GAZIFÈRE ENGINEERING ASSESSMENT FOR HYDROGEN BLENDING

Hydrogen Blending Engineering Assessment Report

Gazifère Inc.

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DNV

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Customer:	Gazifère Inc.	250 – 6 Avenue S.W. Suite 1710
	706 boul. Gréber, Gatineau, Québec J8V 3P8	Calgary, Alberta T2P 3H7
Customer contact:	Benoit Gratton	Tel: 403 250 9041
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Prepared by:

Guohua Li, PhD, P.E.
Principal Engineer, Hydraulic & Flow Assurance

Praveen Babu, M.Sc., CEng
Principal Engineer, Design and Verification

Thomas Joseph Prewitt, P.E.
Senior Engineer, Computational Modelling

Mar ijn van Essen
Senior Specialist, Fuel and Flow Advisory

Zoë Wattis, PhD
Principal Consultant, Risk Advisory Services

Verified by:

Jillian Johnson, M.Sc., P.Eng.
Senior Engineer, Mid/Downstream and labs

Approved by:

Jake Abes, P.Eng.
Vice President, Mid/Downstream and Labs

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DNV Canada Ltd.

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Section Number	Prepared by
3	Guohua Li, Michelle Moyer, Hamid Bidmus, Stephen Bushill, Dean Jennings
4	Praveen Babu, Freya Elliot-McLeod
5	Thomas Joseph Prewitt, Susmitha Kotu, Bill Amend
6	Martijn van Essen, Sander Gersen, Albert van den Noort, Mar in Brown, Lennart van Luijk, Henk Reizebos, Berthil Slim
7	Zoë Wattis, Andrew Phillips, Saul Algar

Table of contents

List of figures

[redacted]

List of tables

[redacted]

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Abbreviations and Acronyms

AFR	Air fuel ratio
BMI	Black malleable iron
BW	Butt weld
BWRS	Benedict Webb Rubin Starling equation
CONIFER	Calculation Of Networks and Installations Fire and Explosion Risk
CO	Carbon Monoxide
CH_4	Methane
CSA	Canadian Standards Association
CTOD	Crack tip opening displacement
CW	Continuous weld
ECV	Emergency Control Valve
EGI	Enbridge Gas Inc.
ERW	Electric resistance weld
FAD	Failure analysis diagram
FCGR	Fatigue crack growth rate
FGR	Flue gas recirculation
GC	Gas chromatograph
GIS	Geographic Information System
GS1	Rockcliffe crossing
GS2	Orleans crossing
HAZ	Heat affected zone
HDPE	High density polyethylene
HP	High pressure
ID	Internal diameter
ILI	In-line inspection
IP	Intermediate pressure
ISIR	Individual Specific Individual Risk
JIP	Joint industry project
kPa	Kilopascal
LEL	Lower explosion limit
LP	Low pressure
LSR	Location Specific Risk
MDPE	Medium density polyethylene
MJ	Megajoule
mmBTU	Million British thermal unit
Mol%	Mole percent
MOP	Maximum operating pressure
MPa	Megapascal
MW	Megawatt
NG	Natural gas
NOx	Nitrous oxides
NPS	Nominal pipe size
OD	Outer Diameter
OEM	Original equipment manufacturer
PE	Polyethylene
PHMSA	Pipeline and Hazardous Materials Safety Administration
psi	Pounds per square inch
PVC	Polyvinyl chloride
QRA	Quantitative Risk Assessment
RCP	Rapid crack propagation
RNG	Renewable natural gas

SCC	Stress corrosion cracking
sm^3	Standard cubic meter
SMAW	Shielded metal arc weld
SMYS	Specified minimum yield strength
ST	Steel
TAD	Through-air dryer
XHP	Extra high pressure
Vol%	Volume percent
WPS	Welding procedure specifications

1 EXECUTIVE SUMMARY

Gazifère Inc., a subsidiary of Enbridge Inc., contracted DNV Canada Ltd. to assess the suitability for hydrogen blending in natural gas within its existing natural gas distribution system. DNV conducted an engineering assessment for hydrogen blending to establish the basis for project planning and execution. This report details the various areas considered as part of the engineering assessment as follows:

- Hydraulic analysis of Gazifère gas distribution network (Section 3)
- Conceptual design of hydrogen injection facilities (Section 4)
- Assessment of network equipment, components, and materials (Section 5)
- Assessment of end-use equipment (Section 6)
- Hydrogen blending risk assessment (Section 7)
- Additional risk and safety considerations (Section 8)
- System wide maximum hydrogen blending (Section 9)

1.1 Hydraulic Analysis of Gazifère Gas Distribution Network

The Enbridge Gas Inc. (EGI) and Gazifère natural gas distribution networks are located in Ontario and Québec, respectively. [redacted] This study included the analysis of hydrogen blending hydraulics of the Gazifère network.

Several hydraulic models were provided by EGI. [redacted]

[redacted]

[redacted] The total volumetric flow rate is the sum of the hydrogen volumetric flow rate and the total natural gas volumetric flow rate. From the parametric study, major observations are:

- [redacted]
- The hydrogen injections do not create new local bottlenecks. And there are no global bottlenecks to affect the demand needed.

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

Note that a "nominal" %H_2 by volume is not an actual hydrogen volumetric flow rate in percentage at any end user due to hydrogen distribution non-uniformity. [redacted]

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[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

1.2 Conceptual Design of Hydrogen Injection Facilities

DNV produced a conceptual design to evaluate various blending options and develop a system design for hydrogen blending at the sites identified for injection based on the hydraulic study carried out in Section 3. The conceptual design evaluates options for hydrogen blending and injection, including advice on options for gas quality measurement, metering and odorization, and guidance on material specification for the components within the site.

1.3 Assessment of Network Equipment, Components, and Materials

The pipeline system, including pipe and ancillary fittings and equipment, is divided into four pressure classes. [redacted] The short-term, envisioned range of hydrogen blends (initially not greater than 20 vol% hydrogen) is likely to result in no integrity management concerns for steel pipe in the low pressure (LP) pressure class. The associated polyethylene (PE) pipe is also unlikely to be significantly mechanically affected by the addition of hydrogen.

The effects on nonmetallic components (e.g., seals and gaskets) are likely to increase as hydrogen partial pressure increases, potentially resulting in increased wear which could manifest in leaks. For PE piping, permeation will increase with increasing amounts of hydrogen; however, the total leakage rate due to hydrogen permeation of PE pipe is negligible compared to baseline fugitive emissions associated with natural gas in PE pipe.

For steel pipe and fittings, some embrittlement, estimated to be not more than a 30% reduction in fracture toughness at the highest partial pressures, could occur with a corresponding increase in fatigue crack growth rate (FCGR). The reduction in toughness will result in a reduced critical flaw size before failure occurs. However, the susceptibility to rupture is considered low in both extra high pressure (XHP) and high pressure (HP) pressure class piping unless seam flaws are very long (i.e., greater than about 200 mm) and deep (i.e., greater than 0.7t). The susceptibility to rupture in other pressure classes is even lower. In addition, the relatively low hoop stresses are not believed to represent a significant susceptibility to fatigue crack initiation or growth unless relatively large planar flaws are already present in seams or fabrication welds.

The greatest susceptibility to hydrogen-related cracking is believed to be at crack-susceptible microstructures associated with hard fabrication welds and electric resistance welded (ERW) seams. Hard fabrication welds are most likely to be related to welds made onto in-service piping, i.e., repair welds and hot taps. Hard ERW seams are most likely to be associated with early vintage ERW pipe that was not normalized after the seam was formed. Guidance is provided on prioritization of pipe sample collection and testing to determine if high-risk metallurgical features are present. The number of samples to be collected in order to generate a defensible summary of likely metallurgical attributes cannot be easily predetermined; it is related to the amount of variation in the properties measured in the initial sample collection.

A second significant factor in hydrogen embrittlement risk management is the presence of large secondary or thermal stresses that could exceed hoop stresses from operating pressure. Examples include residual stress from mechanical damage, axial or bending stresses from ground movement or poor pipelaying practices, and residual stresses from fabrication welds. Of these, only ground movement can be readily identified and monitored.

[redacted]

[redacted] Due to the pressures in the system, the likelihood of long ruptures is small, however not impossible. While the risk of a rupture (rather than a leak) is low due to the low nominal stress in the pipes, long existing flaws can lead to ruptures even in low nominal stress conditions. [redacted] Because the pressure in the system is intended to remain the same with the addition of hydrogen, the change with regard to the integrity of existing flaws is the embrittlement of the steel as the partial pressure of hydrogen increases. Because the amount of embrittlement increases as the partial pressure of hydrogen increases, the risk of rupture related to these flaws will also increase as the % hydrogen blend increases.

While some acceleration in the degradation rate of various elastomers used in mechanical clamps and seals and gaskets could occur in all pressure classes, and some wear components may degrade more quickly and have increased friction, all examined components are expected to perform in hydrogen-blended natural gas service.

Some alloys used in valves and other ancillary equipment may be present in heat-treated conditions that make them susceptible to hydrogen embrittlement and cracking. Examples include some stainless steels and high strength-low alloy steels. Components that meet the requirements of NACE MR0175 or similar industry standards applicable to materials used in hydrogen sulfide service would be suitable (and conservative) for the envisioned hydrogen-blended natural gas service conditions.

Hydrogen leaks more easily than natural gas from mechanical connections. Some increase in susceptibility to leakage may occur at threaded connections and mechanical seals, although the leakage rate for gas blends below about 20 vol% hydrogen is expected to be little changed compared to the leakage rate for 100% natural gas. This leakage rate will increase with higher percentages of hydrogen in the system.

The acceptability of black malleable iron (BMI) in hydrogen-blended natural gas service varies by standards. ASME B31.12 and AIGA 087 do not allow for their use, while IGC 121 allows for the use provided stresses are low enough. Literature on cast iron in hydrogen service has been generally positive for low pressure systems. [redacted]. It is considered prudent to evaluate the need to replace these components by prioritizing based on operating or external stresses and susceptibility for damage. Components with a high potential to be under bending or other supplementary stresses such as elbows or tees are at a higher risk compared to those without these stresses such as caps and plugs.

Only minor modifications to various construction, operating, and maintenance procedures are recommended. Those recommendations include eliminating the use of EXX10 type (cellulosic flux coated) submerged metal arc welding (SMAW) electrodes for root passes made when welding onto in-service piping and grinding out all gouges in XHP and HP piping. Patches are not an approved repair method listed in ASME B31.12, although DNV believes that patches do not pose a significant risk at distribution pressures if appropriate welding procedures are followed. Other current repair methods are acceptable.

1.4 Assessment of End-Use Equipment

The Gazifère distribution system is connected to industrial, residential, and commercial customers. DNV performed an assessment to determine the deleterious effects of hydrogen blending in natural gas for end-use equipment, materials behind the meter, regulators, and metering equipment through both gas interchangeability analysis and industry literature review.

Gas interchangeability analyses

To define (conservative) hydrogen blending levels without knowledge of the performance of individual end-use equipment, a gas interchangeability analysis was performed. A categorization of the end-use equipment typically present in Canada was made based on their combustion principles. This assessment provides insight into whether hydrogen blending provides additional risk of critical failure of end-use equipment as compared to the current compositional range of distributed natural gas. The assessment identified the following hydrogen volume percentages allowed in natural gas for Gazifère's system:

0 - Partially premixed appliances: 8-9.6 vol% hydrogen (flashback is limiting factor)
1 - Fully premixed appliances: 21-26.8 vol% hydrogen (Wobbe index is the limiting factor)
2 - Non premixed appliances: 21-26.8 vol% hydrogen (Wobbe index is the limiting factor)
3 - Home backup generators 6.7-18.9 vol% hydrogen (engine knock as predicted by the methane number is the limiting factor)

Literature inventory and knowledge gaps for domestic and commercial appliances

The gas interchangeability analyses identified a lower allowable hydrogen blending limit than the hydrogen blending percentages at which issues were experienced in the majority of literature and tests performed in the DNV combustion laboratory. However, conflicting results or no data were found for a number of different equipment types and, for the majority of the studies, not all potential failure modes were tested, such as cold/hot start and overheating of materials. The increase in temperature of materials, such as the burner deck, may result in integrity issues. At present, it is unknown to what extent the increase in temperature of materials may affect their lifespan. Furthermore, for most of the studies, the equipment was tested for a limited range of hydrogen volume percentages in natural gas: up to 30 vol%, which is in the same range as the gas interchangeability envelope. To investigate if equipment can run with hydrogen percentages above the interchangeability envelope while considering safety margins for hydrogen blending, information on the performance of end-use equipment when exposed to higher hydrogen volume percentages in natural gas is essential. In summary, the following knowledge gaps were identified:

- Information on the practical experience of hydrogen blending on Canadian appliances is limited, conflicting, or unavailable.
- Limited information is available on the performance of equipment above 30 vol% H_2 blending.

- There is a lack of information on the long-term effects of hydrogen addition on the performance and integrity of end-use equipment.

Consequently, since this information is lacking, it is difficult to develop hydrogen specification in natural gas outside the gas interchangeability envelope. To address the knowledge gaps found in literature, a gap analysis was performed and a strategy to fill the knowledge gaps was developed. This includes suggested test programs for appliances such as furnaces, hot water heaters, ranges, wok burners, griddle plates, home backup generators, BBQs, fireplaces, rooftop air handlers, space heaters, boilers/pool heaters, etc.

Literature inventory and knowledge gaps for industrial equipment

A general overview of the effect of hydrogen is provided for industrial processes and equipment, including indirect heating , direct heating, catalytic heaters, and gas engines.

For indirect heating processes, no major performance issues are expected up to 20 vol% hydrogen in natural gas provided that the Wobbe index of the gas is within the specifications. For higher percentages, it is recommended that a fuel adaptive control system be included to keep the power output and excess air constant. Furthermore, it is recommended that NO_x mitigating strategies such as flue gas recirculation be applied for hydrogen percentages above 20 vol%.

For burners applied in direct heating processes, the main concerns addressed in the literature are the change in burner load, air factor, heat transfer, increase in NO_x emissions, changes in flame length, and the shift of the hot flame zone closer to the burner surface upon hydrogen addition. If NO_x emissions from the installed natural gas burners are far below the legal NOx limits, major performance issues are not expected with up to 20 vol% hydrogen for the burners studied. However, fuel adaptive control is recommended to keep the power output and the air factor at the desired level. Above these percentages, additional research is recommended.

Information on the effect of hydrogen addition on the performance of catalytic heaters is lacking. It is recommended that these heaters be further experimentally investigated to determine their tolerance to hydrogen. For gas engines, manufacturers generally allow a maximum of between 0-5 vol% hydrogen in the fuel gas. In some cases, original equipment manufacturers (OEMs) indicated that their gas engines optimized for high efficiency are suited for hydrogen contents of around 10-15 vol% without derating. However, they note that the compatible amount of hydrogen strongly depends on the current engine setting and on the methane number of the natural gas to which hydrogen is added. For hydrogen percentages between 15-25%, potential issues according to OEMs include insufficient lambda control range, power loss, increased NO_x emissions, misfire, and engine knock. Above 25 vol%, complete retrofitting or replacement of the engine is often needed.

Material inventory downstream of the meter

The literature inventory showed that for the materials, piping, and components typically used in gas infrastructure behind the meter, for non-metallic materials, only silicon containing components may show issues due to reaction with hydrogen. With the exception of cast iron (see Section 5.5 for further discussion), no issues are expected for metallic components in the domestic/commercial low-pressure applications. The partial pressure in the industrial grid can be higher (pressures up to 8 bar); as a result, when hydrogen percentages are above 10 vol%, it is recommended to perform a more detailed assessment of the materials present in industrial applications.

[redacted]

[redacted]

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[redacted]

1.5 Hydrogen Blending Risk Assessment – Sample Calculations

Sample risk calculations have been performed using the DNV CONIFER risk assessment package which was developed specifically for distribution networks to consider whether distribution of hydrogen through an existing gas network is likely to result in a change in risk to the public. .

Risk predictions are presented for a single base case of the natural gas distribution network and two proposed natural gas-hydrogen blend cases: 10% and 20% hydrogen by volume. Furthermore, a number of sensitivity cases have been modelled looking at variations in the network and their impact upon risk when changing from a 100% natural gas distribution network to the two natural gas-hydrogen blend cases.

The base case consists of:

- A single detached house with basement,
- [redacted]
- Most common material type Polyethylene (PE),
- Main diameter of 42.2 mm (NPS 1-1/4),
- Service diameter of 15 mm[redacted]

Using this base case, for natural gas and both natural gas-hydrogen blends, the following variations were considered:

- [redacted]
- Material type – steel,
- Pipe outer diameter (OD) – 60.3 mm (NPS 2), 114.3 mm (NPS 4), 219.1 mm (NPS 8),
- House type – bungalow, semi-detached, multi-detached,
- Service material – steel (18 mm[redacted] OD)

[redacted]

The risk results are presented in terms of indoor Location Specific Risk (LSR) and individual specific individual risk (ISIR) due to both fires and explosions from failures of mains and services outside buildings. The LSR is the probability that a particular person becomes a fatality if they were permanently inside the building for the entire year. The LSR does not take into consideration the likelihood the individual is present at the time of the incident. The individual risk takes into consideration the likelihood a person is inside the building at the time of the incident and is based on typical Canadian occupancy patterns.

The following results were obtained:

- The change in risk following the introduction of hydrogen is small in comparison to the difference in risk due to the pipe material.
- The risk is highest when the property is located close to the main and the decrease in risk with distance from the main becomes more marked as the mains diameter increases.
- The risk of fires decreases with increasing hydrogen blend and the risk of explosions increases with increasing hydrogen blend. For larger diameter pipes, this decrease in fire risk outweighs the increase in explosion risk resulting in an overall decrease in risk as a result of introducing hydrogen.
- The change in risk due to the introduction of hydrogen is more noticeable for the mains only without the contribution from the services.
- The change in risk due to pipe material outweighs any change in risk as a result of introducing hydrogen.
- Increasing the operating pressure increases the risk for both natural gas and hydrogen blends.
- The semi-detached house and multi-attached building show the largest increases in risk when changing from natural gas to 10 vol% or 20 vol% hydrogen blend due to the additional risk from explosions occurring within the attached dwelling(s) increasing the explosion risk level experienced by the house being analysed.
- In order of highest risk to lowest risk, the dwelling types are ranked from multi-attached building, semi-detached house, detached house and finally bungalow.
- The finished basement shows the largest increases in risk when changing from natural gas to 10 vol% or 20 vol% hydrogen blend. Furthermore, the overall risk is greater for the finished basement than the unfinished basement. This is due to the unfinished basement essentially being one unoccupied large room, whereas the finished basement consists of a number of smaller occupied rooms.

1.6 Additional Safety and Risk Considerations

Hydrogen blending in natural gas pipelines leads to a number of additional risk and safety considerations due to the physical behaviour of hydrogen, limitations of existing procedures and equipment, and public awareness considerations.

Due to the physical behaviour of hydrogen, the addition of hydrogen results in a lower mass flow rate but a higher volumetric flow rate in the case of a leak. This will produce a larger flammable cloud outdoors or reach a flammable concentration within a building more quickly. Using a correlation based on the pressure within the pipe and the square of the diameter of the hole, the ignition probability for both blends and pure hydrogen will be higher than for an equivalent natural gas pipeline.

Based on previous experiments, immediate ignition following the rupture of a high pressure pipeline transporting blends or pure hydrogen would result in thermal incident radiation levels with distances similar to those experienced for equivalent natural gas releases. Limited experimental data indicates that for hydrogen, the potential for significant overpressures to be generated by delayed ignition of the unconfined gas cloud is greater than for natural gas. However, the impact of this on the level of risk is uncertain and part of ongoing experimental programmes on the ignition behaviour of hydrogen following a release.

Consideration should be given to the potential impacts of hydrogen blends on leak detection, odorization, purging, and public awareness [redacted]

2 INTRODUCTION

Gazifère Inc. (Gazifère), a subsidiary of Enbridge Inc., contracted DNV Canada Ltd. (DNV) to assess the suitability for hydrogen blending in natural gas within its existing natural gas distribution system. Gazifère has been serving the Gatineau region since 1959 and is one of two gas distribution companies in Québec. The roughly 1,000 km network reaches 43,000 customers to deliver approximately 260 to 340 million m^3 of natural gas annually. Gazifère has been working towards efficient use of renewable energy through energy efficiency programs and delivering renewable natural gas (RNG) since 2020. Moving forward, Gazifère aims to source and produce both RNG and hydrogen locally to further their vision.

The purpose of this study is to investigate the feasibility of blending hydrogen into the Gazifère distribution network to enable compliance with the provincial requirement for renewable content and meet objectives under the pending Federal Clean Fuel Standards. The provincial renewable content requirement came into effect in 2020 at 1% renewable gas by energy content and will escalate to 2% in 2023 and 5% in 2025.

DNV conducted an engineering assessment for hydrogen blending to establish the basis for project planning and execution. This report details the various areas considered as part of the engineering assessment as follows:

- Hydraulic analysis of Gazifère gas distribution network (Section 3)
- Conceptual design of hydrogen injection facilities (Section 4)
- Assessment of network equipment, components, and materials (Section 5)
- Assessment of end-use equipment (Section 6)
- Hydrogen blending risk assessment (Section 7)
- System-wide maximum compatibility with hydrogen (Section 8)

3 HYDRAULIC ANALYSIS OF GAZIFÈRE GAS DISTRIBUTION NETWORK

3.1 Introduction

Enbridge Inc.'s (Enbridge) natural gas distribution networks in the provinces of Ontario and Québec include the Enbridge Gas Inc. (EGI) and Gazifère Inc. natural gas distribution networks, respectively. The hydraulic study is limited to the Gazifère network but makes reference to the EGI network as it is the source of flow/pressure supply to the Gazifère network.

The main purposes of the hydrogen blending hydraulic study are to:

- Assess the hydrogen injection sites via hydrogen distribution uniformity;
- Assess the effect of the hydrogen injections on the natural gas supply to the Gazifère network;
- Perform a bottleneck study on the Gazifère network;
- Present regulator station performances; and
- Obtain conclusions and recommendations on the overall impact of the hydrogen injections.

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[redacted]

3.1.3 Natural Gas and Hydrogen Compositions

[redacted]

Table 3-3: Compositions of Natural Gas and Hydrogen – Mole %

Component	Natural Gas	Hydrogen
CO2	0.6572	0.0000
HE	0.0200	0.0300
H2	0.0000	99.9700
H2O	0.0000	0.0000
H2S	0.0000	0.0000
N2	0.6097	0.0000
O2	0.0000	0.0000
C1	95.1430	0.0000
C2	3.4161	0.0000
C3	0.1386	0.0000
C4I	0.0062	0.0000
C4N	0.0062	0.0000
C5I	0.0015	0.0000
C5N	0.0015	0.0000
C6N	0.0000	0.0000
C7N	0.0000	0.0000
C8N	0.0000	0.0000

Also, both the heating value and specific gravity for the simulated natural gas and hydrogen sources can be extracted from the model, as shown in Table 3-4.

Table 3-4: Properties of Natural Gas and Hydrogen

Property	Natural Gas	Hydrogen
Heating Value (MJ/m^3)	38.29	12.10
Specific Gravity	0.5808	0.0696

3.2 Hydrogen Injection Site Study

DNV studied the effect of several options of hydrogen injection sites on hydrogen distribution profiles in the Gazifère network. [redacted]

[redacted]

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3.3.2 Volumetric to Thermal Conversions

Since both operational scenarios are based on volumetric flow rates, both scenarios were converted from the volumetric units to thermal units for the hydrogen blending study with the following revisions:

- Switch from volumetric flow to thermal loading for all demands: Volumetric flow rates are applicable to invariable gas compositions. The compositions determine the heating value of the transported gas, or how much energy is available to burn at any specific point. For the hydrogen blending study, two distinct stream flows of natural gas and hydrogen are transported. For each demand node, the volumetric flow rates of natural gas and hydrogen can be varied to meet the heating requirement.

