standards Council of Canada at multiple levels to determine gaps in current codes and develop new standards for adoption; specifically, the CSA *Technical Committee on Energy Efficiency and Related Performance of Fuel-Burning Appliances and Equipment* (JB121) is working on determining field measurements for appliance efficiency and the *NRCan Roadmap – Hydrogen Standards Committee Working Subgroup* is working on developing gas appliance testing and acceptance criteria. Additional committees are working on this topic, including, amongst others, the CSA *Joint Gas Technical Committee Hydrogen Working Group* from the Z21/83 Technical Committee and CSA *Advisory Panel – Hydrogen Blending on in-service appliances*.

5.2 Types of End-Use Equipment

[redacted] While Gazifère operates a domestic rental appliance program, not every customer elects to purchase their equipment through Gazifère. In the case of large commercial and industrial customers, specialized equipment may be in use depending on the application. As a result, there is a wide range of equipment manufacturers, designs, combustion styles and end-uses. In place of surveying and assessing every piece of gas equipment in the network, end-use equipment was categorized based on combustion styles into four main categories of concern:

1. Partially pre-mixed combustion
2. Fully pre-mixed combustion
3. Nozzle-mixed (non-pre-mixed) combustion
4. Internal combustion engines

The design and operation of these general appliance and equipment categories are correlated important correlations important parameters that need to be considered in a change in service fluid, such as flame velocity, burner deck temperature, flame lift-off, flashback, engine knocking, etc.

5.2.1. Partially Pre-Mixed

[redacted] This burner type uses a venturi effect to draw combustion air into the gas stream prior to entering the burner; a secondary air source is then drawn to the combustion area of the burner by either convection in a natural draught appliance or by air pressure created by forced-draught blowers. Appliances using partially pre-mixed burners include furnaces, boilers, hot water heaters, cooking ranges and barbecues. This is illustrated in **Figure 5.1**.

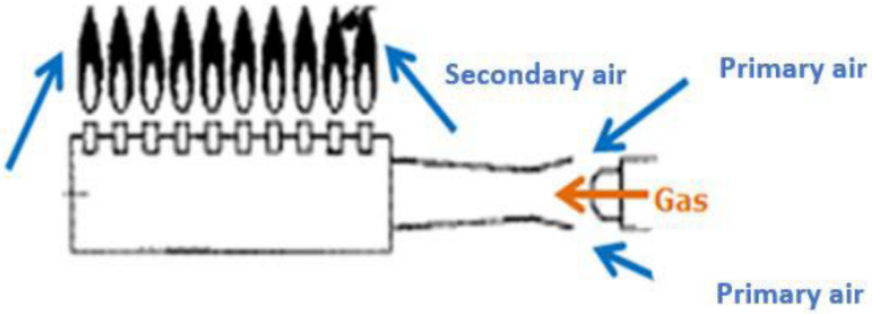

Figure 5.1: *Schematic for a partially pre-mixed burner*

5.2.2. Fully Pre-Mixed

[redacted] As shown in **Figure 5.2**, the flame happens in the face of the burner which is typically made up of a large surface area in either a cylindrical or flat shape. The combustion air for these appliances is pushed into the burner and mixed with fuel before it reaches the face of the burner where it is then ignited. Appliances using fully pre-mixed burners include high-efficiency hot water heaters and furnaces.

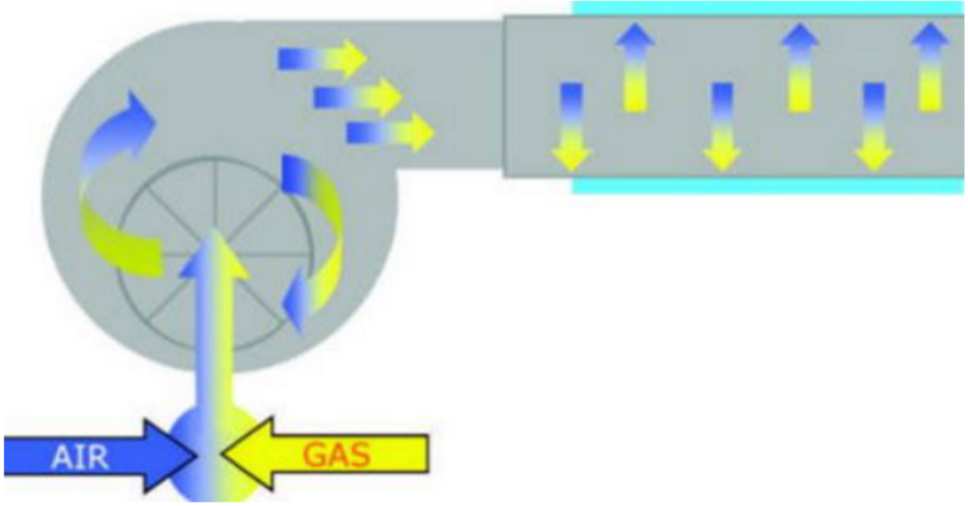

Figure 5.2: *Schematic for a fully pre-mixed burner*

5.2.3. Nozzle Mixed

[redacted] If industrial customers operate non-premixed burners, they are expected to be the nozzle burner type, which is the most common method of non-premixed combustion where fuel and combustion air are brought together in the combustion chamber at the flame tip as shown in **Figure 5.3**.

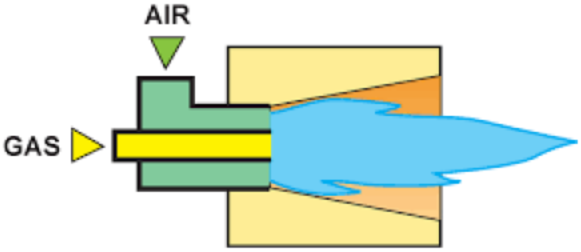

Figure 5.3*: Schematic for a nozzle (non-pre-mixed) burner*

The air and fuel mixture is typically controlled by a fuel system that monitors combustion properties and dynamically adjusts fuel-air ratios to adapt to the operational requirements of the connected system. These are often associated with large, customized processes with variable energy usage.

5.2.4. Internal Combustion Engines

[redacted] It is generally expected that at some level of hydrogen addition, engine knock will start to occur due to early ignition of the hydrogen. This can lead to failure of the engine as timing cannot be adjusted. Examples of internal combustion engines include home or emergency backup generators, natural gas vehicles and ice resurfacers ('Zambonis').

5.3 Gas Interchangeability Analysis

The current portfolio of end-use equipment in the Gazifère network was originally designed, tested, certified, installed and maintained for pipeline-quality natural gas (see Section 4.1.1). The introduction of hydrogen into the gas stream will therefore affect appliance performance and behaviour. In place of individually testing every piece of equipment, a gas interchangeability analysis was conducted for the four types of end-use equipment.

[redacted]

It should be noted that the following parameters that feed into the interchangeability analysis should not be considered in isolation; the ultimate suitability for hydrogen blending is based on the lowest allowable blend concentration from the outputs, including flashback, emissions, heating value, etc. as well as the safety and integrity considerations presented in Section 7.