- The heating value of 38.29 MJ/m^3 is used as a conversion factor between the volumetric flow rates and the thermal loading.
- The relationship between the volumetric flow rates and the thermal loadings is:

$$thermal\ loading\left(\frac{MJ}{h}\right) = volumetric\ flow\ rate\left(\frac{m^3}{h}\right) \times heating\ value\left(\frac{MJ}{m^3}\right)$$

- Enable component tracing: Component tracing allows the model to define the composition of named gasses (or gas streams), which are referenced at source nodes (supplies) and are traced through the system. Synergi calculates the gas specific gravities and heating values as a function of mixed gas component streams. Hydrogen component in percentage, each demand (node), can be derived.
- Define gas streams: A gas stream could be natural gas, or hydrogen, or blended hydrogen/NG. In this study, two gas streams are defined as "NG" for natural gas and "H2" for pure hydrogen. Both gas streams are defined by setting up their compositions in mole %.
- Associate a gas stream to a supply node: A gas stream is associated to a supply source/node. [redacted]
- [redacted]
- Switch from "none" to "compositional" in the model properties calculation method: The hydrogen blending study is based on the composition in the blended gas stream.
- Enable sonic subsystem checking: The hydraulic conditions will change with hydrogen blending so sonic checking needs to be set up in the model.

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3.4 Hydrogen Blending Study

In this hydrogen blending study, the hydrogen injection rate percentage (or %H_2 by volume) is calculated by using the following equation.

$$\% H_2 \; by \; vol. \; = \frac{volumetric \; flow \, rate \; of \; hydrogen}{volumetric \; flow \, rate \; of \; hydrogen \; + \; volumetric \; flow \, rate \; of \; natural \; gas}$$

Using the above equation, the calculated hydrogen injection flow rate is 10,999 sm^3/h for a nominal 10%H_2 by volume. [redacted]

Since the maximum nominal %H_2 by volume has not been determined, a parametric study was performed for the hydrogen blending hydraulics. It is assumed that the maximum nominal %H_2 by volume is 15%H2 by volume. Four nominal %H_2 by volume are used and they are 0%, 55, 10%, and 15% H2 by volume.

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It can be concluded that the hydrogen injections have an impact on the natural gas supply flow rates to the Gazifère network. [redacted]

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3.4.3 Bottleneck Analysis

In this study, a global bottleneck is defined as a discrepancy between the supply pressures/flows and the demand pressures/flows for the entire network. A local bottleneck is defined as a discrepancy between the supply pressure/flow and the demand pressure/flow for a hydraulic component such as a regulator station or a regulator.

In the models, both the supply pressures and the demand flow rates are specified. The demand pressures are specified using minimum pressure constraints. The supply flow rates are calculated by the models. Whenever the network is solved with feasible results, the total supply flow rate can meet the total demand rate, meaning that the network does not have a global bottleneck.

It should be noted that, even if the network does not have a global bottleneck under the specified operational conditions, a local bottleneck could exist. For example, if a regulator station had a utilization factor equal to 1, the regulator station would be fully open. Under this circumstance, the regulator will lose its pressure and/or flow controllability and its flow capacity is maximized. However, the network could have multiple pipe loops. If one regulator station attained its maximum flow rate limitation, other regulators/regulator stations could open wider to make up the required flow rate.

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3.4.4 Analysis of Regulators

[redacted] The capacity of a regulator station is represented by a utilization factor. If the utilization factor of a regulator station is less than 1, the station has enough capacity. When the utilization factor of a station is equal to 1, this station forms a local bottleneck and the flow rate through it is limited. The flow type present at the regulator station is also important to consider. It can either be sonic (velocity reaches speed of sound) or subsonic.

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3.4.4.1 Results of Six Regulator Stations

Note that the "rebuilt" stations drawn in the model are simulated placeholder regulator stations. The rebuilt stations need to be designed in consideration of supersonic flows, and potentially multiple runs to accommodate both low flow and peak flow scenarios. [redacted]

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3.5 Conclusions and Discussion

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- The hydrogen injections do not create new local or global bottlenecks.
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4 CONCEPTUAL DESIGN OF HYDROGEN INJECTION FACILITIES

4.1 Introduction

[redacted] This conceptual design is produced based on the hydraulic study carried out in Section 3 using Synergi Gas for the identification of potential hydrogen injection points. This report summarises the details, findings and recommendations of the conceptual design for a Hydrogen Blending, Injection, and Control Station (HBICS), including advice on gas quality measurement, metering, odorization design, and the associated material specification for pipework, components, and ancillary equipment within the station.

4.1.1 Scope

As part of the Conceptual Design scope of work, DNV:

- Evaluated the options for the gas entry unit to accommodate the load requirements for the gas network – the amount of hydrogen needs to be limited by a flow ratio (flow/volumetric) control system.
- Evaluated options for gas quality measurement of natural gas and hydrogen blends using gas chromatograph or alternatives.
- Evaluated metering options and highlight any restrictions due to the presence of hydrogen.
- Investigated options for mixing quality and measurement of calorific value and any other parameters required to demonstrate gas quality compliance.
- Investigated the safety devices/processes for the system including the operating philosophy, safeguarding systems, communications/telemetry and upstream interfaces.
- Developed an outline system design and layout for a hydrogen odorization system.
- Developed an outline system design for the complete unit including P&ID and high-level site layout.
- Referenced relevant external and internal standards including how the design will comply with the required measurement uncertainties.

4.1.2 Assumptions and Caveats

The following assumptions and caveats have been made during development of the Conceptual Design scope of works detailed within this report:

[redacted]

[redacted]

[redacted]

4. DNV has produced a single conceptual design that can be potentially applied across multiple locations on the network. If, however, there are significant load differentials requirements within the network, then this will require revaluation to assure the applicability of this design.

5. The Conceptual Design scope of work exclude any Environmental Assessments such as Geotechnical Assessments, Ground Movement Assessments, Archaeological, Mining, SSI's, Topographical survey data reviews, etc, for the proposed site to be used.
6. All requirements related to the Civil engineering discipline including foundations, earthworks, ground conditions, fencing, etc, are excluded from the scope of work.
7. The routing of pipelines and identification of potential location(s) for the Hydrogen Blending, Injection and Control Station (HBICS) is excluded from the scope of work, and therefore this report does not evaluate Building Proximity Distances (BPD), Area Classifications and Safety Distances.

4.2 Codes, Standards and Legislative Requirements

The following Codes, Standards and Legislative Requirements shall apply to the conceptual design produced within this section of the report:

CAN-BNQ 1784	Canadian Hydrogen Installation Code
CSA B51	Boiler, Pressure Vessel and Pressure Piping Code
CSA Z662:19	Oil and Gas Pipeline Systems

The following additional Codes and Standards were also considered as part of the conceptual design:

AIGA 087/20	Standard for Hydrogen Piping Systems at User Locations
ASME B31.3	Process Piping
ASME B31.8	Gas Transmission and Distribution Piping Systems
ASME B31.12	Hydrogen Piping and Pipelines
BGCA CP 41	The design, construction, maintenance and operation of filling stations
EIGA IGC Doc 15/06/E	Gaseous Hydrogen Stations
EN 17124	Hydrogen fuel – Product specification and quality assurance
IGC 15/06/E	Gaseous Hydrogen Stations
IGC 121/14	Hydrogen Pipeline Systems
ISO 14687	Hydrogen fuel quality – Product specification
NACE TM0284	Evaluation of pipeline and pressure vessel steels for resistance to HIC
SAE J2719	Hydrogen fuel quality for fuel cell vehicles

4.3 Basis for Conceptual Design

[redacted] As part of the scope of work, DNV will produce a single conceptual design that could be applied to any injection point on Enbridge/Gazifère's network, subject to the design, configuration and equipment/component selection being suitable for the load requirements within each network.

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[redacted]

4.3.1 Hydrogen Injection System

[redacted]

[redacted]

Since the hydrogen is injected in proportion to the natural gas volumetric flow rates and the natural gas flow rates varies with demand, a flow control/ratio device shall be required for proportional hydrogen injection and blending. In addition to this device, flow meters are also required to be installed upstream and downstream of the injection point, all of which have been evaluated as part of the conceptual design.

4.3.2 Hydrogen Storage Sizing

Due to demand uncertainties and any potential downtime associated with the hydrogen production plant/pipeline, hydrogen storage is assumed to be required.

[redacted]

[redacted] Sizing a hydrogen tank involves several engineering considerations and generally requires a detailed analysis of demands, supplies, and the distribution network. For proportional hydrogen injections in terms of natural gas volumetric flow rates, the hydrogen injection rates vary with time since the natural gas flow rates vary with demand. The hydrogen production rates could also be considered as a function of time. The hydrogen tank sizing/volume depend on the difference between the hydrogen production profile and the hydrogen injection profile annually for a specified design period (or several years). The hydrogen pipeline can be line packed and therefore the storage tank sizing is considered to be conservative if the line pack effects are ignored.

Since the hydrogen production data/profile are unavailable, the storage tank sizing cannot be completed at this stage. However, a methodology on general tank sizing is provided for future design consideration when the production profile is available. Figure 4-2 presents a schematic of the methodology to size the storage tank. where the X-axis is time in months. The Y-axis is the production rate minus the injection rate as a function of time. The production is assumed to be larger than the injection rate in summer (hot) season but less than that in winter (cold) season to balance the supply (or production) and demand (or injection) relationship. During the summer season, the hydrogen tank will be used to store the surplus hydrogen. The minimum storage tank volume is the accumulative additional hydrogen volume during the summer season. In winter, the stored hydrogen will be used to make up the differences between the production and injection. For this example, it is assumed that the annual total hydrogen production volume is equal to the annual total hydrogen injection volume. In Figure 4-2, the daily variation of the hydrogen injection volume is ignored.

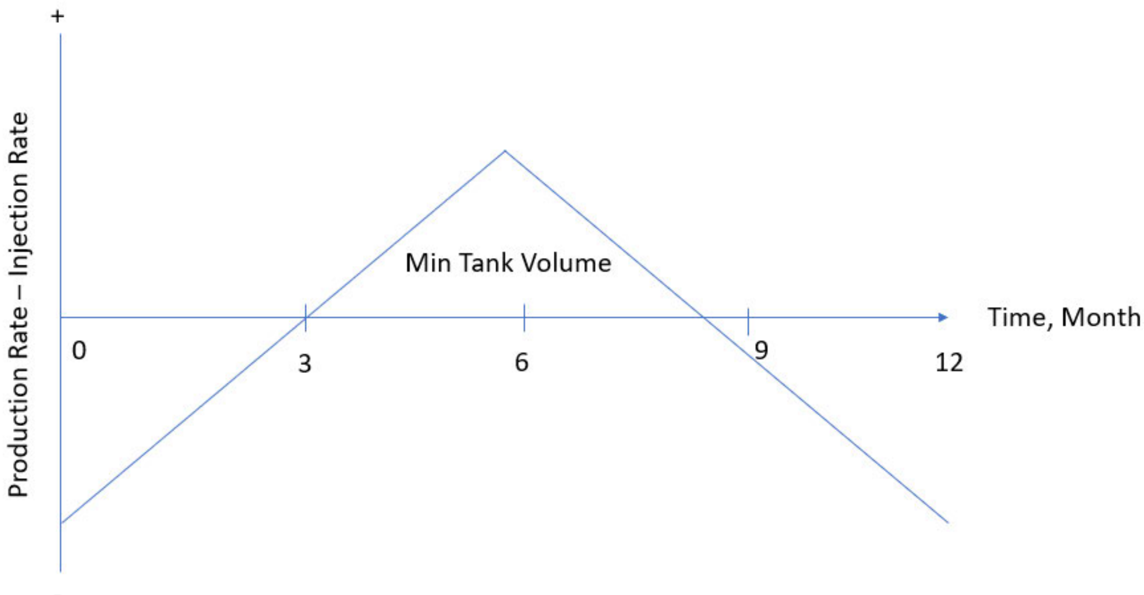

Figure 4-2: Schematic of Methodology to Size Tank Volume

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4.4 Hydrogen Blending, Injection and Control Station (HBICS)

4.4.1 Conceptual Station Layout

The Hydrogen Blending, Injection and Control Station (HBICS) will consist of pipework, components and equipment for hydrogen storage, filtration, pressure regulation, mixing/blending, flow control, feedback loops, metering, gas quality measurement, sampling, actuated control valves, odorization and isolation valves as required. [redacted]

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4.4.2 Conceptual Design Considerations

Where practicable, this conceptual design has been developed with the following considerations:

1. The conceptual design within this report will consider the relevant Codes, Standards and Legislative requirements listed in Section 4.2.
2. In addition to operational requirements, consideration will be given to inspection and maintenance activities.
3. Hydrogen supply interruption will be given due consideration to ensure continuity of energy supply.

4.4.3 Process and Operating Conditions

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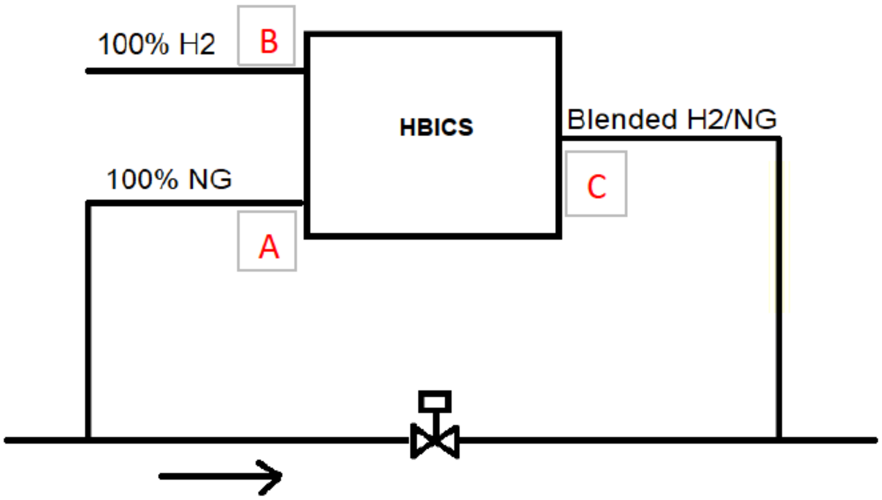

Figure 4-4: HBICS Interface

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4.5.1 Filtration/Purification

Since the HBICS consists of compression and/or pressure regulation equipment and highly sensitive gas quality measurement and metering equipment, it is recommended that filtration of incoming natural gas be carried out prior to commencement of the blending process. Since filtration of 100% natural gas is an existing process carried out on Gazifère's assets, no further guidance is provided on filtration of 100% natural gas within this report.

[redacted] This ensures that any blending inconsistencies or out-of-specification gas is not caused due to contamination from the dedicated hydrogen pipeline.

[redacted]

4.5.2 Compression

[redacted] Increasing the pressure of hydrogen prior to storage will significantly increase the amount of hydrogen that can be stored on site, thereby heavily reducing the cost of storing per unit of hydrogen and significantly reducing the required footprint area of the site.

As part of the conceptual design study, DNV has identified various types of compressors that can be potentially used for on-site hydrogen compression, as summarised in Table 4-4 below.

Table 4-4: Hydrogen Compressors

Type	Hydrogen Application
Reciprocating Compressors	Used in applications that require very high compression ratio
Rotary Compressors	Challenges in hydrogen applications due to tight tolerances for preventing leakage
Ionic Compressors	Commonly used in hydrogen fuelling stations
Centrifugal Compressors	Used in pipelines due to high throughput and moderate compression ratio

Whilst centrifugal compressors are the preferred compression type for pipeline applications, these compressors will need to operate three times faster than that of natural gas compressors to achieve the same compression ratio because of the low molecular weight of hydrogen.

There are several considerations to be taken whilst selecting compression systems for use on the HBICS, these being:

- Since the compression system will contain potentially explosive and highly flammable gases, adequate internal explosion protection measures shall be deployed
- The heating/cooling of hydrogen shall be evaluated, and appropriate cooling/heating systems provided to ensure that the variations in gas temperatures do not adversely affect the operation of the compressors.
- Design of the compression unit shall consider the potential effects of vibrations and/or pulsations emanating during operation of the compressors.

It is recommended that compressors selected for use in hydrogen service meet the requirements of IGC 15/06/E Gaseous Hydrogen Stations or other alternative standards as deemed appropriate for Québec.

[redacted]

4.5.3 Hydrogen Storage

Hydrogen is commonly stored as either a liquid or a gas. Storage of hydrogen as a liquid requires cooling of the gas to cryogenic temperatures since the boiling point of hydrogen at one atmosphere is -252.8°C. For the purposes of this study, DNV has limited the assessment of potential storage options to storing hydrogen in its gaseous form. In its gaseous form, hydrogen can be stored on site using the following solutions:

- Low Pressure Buffer Tank, stored at the incoming hydrogen pressure of 24bar – 34bar

- High Pressure Storage Tanks, stored at typically 350bar – 700bar
- High Pressure Cylinders, stored at typically 200bar – 300bar
- High Pressure Bullets, stored at typically 200bar – 800bar

The storage options listed above typically require large-volume systems in order to store hydrogen in its gaseous form.

If hydrogen is stored on site to act as a buffer volume, then this may be stored at the incoming hydrogen pressure using buffer tanks (or pressure vessels) designed to withstand the design pressure of the hydrogen pipeline. This however means that the energy stored per unit volume of hydrogen would be significantly lower than storing hydrogen at higher pressures. The cost of storing hydrogen would also be higher per unit volume and will increase the overall foot-print area of the site required to store the same amount of hydrogen at higher pressures.

If hydrogen is stored at high pressures in tanks/cylinders/bullets, then this will require compression of the incoming 100% hydrogen (covered in Section 4.5.2) and pressure regulation to reduce the pressure down to injection pressure (covered in Section 4.5.4), prior to blending.

For the purposes of this study, it is assumed that the available footprint area within the site is less critical considering that the site will be a new purpose-built site. Hydrogen storage tanks and cylinders are typically located above ground, positioned either vertically or horizontally. Hydrogen bullets can be installed below ground and can therefore be considered a safer option as this mitigates the potential for any external impact damage, provides better ignition source control and reduces severity in the event of a failure.

The sizing of hydrogen storage is critical in terms of ensuring availability and its impact on the overall footprint area of the site. The sizing should be carried out taking into account the following critical factors:

[redacted]

- Maximum capacity of the 100% hydrogen pipeline
- Capacity of compression equipment
- Required on site back-up
- Above-ground/below-ground type of storage
- Quantitative Risk Assessments (QRA) considering loss of life, property and environment
- Building Proximity Distances (BPD)
- Site specific space constraints
- Storage volume limitations due to Control of Major Accident Hazard (COMAH) Regulations

The selection and/or location of hydrogen storage equipment within the site shall consider the hazards associated with storing gaseous hydrogen, and its risks reduced to ALARP.

[redacted]

4.5.4 Pressure Regulation

If hydrogen is stored on the HBICS site at higher pressures, pressure reduction of stored hydrogen to injection pressures is required to be carried out prior to blending with natural gas. A typical arrangement of the pressure reduction system is shown in Figure 4-5 below.

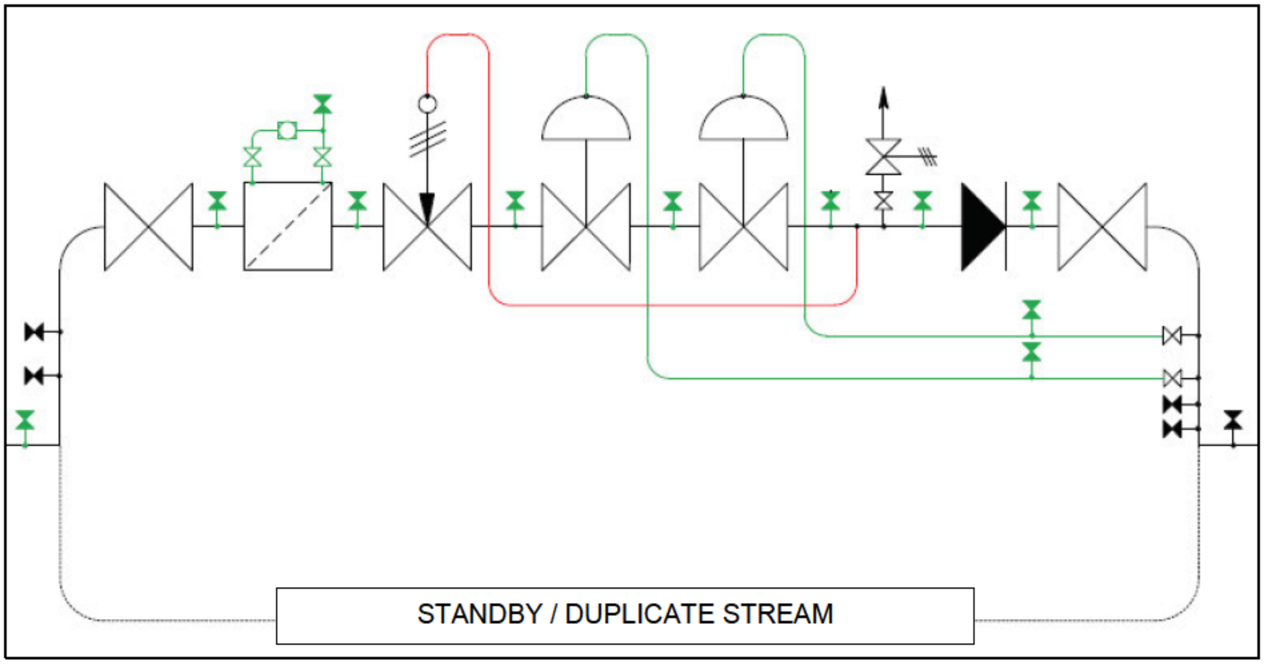

Figure 4-5: Typical Pressure Reduction Stream Configuration [2]

As seen from the figure above, the typical arrangement for a hydrogen pressure reduction system will include a control system, filters, slam shut valves, monitor regulators, active regulators, relief valves and isolation valves.

Existing pressure reduction system configurations used in the natural gas industry can be used for hydrogen, however, the materials selected for each component shall be verified and confirmed for use in 100% hydrogen service.

Even if the hydrogen is stored on site at the incoming pressure i.e., within a buffer tank, a natural gas pressure reduction system may still be required to ensure that the pressure of hydrogen during injection remains higher than that of natural gas.

4.5.5 Flow Metering

Flow metering of the incoming 100% hydrogen, 100% natural gas and blended hydrogen/natural gas should be considered as shown in the conceptual design P&ID and General Arrangement drawing produced by DNV, see Appendix 4: HBICS PFD and General Arrangement Drawing.

See Section 5.6 for current industry research and findings on the existing options suitable for hydrogen and hydrogen/natural gas blends.

Meter options include rotary, turbine, ultrasonic, thermal mass, Coriolis and orifice plate, and all could be adopted for use with hydrogen/natural gas blends. Currently the meters that are most commonly installed are orifice plate and ultrasonic devices.

For fiscal metering requirements, flow together with pressure, temperature and gas composition is required, together with ideal gas deviation calculations relating to compressibility factor, and an Equation of State like AGA-8 and other ISO standards (ISO 6976) to enable calculation of the energy flow.

Hydrogen addition impacts on the calorific value and compressibility and these can be determined to ensure that the user is billed correctly for the energy content of the blend used. The meter type options quoted above would be suitable for fiscal purposes as long as the errors and uncertainties are within the allowable limits set by Measurement Canada and accepted by Regie.

[redacted]

4.5.6 Gas Blending/Mixing

Gas blending/mixing is required to ensure a homogenous gas mixture when hydrogen is added to natural gas, for which there are a number of static mixer types available in the market. DNV has identified two techniques that can potentially be deployed for blending hydrogen with natural gas, these being:

1. Helical Static Mixer
2. Tee Blender

Both the above techniques are well known for their use in the gas industry to efficiently blend unconventional gases such as biomethane with distribution quality natural gas.

The distance it takes for the hydrogen and natural gas to become a homogeneous blended mixture is dependent on the pressures, flow rates, blend ratios and characteristics of the pipe.

4.5.6.1 Tee Blender

A device known as Tee Blender used across the gas industry has been identified as an appropriate method of blending hydrogen with natural gas. The T-shaped device, seen in Figure 4-6 below is placed at the connection point between the incoming natural gas pipeline, a secondary, smaller pipeline (hydrogen injection stream) and the blended natural gas/hydrogen outlet pipeline.

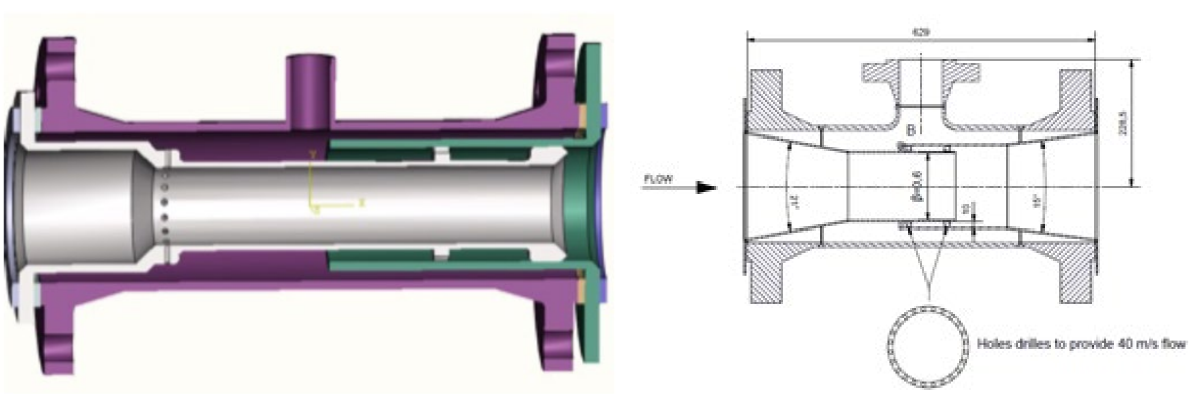

Figure 4-6: Tee Blender

The Tee Blender utilises the Venturi effect, where the high-pressure gas flowing through a constricted section of pipeline experiences a reduction in pressure and an increase in gas velocity. As the low-pressure gas flows around the constricted section of pipework, the high-pressure gas exits the constricted section, at a higher velocity, creating a vacuum at the area surrounding the exit of the nozzle. This vacuum creates a suction by the high-pressure gas and the pressure differential between both gases results in effective blend of both gases in the diffuser.

In re-blend mode, a venturi effect is used to create a pressure drop within the purple section of the spool, providing the differential to enable a flow into the spool of out of specification gas (silver section), which then flows into the downstream system.

The blender performs over a wide range of blending ratios over a wide range of flows. This is due to the robust and open construction, low pressure drop, geometric injection and induced swirl. Some of the advantages of this device are that it has no moving parts, does not require a power supply, and requires zero maintenance.

[redacted]

4.5.6.2 Helical Static Mixer

A device known as Helical Static Mixer has also been identified as a potential method of blending hydrogen with natural gas. The Helical Static Mixer places a fixed helical element into the natural gas parent pipeline, situated after the tee branch where the hydrogen is injected, as seen in Figure 4-7 below.

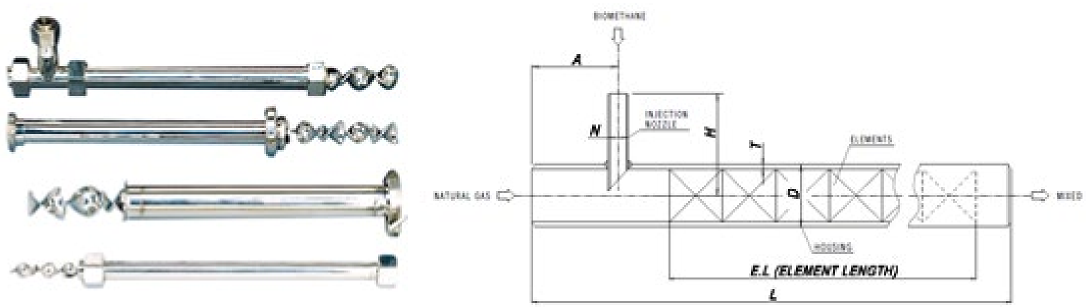

Figure 4-7: Helical Static Mixer

Pressure moves the natural gas and hydrogen over the helical elements, these elements create effective mixing due to the arrangement of the elements by moving gas on the pipe wall to the centre of the element and gas in the centre of the element to the wall. As a result, a velocity difference is created in the gas molecules, which leads to fluid shear. In addition to this velocity increase, an increase in mixing occurs, due to a turbulence increase in the gases by the elements fixed alternating position change of 90°.

This method requires the hydrogen to be compressed to the pressure of the natural gas before introduction into the parent pipeline. This arrangement provides continuous in-line mixing of the gases using alternating helical elements.

As with the Tee Blender this option has no moving parts, requires no power to operate and requires no maintenance once installed. However, unlike the Tee Blender, the helical static mixer requires the hydrogen to be compressed to a pressure equal to the natural gas supply before being introduced into the parent main.

[redacted]

4.5.7 Flow Ratio Control Valve (FRCV)

An actuated flow control valve mounted on the hydrogen inlet to the tee blender will act as the hydrogen injection device, termed as Flow Ratio Control Valve (FRCV), ensuring that the hydrogen is released into the mixing device at the correct flow rates, pressures and time intervals. The gas blend ratio will be maintained by the FRCV and will automatically close in the event of an out-of-specification blend or any upset/fault conditions. The closure of the FRCV can be programmed to open relief and vent to atmosphere, or alternatively, open the Re-Blend Loop to enable re-blending of the out-of-specification gas. The latter option mitigates issues associated with venting and associated flaring.

In case of low flows and based on turndown assessment, it may be necessary to have two control valves in parallel operating in a split range manner. This will depend on minimum and maximum flowrates and the turndown requirements (currently unknown). Example of the use of two flow ratio control valves includes having the first valve to operate at 0- 30% max flow and the second valve to operate at 30-100% max flow.

This arrangement shall be evaluated during the detailed design phase once the natural gas and hydrogen flowrates and turndown requirements are known.

4.5.8 Gas Quality

In order to ensure that the blend ratio of hydrogen/natural gas is maintained throughout, gas analysers or gas chromatographs are required to be installed downstream of the hydrogen injection point but there must also be natural gas measurement upstream to ensure that the hydrogen addition meets gas quality specifications.

Gas analysis and measurement equipment exists for determination of hydrogen content in mixtures of hydrogen and natural gas. However, to ensure that any selected equipment is fit-for-purpose a test evaluation programme is required to ascertain the overall performance of analysers both for billing purposes and control applications.

There are several gas chromatographic equipment suppliers that now offer capability to accurately measure hydrogen in a blend with natural gas. However, existing measurement equipment may need to be modified, upgraded or replaced (see Section 5.6.2.1 for detailed discussion on Gas Quality measurement). In many instruments that have been tested there is a requirement to install separate chromatographic columns and also use a different carrier gas to the analysers. In many instances, helium is used for the natural gas component analysis and argon for the hydrogen content. Instrument accuracy and reliability are good, and although a relatively new application for the analysis of hydrogen in pipeline gas, hydrogen and hydrocarbon mixtures are routinely analysed in refinery applications.

In addition to the gas composition analytical equipment that is required for calorific value determination and to ensure compliance with gas quality standards, faster acting sensors and analysers may be needed to be integrated with the hydrogen injection control system. Here the sensors are required to provide real-time measurement of the hydrogen content to act as a control feature and ensure that there are no excursions in the hydrogen content if there are natural gas flow variation or upset conditions. The range of instruments available is small at the present time, but further research is underway to develop new equipment and provide the rapid analysis required for control systems.

[redacted]

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4.5.9 Station Bypass

A station bypass valve should be installed on the main 100% hydrogen pipeline (identified as VA-01 within the PFD and GA drawing included in Appendix 4: HBICS PFD and General Arrangement Drawing). This valve is an actuated valve and will remain in closed position when the HBICS is in operation, which will ensure that the blended gas mixture does not interact with the upstream 100% natural gas. This is critical in ensuring that the blend percentage of the gas mixture is maintained downstream of the HBICS.

The station bypass valve can be remotely operated and can be programmed to open in the event of an outage of the HBICS, failure of hydrogen supply or any other fault/process upset conditions, which cannot be resolved immediately. The opening of the station bypass valve will be programmed to automatically close the HBICS inlet and outlet valves (acting as Emergency Shutdown Valves) and let the flow of 100% natural gas to go through ensuring continuity of supply to customers. It should however be noted that in this case, issues such as fiscal billing, regulatory limit exceedances, out-of-specification gas issues, etc arising from supplying natural gas (and not blended gas) will require evaluation and addressing prior to this being deployed.

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4.5.11 Pipework

Per ASME B31.12, the design factor of pipelines in hydrogen service is limited to 0.5 (in the case of Option A designs compared to 0.72/0.8 in natural gas). A material performance reduction factor is applied to reduce the allowable design factor for grades higher than X52, which can be avoided if the materials are subject to additional testing requirements as stipulated within ASME B31.12.

The pipework shall be sized appropriately such that the velocity of gas does not cause vibrations, excessive noise levels, pulsations and negative effects on pressure monitoring. [redacted]

4.5.11.1 Below ground pipework

It is recommended that all below ground pipework is of fully welded construction. If flanged or mechanical joints are required, then it is recommended that these are installed with provision for access for inspection and maintenance. All below ground pipework should be adequately protected against corrosion using appropriate techniques such as cathodic protection, coatings, etc.

As per IGC 121/14, underground piping should be adequately buried to protect it from frost taking into account temperature fluctuations particular to the area, casual surface construction, shifting due to unstable soil, back fill damage to the external surface of pipe or the coating, and above ground loads such as vehicles or equipment moving over the path of the pipeline.

Pipe casings, if required, should be installed at railroad or road crossings or where unusual above ground loading can occur. Casings or sleeves require careful consideration and special measures to avoid cathodic protection problems and arcing, which can be caused due to an electrical connection forming between the sleeve and carrier pipe due to settlement, etc. In general, the use of metallic casings or sleeves should be avoided.

Underground hydrogen piping may be vulnerable to damage by lightning strikes or ground fault conditions, which can damage the pipe material. To reduce the likelihood of one of these occurring, electrical continuity between underground hydrogen piping and above ground piping, or other metal structures, should be avoided.

4.5.11.2 Above ground pipework

All above ground pipework should be designed and installed in accordance with good mechanical design practices and should be as applied to existing natural gas piping systems. Due to the higher potential for leakage as a result of the smaller molecular size of hydrogen, the use of welded connections is recommended wherever possible.

All above ground pipework should be painted/coated to an approved specification to protect against atmospheric corrosion. When connecting to pipework below ground, insulation joints should be installed to electrically isolate the pipework and ensure integrity of the underground cathodic protection system.

As per IGC 121/14, all above ground pipelines shall have electrical continuity across all connections, except insulating flanges, and shall be earthed at suitable intervals to protect against the effects of lightning and static electricity. The electrical resistance to earth of the installed pipeline should not exceed 10 ohms for personnel protection against electrical or high voltage shock.

Flange bolting will provide the necessary electrical bond provided the bolts are not coated with a dielectric material or paint and are well maintained to avoid rust. In the case of short above ground sections, where insulating flanges are not used, the pipe should be insulated from the support structure by means of an isolating pad.

Hydrogen piping should not be exposed to external forces which can cause a failure or dangerous situation such as external impingement from hot gas or steam vents, vibration from external sources, leaking oil dripping onto the line, etc.

Above ground piping systems outside plant fence lines can be subject to deliberate or accidental damage. Consideration should be given to installing pipe and valves below ground, with extensions for above ground operators and instrumentation.

4.5.12 Valves

The following valves, as a minimum, are expected to be to be installed within the HBICS.

Table 4-5: Valves to be considered in HBICS

Valve Type	Purpose
Non-Return Valve (NRV)	To ensure that the gas only flows in a single direction.
Emergency Shutdown Valve (ESDV)	Valves designed to close/shut-off gas supply in the event of an emergency or major fault.
Actuated Valves	Valves that operate automatically using a control signal from the HBICS control system, with a manual override function for remote actuation. These valves may also be used to isolate the Hydrogen Blending Unit from the gas network in the event of out of specification gas being monitored.
Pressure Control Valve (PCV)	The PCV ensures continuous flow of gas through the network in the event of a fault that results in a reduced or no-flow condition in the HBICS.
Station Bypass Valve	The Station Bypass Valves
Isolation Valves	Valves that are to be used for manual isolation by Operations and Maintenance personnel, which may be locked in a closed/open position to avoid inadvertent operation

If practical, consider using only fully welded valves in hydrogen service.

4.5.13 HBICS Interface Management

The upstream interfaces / battery limits (boundary limits) between the hydrogen pipeline and the gas grid need to be defined such that the expectations for the design can be understood by the various parties including suppliers, HBICS site operators and gas network owners/operators. In particular, it is critical to establish:

- Who owns what equipment and where the design, construction and start-up responsibilities lie?
- Who will be responsible for operating the equipment e.g., meter calibration activities, controller tuning, control valve maintenance/repairs, gas quality measurement equipment maintenance & repairs and who will hold spare parts?

- Who is accountable in event of emergency/system failure?
- Who is responsible for inspection and/or maintenance of the system?

One of the determining factors could be the distance between the hydrogen generation facilities and the tie-in to the gas grid pipeline. The HBICS could be located relatively close to the gas grid pipeline, but this is not necessarily the case.

The interfaces and other physical aspects that need to be considered during the design and construction phase are as follows:

- Mechanical tie-ins to the low-pressure gas grid
- Instrumentation and control system location and tie-ins for signals
- Telemetry to remote monitoring facilities
- Electrical power for the site i.e., where will this come from?
- Site access and equipment laydown areas for maintenance/repairs/equipment calibrations
- Distance from hydrogen provider's equipment (e.g., Is there a long pipeline and at what pressure?)

4.6 Material selection

Due to the potential exposure to 100% hydrogen, all materials selected for use within the HBICS shall be designed for 100% natural gas, 100% hydrogen and for any percentage of blend ratio between them.

4.6.1 Pipework

The pipework to be installed within the HBICS shall as a minimum, comply with the requirements of ASME B31.12 and IGC 121/14 or other relevant standards as deemed applicable for Québec. For the tie-in and interconnecting pipework within the HBICS, it is recommended that the following materials are used for line pipe:

- Incoming 100% Natural Gas: Existing materials in use within Gazifère's network
- Incoming 100% Hydrogen: Materials specified in ASME B31.12 or IGC 121/14.
- Blended Natural Gas/Hydrogen: API 5L X52 (and lower grade) PSL 2 pipe is used, with the additional material and testing requirements applied from ASME B31.12.
- Compressed High-Pressure Hydrogen: Tungum

Per ASME B31.12, the design factor of pipelines in hydrogen service may be limited to 0.5 (compared to 0.72/0.8 in natural gas), resulting in lower operating pressure limits. A material performance reduction factor is applied to reduce the allowable design factor for grades higher than X52. Additional testing requirements defined in ASME B31.12 may be implemented to qualify materials for use in hydrogen service to operate at higher design factors.

All small-bore tubing shall be in 316L stainless steel with twin-ferrule compression fittings. Type 316L is preferred to 304L for hydrogen gas service because 316L has higher austenite stability and is less subject to hydrogen embrittlement. The use of continuous runs should be maximized to reduce the number of fittings since these can be leak sources.

4.6.2 Fittings

As per IGC 121/14, fully welded connections are recommended for use in hydrogen service. Where welded connections are not practical, flanges are the next best choice. Threaded connections shall be used only where welded (including seal welded threaded connections) or flanged connections are not practical and only in pipework connections of less than 1" (25NB). The sealant shall be hydrogen compatible and should be high temperature resistant to reduce the risk of leaks during a fire. Typical uses of threaded connections are to match equipment, especially instruments, however these are limited by size.

4.6.2.1 Flanges, Gaskets and Bolts

Flanges

In general, ring type joints flanges are recommended for use in hydrogen service. However, leak resistant flange types such as raised face, tongue and groove, etc can also be used. ASME B31.12 permits the use of Cast/Forged Flanges, Threaded Flanges, Lapped Flanges, Slip-on Welding Flanges and Welding Neck Flanges. However, DNV recommends that existing Gazifère's specifications for selection of flanges used in natural gas service be followed for the selection of the type and facing of flanges used in hydrogen service. In any case, it is recommended that welding neck ring type joint flanges be installed on new pipework designed for operation in natural gas/hydrogen service.

Gaskets

Gasket materials should be appropriate for the design pressures and temperatures and be hydrogen compatible and leak resistant. In addition, consideration should be given to resistance to fire, due to the flammability of hydrogen.

As per IGC 121/14, filled spiral wound steel gaskets are preferred with raised flanges, but composition gaskets which are graphite based are also used at lower pressures. Soft metallic rings are preferred with ring joint flanges. In summary, a Teflon or graphite filled spiral wound gasket with a raised face flange or a copper ring with a ring joint flange are typical choices since they embody the desired features to a large extent. Since small leaks to atmosphere present a safety risk, flange covers should be considered.

As per ASME B31.12, flat-ring gaskets with an outside diameter extending to the inside of the bolt holes may be used with raised-face flange steel flanges, or with lapped steel flanges. The material of the rings in ring joint flanges shall be suitable for the service conditions encountered and shall be softer than the flanges, with the dimensions for these in accordance with ASME B16.20.

Bolts

For all flanged joints, ASME B31.12 stipulates that bolting shall be made of alloy steel conforming to ASTM A193, ASTM A320 or ASTM A354, or of heat-treated carbon steel conforming to ASTM A449. However, bolting may be made of Grade B of ASTM A307 for ASME B16.5 Class 150 and 300 flanges at temperatures between -30^{o}C and 200^{o}C. The material used for nuts shall conform to ASTM A194 or ASTM A307. ASTM A307 nuts should only be used with ASTM A307 bolting.

As per ASME B31.12, all carbon-steel bolts and stud bolts shall have coarse threads having Class 2A dimensions, and their nuts shall have Class 2B dimensions. All alloy-steel bolts and stud bolts 25mm (1 in) and smaller shall be coarse thread. Larger bolts shall be an 8-thread series and have a Class 2A dimension. Nuts shall have a Class 2B dimension. Bolts shall have regular square heads or heavy hexagonal heads conforming to ASME B18.2.1 and shall have heavy hexagonal nuts conforming to the dimensions of ASME B18.2.2.

4.6.3 Valves

As per IGC 121/14, the potential for leaks on valves used in hydrogen service can be minimised by ensuring the following materials and/or specifications are met:

- Double seals or packing
- Each casting to be hydrostatically tested.
- Soft seat in a metal retainer for in-line automatic valves and automatic vents, including bubble tight shut-off

- Metal to metal seat or soft seat in a retainer for in-line manual valves; these should be combined with a means of positive isolation if used to block flow before attempting maintenance or inspection.
- Metallic seat with valve outlet blocked. Typical arrangements used are double valves, blind flange, plug, or cap.
- Preferably no through bolting, body flanges or threaded connections in assembly of the body of the valve.
- Mainline isolation valves should be of full port design, when pipeline pigging for inspection is foreseen.

As per IGC 121/14, positive sealing of valve packing glands is important in hydrogen service. Packing materials should be hydrogen compatible and suitable for high temperatures to better maintain their integrity in case of a fire. Graphite based compounds are typically used. Double packing should be used to mitigate the chance of leakage to atmosphere which can present a flammability risk. Any soft materials used shall be compatible for use in hydrogen service.

Only fully welded valves are recommended to be used in hydrogen service. ASME B31.12 allows the use of valves manufactured in accordance with ASME B16.34, ASME B16.38, API 6D, API 609, API 600 and API 602. Any valves or valve components made of cast or ductile iron shall not be used in hydrogen service. As per ASME B31.12, pipelines valves purchased to API 6D requirements shall be capable of passing the pressure tests described in API 6D Annex C, para C4, using helium as the test medium. Other valves shall be capable of passing the pressure tests described in API 598, using helium as the test medium.

Generally, low grade steel is recommended for valve body material to be used in hydrogen service, with the material testing requirements to be met as per BS EN ISO 6892-1 and BS EN ISO 148-1. Although existing materials used for natural gas such as ASTM A105, ASTM A216 WCB, ASTM A350 LF2, ASTM A182 F316, etc can be used for hydrogen service, these shall meet the maximum hardness requirements and be tested in accordance with the requirements of ASME B31.12. Table 4-6 below shows the recommended maximum hardness values for valves that are designed for use in 100% hydrogen service.

Table 4-6: Maximum Hardness/Strength requirements for Valves in Hydrogen Service

Item	Base Material	Heat Affected Zone	Weld
Valve Body	<325HV	<325HV	<325HV
Stem	≤260HV	≤260HV	≤260HV
Ball	<325HV	<325HV	<325HV
Valve Disc (Gate Valve)	<325HV	<325HV	<325HV

Generally, metal to metal seal is recommended for valves operating in hydrogen service. However, soft seals that are compatible with hydrogen may be used in Primary Metal Secondary Sealing (PMSS) applications. Although Viton and high density NBR (Buna-N/Nitrile) are considered safe for use in hydrogen service, these soft goods are subjected to increased amounts of degradation when exposed to hydrogen. Due to the enhanced swelling of buna-n / nitrile and viton when exposed to hydrogen, the frequency of inspection and/or maintenance of these items should be increased.

4.6.4 Hydrogen Storage Tanks / Cylinders

Materials used for hydrogen storage tanks and/or cylinders shall be selected appropriately and qualified and tested for use in hydrogen service. The materials of construction of these should, as a minimum, follow the pipeline requirements in intent and selection criteria. Vessels should be designed with sufficient parent metal and weld zone toughness for leak before break criterion and to withstand fatigue in service. They shall be designed to withstand internal pressure and cyclic loading in accordance with appropriate standards and regulations.

There are four standard types of cylinders that are used for hydrogen storage, these being:

- Type I—all-metal cylinders

- Type II—all-metal hoop-wrapped composite cylinders
- Type III—fully wrapped composite cylinders with metallic liners (e.g., Al-6061)
- Type IV—fully wrapped composite cylinders with non-load bearing non-metallic liners (i.e., usually a polymer such as high-density polyethylene).

For Type I and II cylinders, the mass of the metal required to contain the pressure generally only allows storage of 1% or 2% hydrogen compared to the cylinder mass, which drops to less than 1% hydrogen by mass at pressures above 35 MPa.

As an alternative to the above, hydrogen may be stored at high pressures in cryogenic form, however, this will require additional associated ancillary equipment including compression systems, cooling systems, etc.

4.6.5 Equipment

All pressure containing equipment should be designed against the relevant codes and standards applicable to Québec and shall be suitably rated for the intended design and operating conditions specified within this report.

Any electrical, control and instrumentation equipment on site shall be rated for the hazardous area zone they will be situated based on the Hazardous Area Classification (HAC) and the Hazardous Area Drawing (HAD) produced.