5.3.1. Heat Input (Wobbe)

Wobbe Index or Wobbe number (W) is a ratio of energy (higher heating value, HHV) divided by the square root of the specific gravity (SG) of the combined gas:

$$W = \frac{HHV_{gas\ mixture}}{\sqrt{SG_{gas\ mixture}}}$$

This calculation has long been used to determine the interchangeability of various hydrocarbons within a natural gas stream as quantities of constituents may vary. This interchangeability parameter is used to compare how different mixtures of hydrocarbons are expected to perform during combustion and is preferred over just the heating value as it compensates for the change in gas volumes that can be sent through an appliance.

[redacted]

[redacted]

[redacted]

[redacted] It is important to note that the Wobbe Index is mostly recommended as a reference value and should be used in conjunction with other parameters such as risk of flashback and methane number.

5.3.2. Flashback

Flashback is mostly determined by the burning velocity of the fuel. Hydrogen has a much higher burning velocity (2.6-3.2 m/s) compared to methane (0.36-0.53 m/s) which results in a change in the position of the flame. As hydrogen concentration increases, the flame will move towards the burner tip causing an increase in burner temperature and potentially changing the air-mix ratio of partially pre-mixed appliances. [redacted]

[redacted]

[redacted]

[redacted]

5.3.3. Nozzle Mixed

Often associated with large, variable usages of heat energy in customized processes, nozzle-mixed burners are complex and as a result, its suitability for hydrogen can be difficult to determine. [redacted]

Catalytic conversion can also at times be considered a non-pre-mixed source use of fuel, since the conversion is based on the hydrogen molecule being separated from the carbon and combined with oxygen, it is not expected that blended hydrogen will affect operations of these units as chemically, the hydrogen is expected to continue to react to oxygen.

5.3.4. Internal Combustion Engines

Internal combustions engines represent a largely unknown risk as the effects of increased rate of combustion due to hydrogen addition are currently limited to a theoretical understanding. Actual engine performance will vary and will need to be validated with empirical data. [redacted]

5.4 End-User Emissions

5.4.1. Carbon Monoxide

Information published by the *Ontario Technical Standards and Safety Authority* states that the largest source of risk in apartments and private dwellings in Ontario is related to carbon monoxide (CO) release. Any natural gas burning appliance can be a potential source of hazardous CO levels. Domestic appliances that burn oil, kerosene, coal or wood, such as oil boilers, kerosene heaters and wood stoves, produce an irritating smoke that can alert a victim to a potentially hazardous situation; however, natural gas burns more efficiently and cleanly compared with these other fuels. In circumstances of poor maintenance, inadequate ventilation or faulty exhaust pathways, natural gas appliances may emit potentially harmful amounts of CO without any irritating fumes. In these cases, victims receive no obvious sensory warning that high CO levels are present.

[redacted] The effects of hydrogen on the fuel quality, burning characteristics and potential impacts on burner longevity were determined to be the most likely impacts of hydrogen on carbon monoxide risk for hydrogen-blended fuels in natural gas appliances. [redacted]

5.4.2. Nitrous Oxide Emissions

High combustion temperatures may result in the formation of nitrous oxides (NOx) which may act as precursors to smog, acid rain, global warming and ozone layer damage amongst other adverse health effects.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Provincial requirements for limits to NOx emissions vary widely depending on the type of industry and application. For example, pulp and paper mills have specific requirements for emissions (including flue gas velocity, opacity, etc. in addition to maximum concentrations of pollutants) that differ from natural-gas burning power production facilities. The specific regulations, acts and requirements that govern each of Gazifère’s industrial customers fall beyond the scope of this report. Given the unique nature of industrial installations, a case-by-case assessment will be needed before blending.

[redacted]

5.5 Limiting Equipment Factors and Mitigating Measures

5.5.1. Appliance Efficiency and Performance

Appliance performance testing relies on measuring flue gas composition to determine appliance function and can give an estimate of appliance efficiency when compared to initial manufacturer specifications. Hydrogen addition in natural gas will reduce the carbon dioxide volumes in the flue gas while possibly also affecting the available concentration of oxygen. These readings may falsely indicate to an operator to adjust fuel-to-air ratios in order to restore an appliance back into the manufacturers’ recommended ranges; however, this adjustment can render the appliance less efficient due to undesirable changes in the excess air in the flue. The CSA JB121 *Technical Committee* is working to create new standards for this adjustment of measurement.

5.5.2. Flashback

Flashback is considered the largest limitation in the adoption of hydrogen to existing residential/commercial equipment that was not designed for blended hydrogen fuels. [redacted]

[redacted]

5.5.3. Engine Knock

Engine knock is currently the most limiting factor to the adoption of hydrogen in internal combustion engines due to a lack of empirical data on the effects of blended hydrogen on engine performance. [redacted]

[redacted]

5.5.4. Compressed Natural Gas tanks

[redacted] CNG tanks are highly pressurized containers which should be individually evaluated for hydrogen compatibility or replaced.

According to UN/ECE Regulation No. 110 for CNG vehicles, hydrogen content is limited to 2 vol% if steel cylinders with an ultimate tensile strength exceed 950 MPa are present (UN/ECE, 2011). This limit is intended to mitigate safety risks associated with hydrogen embrittlement of high-strength steels (Section 7). The same limitation is indicated in ISO Standard 11439:13 and DIN 51624, which are international and German national standards respectively. It should be noted that many CNG and hydrogen tanks are made of identical (low-strength) steels. For hydrogen blending above 2 vol%, the presence of pressurized CNG storage tanks must be ruled out.

[redacted]

[redacted]

[redacted]

[redacted]

5.5.7. Licensed Gasfitters

Safety authorities are currently determining if changes to gas fitter training will be required. It is possible that changes to internal company processes and procedures will need to be communicated to the technical authority (RBQ) and adopted for gas fitters. It is not yet known if blends in small concentrations will require changes to gas fitter training or licensing. [redacted] Specific qualification requirements from the RBQ are currently undefined (RBQ, 2022).

[redacted]

[redacted]

[redacted]

[redacted]

6. System Capacity & Operations

This section reviews the operating history and implications of various hydrogen blending scenarios on the existing system from the perspective of hydraulic capacity, system reliability and operational requirements.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6.1.1. Pressure Drop with Blended Hydrogen

Addition of hydrogen into natural gas will result in a proportional increase to the total volume of blended gas due to differences in fluid characteristics as discussed in Section 6.3.2. For the same size of pipe, pressure (and capacity) losses will generally increase with the concentration of hydrogen until an inflection point near ~80 vol% hydrogen. This steady-state estimate is based on *Darcy's Law* and illustrated in **Figure 6.3**:

$$\Delta P_{loss} = -\frac{1}{2}\frac{\rho v^2 f}{D}\Delta x$$

where ΔP_{loss}, ρ, v, f, D and Δx refer to pressure drop, density of the blended gas (kg/m^3), average steady-state gas velocity (m/s), fanning friction factor, pipeline inner diameter (m) and hydrogen concentration (vol%) respectively.

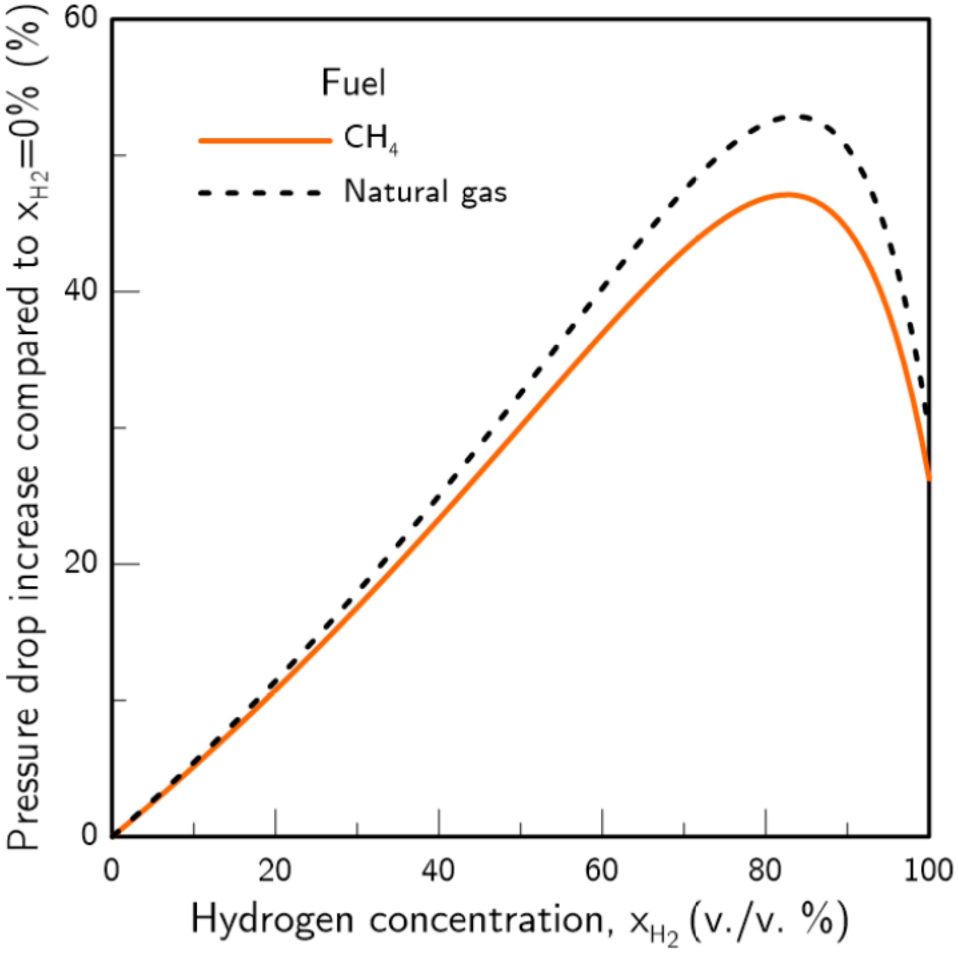

Figure 6.3: *Relative change in pressure loss as a function of hydrogen concentration in natural gas* (Quintino, 2021)

Without an increase in pipe size or operating pressure to counteract the pressure losses associated with hydrogen addition to natural gas, an existing system will see a reduction in total capacity. For example, a 10 vol% and 20 vol% hydrogen blend could see an estimated 5% and 10% increase in pressure drop respectively [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6.5.4. Station Equipment, Regulators and Reliefs

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6.7 Carbon Emissions Reduction

Due to the difference in energy density between natural gas and hydrogen (see Section 6.3.2), reductions in carbon intensity of the blended fuel gas will vary depending on the actual heating values of the two source gases. Assuming an average heating value of 38.3 MJ/m^3 and 12.7 MJ/m^3 for natural gas and hydrogen respectively, complete combustion of the blended fuel mixture is estimated to result in the CO_2 reductions shown in **Figure 6.20**.

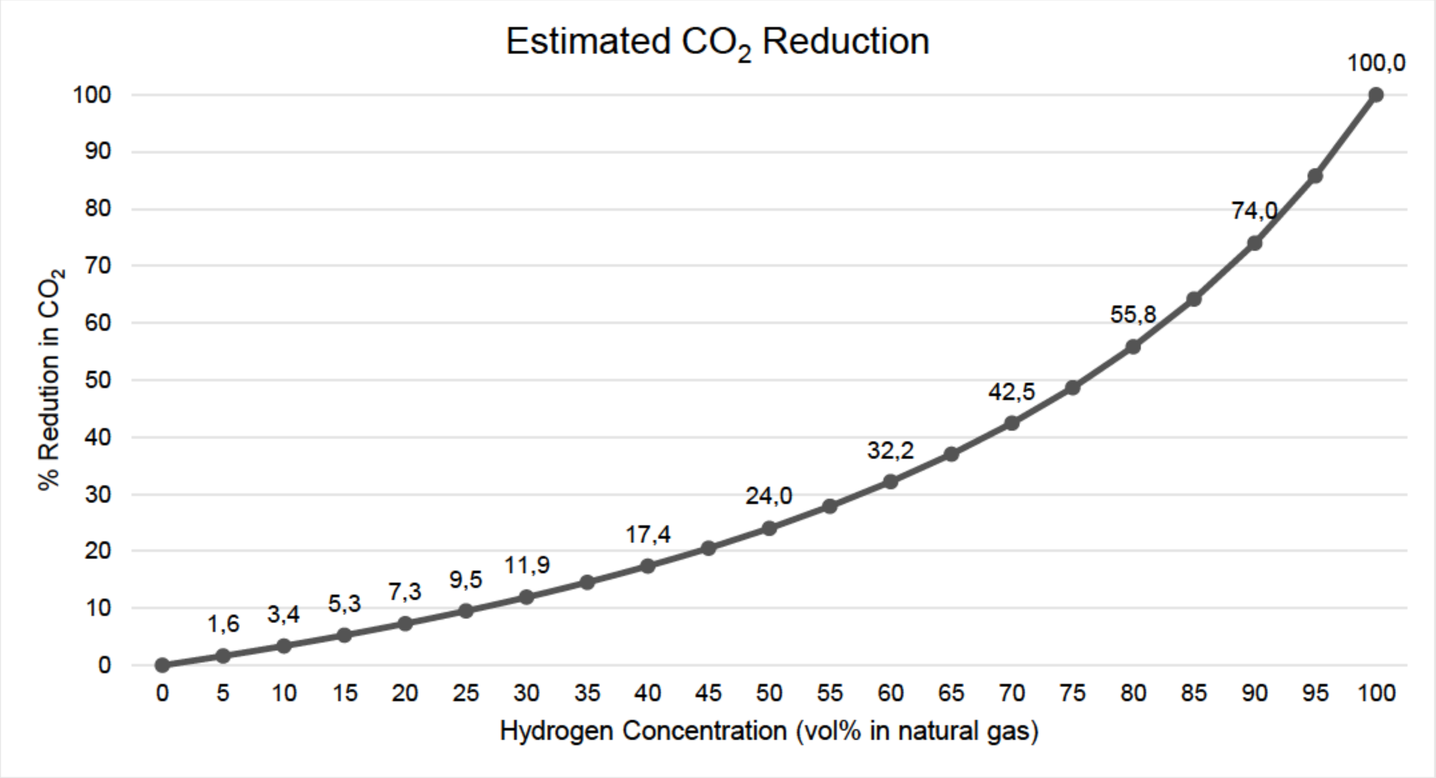

***Figure 6.20:** Estimated carbon dioxide reductions as a function of hydrogen concentration*

[redacted]

[redacted]

[redacted]

6.7.1. Global Warming Potential of Hydrogen

As discussed in Sections 4 and 7, the addition of hydrogen into the natural gas stream may result in a small increase in leakage rates due to the smaller molecular size of hydrogen relative to methane. There are currently no requirements at a provincial, federal or international level to designate hydrogen as a greenhouse gas (GHG); however, hydrogen can be considered an indirect greenhouse gas (Derwent, 2006).