4.7 Control, Instrumentation, and Safety requirements

4.7.1 Control Systems

The control system should be designed such that the station can be unstaffed, with automatic operation and remote monitoring/control from the Central Control Room (CCR). Remote monitoring of the site should be available to the Gas Network Owner/Operator and the HBICS operator.

The Flow Ratio Control system contains

1. The measurement elements, (flow, temperature and pressure measurement devices) in both the natural gas and H2 gas streams
2. A processor (flow ratio control Computer)
3. The flow ratio control valve (denoted FRCV), discussed in Section 4.5.7

The description of the system operation is as follows:

- Flow, temperature and pressure of the natural gas should be measured and used to derive the accurate volumetric flowrate of the natural gas. A similar system should also be used for the hydrogen gas stream such that the volumetric flows of both gas streams will be monitored.
- The set point of the controller (pre-set by agreement) will determine the proportion of hydrogen gas to be supplied into the downstream system. The flow ratio controller will compare the allowable flowrate of hydrogen with the measured value and the output from the controller will modulate the flow ratio control valve to maintain the set ratio.

The following table provides an example of the percent H_2 versus natural gas ratio in downstream gas.

Table 4-7: Blend Ratio Set-Point

Mole %H_2 in blended gas	Ratio Set point (NG:H_2)
5%	19:1
10%	9:1
20%	4:1

4.7.2 Safety Requirements

4.7.2.1 Safeguarding Systems

The safeguarding system is used to minimize the risk to the community, facility, and environment resulting from abnormal operating conditions and/or external hazards. There are three principal objectives:

- To protect the mechanical integrity of equipment and piping systems
- To place the equipment in a safe state when conditions deviate beyond acceptable limits
- To reduce incident severity and risk of escalation in the event of breach of mechanical integrity.

The safeguarding system is independent from the control computer and should in principle be managed via an independent, appropriately rated PLC. The following alarms and safeguards are anticipated:

Table 4-8: List of Alarms required on the HBICS, as a minimum

Alarms		
Parameters	**Set Point**	**Comments**
Low Natural Gas Flow	TBA	Low Demand Period
Low Natural Gas Pressure	TBA	Could be insufficient NG for blending
High Hydrogen Flow	TBA	Could be FRCV failing fully open
High Hydrogen Pressure	TBA	Within 10% of downstream design pressure
Low Hydrogen Pressure	TBA	Back-flow from NG. Only safeguard is NRV
Parameters	**Set Point**	**Comments**
Low-Low Natural Gas Flow	TBA	Closes Station Inlet/Outlet Valves and Opens Station Bypass Valve
High Hydrogen Flow Ratio	TBA	Closes Station Inlet/Outlet Valves and Opens Station Bypass Valve
High Hydrogen Pressure	TBA	Closes Station Inlet/Outlet Valves and Opens Station Bypass Valve
Low-Low Hydrogen Pressure	TBA	Closes Station Inlet/Outlet Valves and Opens Station Bypass Valve

Leak Detection

Hydrogen is odourless, colourless, high tendency to leak and difficult to detect gas. Theoretically, the existing detection devices can still be used to detect hydrogen. For example, semiconductors, thermal conductivity, ultrasonic and catalytic sensors are considered as suitable for detecting H2 or NG or mixtures. However, a recalibration might be necessary depending on hydrogen concentration.

As hydrogen is more prone to leakage than other gases, it is particularly important to survey pipelines with a hydrogen detector periodically. Pipeline survey frequency should be evaluated, depending upon the population density in the area, and as defined by applicable regulations. Particular attention should be paid to flanged connections, valve stems, and compression fittings. Additional considerations are provided in Section 8 of this report.

4.7.2.2 Safety Studies

As part of the detailed design stage, it is recommended that safety studies are carried out to ensure safe operation of the HBICS. The safety studies listed in the sections below is only intended to be a guide and as such, is not an exhaustive list of the studies to be carried out. Other safety studies may need to be applied depending on the location of the site and design of the HBICS.

Furthermore, ASME B31.12 prescribes that if one or more buildings, intended for human occupancy, are found to be within the potential impact area, a full risk assessment shall be carried out. DNV suggests performing a Quantitative Risk Assessment (QRA) for the station based on its location. The QRA is typically used to determine the individual and societal risk and assess whether it is within acceptable limits.

Hazard Identification Study (HAZID)

HAZID is a structured assessment technique for identifying hazards and is undertaken using guidewords. The aim is to identify main hazards, review the effectiveness of selected safety measures and where required, to expand the safety measures in order to achieve an acceptable risk level.

Hazard and Operability Study (HAZOP)

Similar to a HAZID, a HAZOP is a structured assessment technique to identify potential hazards and operability issues. During HAZOP, the process is broken down into a number of simpler sections known as 'nodes' which are then individually reviewed during the study. HAZOP is a more detailed review technique than HAZID. The purpose of the HAZOP is to investigate how the system or plant deviate from the intended design and create risk for personnel, equipment and operability problems.

Safety Integrity Level (SIL) Assessment

A Safety Instrumented System (SIS) consists of a combination of logic solvers, sensors and final elements. Examples include safety interlock systems and emergency shut-down systems. It is designed to prevent or mitigate hazardous events by taking the process to a safe state when certain parameters exceed specified safety limits.

SIL is a system used to quantify and qualify the requirements for Safety Instrumented Systems (SIS). There are four SIL levels. The higher the perceived associated risk, the higher the performance required of the safety system and hence the higher the SIL rating number (SIL4 being the highest). SIL ratings are determined using the Frequency/Consequence matrix. The possible hazards are identified, and the risk is determined by assessing and assigning a number to the frequency of occurrence and the severity of the potential consequences. The product of the severity and frequency determines the SIL level. Safety systems designed into the process will have to satisfy the assessed SIL level.

Gas Dispersion and Consequence Modelling

This type of study assesses scenarios based on common leaks, worst case leaks and other scenarios relevant to the design of the system. The modelling reviews the dispersion of gas and in this case hydrogen and natural gas and assess the possibility of gas accumulation that can form an explosive mixture. This can help in safety reviews and in the provision of fire and gas detection systems.

Hazardous Area Classification (HAC)

The Hazardous Area Classification (HAC) will determine hazardous area zones associated with the HBICS operations and the corresponding Hazardous Area Drawing (HAD) will determine the ATEX rating of the Electrical, Control and Instrumentation equipment to be situated and various locations within the HBICS.

The classification system by group is intended to define, in the European Union, the specifications on electrical equipment implemented or used in the areas where potentially explosive atmosphere can be present, as it is required since 1999 by the European directives 1999/92/CE and 2014/34/EU It is also a way to estimate the probability of ignition of pure gases or gases mixtures, by classifying their reactivity. The knowledge of the explosion group for these hydrogen/NG (H2NG) mixtures is a necessary information for the choice of equipment and protective systems intended for the use in potentially explosive atmospheres of these mixtures. According to the current IEC 60079-20-1 standard, a classification in Group IIA is sufficient for up to 25 vol.% of hydrogen in a methane/hydrogen mixture. Other standards should be reviewed and assessed to determine applicability for Québec.

4.7.3 Instrumentation/Telemetry

Communications and telemetry should be required for all control parameters (flow, gas quality, CV, pressure and temperature measurements) as well as all Alarms and SIFs tabulated in table 8-2 above. In addition, valve position on control valves and ESD valves should also be required. HMI interfaces and control systems associated with the HBICS should integrate appropriately with Gazifère's existing SCADA systems.

The local control room should be equipped with the following:

- Fire and gas panel
- Building services including power distribution and communication system
- Heating and air conditioning
- Lighting

4.8 Integration with Gazifère's Network

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It should be noted that the above list is not exhaustive and is to be taken as the minimum considerations to be given when integrating the HBICS into Gazifère's network. A detailed assessment of Gazifère's operations, maintenance and inspection procedures is recommended to be carried out to identify the updates required post-integration.

5 ASSESSMENT OF NETWORK EQUIPMENT, COMPONENTS, AND MATERIALS

5.1 Introduction

This section addresses the materials integrity assessment for network equipment, components, and materials.

Section 5.2 provides a summary of the different materials and their characteristics in the Gazifère distribution network system being considered for hydrogen blending. The entire system is categorized based on the materials of construction (steels, plastics, and soft goods) and other characteristics relevant for the determination of material integrity for pipelines, valves, meters, regulators, and other components in the Gazifère network. Unknown materials and material properties are also highlighted.

Section 5.3, 5.4, and 5.5 discuss the impacts of hydrogen blending into the Gazifère network on the material integrity. The changes to toughness, crack growth rate, and yield strength when hydrogen is introduced to steel, as well as the impact of hydrogen service on cracklike flaws, dents, gouges, and corrosion are discussed. The integrity impacts on plastics, most notably polyethylene, are also described.

Section 5.6 discusses the impacts of hydrogen blending on flow metering systems, metering and regulator capacity, and material compatibility.

Section 5.7 summarizes the requirements in relevant standards, specifications, and regulations for hydrogen and hydrogen-blended natural gas pipeline systems.

Section 5.8 describes the compatibility of the various materials currently used in the Gazifère network with hydrogen and hydrogen-blended natural gas service. The current integrity status of the various pipelines and welds, and possible failure mechanisms of polyethylene materials and the impacts of hydrogen service on polyethylene pipelines, valves, and other components are described. Gaps identified through the review of Gazifère's current operating and maintenance procedures are highlighted, and recommendations for future inspections and welding are described.

Section 5.9 summarizes the highlights of various aspects of the report and provides conclusions for the materials integrity assessment for hydrogen blending in the Gazifère network.

5.2 Materials in the Gazifère System

5.2.1 Carbon Steels and Other Metals

5.2.1.1 Mains

The total length of main lines in the Gazifère network is approximately 1,022 km. [redacted] The installation year of the carbon steel pipe is indicative of pipe characteristics, such as steel metallurgy, that are important to consider when assessing compatibility with hydrogen blended natural gas service.

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5.2.1.3 Services

Service lines contained in the summary below represent only the validated data provided by Gazifère. Services with the service status identified as 'Abandoned', 'Deleted', 'Inactive', 'Proposed' or 'Removed' were not validated and were therefore not considered in this study. Because these statuses refer to lines which are not currently pressurized, there is no recommendation at this time to review these lines.

The total assessed length of services in the Gazifère network is approximately 754.5 km. [redacted]

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5.2.1.4 Components

Steel and other metals are widely used in the different components and fittings in the Gazifère network. [redacted]

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The vulnerability of some of these components to degradation of properties by hydrogen is highly dependent upon whether the components are directly exposed to the natural gas and hydrogen mixture. Materials on the outside of the components, such as assembly bolts that are isolated from the hydrogen by effective seals or gaskets, would not be affected by hydrogen. Similar alloys exposed to the gas may be subject to embrittlement. Examples include cast iron covers and high strength nuts and bolts. Stainless steels may be resistant to hydrogen embrittlement depending upon grade and heat treatment. Most 300 series stainless steels are resistant to hydrogen embrittlement unless highly cold worked. For example, 16% of the austenitic microstructure of 300 series stainless steel was transformed to martensite when subjected to 35% cold reduction. The amount of martensite increased to 44% with 65% cold reduction [4]. Cold worked stainless steel might be present in some pipeline components, but the amount of cold working is not often described in descriptions of the materials of construction. Some 400 series and precipitation hardenable stainless steels (examples: Type 410 stainless steel or 17-4 PH stainless steel) are acceptable only after the application of specific heat treatments.

5.2.2 Plastics

5.2.2.1 Mains

Polyethylene is the only plastic material used for the main pipelines. Polyethylene (PE) is a semicrystalline polymer composed of long, chain-like molecules of varying lengths and numbers of side branches, the latter of which reduces the density as the number of branches increases. The density is an important factor in the mechanical behaviour of PE pipes, with higher densities producing increased stiffness, hardness, and tensile strength at the cost of decreased permeability and stress crack resistance.

[redacted]

The two types of PE pipelines found in the Gazifère infrastructure are medium density polyethylene (MDPE) material nominally referred to as PE 2406 and PE 2708. These polymers are alternatively denoted as PE-80 rated, as they must be able to withstand a minimum circumferential hoop stress of 8,000 kPa for up to 50 years at 20°C. PE 2708 has replaced PE 2406 over the years as a higher performance material exhibiting at minimum an order of magnitude of improved resistance to slow crack growth. Additionally, recent advancements in technology have differentiated these two material types as either unimodal or bimodal.

Bimodal PEs contain a higher degree of entanglement of polymer chains, which enhances the mechanical properties when compared to unimodal resins [5]. Bimodal MDPEs are more modern, having been developed in the 1980s and increasing in popularity in the late 2000s for usage in MDPE materials for pipeline transportation systems [6]. For instance, small-scale steady state (S4) tests have been developed to estimate the critical pressure at which rapid crack propagation occurs at a constant temperature of 0ºC. Results indicated that the bimodal MDPE contained at least a 10-fold increased resistance to the onset of rapid crack propagation than their unimodal counterpart, with critical pressures of 10,000 kPa vs. 1,000 kPa. [redacted]

It should be noted that older versions of PE pipe, most notably pipe manufactured before 1973, were composed of an MDPE polymer known as Aldyl-A. These pipes had low ductile inner wall characteristics resulting from excessive temperature settings during the extrusion process, affect approximately 30-40% of these Aldyl-A pipes. The manufacturing error produced pipes having oxidized inner surfaces, which resulted in faster crack initiation with the application of internal pressure and a corresponding pipeline longevity decrease by almost tenfold. [6] Therefore, this piping material has been phased out of pipeline service in favour of PE-80 and PE-100 grade pipes due to premature cracking and poor joining in natural gas lines, which has resulted in the deaths of over 50 people in the United States since 1971. Because of the rarity of surviving material, DNV did not identify existing research on the increase of risk associated with hydrogen exposure to Aldyl-A compared to natural gas. It is possible this material would be relatively unaffected by the change to hydrogen service, however, this is unknown. [redacted]

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5.3 Effects of Hydrogen Service for Carbon Steels

The introduction of a hydrogen environment has varying effects depending on the material being assessed. [redacted] Because these effects vary, the impacts for each material will be discussed separately. If the material is not affected by hydrogen, a summary will not be provided in this section, but will be summarized in later sections.

Hydrogen affects steel properties, especially toughness, when hydrogen atoms (H^+) diffuse into the steel. The hydrogen atoms are formed at the steel surface either because of high cathodic protection potentials (<-1.14 Vcse [10]) on the outside surface of the pipe, by corrosion, or by dissociation of hydrogen molecules (H_2) at the inside surface of piping in hydrogen service resulting in diffusible H^+. The H^+ enters the steel through adsorption. Hydrogen atoms are small enough to enter and diffuse through steel, whereas diatomic hydrogen (H_2) is not. Generally, H^+ that forms as the result of corrosion results in rapid combination of hydrogen atoms into hydrogen molecules, thus minimizing the amount of atomic hydrogen that can enter the steel. However, in the presence of H_2S and some other compounds, the recombination process can be slowed to the extent that H^+ is present at the steel surface long enough to result in appreciable amounts of hydrogen adsorbing into the steel. In hydrogen service, some of the hydrogen molecules react at the steel surface to form diffusible hydrogen.

Hydrogen diffusion through the steel results in a concentration gradient of hydrogen ranging from relatively high near the adsorbing surface to somewhat lower at the opposite surface. The rates of adsorption, diffusion, and the concentration of hydrogen in the steel depend upon the operating temperature, the system pressure and concentration of hydrogen at the pipe surface (i.e., hydrogen partial pressure), presence of oxide films or other compounds at the steel surface that inhibit adsorption, and various metallurgical characteristics [11] [12]. Influencing metallurgical characteristics include the type of microstructure, grain size, and presence of subsurface anomalies such as laminations, large inclusions, and embedded weld flaws.

Hydrogen in the steel will generally manifest as:

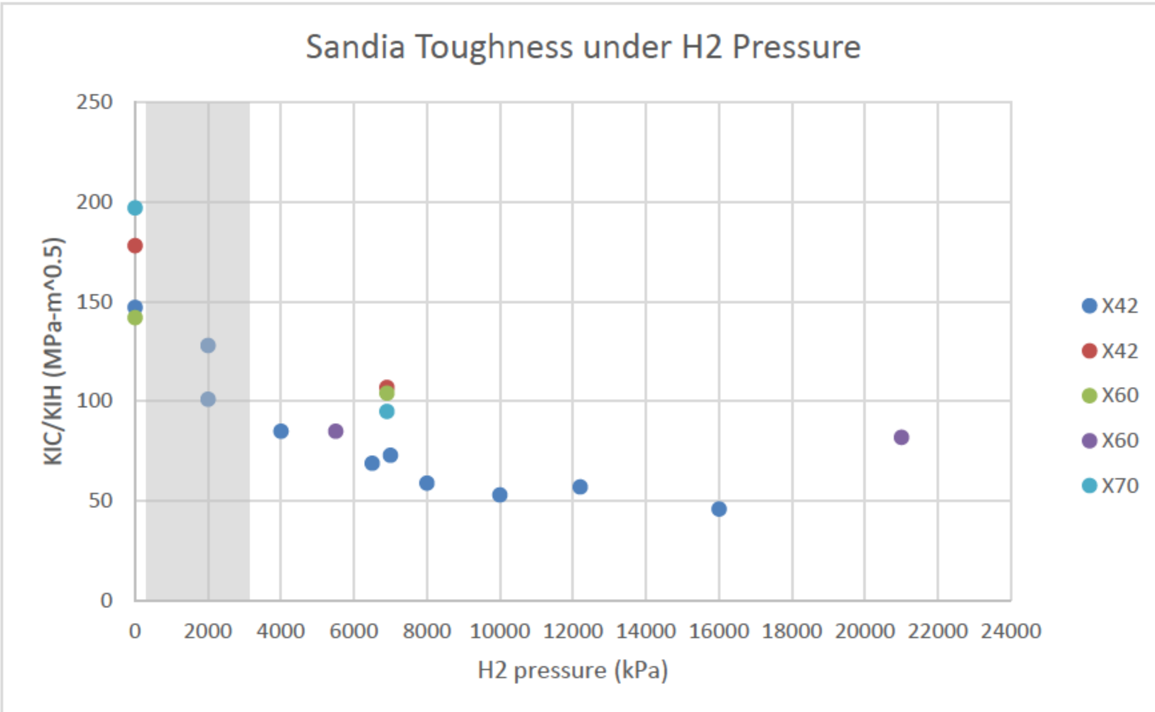
1. Decreased ductility
2. Decreased fracture toughness (“hydrogen embrittlement”)
3. Decreased resistance to initiation of cracking in low cycle fatigue (although this effect is relatively small compared to the increase in fatigue crack growth rate)[3]
4. Increased fatigue crack growth rate (FCGR)
5. Small and inconsistent reductions (on average) of yield strength and ultimate tensile strength (see section 5.3.3)

The hydrogen concentration is more likely to be greatest at the inside surface for piping in hydrogen service. Therefore, flaws at the inside surface are likely to be more significant in terms of effects on long-term pipeline integrity than the same flaw on the outside surface. However, flaws on the outside surface are still subject to detrimental effects of hydrogen service. In other words, flaws at the inside surface have a higher priority for assessment and mitigation than the same flaws on the outside surface, but the flaws on the outside surface should still be considered when performing integrity assessments. The largest impacts of hydrogen are on the fracture toughness of the material as well as increases to the fatigue crack growth rate.

5.3.1 Decreased Toughness

Hydrogen embrittlement occurs relatively quickly, i.e., in the time frame of hours or days, rather than months or years. Partial pressure is defined as the molar fraction of a particular gas multiplied by the total pressure (ex: a molar percentage of 20% H_2 in 100psi mixed gas yields a partial pressure of 20psi). The extent of embrittlement tends to increase with increasing partial pressures of hydrogen, rather than with increases in exposure time [11], but significant embrittlement (i.e., at least 25% reduction in fracture toughness) has been reported for steels exposed to as little as 85 kPa partial pressure of hydrogen. Little or no data exists regarding the effects of hydrogen at lower partial pressures. The largest reviewed set of data on the effects of toughness with varying amounts of hydrogen gas was published by Sandia [12] and is plotted in Figure 5-9.

[3] In a paper presented at the 29th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2010), Shanghai, China, 6-11 June 2010, TWI staff reported that the fatigue endurance limit of C-Mn steel specimens tested in hydrogen was shorter than that in nitrogen, and shorter at lower loading frequencies, although most specimens of low alloy steel did not fail at lower stress ranges when tested in hydrogen gas. They noted that because the effect of hydrogen is much more pronounced on crack growth rates, there is comparatively little research regarding the effect on fatigue endurance limits.



Note: The vertical shaded bar corresponds to the approximate hydrogen partial pressure range for 10-100% hydrogen blended into the highest-pressure gas in the Gazifère system, i.e., 321-3206 kPa.

Figure 5-9: Published toughness data from Sandia showing the reduction in fracture toughness under various pressures of hydrogen.

These hydrogen pressures shown are much higher than what is expected in Gazifère's network. [redacted] Given that pure hydrogen is not expected to flow through Gazifère's existing system, the partial pressure of hydrogen will be less than this. What this graph shows is that the percentage of toughness reduction is variable and depends on the material being tested and the partial pressure of hydrogen. However, even at low partial pressures of hydrogen, the embrittlement effect is still present, albeit to a lesser extent. Given the data, a conservative assumption for a 10-20% blend of H_2 would reduce the fracture toughness by 30% following trends in Figure 5-9. The effects of hydrogen embrittlement have been shown to depend on the loading rate, with the most significant effects exhibited under static or quasi-static loading. The effects are less likely to be apparent under dynamic loading conditions. Consequently, hydrogen embrittlement effects may be less dramatic during Charpy impact testing, which is a highly dynamic loading. Therefore, K_{IC} fracture toughness values obtained through crack tip opening displacement (CTOD) testing via ASTM E1820, in which loads are applied more slowly, better represent the fracture toughness conditions anticipated under hydrogen embrittlement and operational loading. While these values both measure the toughness of the material, they are not directly calculated from each other. Correlations between these values must be used to determine the appropriate value.

The effects of hydrogen are most apparent at areas of high local stress, such as at the tips of axially oriented planar flaws in pressurized pipe or at circumferentially oriented planar flaws for pipe subjected to axial stress or bending stress.

Hydrogen embrittlement occurs most dramatically in high strength steels, especially those having a martensitic microstructure. Examples of pipeline features that can have martensitic microstructures include quenched and tempered fittings, hard weld heat affected zones, and some types of seams (including some ERW seams that have not been normalized). Companies who have operated hydrogen pipelines have historically favoured low strength pipe along with targeted use of post weld heat treatment or careful control of welding practices to prevent formation of martensite. In recognition of the general trend toward greater susceptibility to significant embrittlement as strength increases, ASME B31.12 applies more conservative design criteria when specified minimum yield strength (SMYS) exceeds the equivalent of API 5L grade X52. B31.12 nonmandatory Appendix G and IGC Doc 121/14 Appendix D, provide recommendations for metallurgical attributes that minimize susceptibility to severe embrittlement (see Section 4). Those recommendations provide useful guidance for specifying new pipe and fittings for future construction, as well as being a resource for evaluation of existing assets.