When hydrogen leaks into the air, 70-80% is estimated to be removed via soil diffusion and bacteria. The remaining 20-30% of hydrogen is oxidized in the atmosphere with naturally occurring hydroxyl (OH^-) radicals which are also responsible for the breakdown of methane in the troposphere. As a result, hydrogen emissions will result in a longer atmospheric lifetime for existing methane in the atmosphere, as there are less hydroxyl radicals to break down the methane (Ocko, 2022).

It is important to note that any trace gas in the atmosphere can interact with incoming solar or outgoing terrestrial radiation and consequently pose global warming potential (GWP). Trace gases are termed as direct GHGs and direct radiatively active gases, or indirect GHGs and indirect radiatively active gases; indirect GHGs or indirect radiatively active gases act like their direct counterparts in that their presence in the atmosphere disrupts the global distribution of existing GHGs (Warwick, 2022). Natural gas (methane) has a GWP of ~21 whereas hydrogen, as an indirect GHG, has a GWP of ~6 (NRCan, Global warming potentials, 2019). Moreover, hydrogen is a short-lived atmospheric gas with a lifespan of only a few years.

The injection of hydrogen, with its lower GWP compared to natural gas, into Gazifère's existing gas distribution network, will result in a reduction in both Scope 1 (i.e. leaks and fugitive emissions) and Scope 3 (i.e. combustion and end-use) emissions. Clear regulations are needed to properly account for carbon intensity, CO_2-equivalent reduction and carbon trading credits.

Ultimately, while hydrogen blending presents an opportunity to decarbonize the existing natural gas grid, the need to effectively manage and eliminate Scope 1 emissions must remain a critical consideration to the design, construction, operation and maintenance of the network. Improved leak detection equipment, enhanced leak management programs and design for leak-tight joints (Sections 4 and 7) will all play a critical role in enabling Gazifère's drive to net-zero by 2050.

7. Integrity, Asset Health and Risk Review

7.1 Failure Mechanism or Mode

The effects of hydrogen embrittlement, swelling and deterioration of material performance, including requisite assessment of anomalies, response to identified defects and management of loading situations are presented in the following sections. [redacted]

7.1.1. Mechanism or Mode of Imperfection Formation, Growth and Failure in Metals

The primary failure mode of steel pipelines in hydrogen environments is expected to be hydrogen embrittlement (J.Song, 2014) (Piche, 2020). This failure mode is a function of lower fracture toughness, higher fatigue crack growth rate, and increased brittle area in the steel microstructure. Factors that could lead to embrittlement are high temperatures, pressure, operating stresses and hydrogen concentration (H.Barthélémy, 2011) (Piche, 2020). [redacted]

[redacted]

[redacted]

Ductile-Brittle Transition Temperature

Toughness properties of steel piping at low temperatures are adversely affected by hydrogen with the magnitude of reduction dependent on the thickness of the steel. Studies have found that the transition temperature shifts towards a higher temperature in a hydrogen environment if the sample is sub-sized, though no change was observed for full-size specimens (Kpemou Apou Martial, 2022). Similar findings were reported by (P. Fassina, 2012).

[redacted]

7.1.2. Mechanism or Mode of Deterioration of Non-Metallic Materials

[redacted] The exact effects on non-metallic materials including swelling, permeation and leakage are under active research.

A summary of the effects of hydrogen on the non-metallic components expected within the Gazifère system is provided below. Their acceptability for hydrogen blending is discussed in **Section 4**. The expected failure mode for these components is leakage or a deterioration in performance. In general, non-metallic materials are mostly found above-ground and outside of buildings and are subject to regular inspections in accordance with company operating standards. In the event of a failure, they are relatively easy to repair or replace. [redacted]

Plastic Pipe and Components

Plastic pipe and fittings are generally found to withstand the effects of hydrogen exposure without any notable degradation mechanisms since plastic is inert to hydrogen. Hydrogen has shown no effect on tensile, creep, ductile properties, and slow crack growth fatigue (**Appendix II**). Although hydrogen is more permeable than methane in polymers (see **Section 7.4.3**), plastic piping is not expected to fail.

Soft Goods

Soft goods may be subject to increased degradation in hydrogen service (**Appendix II**). Buna-N, nitrile and Viton rubbers may experience reversible swelling, increased friction and permanent deformation when exposed to hydrogen; however, some studies have shown conflicting results which suggest improved sealing as well as irreversible swelling in hydrogen (Byrne, 2022). The variability in performance of soft goods is posited to be related to differences in manufacturing and source materials. Hydrogen-induced swelling of soft goods may result in premature degradation and increased maintenance. Most soft goods used for natural gas service are generally acceptable for use in hydrogen blending; however, Delrin and silicone rubbers in particular may no longer provide effective sealing.

In fabricated components such as valves, hydrogen will leak more readily than methane through valve packing; this can be reduced through improved designs including double seals and graphite packing (**Appendix III**).

7.1.3. Types of Imperfections

The most common modes of failure or degradation for natural gas steel pipelines, along with the implications of hydrogen blending are presented below. Recommended changes to acceptance criteria are provided in **Section 7.2.4**.

Corrosion

Corrosion is the degradation of metal due to electrochemical reaction with the surrounding environment. This deterioration gradually creates metal loss by oxidation followed by rust.

Research suggests corrosion can act as a preferential site for hydrogen dissociation and absorption into the pipe wall which could increase likelihood of embrittlement and crack formation (**Appendix I**).

[redacted]

Stress Corrosion Cracking

[redacted] If SCC were to occur, the most likely locations would be those of high localized stress, such as areas of mechanical damage or ground deformation/movement.

Cracks and Crack-Like Features

Cracks and crack-like features can focus the effects of and expedite hydrogen embrittlement. Cracks can occur in the pipe body, long-seam or girth welds. Localized stress and hardness are conditions that can result in preferential formation of cracks.

An important consideration for cracks and crack-like features is the fatigue crack growth rate (FCGR). This is the amount by which a given flaw will increase in size under a particular set of pressure-cycling conditions. FCGR is highly dependent on material properties and pressure conditions for axial flaws. [redacted] Conditions could occur where cracks might initiate when they otherwise would not have in natural gas service such as areas of high localized stress or hard spots.

Another consideration is the effect of the reduction in material toughness on the behaviour of possible pre-existing crack-like flaws. Crack propagation is highly dependent on toughness properties. A reduction in toughness can increase the likelihood that a crack-like feature will propagate and eventually cause failure. [redacted]

[redacted]

Further study into the effects of embrittlement and reduced toughness on the behaviour of potential cracks in the system is required before blending hydrogen.

Geometric Deformations

The effects of hydrogen are amplified in areas of high local stress. Geometric deformations (dents) could provide preferential sites for higher hydrogen absorption and embrittlement. As with natural gas service, rounded dents are less of an integrity concern than sharp dents or dents with interacting features.

Ripples, Wrinkles and Buckles

[redacted] Similar to dents, these features have been found to increase susceptibility to failure because they act as a stress concentrator, and the increased strain can concentrate hydrogen absorption and cause embrittlement.

Mechanical Damage

Along with wall loss, mechanical damage (gouges, grooves, scrapes) can have thin layers of cold-worked, crack-susceptible microstructures in addition to being an area of greater localized stress which increases potential hydrogen accumulation and embrittlement. Mechanical damage may be associated with inadvertent third-party excavation damage or poor pipeline installation practices. Gouges may be associated with dents.

[redacted]

Arc Burns and Hard Spots

Arc burns are a localized condition or deposit that is caused by an inadvertent contact with an electric arc. The feature consists of a combination of re-melted metal, heat-affected metal and change in surface profile. Under high stress conditions, these localized hard spots can lead to crack formation. The hard microstructures associated with arc burns are susceptible to hydrogen-induced cracking in the presence of atomic hydrogen.

Welding, Fabrication and Construction Flaws

Welding is the most common metallic joining method and is a significant part of the pipe fabrication process; however, poor welding practices can create issues which may have a detrimental effect in the presence of hydrogen. **Table 7.1** lists the most common fabrication-related flaws and their causes:

Table 7.1: *Common fabrication-related flaws*

Flaws Type	Causes
Spatter	High current, incorrect polarity, insufficient shielding
Porosity	Presence of moisture, rust, grease, paint, etc.
Undercut	High arc voltage
Distortion	Inaccurate welding procedure and sequence, e.g. too many thin beads, insufficient clamping, etc.
Cracks	Thermal stress, brittle weld surface
Incomplete Penetration and Fusion	Incomplete fusion of weld (ST) or fusion (PE) joint and/or filler material
Slag inclusion	Entrapped flux inside the weld
Brittle weld	Improper heat treatment
Arc Burn	Electrode contacting the body of the pipe, outside of the weld area. Creates localized hard spots.

[redacted]

[redacted]

[redacted]

7.1.5. Potential Presence and Significance of Undetected Imperfections

[redacted]

The embrittlement effect of hydrogen on steel components makes it possible that if there are any very large currently existing flaws, they would likely fail sooner than they would have otherwise. [redacted]

[redacted]

7.1.6. Additional Threats

Geotechnical Threats and High Localized Stresses

Geotechnical threats such as seismic activity, river meander/scour, shifting/sliding slopes or poor backfill conditions can introduce localized areas of high stress and strain on pipelines (**Section 4.4.1**).

High-stress areas are more susceptible to the effects of hydrogen. [redacted]

---

[22] Spike testing is a type of pressure testing that can be used to requalify an existing pipeline to ensure the absence of surviving time-dependent flaws that might otherwise grow during operations.

Time-Dependent Material Degradation

Time-dependent material degradation is a concern for material in hydrogen service. The presence of hydrogen may adversely deteriorate materials over time and render them vulnerable to failure such that acceptable imperfections in natural gas may become defects in hydrogen blending service. Three time-dependent features of concern are (1) fatigue, (2) reduction of toughness and (3) microstructural response to hydrogen permeation.

[redacted] As discussed in Section 6.1, historical operations from SCADA indicate benign pressure cycling which marginally shifts the shape of the S-N fatigue curve. While hydrogen increases fatigue crack growth rate, FCGR is a function of stress, temperature, hydrogen partial pressure, and time (San Marchi, 2012)[redacted]

[redacted] Reduced toughness implies that existing flaws may propagate at lower stress and result in unexpected failure that would not have otherwise occurred in natural gas service. The fracture toughness reduction is related to service temperature and pressure (Thanh Tuan Nguyen, 2021) (San Marchi, 2012). [redacted] Lower operating pressure and hoop stress may reduce the magnitude of reduction in toughness. [redacted]

[redacted] When hydrogen is introduced into the network, it permeates into the steel depending on the partial pressure and can impact the overall material properties. Eventually, hydrogen transforms the fracture mode from ductile to brittle which increases the possibility of failure by rupture rather than leak. Critical factors affecting this behaviour are temperature, pressure, load, and hydrogen concentration (Thanh Tuan Nguyen, 2021). [redacted]

External Loads and Dynamic Effects

Additional stress and strain act as concentrators for the effects of hydrogen. Situations of additional loading and dynamic effects could lead to increased embrittlement and hydrogen-assisted failure.

[redacted]

[redacted] Pipe material, thickness and crossing depth are selected to meet these requirements.

[redacted]

[redacted]

7.1.7. Classification of Defects

[redacted] The code requires that imperfections in the system be assessed and provides acceptance criteria for varying types of imperfections. [redacted]

[redacted]

Sharp Features and Geometric Deformations

Assessment calculations for crack-like features are highly dependent on toughness and would warrant consideration of reduced toughness due to hydrogen embrittlement. ASME B31.12, also provides acceptance criteria for anomalies specifically in hydrogen service. Many of the criteria are similar to those in CSA Z662, but some are more conservative, particularly regarding dent strain limitations. [redacted]

[redacted]

[redacted]

Welding, Fabrication and Construction Defects

[redacted] A review of company purchase specifications must be undertaken to ensure suitability for hydrogen.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

7.2.2. Cathodic Protection Records

Cathodic protection (CP) is an effective prevention method for corrosion. CP is applied to steel piping through a sacrificial anode system or an impressed current system with rectifier and anodes. [redacted]

Applying CP requires attachment of copper wire leads through thermite welding of the dissimilar material with the pipe body or through capacitive discharge stud welding. Thermite welding uses a process that generates higher localized temperatures (approximately 1400°C) which may result in hard spots, brittle microstructure and reduced ductility at the joint area. [redacted]

[redacted]

[redacted]

Both internal and external pipeline coatings, including Fusion Bonded Epoxy (FBE), Yellow Jacket (YJ) and Coal Tar (CT), are considered permeable to hydrogen over time. [redacted] The permeation rate through the pipe wall is considered sufficiently slow that the likelihood of collection of hydrogen between the pipe wall and external coating is considered to be negligible (HyReady, 2022). External coatings, including above-grade high-performance paints, are not expected to be at risk of increased disbondment due to hydrogen permeation through the pipeline wall.

CP serves to protect steel assets from corrosion, however, a phenomenon known as cathodic over-protection should be considered. This condition of excessive negative potential applied to pipelines can accelerate coating disbondment and promote hydrogen embrittlement through reactions at the pipe's exterior [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

7.2.4. Appropriateness of Repair Methods

A variety of repair methods are available depending on the specific type of pipeline defect. [redacted] The following repair types have been considered for their appropriateness in blended hydrogen service.

Mechanical Fittings

[redacted] The materials used in repair clamps are expected to perform well in hydrogen blended service.