High-strength steels such as tempered martensite that may be found in some high strength fittings or used in some valve components (especially valve stems) are more susceptible to hydrogen embrittlement because of the high concentration of crystallographic defects present in the steel. Crystallographic defects called dislocations, which are the driving force for plastic deformation, act as sinks where hydrogen settles. Dislocation mobility increases with increasing stresses, which allow the hydrogen to move throughout the microstructure and situate at grain boundaries, which are interfaces separating collections of atoms oriented in a similar manner. As the hydrogen concentration builds up within the microstructure, it results in the formation of more dislocations, whose interactions with each other can also create defects such as vacancies (clustered gaps of missing atoms in the crystal structure). As these vacancies build up at interfaces such as grain boundaries, they coalesce and grow larger, eventually leading to microscopic cracks in the grain boundaries that propagate into macroscopic failures.

Fracture toughness tests using quasi-static loading are strongly favoured over Charpy impact tests for evaluating effects of hydrogen on toughness. However, when measuring initial toughness before exposure to hydrogen service, Charpy data can still be useful if fracture toughness data from quasi-static loading tests are unavailable. Empirical relationships between Charpy impact toughness and fracture toughness in quasi-static loading can be used to estimate fracture toughness. Typically, there is quite a bit of scatter in the graphical depiction of Charpy results versus fracture toughness test results, and the various established relationships tend to only be valid between boundary conditions related to steel strength and temperature relative to transition temperature. The relationship between Charpy absorbed energy and fracture toughness is corollary.

A significant unknown is the extent to which very low toughness pipe, for example, early vintage electric resistance weld (ERW) seams which were not heat treated (generally manufactured before the 1970's [14]), will be further embrittled by exposure to hydrogen service. While moderate to high toughness steels can lose 50% or more of their fracture toughness, there is insufficient test data to conclude that the same amount of decrease in fracture toughness will occur in very low toughness seams. Low operating stresses limit the likelihood that a failure will be in the form of a long rupture. ASME B31.12 section PL-3.21 *(l)* states that if the steel pipe cannot be qualified to the fracture control and arrest requirements of Option A or Option B then "the MAOP shall be selected to limit hoop stress to 40% SMYS…". The origin of the 40% SMYS limit is unknown, and ruptures have occurred in natural gas pipelines at hoop stresses less than 30% SMYS, particularly when low toughness ERW pipe is combined with interacting integrity threats [15].

Research is still ongoing on the effects of hydrogen in a variety of materials and variability exists in the amount of embrittlement that occurs between each sample tested.

5.3.2 Increased Crack Growth Rate

In addition to a reduction in toughness, a well-documented increase in fatigue crack growth occurs in carbon steel in the presence of hydrogen. This crack growth is also material dependent, but an upper bound value is provided in ASME B31.12 as:

$$\frac{da}{dN} = a1\Delta K^{b1} + \left[\left(a2\Delta K^{b2}\right)^{-1} + \left(a3\Delta K^{b3}\right)^{-1}\right]^{-1} \quad (1)$$

Here, $\frac{da}{dN}$ is the amount of crack growth per pressure cycle, ΔK is the change in stress intensity, and the variables a and b are provided in Table PL-3.7.1-5 in ASME B31.12 and reproduced below. Stress intensity is a fracture mechanics parameter and is closely related to the loading applied to the crack. For an axially oriented crack in a pipe body, the change in stress intensity is closely related to the change in internal pressure.

Table PL-3.7.1-5 Material Constants for Fatigue Crack Growth Rate, *da/dN*

Material Constant	Values	
	SI	U.S. Customary
$a1$	4.0812 E−09	2.1746 E−10
$b1$	3.2106	3.2106
$a2$	4.0862 E−11	2.9637 E−12
$b2$	6.4822	6.4822
$a3$	4.8810 E−08	2.7018 E−09
$b3$	3.6147	3.6147

By taking equations from API 579 on the fatigue crack growth rates and plotting them against those from the ASME B31.12 curves for crack growth rates, we obtain Figure 5-10 which plots the crack growth per cycle against the change in stress intensity.

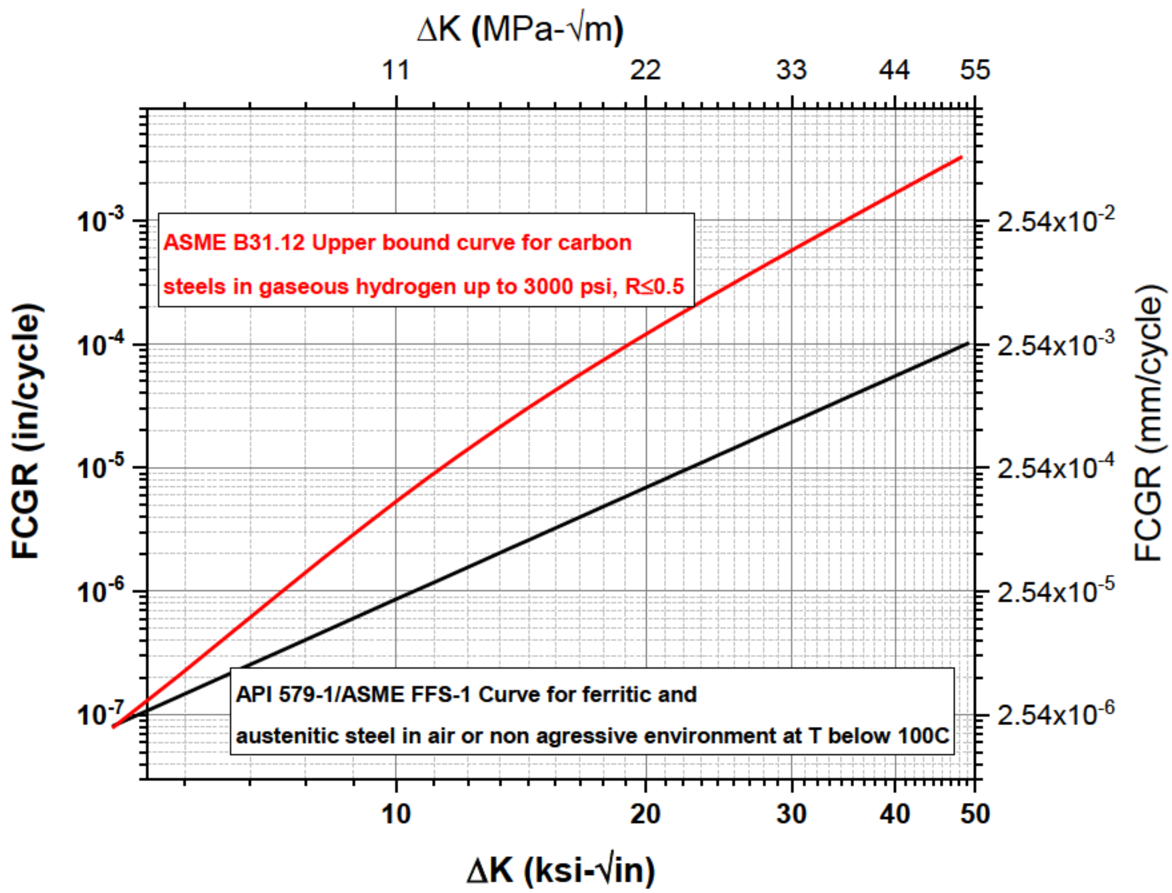


Figure 5-10: Fatigue crack growth rates from API 579 for non-hydrogen atmosphere (black) and B31.12 for gaseous hydrogen atmosphere (red).

For reference, using calculations provided in API 579, a theoretical 50% through wall axial flaw in an NPS 8 pipe with an MOP of 3206 kPa would generate a ΔK of 8 ksi√in when subjected to a pressure cycle of 50% MOP. This would increase the crack growth rate from roughly $6*10^{-7}$ in per cycle to $2*10^{-6}$ in per cycle – 3.3 times higher. This value would change depending on the pressures used, the orientation of the flaw, the location of the flaw, and assumed residual stresses among other parameters. However, this does provide some context for the values shown. Further reducing the size of the pressure cycle will reduce the ΔK value further (roughly linearly in this particular example), which both reduces the actual amount of crack growth and reduces the difference between fatigue crack growth in natural gas versus that in hydrogen. At a theoretical ΔK of 6 ksi√in, the difference between crack growth in these two curves decreases from a multiple of 3.3 to slightly over 2. [redacted] DNV has performed fatigue crack growth analyses in which real pressure cycle data from gas pipeline operators consisting of daily cycles much lower than 50% of MOP was found to result in unacceptable crack growth rates when credible flaw sizes and seam toughness values were considered along with the desired design life of the pipeline. Depending on the change in stress intensity, which is correlated to the change in loading on the pipe, the fatigue crack growth rate can be more than an order of magnitude higher than is normally expected in carbon steel not exposed to hydrogen. The change in stress intensity is not dependent on the concentration of hydrogen in the pipe; however, the effect of that change in stress intensity is affected. There also exists a threshold change in stress intensity below which cracks are not expected to initiate, especially in low cycle fatigue. Hydrogen has the additional effect of lowering this threshold ΔK value, meaning cracks may initiate with lower pressure cycles than under a natural gas environment. Static crack growth may dominate in systems with very few or low magnitude pressure cycles, however, research is still being conducted on quantifying growth rates and threshold values for this mechanism.

The frequency of cyclic stressing in fatigue testing can influence the apparent FCGR, with slower rates typically resulting in greater crack growth per cycle. However, since most fatigue testing involves cyclic stress rates much faster than cyclic stress rates in actual pipeline operations, the fatigue test results are most likely not a conservative indicator of FCGR in service if the R-ratios (stress min/stress max) in testing are similar to those in service.

5.3.3 Changes in Yield Strength

Minimal changes in yield strength have been reported in literature for pipe steel exposed to hydrogen. In their "Hydrogen Getting into Focus" paper for the Pipeline Technology Conference 2020 [16], N. Gallon, L. Guest, et al. summarized work by San Marchi et al. for Sandia National Labs report SAND2012-7321 "Technical Reference for Hydrogen Compatibility of Materials" in which they reported tensile test results that included results for samples of API 5L grades X42, X52, X60, X65, and X70 tested in 6.9 MPa (1000 psig) hydrogen gas at room temperature. The results for the API 5L steels showed average reductions of YS and UTS of 2%, but the standard deviations were relatively large; 2.3% and 2.7% respectively. There was no significant trend of percent reduction vs. the reference strength (i.e., strength in air). Industry consensus standards currently do not contain any recommendations to reduce the assumed strengths for hydrogen pipeline operations or for flaw assessment procedures.

5.3.4 Changes in Threat Susceptibility

5.3.4.1 Crack-like Flaws

Hydrogen can have a large impact on a material's resistance to fracture. The failure pressure of crack-like flaws can decrease and susceptibility to rupture versus leakage can increase in hydrogen service because of the reduction in steel toughness. The extent of the change depends in part on the initial steel toughness, the amount of toughness reduction, the hoop stress relative to the yield stress, and the dimensions (length and depth) of the flaw.

In general, the effect of embrittlement on the survivable size of a crack-like flaw at MOP is greater when:

- The flaw is long and shallow, as opposed to short and deep (short, deep flaws are less affected by changes in toughness).

- The reduction in toughness as a percentage of the initial toughness is greater vs. a small change in toughness.
- The operating stress is lower, i.e., at 20% SMYS the critical flaw size is larger than at 60% SMYS, but the critical flaw size is more sensitive to changes in toughness at 20% SMYS.

The effect of stress level and changes in toughness can be illustrated by calculating the approximate length of a deep flaw (0.85t) that fails at 20% SMYS v. 60% SMYS for a hypothetical NPS 20 x 6.35 mm. wall thickness grade X42 pipe. At 60% SMYS the critical flaw length decreases by 8% (from approximately 66 mm long to approximately 61 mm long) when Charpy impact toughness decreases from 13.6 J to 6.8 J. At a lower operating stress of 20% SMYS, the same toughness change decreases the critical crack length by 31% (from 274 mm to 190 mm).

Figure 5-11 illustrates another example of the effect of reduced Charpy impact toughness on critical flaw size, using an NPS 8 x 4.8 mm thick, grade X42 pipeline operating at either 3,447 kPa (500 psi) or 1,207 kPa (175 psi) as an example. This figure is generated using the Ellipseq software which uses the modified log-secant equation to perform the analyses. The illustration assumes that the initial Charpy impact toughness of 15 ft-lbs (20 J) is reduced by hydrogen embrittlement to 7.5 ft-lbs (10 J). The illustration shows the combination of flaw depth and length that can cause failure at each MOP. The three red curves correspond to performance at 15 ft-lbs and the three black curves are the degraded flaw tolerance at 7.5 ft-lbs. The leak/rupture boundary is shown as a green curve (solid line for 15 ft-lbs and dashed line for 7.5 ft-lbs, also generated using the Ellipseq software.) Flaw sizes to the left of the green lines fail as leaks while flaws to the right of the green lines fail as ruptures. In this example, flaws having a depth of 0.7t do not fail at 3,447 kPa unless the length is much longer than 8 inches (203 mm). At 15 ft-lbs, a flaw 0.8t deep would fail at a flaw length of a little more than 8 inches (203 mm) when operating at 3,447 kPa. At a reduced toughness of 7.5 ft-lbs the same depth flaw would fail at an axial length of about 6.25 inches. Flaws 0.9t deep are expected to fail at an axial length of between about 2.6 and 2.7 inches (66-69 mm), at both assumed toughness levels. At the lower operating pressure of 1,207 kPa, flaws 0.9t deep would only fail if they were considerably longer than 8 inches (203 mm). For both assumed toughness levels, flaws not longer than 8 inches (203 mm) would all be expected to fail as leaks for pressures equal to or less than 3,447 kPa.

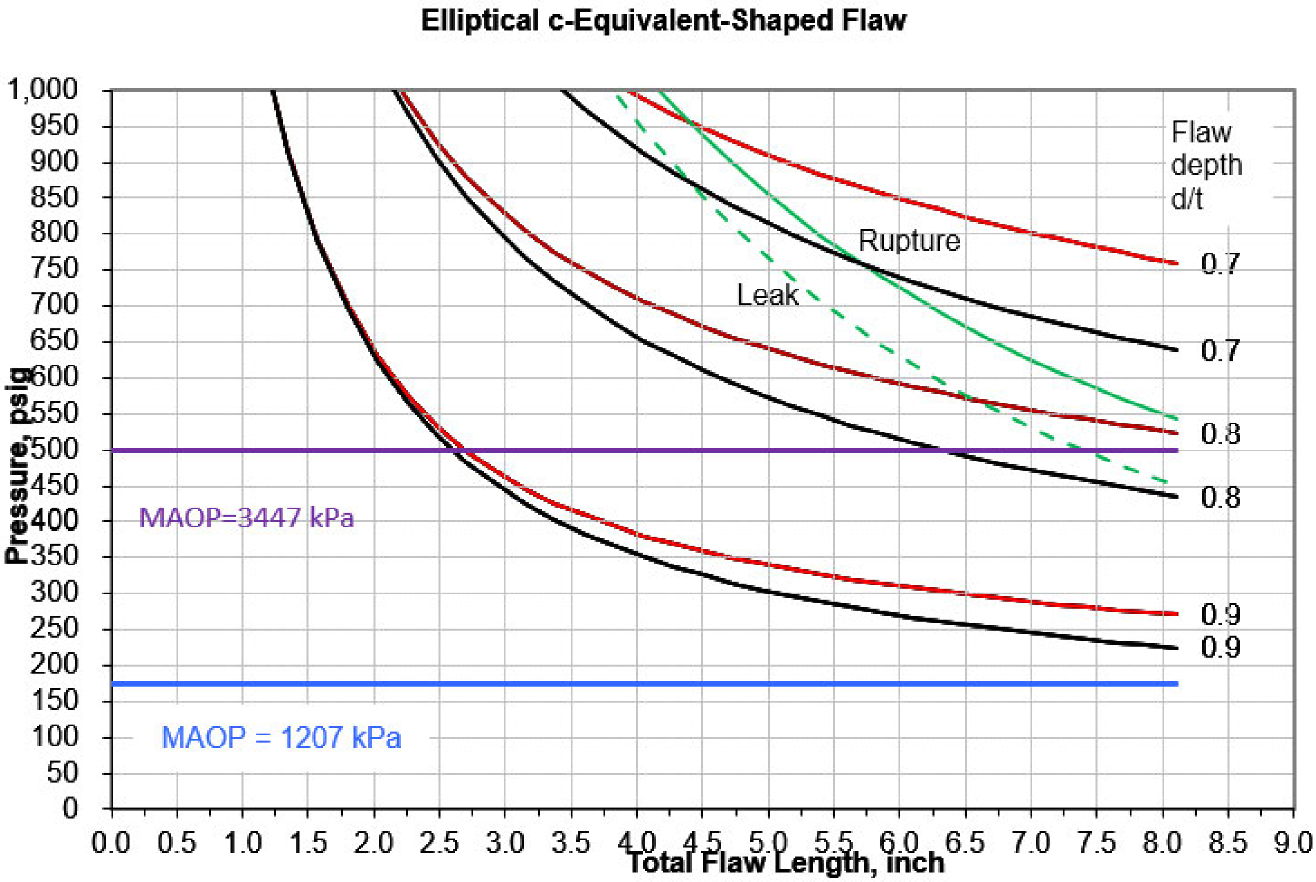


Figure 5-11: Flaw tolerance for a hypothetical NPS 8 pipe. x 4.8 mm wall thickness having a toughness of 15 ft-lbs (red curves) and an embrittled toughness of 7.5 ft-lbs (black curves).

Figure 5-12 illustrates the failure pressures and leak/rupture boundary for flaws in a hypothetical ERW seam having near worst case low toughness resulting from poor seam heat treatment and early vintage steel. The graph shows that leaks rather than ruptures are expected for service pressures of 1207 kPa unless the flaws are both very deep (deeper than 80% of the wall thickness) and much longer than 8 inches (203 mm). The Ellipseq software generates the leak vs rupture line where a through-wall flaw at the length dictated by the bottom axis would be expected to remain at the current length if to the left of the leak/rupture line or grow in length if to the right of the line. At 3447 kPa a rupture could occur if the flaw is longer than about 5.5 inches (140 mm). Failures at 3447 kPa would not be expected for flaws shorter than about 8 inches (203 mm) unless the flaw depth was at least 70% of the wall thickness deep. Note that the XHP system consists of modern ERW pipe where toughness values this low are very unlikely.

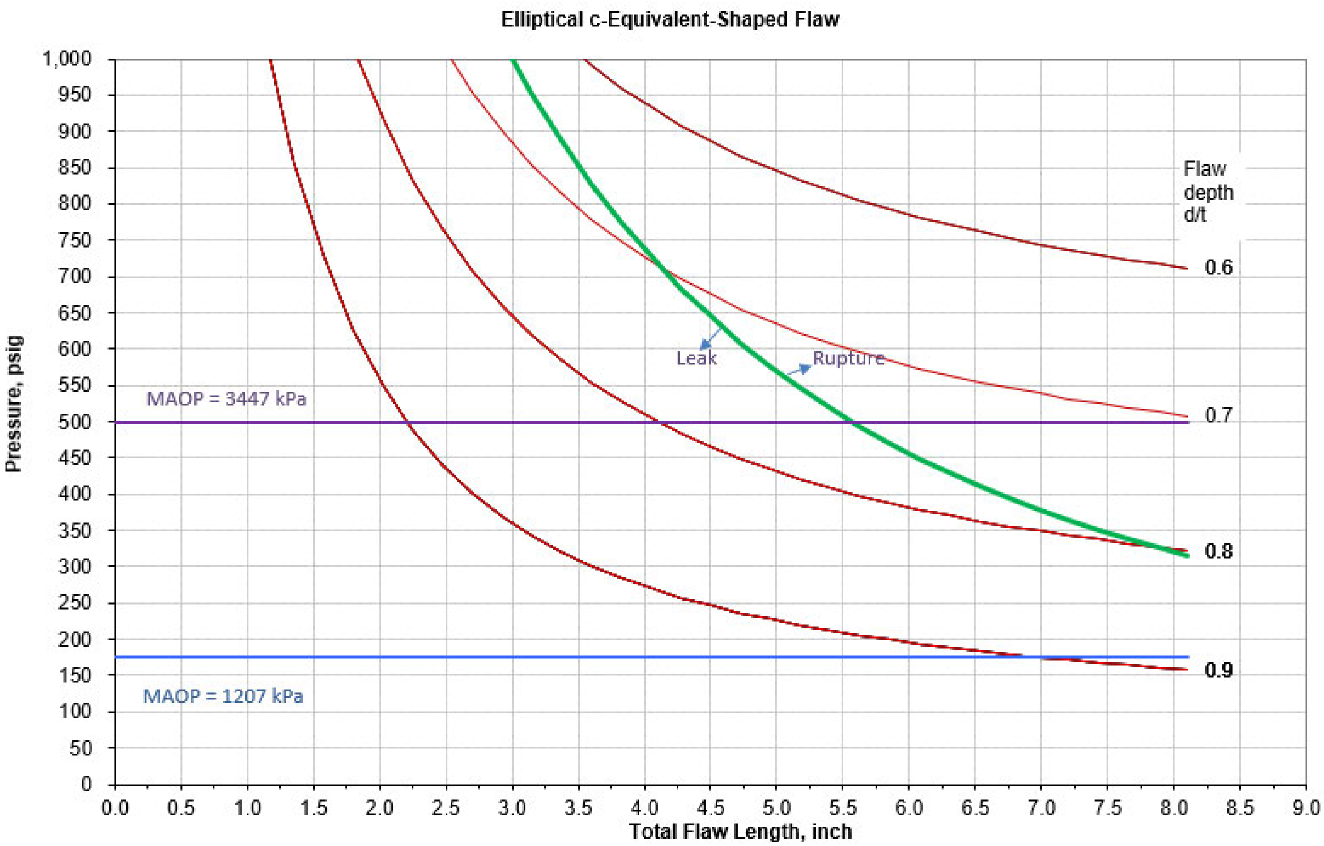


Figure 5-12: Flaw tolerance for a hypothetical NPS 8 pipe x 4.8 mm wall thickness with low toughness ERW seam having a toughness of 4 ft-lbs (5 J).

5.3.4.2 Dents and Dents with Gouges

The effects of hydrogen are most apparent at areas of high local stress, such as at the tips of axially oriented planar flaws in pressurized pipe or at circumferentially oriented planar flaws for pipe subjected to axial stress or bending stress. However, as noted by Li, Wang, et al. [17], the amount of hydrogen in the steel increases with pre-strain prior to testing. As a result, DNV concludes that deformation at dents and gouges could become preferential sites for higher-than-average accumulations of atomic hydrogen, with the potential for somewhat greater than average amounts of embrittlement at those areas. Gouges can be expected to be especially problematic since they can be associated with thin layers of highly cold worked, crack-susceptible microstructures, in addition to being locations of greater hydrogen accumulation. [redacted]

Rounded dents that meet the size limitations described in standards applicable to natural gas service are not likely to be as much of a risk unless dent re-rounding has resulted in cracking. In the absence of cracking or gouging, the stress concentration at a smooth dent is not typically very high and crack initiation in dents from cyclic pressures in gas service are rare, especially if the dent is restrained by a rock or a similar feature that prevents the dent from rebounding/re-rounding under the influence of internal pressure. The definition of "injurious dent" in B31.12 is similar to that of B31.8. While not using the term "injurious" CSA Z662 also includes descriptions of limitations on dents. All three include reference to smooth dents having a maximum allowable depth of 6% of the pipe diameter. CSA Z662 includes a separate criterion for small diameter pipe, i.e., not deeper than 6 mm for pipe 101.6 mm OD or smaller. B31.12 and B31.8 both include limitations on strain with B31.12 being considerably more conservative. B31.12 allows a maximum of 2% strain vs. B31.8 which limits dent strain to the lesser of 6% strain, 40% of the average elongation reported in mill test reports, or half the specified minimum tensile strap elongation. (Typically, 40% of the average reported tensile test strain and half the specified minimum tensile strap elongation are both much greater than 6% strain). Z662, Clause 10.10.4.2 allows the previously described depth limits to be exceeded if the strain associated with dents on the pipe body is less than 6%, i.e., the same as B31.8 and less conservative than B31.12. Z662 includes additional requirements that further limit the size of dents associated with corrosion, stress concentrators (gouges, grooves, cracks, or arc burns) exposure to pressure cycling, or proximity to seams or field welds

Mechanical damage can be a preferred location for stress corrosion cracking (SCC) because of the locally higher stresses at the deformation combined with likelihood of coating damage. However, in the absence of stress cycling DNV considers the probability of SCC to be relatively low.