Material compatibility of historical mechanical couplings was investigated in Table 24 of Appendix III and found to be compatible. [redacted] There are no potential issues with respect to material compatibility of these fittings, so there are no additional recommendations resulting from the introduction of blended gas. [redacted]

Pressure-Containing Sleeves

Pressure-containing (Type B) sleeves are a suitable repair method for most defects. They are permitted by ASME B31.12 for use in hydrogen service. [redacted]

Weld Repair Patches

[redacted]

Weld repair patches may be subject to higher stresses in the longitudinal axis, and embedded voids (area beneath the patch) in which hydrogen could theoretically accumulate, presenting a situation which favours hydrogen embrittlement; therefore, their continued use need to be re-evaluated for future repairs on blended hydrogen pipeline systems.

Pipeline Cut-out (Replacement)

Pipeline cut-out or replacement continues to be a suitable repair method for any type of defect.

Composite Wraps

Composite wraps such as ‘Clocksprings’ are permitted for pipeline repair per ASME B31.12 provided they are proven through reliable engineering tests and analysis. Hyready Engineering Guidelines indicate that composite repairs are acceptable for blended hydrogen pipelines (HyReady, 2022).

Grinding

Grinding repairs are performed to precise limits under controlled conditions in order to effectively remove stress concentrators such as cracks or localized hard spots. Grind repairs are an acceptable repair method for blended hydrogen networks. It is recommended that grind limits and safe working pressure requirements be reviewed and revised as appropriate for the expected concentration of hydrogen and associated risks (**Section** 7.4-7.5).

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

---

[25] Valve asset ID: 517583 and 512394

7.4 Safety Considerations

7.4.1. Pressure Control and Protective Devices

The current design requirements for overpressure protection are not affected by blending of hydrogen in natural gas. This is due to the low compressibility of hydrogen relative to the other constituents of natural gas. This relative incompressibility will decrease the amount of gas contained in a fixed volume as pressure increases relative to the volumes that would have been present in natural gas alone. [redacted]

[redacted]

[redacted]

7.4.2. Hazardous Areas, WIGA & Hot Work Requirements

Electrical equipment in Québec is regulated by the RBQ. As indicated in **Section 5.5.7**, the current construction code does not include hydrogen within its scope; however, the use of BNQ 1784 is strongly recommended until legislative gaps are addressed (RBQ, 2022). BNQ 1784-22 Clause 6.2 specifies that hazardous areas are to be determined in accordance with IEC 60079-10-1 and CSA C22.

Proposals are underway to update the Canadian Electrical Code Part III and CSA C22 to address clearance and hazardous area separation requirements for hydrogen. [redacted]

For up to 10 vol% hydrogen, change in gas behaviour (flammability limits, ignition temperature, etc.) is minimal (**Section 7.4.4**). The lower explosive limit remains constant at about 4 vol% (mixture in air) and the upper explosive limit increases from 16 vol% to about 18 vol%. A maximal enhancement of the explosion protection zone of 10% can be expected.

According to IEC/EN 60079-10-1, a standard safety margin of 20% is added to the extent of calculated Ex-Zones. The expansion of new Ex-Zones due to the addition of hydrogen to natural gas would stay within this safety margin.

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

7.4.3. Safety and Loss Management

General safety considerations and management of gas losses in blended hydrogen-natural gas systems are presented in this section and should be incorporated, as applicable, to required updates to company manuals.

Permeation

Permeation through sound material differs from leaks where fluid escapes through a direct path or discontinuity in the material (e.g. through-wall defect or incomplete joint). Permeation does not occur in metals the same way it does in plastics due to differences in material structure. Molecular hydrogen (H_2) can pass through plastic materials, whereas the denser microstructure of metals permits only atomic (H^+) absorption. [redacted]

Studies have shown that loss through permeation of pipe walls is negligible (0.00005~0.001%) compared to fugitive emissions attributed to leakage through pipe damage and mechanical joints (Melaina, 2013). Hydrogen permeation through plastic depends on the type of resin (MDPE, HDPE, unimodal, bimodal, etc.), operating temperature and partial pressure of hydrogen. [redacted] As discussed in Section 4.2.1 and Section 6.7, controlling hydrogen permeation through plastics and elastomers should still be considered to support reductions in scope 1 emissions.

Leaks

The effect of hydrogen blending on leakage rates through mechanical joints has been studied and results presented by (HyReady, 2022). Tests have shown that with increased hydrogen concentration, a decrease in mass flow rate and an increase in volumetric flow rate are seen; this is due to difference in volumetric energy density between hydrogen and methane (see Section 6.3.2).

Despite an increase in total volumetric leakage rates, the total carbon (methane) emissions from pipelines decrease as hydrogen is added to the network[26]. Generally, the increase in leakage rates are negligible from a safety perspective (Mejia, 2020); however, these differences are still considered when performing Quantitative Risk Assessments (QRAs).

[redacted]

[redacted]

Leak Detection

The effectiveness of leak detection technology in hydrogen blends is a subject of ongoing research worldwide. Some manufacturers are developing combination hydrogen/methane detectors. GMI is currently working on a modified version of the GS700 to detect levels of both gases.

[redacted]

Types of leak detectors and their compatibility with hydrogen are presented below in **Table 7.3**. A review of leak detection devices and procedures in use at Gazifère is required prior to blending.

[redacted]

[redacted]

---

[26] HyReady studies have shown an 8-12% reduction in methane emissions for a ~20 vol% hydrogen blend, or a 25-33% reduction in methane emissions for a ~50 vol% hydrogen blend.

[redacted]

[redacted]

Odorization

Odourant is blended into the network at concentrations that act as an olfactory warning when concentrations of gas are below the lower explosive limit (LEL).

The latest research indicates there are no known negative impacts on odourant due to hydrogen in a blended network. The odourant is expected to continue to be compatible and carried with the natural gas in the system.

Odorization of a blended network will need to consider the theoretical risk of hydrogenation or oxidation of sulphur-free odourants such as acrylates which could result in odourant masking in the presence of hydrogen. For this reason, injection rates must be based on the total combined flow, not only the natural gas component (MARCOGAZ, 2021).

Studies are being performed on the compatibility of different odourants with 100% hydrogen. [redacted] Since sulphur-based compounds like THT and mercapatans are fully saturated, no adverse reaction is expected with elemental hydrogen. The same concentration of THT (18 mg/Nm^3) can be applied for both a pure hydrogen or pure natural gas system. THT is the only odourant used in the Netherlands natural gas grid (, 2020).

[redacted]

Another paper published for the My4Heat program found that several options exist for odourant in a distribution grid for blends up to 100% hydrogen (Murugan, 2020). One leading performer in up to 100% Hydrogen is “Odourant NB” which is commonly used in the United Kingdom’s natural gas grid and has a similar composition to Spotleak 1420.

Two important considerations with odourants in hydrogen are fouling of fuel cells and cost. Odourants can cause problems in hydrogen fuels cells which require very high purity hydrogen. If fuel cell applications are expected, consideration for omitting odourant may be warranted, similar to some high-pressure transmission natural gas pipelines; purification or odourant stripping and gas purification facilities may be feasible depending on the required gas quality specifications and costs. Further international study is underway researching odourants that will not damage fuel cells.

Odourant injection levels shall be evaluated based on projected changes to blended gas flow. During the initial period of hydrogen blending, additional sniff testing to confirm sufficient odorization is recommended. Increased periodic odorization checks should be considered. Current research indicates odorization of the dedicated hydrogen line is possible with conventional odourants, although end-use purity and fuel cell compatibility would be affected.

[redacted]

Underground Vaults and Pits

Underground vaults and pits refer to below-grade station installations that were typically installed in highly developed areas. [redacted]

[redacted]

Inside Meter Sets and Regulators

Lower-pressure (≤440 kPa) inside meters are not expected to pose a significant leak risk. If a failure were to occur with the soft internal diaphragm, the meter exterior is sealed to prevent external leaks.

[redacted]

While the regulators used indoors are different from typical outdoor regulators in the sense that they are not designed to vent gas in an overpressure or failure situation (e.g. OPCO/OPSO devices), some of the materials in these assemblies may be susceptible to leakage from hydrogen.

It is recommended that if inside regulators are identified or found, the regulators used indoors be replaced if practical, or closely reviewed for material compatibility and if any are identified as incompatible, they be appropriately mitigated.

7.4.4. Blended Gas Behaviour

The properties of pure hydrogen are sufficiently different from pure and blended natural gas to warrant new, specific Quantitative Risk Assessments, Operating Standards, leak detection equipment, etc. for the proposed pure hydrogen assets (producer station, blending station, dedicated hydrogen pipeline, etc.). As briefly discussed in **Section 3**, these topics are out-of-scope for this report and will be addressed during detailed design.

[redacted]

[redacted]

[redacted]

[redacted]

Explosions

Hydrogen is more reactive than natural gas and is associated with higher flame speeds and ability to generate higher overpressures[28]. At low concentrations (5-10% natural gas in air), natural gas clouds have the potential to produce higher overpressures than hydrogen; however, if an equivalent point in the flammable range is considered (near-stoichiometric concentration for both gases), then hydrogen can produce higher explosion overpressures than natural gas. [redacted]

Fire and Radiation

Fires from hydrogen-natural gas blends for a given hole size and pressure have reduced radiation field in comparison to a natural gas fire. Hydrogen has the effect of faster depressurization of the system due to higher flowrates, leading to a quicker reduction in radiation levels at farther distances in comparison to natural gas. [redacted]

Spontaneous Gas Separation

Differences in the density of natural gas and hydrogen may result in separation of the blended mixture. This could impact appliance operation, measurement and billing, as well as lead to localized higher concentrations of hydrogen than intended. This theorized effect was studied during the *Underground Sun Storage Project* and was found to not be of concern (HyReady, 2022). In this project, there was an investigation into separation, where 7 m vessels were filled with sand and a mixture containing 8 vol% hydrogen. Weekly measurements were taken at the top and bottom of the vessel for a year; measured blend concentrations remained stable, and no separation was found. [redacted]

Depressurization

Depressurization activities, including controlled blowdown are occasionally used to isolate sections of the system for maintenance or replacement work. These activities are performed in controlled circumstances following company procedures.

Hydrogen has been known to ignite more readily when released. A combination of lower ignition energy, static discharge, reverse Joule-Thomson effect and autoignition temperature amongst other factors can impact the likelihood of ignition upon release (HyReady, 2022) (Proust, 20119). [redacted]

Procedures involving the release of gas, particularly for pure hydrogen assets, must be reviewed. Added caution and removal of possible ignition sources and static electricity discharge may be required.

---

[28] Overpressures (blast waves) refer to the sudden onset of a pressure wave after an explosion caused by the energy released in the initial explosion (NOAA, 2019)

7.4.5. Damage Prevention

Public Awareness

As part of implementation, the customers within the Gazifère network will need to be informed about the addition of hydrogen into their gas stream. Relevant information including any additional safety considerations, impacts on energy usage and billing will need to be provided.

Specific training will need to be developed and presented to regional emergency personnel to educate them on safety-related differences between natural gas, hydrogen and natural gas/hydrogen blends. Implementation plans from the Markham blending project can be leveraged.

Right-of-Way Inspection and Maintenance

The risks associated with accidental line hit, maintenance activities and leak detection are similar to a non-blended distribution system. [redacted]

Third-Party Damage

Third-party damage is a threat to all pipeline systems and is a leading cause of failure in distribution systems (Santarelli, 2019) [redacted] The damage mechanisms, however, can behave differently on pipeline steels subjected to hydrogen service. When third party damage occurs, the result of the damage is often gouges or dents with associated gouges. Gouges present a risk of local hardening of the steel, and subsequent possibility of cracking. [redacted]

[redacted]

7.5 Hazards and Consequences of Failure

7.5.1. Potential Impact Radius & High Consequence Areas

The proposed draft Table 17.1 of CSA Z662-23 indicates that class location assessment areas should be re-assessed in consideration of impacts to the area due to changes in explosion risk in the event of a failure or leak. It also notes that the class location area methodology for gas pipelines in Clause 4.3.2.1 does not specifically account for the presence of hydrogen [redacted]

Sample calculations are provided below to illustrate the difference in potential impact radius calculations provided for natural gas from CSA-Z662 and ASME B31.12 for hydrogen systems.

CSA Z662-19 Clause 4.3.2.1 uses a risk-based approach to class location area calculation via a modified version of the potential impact radius equation derived from ASME B31.8S Clause 3.2.1 to identify the width of an assessment window in which dwellings and locations of interest are quantified to establish a class location assessment area:

$$PIR_{CSA\ Z662,NG} = 0.20\sqrt{PD^2}$$

Where the potential impact radius (PIR), design pressure (P) and pipe outer diameter (D) are in m, MPa and mm respectively.

ASME B31.12 PL-3.5 similarly uses a modified version of the potential impact radius equation from ASME B31.8S. In the case of ASME B31.12, the equation is modified to account for the difference in potential impact radius under 100% hydrogen service:

$$PIR_{ASME\ B31.12,H_2} = 0.47\sqrt{PD^2}$$

Where the potential impact radius (PIR), design pressure (P) and pipe outer diameter (D) are in ft, psi and in respectively.

[redacted]

Many factors are involved in the development of these PIR equations. This reduction in the potential impact radius for hydrogen in comparison to natural gas is, at a high level, a reflection of the difference in physical and burning characteristics of the gases (Section 7.4.4). Hydrogen is lighter, more buoyant and travels at higher velocities than natural gas. This results in faster dispersion for a release of similar size and pressure. The energy content of hydrogen is less than natural gas and results in less radiative energy produced when ignited.

7.5.2. Risk Assessment and Modelling

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Research, Literature and Public Studies

Global interest in hydrogen and hydrogen blending as a green energy carrier has led to a multitude of research, pilot projects and studies on material impacts, safety and risk topics. Varying risk topics have been explored, from gas dispersion to explosion characteristics, some of which quantify the relative risks of hydrogen blending under specific circumstances. [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

8. Conclusions & Recommendations

8.1 Conclusions

[redacted]

[redacted]

[redacted]

It is important to note that rapidly evolving research into hydrogen blending and changes in codes, industry best practices and lessons learnt are in constant flux; as such, the target limit for hydrogen blending may shift in line with these changes.