5.3.4.3 Wrinkles, Buckles, and Other Geometric Irregularities

Wrinkles, ripples, buckles, and related geometric irregularities can increase susceptibility to failure because they represent a stress concentrator as well as pre-strain that is associated with plastic deformation, much like a dent. Embrittlement has been found to increase in the presence of pre-existing strain, with peak effects having been reported at about 3% strain [16]. For the same reason, cold field bends made in the field as an alternative to factory made fittings could possibly be more susceptible to embrittlement than adjacent straight pipe. The strain associated with these types of geometric irregularities could be calculated and used as an indicator of the likely amount of increased risk associated with them.

5.3.4.4 Corrosion

There is little information in published literature and no precautionary notes in related standards indicating that susceptibility to internal or external corrosion is increased when natural gas pipelines are converted to hydrogen service or to NG+H_2 service. Note that in this context, "corrosion" is considered to be metal loss, either general or localized, that is not associated with traditional forms of external SCC, either high-pH SCC or near neutral SCC. However, W. Li, R. Cao, et al. propose that hydrogen could affect the anodic dissolution of metal and cause both pitting and stress corrosion cracking [18]. Hydrogen charging has been found to increase the rate of SCC in duplex stainless steel through the process of hydrogen-facilitated anodic dissolution (HFAD) [19]. W. Li, R. Cao, et al. describe work by Tang and Cheng in which experiments showed that the presence of both hydrogen and stress on cracked samples resulted in an increased anodic dissolution of pipeline steel by a factor of 5 times over the rate when stress is present, but hydrogen is absent. Leakage from SCC could also become more likely since the embrittlement would reduce the critical flaw size, and thus the amount of SCC growth that occurs before the critical crack size is reached. [redacted]

5.4 Effects of Hydrogen Service on Polyethylene Components

Tensile, creep, and ductile tests performed on polyethylene exposed to high concentrations of pressurized hydrogen were shown to have no effect on the tensile properties of MDPE, even up to 10,000 kPa of pressurized hydrogen. Static properties, such as the modulus and yield stress, also exhibited no significant hydrogen effects. Creep tests performed at different

[4] ASME STP PY-011 "Integrity Management of Stress Corrosion Cracking in Gas Pipeline High Consequence Areas" noted that in-service SCC failures have occurred between 25% and 72% SMYS, but that two sources reported that two-thirds of the failures from high-pH SCC occurred at hoop stresses above 60% SMYS. A survey of project participants found that 87% of in-service failures and 96% of hydrotest failures related to high-pH SCC occurred in pipelines designed to operate at 60% SMYS or higher. Almost all failures below that threshold were in pipes with diameters of 12-inches or smaller and there were only leaks (no ruptures) below 48% SMYS. The same ASME report summarized the results of excavations made to inspect for evidence of near-neutral pH SCC. Of 4414 excavations, SCC was found in 696 excavations, but no SCC was found in the 53 excavations that were made on pipelines operating at a hoop stress of 60% SMYS or less.

temperatures on PE material concluded that hydrogen has no noticeable effect on creep-induced ductile fracture [19]. Long-term ageing for exposure times of up to thirteen months at pressures ranging from 500 to 2000 kPa and temperatures of 20, 50, and 80°C also displayed no deleterious effects from the hydrogen exposure.

Slow crack growth fatigue, the primary failure mechanism in PE materials, has also been shown to be negligibly affected by interaction with hydrogen. [redacted] These results indicated no deviation in trends compared to exposure to air at various temperatures for tensile properties [21].

Although studies on hydrogen's effect on PE are sparse, several studies have been performed on the permeability of hydrogen through PE resin matrices. Permeation in PE materials is affected by crystallinity, chain orientation, fillers, microstructure, and the complexity of the side chain [21]. It has been shown that the permeability of hydrogen is approximately 5 times greater than that of methane. Hydrogen permeation tests showed an expected increase in permeability with increasing temperatures and were well represented by an Arrhenius law. The rate of increased permeation with increasing temperatures was shown to be lower than that of methane [22]. Leak rates through PE materials were determined to be less than 0.02% per day through PE liners of around 5 mm in thickness. For reference, calculations based on the 415,000 miles (~668,000 km) of PE pipe in the United States for a 20% hydrogen blend estimated total leakage amounting to 43 million ft3/year (1.2 million m3/year), which would have accounted for approximately 0.0002% of all the natural gas consumed in the year 2010. The ratio leakage was estimated to be approximately 60% hydrogen and the balance coming from methane [23].

Additionally, PE materials are electrically nonconductive and show no adverse reactions to naturally occurring soil conditions. Therefore, they are not subject to galvanic action and exhibit no corrosion or rusting, as steel does [24]. Studies on similar MDPE pipes exposed to pure hydrogen without previous exposure to methane exhibited no adverse effects from hydrogen transport after 4 years of exposure, assuring the long-term integrity of the pipe. Pipes with previous exposure to methane for over 20 years were also determined to show no significant changes in tensile properties after the introduction of hydrogen to these pipelines. It was suggested that an increase in the modulus could occur over longer previous exposure times to methane, but more tests would need to be completed [25]. PE pipes have consistently been shown to exhibit no degradation when exposed to both pure hydrogen and hydrogen-methane mixtures, and current research suggests that nominal mechanical properties are maintained even after exposing these materials to pressurized hydrogen environments. The unimodal plastics and vintage Aldyl-A pipes discussed in section 5.2.2 for having higher rates of failure due to cracking are not expected to behave notably differently in blended hydrogen service compared to pure natural gas service.

5.5 Effects of Hydrogen Service on Black Malleable Iron and Other Types of Cast Iron

Though limited studies have been performed on the effect of hydrogen on mechanical properties of cast iron, the results of the studies indicate that microstructure was shown to have a large effect on the performance of cast iron when exposed to hydrogen. A study by Yoshimoto et al. [26] analyzed the effects of graphite size on hydrogen absorption and subsequent tensile properties. It was concluded that increased graphite diameter sizes result in larger concentrations of hydrogen being absorbed. The increased hydrogen concentration results in significant hydrogen embrittlement up to a critical graphite diameter size. Cast iron has also been shown to exhibit a significant decrease in overall ductility with increasing concentrations of hydrogen. Small cracks were shown to appear at the graphite/ferrite interface under increased hydrogen immersion that were not present in ambient air [27]. Another study showed that as cracks propagate, hydrogen is attracted to the crack tips through the process of stress-induced diffusion, which results in a time-dependent ductility loss [28]. Similar studies have shown that cast irons become more embrittled when exposed to hydrogen with increased fraction of pearlite in the microstructure due to hydrogen saturation in the cementite (iron-carbide precipitates with chemical formula Fe_3C) [29].

5.6 Metering and Regulators Assessment

In this section, the following questions regarding metering and regulators are considered:

- Are there potential drift or systematic errors in the metering systems and the energy calculations when hydrogen is introduced?
- Are there metering and regulator capacity issues when equal amounts of energy are transferred across the system?

Metering systems comprise the flow meters themselves, the gas composition measurement system, flow computers, and pressure and temperature measurements. This analysis is focused on the flow metering part of metering systems.

5.6.1 Flow Metering Systems

Flow metering systems function within a certain agreed range, the so-called "rated operating conditions". When hydrogen is added to the natural gas, the volumetric heating value (in MJ/m^3) decreases and, hence, the volumetric flows need to be increased to maintain the same energy transmission capacity. [redacted]

[redacted]

Two aspects are important to consider, the rangeability and the performance (systematic errors).

Rangeability issues

In general, the high-end flow metering systems are considered fit-for-purpose up to 30% hydrogen as long as they can continue to operate within their operational ranges. For high-end volumetric flow systems (turbine meters, ultrasonic flow meters, or rotary meters), the (volumetric) flow value has to be between minimum flow Q_{min} and maximum flow Q_{max}. Flow values increase in hydrogen blending cases.

[redacted]

[redacted]

[redacted]

Performance

A JIP study has been completed recently to study the effects on performance of high-end flow systems consisting of ultrasonic flow meters and turbine flow meters. The results have been published at the North Sea Flow Measurement workshop in 2021 [30].

The impact of hydrogen on the metrology depends on the quantity of hydrogen in the natural gas, the metering technology, and the system configuration. For turbine meter technology, the performance is better than that of ultrasonic meters, with better reproducibility and less risk of systematic errors. On many pressure regulating stations in the gas network, ultrasonic flow metering technology has been made available. It has been established by recent investigation that ultrasonic flow meters might experience systematic drift due to the presence of hydrogen. These tests verify that most ultrasonic flow metering systems are robust instruments and still produce valid flow data up to 30% hydrogen, but the reproducibility can vary, and systematic error or drift can occur up to 0.5% - 1%. Drifts can likely be minimised by proper configuration of the meters and by treating the flow computer (FC) corrections based on Reynolds number. However, the changes in gas composition require a Reynolds based approach for implementing flow meter calibration results towards field conditions. This is not present in most of the current flow computers, and this might require a replacement of flow computers to allow for a live-Reynolds based correction approach. Further research related to ultrasonic meter drift and its origin is still ongoing.

5.6.1.1 Flow Computer Calculation Schemes

The flow computer requires information on throughput, temperature, pressure, and composition to be able to calculate volumes and amount of energy transported. This is crucial for the billing process for the gas transported (custody transfer). According to provided information, it is not clear which scheme is used in the metering stations across the grid. The best scheme is AGA8 and GERG-2008, calculation schemes using the full input of 20 gas composition components including hydrogen.

The AGA-8 compressibility is within 0.01% equal to the AGA10Ex, and no systematic errors are present when conversion to hydrogen is enforced, provided the hydrogen percentages are measured correctly.

Many times, users still make use of correlative compressibility schemes. Note: in that case the calculation formula conforms to the ISO12213-3:2006 standard used to determine the coefficients for calculating the compressibility of the gas (Z) using the set of preferential parameters (Hs, density, xCO_2, xH_2) as input.

Calculations conforming to ISO 12213-3 Standard are used in the SGERG-88 method. In order to use this method, it is necessary to know the temperature and pressure of the natural gas and the hydrogen (H_2) mole fraction. Three out of the following four parameters need to also be known: the carbon dioxide (CO_2) mole fraction, the nitrogen (N_2) mole fraction, the relative density, and the superior calorific value H_S. This method has been approved for up to 10 vol% H_2. [32]

DNV has performed calculations with Flow-Xpert (flow property calculation software by ABB). The reference is a full composition calculation scheme like GERG2008 or AGA10Ex (2017). Reference pressure and temperature are chosen as 4 bar and 10°C respectively.

[redacted]

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

[redacted]

[redacted]

[redacted]

[redacted]

5.6.2 Metering and Regulator Capacity

The transport capacity of a transmission system changes with varying gas compositions. Adding hydrogen will affect the amount of energy per cubic meter of gas. The gross calorific value of natural gas is around 35 to 40 MJ/Nm^3 for low and high calorific natural gas, respectively. The gross calorific value of hydrogen is about 12 MJ/Nm^3. The energy content of a normal cubic meter of hydrogen is about 3 times lower than the energy content for natural gas. Therefore, at atmospheric conditions the velocity of pure hydrogen would need to be roughly 3 times that of natural gas for transporting an equal amount of energy. However, hydrogen is not as compressible as natural gas, which means that a lower amount of normal cubic meters 'fits' in an actual cubic meter. This compressibility adds an additional increase to the required velocity of gas. This additional increase becomes higher with increasing pressure.

Furthermore, as the energy demand from customers will not change, all calculations are made under the assumption that the total energy demand (e.g., in MJ/day) remains the same. Combined with the lower energy content, the gas velocity will have to increase to fulfil this equal energy demand.

[redacted]

DNV

[redacted]

5.6.2.1 Equipment Details: Gas Chromatographs

The gas chromatograph (GC) is an analytic stand-alone device that has multiple columns for measuring gas components, and is suitable for determining the composition within fiscal metering accuracy standards. The inner workings of a GC usually contain two columns, each one specified in detecting a specific range of gases. In the case of hydrogen blending in natural gas, an additional column is to be used.

For the measurement of the natural gas composition, Helium is mostly used as a carrier gas on the already installed columns. A separate column with argon as a carrier gas can be used to determine the hydrogen content, as helium is incompatible for detecting hydrogen on a GC column due to the similarities in thermal conductivity of helium and hydrogen.

Based on the age of the specific model, GC's may be upgraded with an additional column and a separate argon carrier gas connection to detect the hydrogen contents in the gas. Older GC models cannot be expanded to reliably measure hydrogen, but this depends on each manufacturer. Refurbishment or upgrade of GC's is recommended in cases where hydrogen is used as existing GC's are generally only suited for natural gas, both due to the columns installed in the GC and the carrier gas in use.

5.6.2.2 Equipment details: Ultrasonic Flow Meters

Ultrasonic flow metering technology has been adopted on many pressure regulating stations. It has been established through recent investigation [33], that ultrasonic flow meters might experience systematic drifts due to presence of hydrogen. These tests verify that most ultrasonic flow metering systems are robust instruments and still produce valid flow data up to 30% hydrogen, but the reproducibility can vary, and systematic error or drift up to 0.5% - 1% can occur.

Before the meter can work in high blending rates such as 50% hydrogen or in full hydrogen, the manufacturer needs to refurbish or replace the sensors, change the configuration, and recalibrate the meter as a minimum. From recent experience, DNV is aware that all manufacturers would need to replace sensors in existing gas US meters to make these suitable for hydrogen. Refurbishment cost would be at minimum 50% of the cost of a new meter, but likely even up to 70%.

Going back to blend rates of up to 20%, the meters require a proper calibration, which is a challenge because there is no accredited hydrogen flow calibration facility available in the world yet. As an intermediate solution, for blending percentages such as 5% to 20% for Gazifère, the alternative is to perform a 'Reynolds number calibration'. This means that the flow meter will be calibrated on different pressures of natural gas and possibly on atmospheric air, to cover the same Reynolds number area as where the meter will operate under hydrogen blending.

Drifts of a US meter installed in the field can likely be minimized by proper configuration of the meters and by treating the Flow Computer (FC) corrections based on Reynolds number, which is a method that is currently not present in most Flow computers. Flow corrections based on Reynolds number may in the meantime be carried out at the data collection point (or DCS) as an alternative, which would require strict administration and management of change procedures. More information can be found in a recent North Sea Flow Measurement Workshop paper by H.J. Riezebos (DNV) published in October 2021 [31].

Apart from potential drift upwards, hydrogen mixing is accompanied by increased velocities in each of the scenarios and this might impose limitations of the metering capacity. The increase in gas velocity, as indicated above, would be up to 21% for up to 20% hydrogen. Typically, maximum flow velocities up to 25 m/sec may be possible in ultrasonic metering lines. At some stations, the number of flow lines might need to be increased or the metering lines themselves would need to be replaced by a larger diameter metering skid.

As a general recommendation, for cases where the maximum acceptable drift is <0.2% this implies on the basis of the drift risk that the meter is fit-for-purpose up to 10% of hydrogen and should be refurbished and recalibrated or replaced beyond those percentages (unless a further investigation proves compliance).

For blending up to 20% hydrogen in the case of Gazifère, it is recommended to perform a recalibration with the Reynolds number method and to apply the results either directly in the meter (when possible), or in a centralized system within the IT infrastructure. Any meter that is already operating close to its maximum velocity will have to be replaced by a larger diameter version.

5.6.2.3 Equipment Details: Turbine and Rotary Flow Meters

For turbine and rotary meters, the increase in gas velocity is the main effect that impacts the metering capacity and ability. These types of rotating meters can both handle hydrogen, but there are two main effects to consider. First is whether the meter is still rated for the higher gas velocity. This would only be an issue if the meter is frequently operating close to its maximum capacity because the increase of 21% in gas velocity is relatively low. Second is the calibration of the flow meter to maintain its accuracy, which is the same as for ultrasonic flow meters as described above. The meter needs to undergo a Reynolds Number calibration, to ensure it is calibrated with natural gas or air under the conditions in which it will operate in the field when hydrogen is part of the gas blend.

5.6.2.4 Equipment Details: Pressure Reduction Valves

Pressure reduction valves have sonic velocities in the throat when the pressure reduction factor is about two or higher. This sonic velocity (gas velocity equal to the speed of sound) is a physical limitation of the valve throughput capacity. For hydrogen blends with natural gas and up to full hydrogen, this pressure reduction factor of two does not change significantly and is still valid as a rule of thumb.

As the speed of sound increases when blending hydrogen, the capacity of the valve in terms of volume flow increases, but so does the actual volume flow itself. Therefore, it is important to know which of these increases the most compared to the other, to determine if valve capacity will increase or decrease. The result of both these calculations compared to each other are shown below.

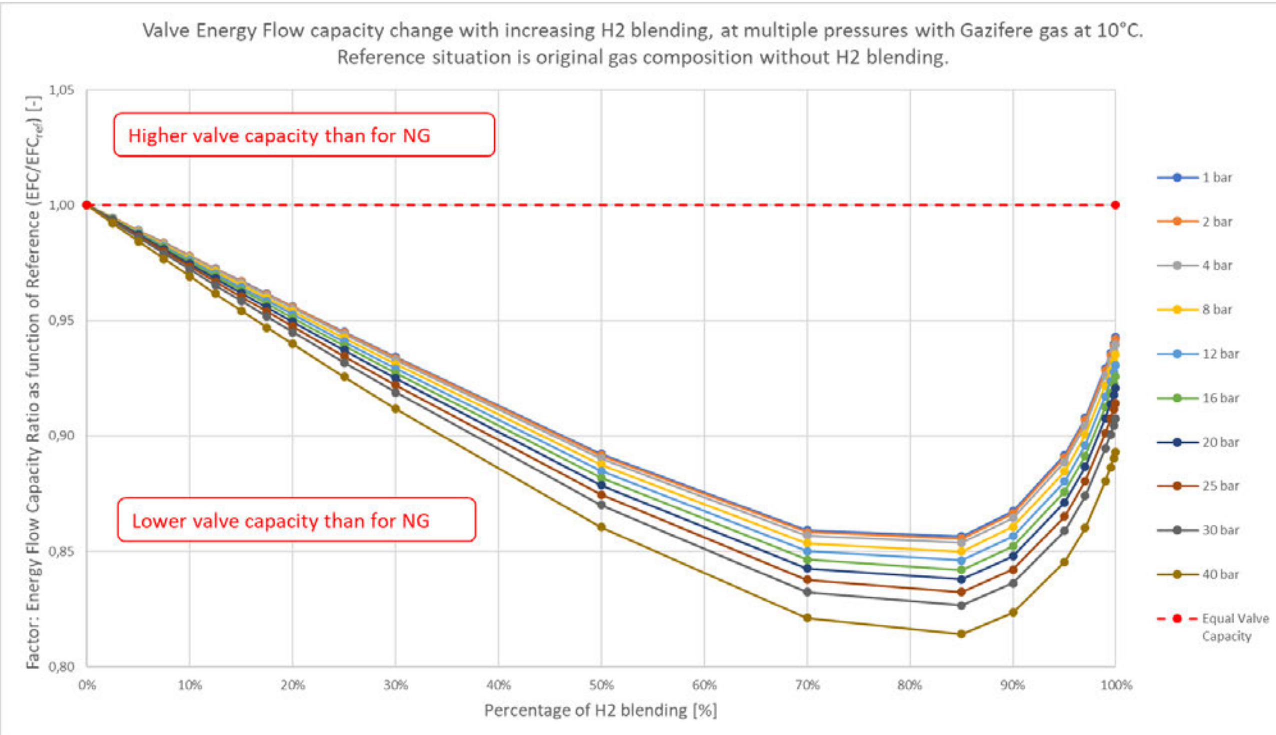


Figure 5-17: Change in pressure reduction valve energy capacity when blending hydrogen

The chart above shows that although the speed of sound increases, the gas velocity increases faster. Therefore, for a valve that is operating at its maximum flow rate the capacity will decrease as shown above, depending on pressure and hydrogen blending percentage. As a rule of thumb, maximum valve capacity is used at a pressure drop of a factor two or higher. Therefore, any valve that is currently operating under a higher pressure drop than this factor of two will see a lower throughput capacity in energy flow. [redacted]

However, pressure losses over all elements that have a pressure drop will increase. This is not only true for pipelines but for every piece of equipment with a pressure drop. Hence, the pressure drop over pressure reduction valves will also increase. Therefore, even though a valve might have sufficient capacity to handle the gas flow with a percentage of blended hydrogen, the network conditions need to be kept in mind.

5.6.3 Material Compatibility

A general review of material compatibility with hydrogen is provided in section 6.6 that may also be applied to materials that may be present in meters, regulators, pressure recorders, and other equipment. However, as there can be variability in the materials and production methods used, DNV's recommendation is that the compatibility with hydrogen of specific equipment and components be discussed with the individual manufacturers.

5.7 Standards Based Requirements

Due to the increased interest in introducing hydrogen into natural gas systems, several international standards have been written, or are in the process of being written, to regulate various aspects of pipeline networks. A summary of pertinent standards is contained below in Table 5-13.

Table 5-13: Summary of industry standards pertaining to the integrity of pipeline during the transportation of hydrogen

Document number	Title	Year of publication	Author	Comments
ASME B31.12	Hydrogen Piping and Pipelines	2019	ASME	Applies to the design, construction, operation, and maintenance for pipelines and distribution systems in hydrogen service. It is applicable to pipeline systems with a hydrogen content above 10% by volume, although it has been used primarily for pipelines transporting 100% hydrogen
CSA Z662:19	Oil and Gas Pipeline Systems	2019	CSA	Oil and Gas Pipeline Systems does not currently contain any requirements specifically for hydrogen or hydrogen blended natural gas pipelines. A CSA Z662 Task Force has been set up to review and recommend requirements for the 2023 edition of the standard.
EIGA IGC 121/14	Hydrogen Pipeline Systems	2014	EIGA	For pure and mixed hydrogen systems with pressures between 150 and 3000 psig or hydrogen partial pressure greater than 29 psi for stainless steels.
AIGA 087/20 (originally published as CGA G5.4)	Standard for Hydrogen Piping Systems at User Locations	2020	AIGA	Asia Industrial Gases Association on the transportation, handling and storage of hydrogen in a supply system (to the source valve) and to customer piping from the source valve to the point of use.

The Gazifère system is designed and operated in accordance with the CSA Z662 standard. While there are currently no hydrogen-specific requirements included in the standard, requirements of other industry standards should be reviewed and considered as applicable.

The consensus standards tend to be more focused on selection of materials for new pipelines and piping systems than on the suitability of existing pipelines for hydrogen service, although IGC Doc 121/14 describes the requalification of existing pipelines for hydrogen service in Appendix H and ASME B31.12 sets some requirements for steel pipeline service conversion in PL-3.21. Some types of iron and steel and the types of seam manufacturing processes used to make the pipe present in existing pipelines have not been used for several decades. As a result, not all the steels, types of seams, and field fabrication methods that are often encountered in existing pipeline systems are explicitly addressed by the consensus standards. However, the related requirements or recommendations for new piping can be used to judge the suitability of existing pipe for hydrogen service.

For example, IGC Doc 121/14 states that the most important metallurgical considerations include resistance to both stress corrosion cracking and hydrogen embrittlement. It notes that low stresses are more suitable for exposure to hydrogen environments and lists closer pipe support spacing (if pipe supports are used to limit bending/axial stress), thicker pipe walls, and thermal stress relief of welds as being beneficial. "Low stress" is described as below 30% of the minimum yield strength of the pipeline. Similar statements are included in ASME B31.12 [redacted]

The ASME B31.12 approach to pipe size and grade selection for a targeted MOP generally results in a requirement for thicker pipe walls compared to the approaches used in ASME B31.8, especially when high strength steels are used. IGC Doc 121/14 and ASME B31.12 both recommend that only grades X52 and lower be used, although B31.12 specifically includes options for the use of higher strength steels. IGC Doc 121/14 notes that some operators limit the operating stress to less than 30% SMYS or 20% of SMUTS along with a minimum wall thickness of 0.250 inches. The wall thickness limitations and lower operating stresses minimize the likelihood of severe mechanical damage as well as reduce the potential for hydrogen damage. It also notes a preference for normalized pipe seams for pipe operated at high stress levels. A maximum actual tensile strength of 116 ksi is recommended.

ASME B31.12 provides users with two options for selecting combinations of grade and pipe thickness that meet a targeted MOP. Option A is the "prescriptive" approach which minimizes the requirement for material testing in exchange for the use of low operating stresses. Option B is the "performance-based" approach which relaxes the restrictions on grade and allows reduced wall thickness in exchange for rigorous testing procedures to demonstrate the performance of the intended steel in hydrogen environments, including determination of fatigue crack propagation rates and fracture toughness (beyond simple Charpy impact testing). The Option A prescriptive method is an example of an approach in which gaps in technical information can be at least partially compensated for by restricting stresses to low values and by favouring use of low strength steels that have had the longest successful commercial use in hydrogen service. The Option A method imposes design penalties that nearly eliminate any advantage of using high strength steel that ordinarily would reduce the cost of pipe by reducing the required wall thickness. Table 5-14 summarizes the required inputs for using either ASME B31.12 design Option A or Option B and shows the increased data burden for Option B, particularly with respect to knowing the steel-specific facture toughness and fatigue crack propagation behaviour in hydrogen service.

Table 5-14: List of Metallurgical Inputs/Mechanical Property Inputs Required for ASME B31.12 Determination of Required Design Wall Thickness and Acceptability of Candidate Steels

Variable	Input	Used for Option A	Used for Option B	Source
S	Specified minimum yield strength	YES	YES	Design parameter for new pipeline; Pipeline records or testing for existing pipelines
E	Seam type and corresponding longitudinal joint factor	YES	YES	Design parameter for new pipeline; Pipeline records or direct observation for existing pipelines
UTS	Ultimate tensile strength	NO	NO	MTRs for new pipe; Pipeline records or testing for existing pipelines. Maximum allowable values are limited by B31.12
	Initial flaw size	NO	YES	Inspection data or hydrotest data
Da/dN	Fatigue crack growth rate	NO	YES	Calculated or from test data.
K_{IH}	Threshold stress intensity factor in hydrogen	NO	YES	Test data from specific or "similar" steel
-	Charpy impact test absorbed energy	YES	YES	Test data from specific steel
-	Charpy impact test shear%	YES	YES	Test data from specific steel
-	Actual ultimate tensile strength of pipe	YES	YES	Test data from specific steel
-	Actual ultimate tensile strength of weld metal	YES	YES	Test data from specific steel
-	Actual phosphorous content of steel	NO	YES	Test data from specific steel
-	Hardness of base metal (pipe, fittings, bends)	YES	YES	Test data from specific steel
-	Hardness of weld zones	YES	YES	Test data from specific steel

Both IGC Doc 121/14 and ASME B31.12 impose limitations on hot tapping, although the emphasis is on safety of making new hot taps rather than the long-term integrity of existing hot taps. IGC Doc 121/14 does require that hot tap welds be checked to ensure that hardness does not exceed 225 BHN. (Note that Appendix D of the same IGC document refers to a preferred maximum hardness of Rockwell C22 or HV 248, which is harder than HBN 225, but Brinell hardness test methods may underestimate the maximum hardness of the weld heat affected zone (HAZ) because of the relatively large size of the indenter compared to the size of the hardest portion of the HAZ). Furthermore, IGC Doc 121/14 notes the importance of having crack-free root pass and final pass of hot tap welds.

IGC Doc 121/14 Appendix D "Metallurgical Factors Affecting Hydrogen Toughness and Brittle Fracture Mechanisms" emphasizes the importance of good toughness and notes that the following key metallurgical controls impact toughness:

- Controls on alloy composition including sulfur not greater than 0.01% and phosphorous not greater than 0.015%;
- Inclusion shape control via addition of rare earth elements or calcium;
- Fine grained microstructures;
- Use of killed steels (i.e., steels containing controlled amounts of silicon or aluminum to promote deoxidation and finer grain size);
- Low, or reduced, carbon equivalents (0.43 CE IIW or 0.20 Pcm preferred); and
- Microalloying.

Similarly, ASME B31.12 includes requirements related to composition, hardness, strength, and toughness to optimize long-term integrity in hydrogen service. In some cases, especially for Option B applications, those requirements surpass the standard requirements of API 5L PSL 2 pipe, as summarized in Table 5-14. PSL 2 pipe has requirements that far exceed the requirements for pipe made to the API 5L standard before 2000 (unless various supplemental requirements or "SRs" were invoked at the time of purchase). Therefore, it's evident that early vintage pipe can have actual properties that are far from meeting the minimum requirements of ASME B31.12. The extent to which those early vintage pipes are acceptable relate greatly to how different the actual properties are from the current recommended properties, and how severe the hydrogen service will be in terms of partial pressure and stress level relative to the pipe strength.

Like most consensus standards, the content of the standards related to hydrogen service lags behind the development of new technical information pertinent to pipeline integrity in hydrogen service by at least a few years. The recommendations and requirements of the standards represent what are, or were, good or best practices at the time of publication, but do not necessarily represent the most current information being developed by a wide range of research activities, or the evolving opinions of subject matter experts. Understanding the influence of various metallurgical characteristics on the performance of steel in hydrogen service is a rapidly evolving area of research with substantial government and industry funding and frequent publication of relevant technical papers.

Table 5-15: Comparison of API 5L PSL 2, CSA Z245.1 Cat II and ASME B31.12 Requirements

Characteristic	API 5L PSL 2	CSA Z245.1 Cat II	ASME B31.12 Option A (Prescriptive determination of MOP)	ASME B31.12 Option B (Performance-based determination of MOP)	Notes
Charpy Test Temperature	0°C (32°F) or as specified	per P.O.	Lower of 0°C (32°F) or minimum operating (or minimum pressure testing temperature)	Same as Option A	1
Fracture Shear %	85% (average) in Charpy At least 85% (average) for DWTT	No individual specimen <50% shear, at least 60% shear for any test and at least 85% shear (average) for orders of 5 or more heats	At least 80%(average) for full size Charpy At least 40% (average) for DWTT	Same as Option A	2
Charpy Base Metal Absorbed Energy	27 J (20 ft-lbs) for not greater than X70	Minimum of 27 J for <457 mm OD, 40 J for OD ≥457mm or per P.O.	CVN $=0.008(\sigma^2)\ [(RT)^{0.39}]$ Example requirement for 30 in. X52 at 1480 psig and 50% SMYS at 1.0 seam factor= 19.9 J (14.7 ft-lbs)	Same as Option A	3
Charpy Weld (weld metal and HAZ) Absorbed Energy	27J (20 ft-lbs) (average)	Minimum of 18 J or per the P.O. for SAW; Minimum of 27 J for <457mm OD, 40 J for OD ≥457 mm or per P.O. for ERW, 18 J at ERW fusion line	27 J (20 ft-lbs) full size (average)	Same as Option A	4
Fracture Toughness & Stress Intensity K_{IA} and K_{IH}	Not addressed	Not addressed	Not addressed	Tested per KD-1040 Calculate max K_{IA} K_{IH} may not be less than 50 ksi √in. Values may come from "similar" steels as grouped by Table PL-3.7.1-4 and strength does not exceed material used in qualification tests by more than 5%	5
Ultimate Tensile Strength (UTS)	Per Table 7	Per Table 8	689.5 MPa (100 ksi) max	Max UTS of pipe = 758.4 MPa (110 ksi) Max UTS weld = 758.4 MPa (110 ksi)	6
Yield Strength (YS)	Per table 7	Per Table 8 (grade 483 = 70 ksi YS; grade 550 = 80 ksi)	70 ksi max (therefore X70 is unacceptable based on actual SMYS specified in 5L)	SMYS 80 ksi max (therefore X80 is not acceptable based on actual specified SMYS in 5L)	7
Steel Composition and Processing	Per table 5 (Note: 0.025% max P allowed)	Per table 5 (Note 0.030% max P allowed)	Not addressed	P 0.015% max Must be inclusion shape control	8
Thickness	Table 11 wall thickness tolerance is +/- 10% for wall less than 15 mm (0.591 in.) and +/- 1.5 mm (0.060 in.) for thicker wall.	Table 3 thickness tolerance includes minimums of -8 to -12.5% depending upon pipe size and type. Grinding is limited to the wall thickness tolerance	Not addressed	Repair and other activities may not reduce t to less than 87.5% of calculated nominal required wall thickness	9

Characteristic	API 5L PSL 2	CSA Z245.1 Cat II	ASME B31.12 Option A (Prescriptive determination of MOP)	ASME B31.12 Option B (Performance-based determination of MOP)	Notes
Design Pressure Limits	Not addressed	Not addressed	Not addressed	Limited to the greater of 85% of mill test pressure or field hydrotest pressure. Cold worked pipe subsequently heated has a reduced P to 75% of design pressure formula	10
Weld Hardness	Pipe body hard spots of up to 345 HV 10 or 327 HBW allowed. No hardness tests of seams or jointer girth welds in DSAW pipe is required	24 HRC max; 30 HRC for non-sour service grades 483 and higher	200 HV10 or Brinell HBW 200 maximum	HV 200 or Brinell HBW 200 maximum	11

Notes:

1. No differences between ASME B31.12 and current edition of API 5L; no supplemental requirements needed for new API 5L pipe. However, many older editions of API 5L did not have requirements for toughness testing. Z245.1 conformance to ASME B31.12 depends upon what is specified as a test temperature in the P.O.

2. The requirements for the current edition of API 5L are equal to or more stringent than those in ASME B31.12; no supplemental requirements are needed for new API 5L pipe. However, many older editions of API 5L did not have requirements for toughness testing. Z245.1 can be more or less conservative than B31.12, depending upon how many heats are in the order.

3. The minimum required Charpy absorbed energy described in ASME B31.12 is dependent upon hoop stress, pipe wall thickness, and pipe diameter, but the calculated values tend to be lower than or approximately equivalent to the required 20 ft-lbs described in API 5L for hoop stress values not greater than about 60% of SMYS. It is unlikely that the Charpy impact energy requirements will be a significant challenge for modern steel pipe, but the required toughness should be communicated to the pipe supplier. Existing pipe may fail to meet the toughness requirements of ASME B31.12 since toughness testing was not required in many editions of 5L. The requirements of Z245.1 are comparable to or more conservative (for large diameter pipe) than those of 5L.

4. No differences between ASME B31.12 and current API 5L requirements; no supplemental requirements needed for new API 5L pipe. However, most editions of API 5L did not have requirements for toughness testing of seams. The requirements of Z245.1 are less stringent than B31.12 for SAW weld metal and for ERW fusion line.

5. There are no fracture toughness testing requirements for API 5L or Z245.1 that are comparable to the ASME B31.12 Option B requirements, and pipe mills are unlikely to have the ability to perform the required mechanical testing. It is likely that the pipeline operator would have to obtain pipe samples and have testing performed by a third-party service provider. ASME B31.12 does allow tests to be performed on pipe that is comparable to the project pipe. The standard defines what is sufficiently similar in Table PL-3.7.1-4 and PL-3.7.1(b)(2) (-a) (-3) (pages 137 and 136 of the standards, respectively).

6. The maximum allowable ultimate tensile strength in ASME B31.12 Option A and Option B are both lower than the allowable maximum tensile strength for grades higher than X46 in the current edition of API 5L. A purchase specification for new pipe would have to impose UTS limits that are lower than API 5L for grades stronger than X46. Also, prior to the adoption of PSL 1 and PSL 2 subgroups in 2000, API 5L did not impose upper limits on strength for

any grade. For Z245.1 the allowable tensile strength upper limits exceed the B31.12 allowable values for all listed grades. Supplemental upper limits on UTS would have to be applied to purchases of new pipe. It is possible that some existing pipe can have UTS that exceeds the limits of ASME B31.12.

7. The API 5L SMYS values applicable to X70 and X80 pipe are 485 MPa (70.3 ksi) and 555 MPa (80.5 ksi), respectively, for the current edition of API 5L. The SMYS for X70 and X80 meet the SMYS requirements in ASME B31.12 for pipe manufactured before October 2008. Z245.1 grades up to and including grade 483 meet the requirements of B31.12 Option A and grades up to and including grade 550 meet the requirements of B31.12 Option B.
8. The requirements of ASME B31.12 are more restrictive than the requirements of API 5L and Z245.1. Supplemental requirements would have to be imposed on API 5L and Z245.1 pipe.
9. For recent editions of API 5L, the current wall thickness tolerances for PSL 2 pipe are more stringent than the allowable wall thickness reductions described in ASME B31.12. Therefore, no additional requirements need to be imposed on new API 5L pipe. Wall thickness tolerances in older editions of API 5L differ from recent editions. The wall thickness tolerances and limits on grinding repairs in Z245.1 are equal to or more stringent than the limits in B31.12.
10. This pressure limitation indicates that either the pre-service field hydrotest or the mill hydrotest would have to be at least 1.18X the desired MOP. In addition, it is unclear if post weld heat treatment (PWHT) stress relief for thick joints triggers the requirement to reduce the pressure to 75% of the calculated maximum allowable operating pressure. ASME B31.12 requires PWHT for joints in P1 steels greater than 31.8 mm (1.25 in.), including weld reinforcement height, thickness or to reduce weld hardness to less than the limit of HV 200.
11. The hardness limits of ASME B31.12 are more stringent than the current edition of API 5L and Z245.1 with respect to hard spots and welds. For new pipe, the pipe mill needs to be aware of these limits and the hardness of field welds needs to be addressed in welding procedure development and testing. Rationale for selecting the specified conservative hardness limits is not publicly available.

5.8 System Integrity

5.8.1 Material Compatibility

Based on the review of information provided by Gazifère, the following materials are known to be incorporated within the system in various components:

Table 5-16: Material Compatibility for H2 Service

Material	Acceptable/ Unacceptable	Notes
Carbon Steel	Acceptable	Carbon steel will embrittle with hydrogen service. Embrittlement will increase with increased partial pressures of hydrogen. Weld and seam heat affected zones may have crack susceptible microstructures (may be assessed though hardness testing).
Polyethylene Piping/Components	Acceptable	No material property changes are expected. 5X increase to permeability for hydrogen which should be considered in risk assessment.
Brass Fittings	Acceptable	No material changes are expected.
Copper Fittings	Acceptable	No material changes are expected. The permeability of hydrogen in copper is quite low.
Stainless Steel Fittings	Acceptable (see notes)	Austenitic steels are resistant to hydrogen embrittlement. Ferritic and martensitic stainless steels (i.e.: 410, 430, 440, 17-4PH) are very susceptible to hydrogen embrittlement and not compatible unless specifically heat treated for hydrogen service. See for example, the limitations described in NACE MR-0175 for use in H_2S service. Only austenitic stainless steels were identified in Gazifère's network.
Cast Iron Fittings	Unacceptable (see notes)	Cast iron usage is not allowed in hydrogen service per ASME B31.12 and AIGA 087 due to lack of ductility, and sensitivity to thermal and mechanical shock. However, conflicting guidance regarding the use of cast irons does exist. Refer to section 5.8.1.1.
Forged Steel Fittings	Acceptable	Heavily worked materials result in higher levels of embrittlement. Under low stresses, this is not expected to be a concern. Also, heat treatments commonly applied to forgings minimize the detrimental effects of plastic deformation during forming.
Alloy Steel Bolts	Acceptable (see notes)	Per B31.12, on flange joints, all alloy-steel bolts and stud bolts 25 mm (1 in) and smaller shall be coarse thread. Larger bolts shall be an 8-thread series and have a Class 2A dimension. Nuts shall have a Class 2B dimension.
Black Malleable Iron (BMI)	Unacceptable (see notes)	As with cast iron, not acceptable for hydrogen service per B31.12 due to low ductility and susceptibility to thermal and mechanical shock. See section 5.8.1.1.
PTFE/Teflon	Acceptable	Slight increase to stiffness in hydrogen environment and an approximate 1.5X increase in frictional coefficient.
Buna-N/Nitrile	Acceptable	Hydrogen exposure can lead to reversible swelling of up to 57% volume change/gram and increased frictional coefficient of approximately 1.4X that in ambient air.
Viton	Acceptable	Hydrogen exposure can lead to reversible swelling of up to 69% volume change/gram and almost doubled permanent deformation under compressive state.
Delrin	Unknown	Direct exposure to hydrogen has not been extensively studied, however exposure to sour service contaminants such as hydrogen sulfide and sulfuric acid have exhibited some problematic compatibility issues. [34]
Neoprene	Acceptable	Hydrogen permeability is about 1/5th to 1/6th when compared to rubber.

5.8.1.1 Cast Iron and BMI

The use of black malleable iron (BMI) for hydrogen blended natural gas service varies by standard. Pressure-containing components made of BMI or cast iron are not permitted in hydrogen blended natural gas service per ASME B31.12 due to the lack of ductility and susceptibility to thermal and mechanical shock. While pipeline systems at concentrations below 10 vol% hydrogen are outside the scope of B31.12, it is understood that the eventual goal of Gazifère is to exceed a 10% hydrogen blend. Similarly, AIGA 087/14 does not allow for grey, ductile, or malleable cast iron in hydrogen service. NACE MR0175, applicable to components exposed to wet hydrogen sulfide, is generally considered to be conservative for most hydrogen blended natural gas applications. MR0175 does not allow the use of grey cast iron, white cast iron, or austenitic cast iron for pressure-containing parts but does allow the use of ferritic ductile cast iron (also known as nodular cast iron) components that meet the ASTM A395 specification. IGC 121/14, however, does not make specific statements regarding the acceptability of BMI or cast iron; they provide guidance if less than ideal materials are used in a system. In section 4.3.1, it is stated that "If the above conditions cannot be fulfilled, it might be necessary to operate the equipment at a reduced stress/pressure (below 30% of the specified minimum yield strength SMYS or 20% of the specified minimum ultimate tensile strength SMUTS, whichever is lowest)."

Literature on cast iron in low pressure hydrogen service has been generally positive. Melaina, Antonia, and Peney [23] summarized work performed by the Gas Research Institute (GRI) and noted that GRI observed that ductile iron and cast iron pipes have operated for decades at pressures up to 60 psig without evidence of hydrogen damage and concluded that "…there is no concern of hydrogen damage under general operating conditions in natural gas distribution systems". DNV notes, however, that at least some of the long operating experience was in town gas. Town gas often has gas constituents which appear to reduce the adsorption of hydrogen into steel, and presumably into other ferrous alloys. UK HSE has accepted cast iron usage at 20 vol% H2 blend at 1 psi distribution pressure for HyDeploy 2 trials. Another study found that cast iron pipes had "no concern of hydrogen damage under general operating conditions in natural gas distribution systems". These distribution systems were operating at a distribution pressure generally between 0.25 psi to 60 psi with some up to 250 psi (1720 kPa). [redacted]

[redacted]

5.8.2 Current Integrity Status

5.8.2.1 High-Stressed Girth Welds

High stresses at girth welds are likely to be weakly related to hoop stress from operating pressures. High stresses at girth welds or at circumferentially oriented fillet welds at full encirclement sleeves or reinforcements are usually from the combination of residual stress from welding (present to some degree in all welds) plus the effects of ground deformation or inadequate trench profile that results in bending stresses on the pipe. [redacted]

Ground deformation can be detected visually or monitored by surveying methods. Pipeline displacement caused by ground deformation can also be detected by purpose-built in-line inspection pigs. In some cases, pipeline operators elected to monitor pipe strains with strain gauges and then periodically excavate the pipeline and allow it to rebound or relax into a relatively unstressed position when slow, but significant, ground displacements are noted over long periods of time. [redacted]

[redacted]

5.8.2.2 High-Stressed Mains

In the absence of axial or bending stresses associated with geophysical conditions, the primary source of stress in the mains will be hoop stress from internal pressure plus residual stress from longitudinal seam welding. The residual stresses from seam formation are likely to be highest for SAW seams that were not cold expanded and ERW seams that were not subjected to a normalizing heat treatment. Brief heat treatment to eliminate untempered martensite at about 1000°F (538°C) would have a less beneficial effect on residual stresses.

Failure associated with flaws in pipelines operating at hoop stresses less than about 30% SMYS are more likely to result in leaks, rather than a very long rupture, even if the pipe is embrittled by hydrogen (see section 5.3.4.1).

Highly stressed pipe, or highly stressed localized areas of pipe are more likely to be embrittled by hydrogen than locations at which stresses are lower. Examples of localized areas of high stress that would not be discoverable only by review of pipe dimensions, grade and MOP can include areas around welds (as a result of residual stress), the tips of planar flaws, areas of geometric irregularity such as abrupt changes in thickness, and locations subjected to cold deformation, such as field bends and areas of mechanical damage. Note that welded transitions between two different nominal wall thicknesses of pipes following the guidance in CSA Z662 or ASME B31.8 do not constitute an abrupt change in thickness.

5.8.2.2.1 Summary of Gazifère Stress Level

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All pipe for which the grade was listed was grade X52 or a lower strength grade. Pipe grades X52 and below are recommended for use by ASME B31.12 and have the longest history of successful use in hydrogen service.

[redacted]

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[redacted] Depending upon the grade and vintage, ERW pipe may or may not have received a post-seam welding heat treatment that would have effectively removed hard zones that are subject to hydrogen cracking. Seamless pipe is unlikely to have areas of high hardness or crack-susceptible microstructures.

5.8.3 Polyethylene

5.8.3.1 Nominal Failure Mechanisms of PE Materials

Outside of accidental line hit damage during excavations, which has been shown to be the cause of approximately 65% of all failures in PE pipes [35], the four main causes of pipe failure are ductile rupture, rapid crack propagation failures, cold fusion, and brittle-like slow crack growth failures, which is the most common form of failure.

Ductile rupture results from the presence of high internal pressures (typically greater than 2750 kPa), which far exceed any loads imposed on the PE materials composing the Gazifère pipeline infrastructure. Therefore, it is not expected that this would be a potential failure mechanism for any PE pipelines existing in the Gazifère network.

Rapid crack propagation (RCP) failures are catastrophic brittle cracks that propagate at high speeds (over 300 ft/sec, 91 m/s) axially over a long span of the pipe. They are most common at lower temperatures due to decreased dynamic fracture resistance, and PE pipe susceptibility to this type of fracture increases with increasing pressure, increasing pipe diameter, increasing dimension ratio, and decreasing modulus of elasticity. With respect to increased pipeline diameters, RCP failures are based on the release of stored elastic energy required to sustain crack propagation. The energy required for RCP crack growth has been correlated to the following equation [33]:

$$J = \frac{11.25 p^{2.5} D \left(\frac{D}{t-1}\right)^2}{E_D^{\frac{3}{2}}} \quad (2)$$

Where J is the driving energy, p is the internal pipe pressure, D is the pipeline diameter, t is the pipe thickness, and E_D is the dynamic modulus, which is a materials property that is dependent on temperature. When $J \leq J_c$, the dynamic toughness of the material, the crack will stop propagating and arrest until the driving energy increases again. Although not an immediate threat to the existing PE infrastructure, and nominally resulting in approximately 1% of PE pipeline failures, the future threat for rapid crack propagation failures will increase as manufacturers increase the diameters of transportation pipelines to maximize hydrogen distribution.