[redacted]

Company standards and procedures for design, purchasing, construction, testing and maintenance will need to be updated for hydrogen-readiness, ideally accommodating up to 100% hydrogen. These efforts will need to maintain line of sight to the rapidly changing state of industry research, emerging codes and standards, and novel developments in materials, equipment and technologies.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

References

Battelle. (2005). *Integrity Characteristics of Vintage Pipelines.* Columbus: INGAA Foundation.

BloombergNEF. (2020, Mar 30). *Hydrogen Economy Outlook: Key messages*. Retrieved from Bloomberg Professional Services: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

BMT. (2016). *Fatigue Considerations for Natural Gas Transmission Pipelines.* Kanata: Interstate Natural Gas Association of America (INGAA).

Byrne, N. E. (2022). Assessing the Compatibility of Current Plastic and Elastomeric Materials used within the Australian Gas Pipeline Network with Hydrogen-Containing Fuel. *23rd Joint Technical Meeting.* Edinburgh: EPRG-PRCI-APGA.

Charles C. Roberts, J. P. (2022, 08 24). *WATER PIPE LEAKAGE FROM EROSION-CORROSION.* Retrieved from Robert Consulting Engineers: http://www.croberts.com/erosion-corrosion.htm

Cummins. (2019, Feb 21). *State of Play and Developments of Power-to-Hydrogen Technologies*. Retrieved from Hydrogenics: https://etipwind.eu/wp-content/uploads/A2-Hydrogenics_v2.pdf

Derwent, R. S. (2006). Global Environmental Impacts of the Hydrogen Economy. *International Journal of Nuclear Hydrogen Production and Applications*, 1(1):57-67.

DNV-GL. (2020). *Odor Assessment of Selected Odorants in Hydrogen and natural Gas-Hydrogen Mixtures.* Flow and Gas Labs. Groningen: DNV-GL. Retrieved from https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_410b983c4d.pdf

H.Barthélémy. (2011). Effects of pressure and purity on the hydrogen embrittlement of steels. *International Journal of Hydrogen Energy*, 2750-2758.

Haine, S. (2014). *Hazard Analysis & Mitigation Report On Aldyl A Polyethylene Gas Pipelines in California.* California: California Public Utilities Commission.

Hanji Park, B. M. (2021). Hydrogen Stress Cracking Behaviour in Dissimilar Welded Joints of Duplex Stainless Steel and Carbon Steel. *metals, 11*(1039).

HyReady. (2022, 08 25). Retrieved from HyReady: https://hyready.org/Special:UserLogin

J.Song, W. (2014). Mechanisms of hydrogen-enhanced localized plasticity: An atomistic study using a-Fe as a model system. *Acta Materialia*, 61-69.

Jeroen Wassenaar, P. M. (2020). *HDPE PIPE .* Altona Victoria, Australia: WHITE PAPER.

Kim Domptail, S. H. (2020). *Emerging Fuels - Hydrogen SOTA Gap Analysis and Future Project Roadmap.* PRCI.

Kpemou Apou Martial, P. G. (2022). Safety margin on the ductile to brittle transition temperature after hydrogen embrittlement on X65 steel. *Procedia Structural Integrity, 35*, 254–260.

Leis, B. (2022, 06 09). Vintage Pipelines. *PHMSA R&D Forum*. Battelle Pipeline Technology Center.

Li J, S. Y. (2021). Influences of Hydrogen Blending on the Joule-Thomson Coefficient of Natural Gas. *ACS Omega*, 6(26): 16722–16735.

MARCOGAZ. (2021). *Odorisation of Natural Gas and Hydrogen Mixtures.* Brussels: MARCOGAZ.

Mejia, A. B. (2020). Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure. *International Journal of Hydrogen Energy*, 45(15).

Melaina, M. A. (2013). *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues.* Golden: National Renewable Energy Laboratory.

Murugan, A. B. (2020). *Hydrogen Odorant and Leak Detection - Part 1, Hydrogen Odorant.* London: Hy4Heat.

NOAA. (2019, Apr 17). *Office of Response and Restoration*. Retrieved from Overpressure Levels of Concern: https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/overpressure-levels-concern.html

NRCan. (2016, Apr 20). *Research Gate*. Retrieved from https://www.researchgate.net/post/What_is_the_environmental_impact_of_1m3_of_natural_gas_used_for_heating

NRCan. (2019, Feb 18). Retrieved from Global warming potentials: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/quantification-guidance/global-warming-potentials.html

Ocko, I. a. (2022). Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, 22: 9349-9368.

P. Fassina, F. B. (2012). Influence of hydrogen and low temperature on mechanical behaviour of two pipeline steels. *Engineering Fracture Mechanics, 81*, 43-55.

Piche, A. (2020). *Effects of blended hydrogen enriched natural gas on the microstructure and mechanical properties of a X42 steel pipeline and Grade 290 weld.* Vancouver: University of British Columbia.

Proust, C. (20119). Fire and Explosion Safety in Hydrogen Containing Processes : State of the Art and Outstanding Questions. *9th International seminar on fire and explosion hazards* (pp. 28-40). Saint Petersbourg: HAL Open Science.

Quintino, F. N. (2021). Aspects of Hydrogen and Biomethane Introduction in Natural Gas Infrastructure and Equipment. *Hydrogen*, 2(3), 301-318.

RBQ. (2022, Oct). *Dates d’entrée en vigueur des normes*. Retrieved from https://www.rbq.gouv.qc.ca/domaines-dintervention/gaz/reglementation-applicable/normes/dates-dentree-en-vigueur/

RBQ. (2022). *Installations à l’hydrogène : exigences spécifiques*. Retrieved from Régie du bâtiment du Québec: https://www.rbq.gouv.qc.ca/domaines-dintervention/installations-sous-pression/reglementation/installations-a-lhydrogene-exigences-specifiques/

San Marchi, C. (2012). *Technical Reference for Hydrogen Compatibility of Materials.* Livermore, CA: Sandia National Laboratories (SNL).

Santarelli, J. S. (2019). *Risk Analysis of Natural Gas Distribution Pipelines with Respect to Third Party Damage.* London: Western University.

Thanh Tuan Nguyen, J. S. (2021). Evaluation of hydrogen related degradation of API X42 pipeline under hydrogen/natural gas mixture conditions using small punch test. *Theoretical and Applied Fracture Mechanics, 113*.

UN/ECE. (2011, May 7). *Regulation No 110 of the Economic Commission for Europe of the United Nations*. Retrieved from Uniform provisions concerning the approval of I. specific components of motor vehicles using compressed natural gas (CNG) in their propulsion system; — II. vehicles with regard to the installation of specific components of an approved type for the use of : https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A42011X0507%2801%29

Warwick, N. G. (2022). *Atmospheric implications of increased Hydrogen use.* London: University of Cambridge and University of Reading.

Windmeier, C. &. (2013). *Ullmann's Encyclopedia of Industrial Chemistry: Cryogenic Technology.* Weeinheim: Wiley-VCH Verlag GmbH & Co. KGaA.

Appendix I – Literature Review

Appendix II – DNV-GL Engineering Assessment

Appendix III – Markham Engineering Assessment

[redacted]

[redacted]

[redacted]

[redacted]