Cold fusion refers to the incomplete fusion of two pipe halves. A cold fusion joint typically passes hydrostatic pressure testing of the pipe system but fails after some service time, normally due to either thermal ratcheting or some time-wise change in the piping system similar to fatigue or creep failure. These joints provide a weak point when compared to the parent pipe and consequently designate areas in the pipeline that could potentially fail during service.

Finally, the most common failure mechanism for PE pipes, slow crack growth failures, occurs over extended periods of time at low loads below the yield point of the material. The cracks tend to initiate at points of high stress risers caused by inclusions, contaminants, scratches, defects, cavities, etc. The cracks grow in a stepwise fashion, with damage zones consisting of a main craze with a continuous membrane at the crack tip. Arrest periods are related to the duration of each craze, and the main part of the craze fractures at the end of the arrest period. Consequently, the number of visible striations directly corresponds to the number of step jumps in the progressive craze formation and fracture process. Therefore, newer PE materials that have been shown to be more resistant to SCG will show significantly more striations [34].

5.8.3.2 Fracture Properties of MDPE Materials

Fatigue crack growth tests on MDPE materials have been performed to estimate their fatigue life and fracture properties under nominal conditions. MDPE materials have significant strength and elongation to failure results in a ductile to brittle fracture mechanism. Crack growth rates exhibit linear relationships on double logarithmic diagrams, with ductile fracture occurring initially until a ductile/brittle transition occurs, observed to be at around 0.8 MPa*m$^{0.5}$. Little deviation was shown between tests performed on three separately manufactured MDPE specimens [35]. In experiments testing rapid crack propagation in MDPE materials, it was observed that the plastic deformation occurs through either forced-elastic shear strains with the formation of shear bands or forced elastic tensile strains with the formation of microcracks, alternatively known as craze formation. Because RCP initiates from a high stress concentration or at initiated sites of SCG, a thorough inspection of existing PE pipes would be required to identify potentially susceptible regions. These regions are most vulnerable when temperatures drop rapidly, such as during the onset of a polar vertex, which can result in catastrophic failures [36]. Due to the negligible effects of hydrogen on MDPE, it is unlikely these risks change appreciably due to hydrogen's effects on the piping's material properties. [redacted]

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5.8.5 Future Integrity Recommendations

5.8.5.1 Inspection Recommendations

Metallurgical examination of samples of welds, especially of welds made onto in-service piping (i.e., repairs and hot taps), can be performed to detect the presence of planar flaws and crack-susceptible microstructures and to measure important mechanical properties. Destructive, laboratory testing is preferred but metallographic examination and hardness testing can both be performed non-destructively in the field. DNV has provided Gazifère with guidance [37] regarding selection and prioritization of lab testing for various pipe samples, which is included in Appendix 5: Pipe Sample Collection and Testing Guidance of this report.

Hydrogen leaks more easily than nitrogen from "leak tight" mechanical connections, although available data suggest that at low hydrogen concentration in blended pipelines operating at low pressures (especially in distribution pipeline systems), leakage rates were not significantly higher than those of natural gas pipelines [38]. Considering the possibility of enhanced leak rates and consequently a surge in the amount of escaped gas, leak detection equipment and procedures should be reviewed to evaluate their effectiveness and compatibility at the targeted hydrogen concentrations. Equipment determined to be ineffective or incompatible should be replaced. Additionally, age or condition-based replacements should also be with effective and compatible equipment in anticipation of hydrogen service. While inspecting leak detectors, special attention should be devoted to the efficacy of fixed gas detectors located in restricted areas or in the vicinity of buildings. Note that at lower hydrogen concentrations (<20 vol%), for any system that is compatible with hydrogen-natural gas blends and under properly ventilated conditions, leakage rate is not significantly increased compared to pure natural gas [11] [39]. DNV recommends that Gazifère consider performing a supplemental leak survey of mechanical connections after the introduction of more than 20% hydrogen. The results of the initial post-hydrogen leak survey can be used to guide the determination of intervals between future leak surveys.

Additionally, because hydrogen embrittles steel, it is possible that existing flaws may create leaks in certain conditions. Given the low pressures of the system, development of a leak would require an exceptionally large flaw which has not been identified by any records reviewed by DNV, although it remains theoretically possible. If such a flaw were to fail, it would be expected to leak rather than rupture due to the low pressures in the system as evidenced by Figure 5-11.

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In general, soft goods are subjected to increased amounts of degradation when exposed to hydrogen. Specifically, materials such as buna-n / nitrile, and viton experience reversible swelling of 57% to 69% when exposed to hydrogen, as well as increased frictional coefficients and enhanced permanent deformation [40]. As such, the lifespan of these items may be shortened after hydrogen is introduced when compared to other polymers such as medium- and high-density PE and thermoplastics such as PTFE. Maintenance on these items may be increased due to the introduction of hydrogen along with the shutoff time due to the enhanced swelling of buna-n / nitrile and viton. However, the swelling in these materials has been shown to be reduced rather quickly when removed from hydrogen environments, with buna-n / nitrile exhibiting a 3.9% volumetric change and viton displaying a 11.5% volumetric change 48 hours after removal from the hydrogen environment.

5.8.5.2 Welding Recommendations

[redacted]

[redacted] The risk of cracking, either for natural gas service or hydrogen-blended natural gas is greater as gas pressure and velocity increase since those attributes influence the weld cooling rate, which then influences the likelihood that crack-susceptible microstructures will form. The risk associated with HP and XHP piping depends upon the weld cooling rate, which is related to the flow rate of the gas, the welding parameters used (current, voltage, travel speed, use of preheat, etc.), and the pipe and fitting dimensions. Weld cooling rate modelling can be used to assess whether the gas flow conditions are contributing significantly to accelerated cooling of the weld. DNV has found that gas at LP and IP conditions has minimal effect on weld cooling rates, and therefore the hydrogen cracking risk in those piping classes is expected to be low. The existing NDT practices should be sufficient for welds made onto pipe in hydrogen-blended natural gas service.

Proprietary work at DNV performed as part of an on-going joint industry project showed that on thin pipe (<6.4 mm), hydrogen in the gas can contribute to some increased risk of burn through, although no work has been done using blends less than 30 vol% hydrogen.

5.8.5.3 Material Recommendations

Guidance for steel intended for use in hydrogen service is included in ASME B31.12 and IGC 121/04. Those recommendations include the following:

- Alloy composition: Low limits on elements, such as sulfur, phosphorous, antimony, tin, and arsenic, which promote hydrogen charging by inhibiting hydrogen atom recombination to H_2 at the steel surface. Maximum of 0.015% phosphorus and 0.01% sulfur. Manganese/carbon ratios greater than 3:1, which is common practice for pipeline steels. Microalloying, including use of small additions of niobium, vanadium, titanium, calcium, and/or rare earths, produces good toughness and fine grain size.
- Inclusion shape control via addition of calcium or rare earth elements.
- Fine grain size (ASTM 9 or finer) obtained through thermomechanical processing or microalloying or addition of aluminum improves toughness.
- Use of low carbon equivalent (CE), as higher CE is often associated with much greater susceptibility to formation of hard zones that are susceptible to cracking. Recommended CE maximum values in B31.12, using the Pcm formula, are 0.15% for X52-X60 (Gr.359-414), and 0.17% for X65-X80 (Gr.448-550).
- Use of killed steels, through additions of silicon, aluminum, or other reactive elements.
- Slab macro etch for evidence of centreline segregation with a maximum rating of “2” on a scale of 1-5.

In general, the emphasis for steel pipe and fittings should be on two attributes:

- Maximizing as-received toughness so that subsequent “embrittlement” in service still results in enough toughness to produce good planar flaw tolerance (large critical flaw size) and resistance to long ruptures. Broadly speaking, this could conservatively translate to specifying at least twice as much toughness as would normally be required for the intended combination of stress, pipe grade, and pipe dimensions. In view of the combinations of pipe sizes and low operating stress in the pipelines, pipe with sufficient as-received toughness should be widely available.
- Controlling carbon equivalents to low values to maximize the ability to make welds (either during construction or while the pipe is in service, without the production of hard heat affected zones that are more susceptible to hydrogen cracking.

The acceptability of other alloys, such as stainless steel, depends upon the details of how they are used, i.e., whether they are hardened by heat treatment, cold worked, or used in the annealed condition. Non-steel components in valves, regulators and other appurtenances that may be exposed to hydrogen should be reviewed and compared to the commentary of B31.12 and IGC 121/04.

5.9 Conclusions

The pipeline system, including pipe and ancillary fittings and equipment, is divided into four pressure classes. [redacted]. The envisioned range of hydrogen blends (initially not greater than 20 vol% hydrogen) is likely to result in minimal integrity management concerns for steel pipe in the LP pressure class. The associated PE pipe is also unlikely to be significantly mechanically affected by the addition of hydrogen.

The effects on nonmetallic components (other than PE pipe) are likely to be more dramatic as hydrogen partial pressure increases. For instance, an HDPE material for a specific diameter and wall thickness exposed to an 80/20% mixture of hydrogen and methane was shown to leak about 2.3 litres/km/day as opposed to the same material in 100% hydrogen, which exhibited a leakage rate of 5.0 litres/km/day. This example is provided as an illustration of the effects of hydrogen content and is based on a single material, diameter and wall thickness combination. The amount of leakage will vary depending on a range of parameters including the diameter, wall thickness, material and more. Other effects on nonmetallic components such as increased wear will also increase as the ratio of hydrogen increases.

For steel pipe and fittings, some embrittlement, estimated to be not more than a 30% reduction in fracture toughness at the highest partial pressures, could occur with a corresponding increase in FCGR. The reduction in toughness will result in a reduced critical flaw size before failure occurs. However, the susceptibility to rupture is considered low in both XHP and HP pressure class piping unless seam flaws are very long (i.e., greater than about 200 mm) and deep (i.e., greater than 0.7t). The susceptibility to rupture in other pressure classes is even lower. In addition, the relatively low hoop stresses (<30% SMYS) and low pressure cycling are not believed to represent a significant susceptibility to fatigue crack initiation or growth unless relatively large planar flaws are already present in seams or fabrication welds.

The greatest susceptibility to hydrogen-related cracking is believed to be at crack-susceptible microstructures associated with hard fabrication welds and ERW seams. Hard fabrication welds are most likely to be related to welds made onto in-service piping, i.e., repair welds and hot taps. Hard ERW seams are most likely to be associated with early vintage ERW (generally manufactured before 1970's) pipe that was not normalized after the seam was formed. Guidance is provided on prioritization of pipe sample collection and testing to determine if high risk metallurgical features are present. The number of samples to be collected in order to generate a defensible summary of likely metallurgical attributes cannot be easily predetermined. It is related to the amount of variation in the properties measured in the initial sample collection.

A second significant factor in hydrogen embrittlement risk management is the presence of large secondary or thermal stresses that could exceed hoop stresses from operating pressure. Examples include residual stress from mechanical damage, axial or bending stresses from ground movement or poor pipelaying practices, and residual stresses from fabrication welds. Of these, only ground movement can be readily identified and monitored.

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While some acceleration in the degradation rate of various elastomers used in mechanical clamps, seals and gaskets could occur in all pressure classes, and some wear components may degrade more quickly and have increased friction, all examined components are expected to perform in hydrogen-blended natural gas service.

Some alloys used in valves and other ancillary equipment may be present in heat-treated conditions that make them susceptible to hydrogen embrittlement and cracking. Examples include some stainless steels and high strength-low alloy steels. Components that meet the requirements of NACE MR0175 or similar industry standards applicable to materials used in hydrogen sulfide service would be suitable (and conservative) for the envisioned hydrogen-blended natural gas service conditions.

Hydrogen leaks more easily than natural gas from mechanical connections. Some increase in susceptibility to leakage may occur at threaded connections and mechanical seals, although the leakage rate for blends below about 20 vol% hydrogen is expected to be little changed compared to the leakage rate for 100% natural gas. This leakage rate will increase with higher percentages of hydrogen in the system.

The acceptability of black malleable iron (BMI) in hydrogen-blended natural gas service varies by standards. ASME B31.12 and AIGA 087 do not allow for their use, while IGC 121 allows for the use provided stresses are low enough (<30% SMYS and <20% SMUTS). Literature on cast iron in low-pressure hydrogen service has been generally positive in low-pressure systems (see section 5.8.1.1). [redacted]

Only minor modifications to various construction, operating, and maintenance procedures are recommended. [redacted]

[redacted]

[redacted]	[redacted]			
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6 ASSESSMENT OF END-USE EQUIPMENT

6.1 Introduction

The Gazifère distribution system is connected to industrial, residential, and commercial customers. This section addresses the assessment of the allowable hydrogen percentage in natural gas recommended for the equipment and processes connected to Gazifère's network.

All end-use equipment installed in the Gazifère network is designed, engineered, with possible adjustments for the locally distributed natural gases. Hydrogen blending can have a detrimental effect on combustion performance. These effects are different for each type of combustion equipment. To roughly estimate the types of end-user equipment connected to the Gazifère natural gas grid, a brief inventory was conducted based on information provided by Gazifère. Gazifère provided a list of approximately 45,000 rental appliances installed in their domestic market. DNV categorized in Section 6.2 the different end-use equipment based on their combustion mode, which is used as an input for the hydrogen blending assessment described in this report.

To determine if there is an additional risk when blending hydrogen in natural gas in comparison to the distribution limit gases, a gas interchangeability analysis was performed (see Section 6.3) for the appliance type categories present in the Gazifère network. In the interchangeability approach, rather than testing appliances to assess changes in performance with different fuel mixtures, the variation in the relevant combustion properties (such as burning velocity or adiabatic flame temperature) with fuel composition is used as a representative for performance change.

To get insights into how the maximum hydrogen percentages based on the interchangeability analyses relate to experimental data, in Section 6.4, DNV compared the results of the gas interchangeability analyses with data measured by DNV and data found in the literature for the combustion performance of different domestic and commercial end-use appliances. The outcome of this assessment provides insight into the maximum amounts of hydrogen blending allowed based on current end-use equipment and identifies a 'hierarchy' of the most sensitive equipment connected to the gas grid. Based on the domestic and commercial appliance inventory, knowledge gaps were identified and strategies to fill this knowledge are proposed in Section 6.4.4.

For large commercial and industrial equipment, a hydrogen blending literature inventory was performed on the combustion performance. Special attention was paid to the impact of hydrogen blending on NOx formation, flame stability and changes in flue gas flows and compositions for equipment that contains burners. For gas engines, the impact on engine knock is taken into account. These results are presented in Section 6.5.

To determine the impact of blended hydrogen in natural gas on materials behind the meter, a literature inventory was performed and described in Section 6.6. The effects of hydrogen blending on metering and regulators are described in Section 5.6.

As presented in Section 6.5, the degree of sensitivity for the presence of hydrogen in natural gas depends upon the process and combustion equipment installed. [redacted]

6.2 Appliance Inventory

A brief overview of the different combustion modes and functioning of the end use equipment installed in the Gazifère network is discussed in the following section.

6.2.1 Types of Gas Consuming Appliances at End Users

[redacted] Other equipment that is also present in the domestic and commercial market in Canada but is not present on the rental list includes barbeques, ranges and home backup generators that contain gas engines. Additionally, industrial customers are present in the Gazifère network. These industries often use heat-generating equipment such as industrial burners present in steam and hot water boilers.

[redacted]

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Analyses performed by DNV and others show that different types of combustion equipment can have significantly different sensitivities to hydrogen addition. This is manifested in the nature of the impact on performance. For example, in gas engines, hydrogen addition can cause engine knock and increased NO_x emissions; in partially premixed burner systems such as ranges, hydrogen addition increases the risk of flashback.

An inventory of appliances was performed to categorize and identify the typical burner systems present in these appliances using manufacturer information, knowledge within DNV, and information supplied by Gazifère (rental list). Before discussing the appliance categorization, the working principles of the different end-use equipment are briefly discussed below.

The different combustion types can be broadly categorized as internal combustion and as catalytic conversion, fully premixed, partially premixed and nozzle mixed burner systems as described below.

6.2.1.1 Categories of End-Use Equipment

6.2.1.1.1 Internal Combustion

[redacted] These gas engines operate via the Otto cycle. In the Otto cycle the fuel/air mixture is ‘premixed’, compressed by a piston, and subsequently ignited by an external heat source such as a spark plug. The unwanted occurrence of engine knock can be attributed to engine sensitivity due to variation in gas composition in constituents such as H_2 or C_2+. One of the issues of gas quality variations is the unwanted occurrence of engine knock. The knock resistance of a gaseous fuel is characterized by a methane number, which is similar to the octane number used to qualify gasoline. All original equipment manufacturers (OEMs) prescribe the minimum methane number allowed in their gas specification.

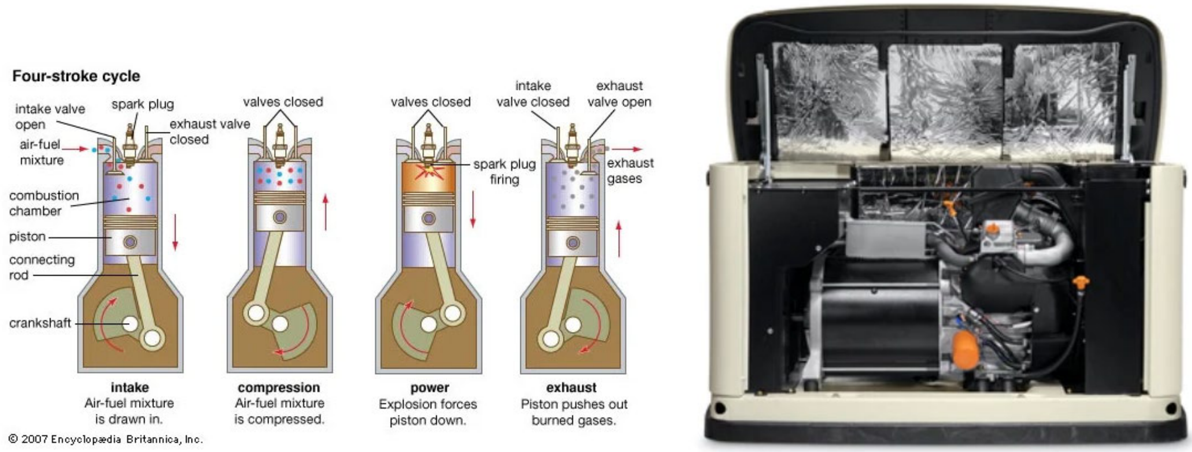

Figure 6-1: Principle of the internal combustion engine (Left [43]) and example of its use in home backup generator (Right [44])

6.2.1.1.2 Catalytic Burner

In gas catalytic heaters, natural gas or propane is converted into infrared radiation using an electrical pre-heated catalyst (often platinum). Methane (main constituent of natural gas) burns catalytically at 300-450°C, which means that at cold start, the catalyst needs to be preheated using an electric heater. The flameless catalytic reaction primarily produces H_2O and CO_2 [43]. Catalytic combustion occurs at low temperatures far below the threshold temperature for NOx formation, resulting in almost no NOx in the exhaust gases. Catalytic heaters are used in several applications such as instrument heating, building heat, and anti-freeze protection [44]. Because of the homogeneously distributed infrared radiation in the panels, the heaters are also beneficial for industrial applications where uniform, distributed heat over a large area is required, such as in drying and curing processes.

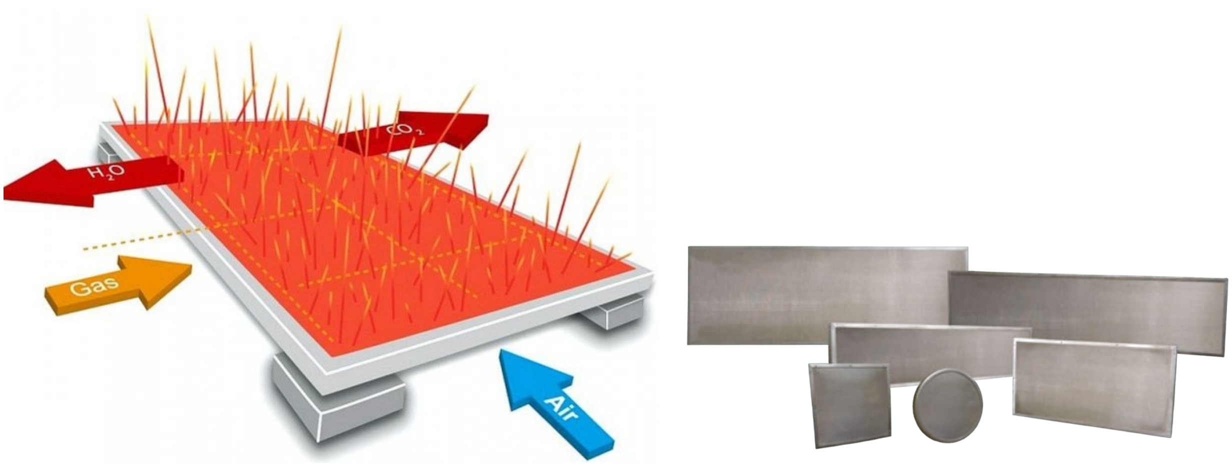

Figure 6-2: Principle of the catalytic burner (Left [47]) and example of its use in catalytic heaters (Right [46])

6.2.1.1.3 Fully Premixed Burner

In fully premixed burners, air and natural gas are fully mixed before entering the burner, as shown in Figure 6-3 below.

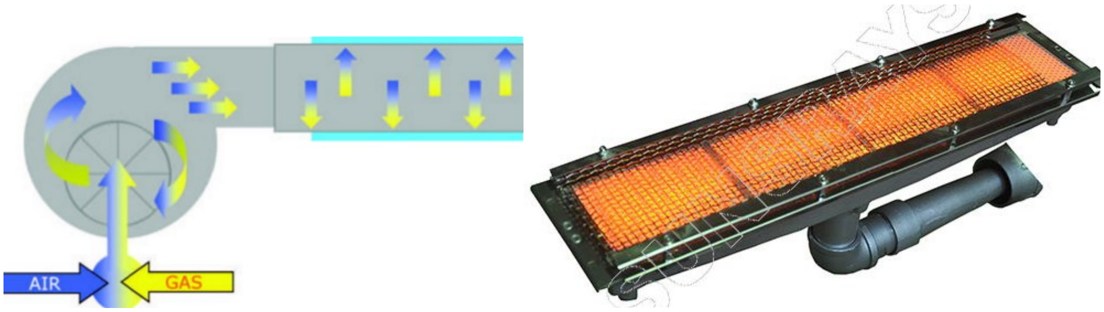

Figure 6-3 : Principle of the fully premixed burner (Left) and example of its use in an industrial radiant burner (Right)

Premixing is normally performed using a venturi mixer, requiring accurate design of fuel and air inlets. The mixture velocity is kept high enough in the venturi exit to prevent flashback, and combustion is avoided until the mixture exits the burner. Appliances that use this burner type often include some high efficiency hot water heaters and furnaces.

6.2.1.1.4 Partially Premixed Burners

In partially premixed burners, primary air and natural gas are partially mixed before entering the burner head and the secondary air is supplied from outside (draught), as shown in Figure 6-4. A gas stovetop burner is an example of a partially premixed burner.

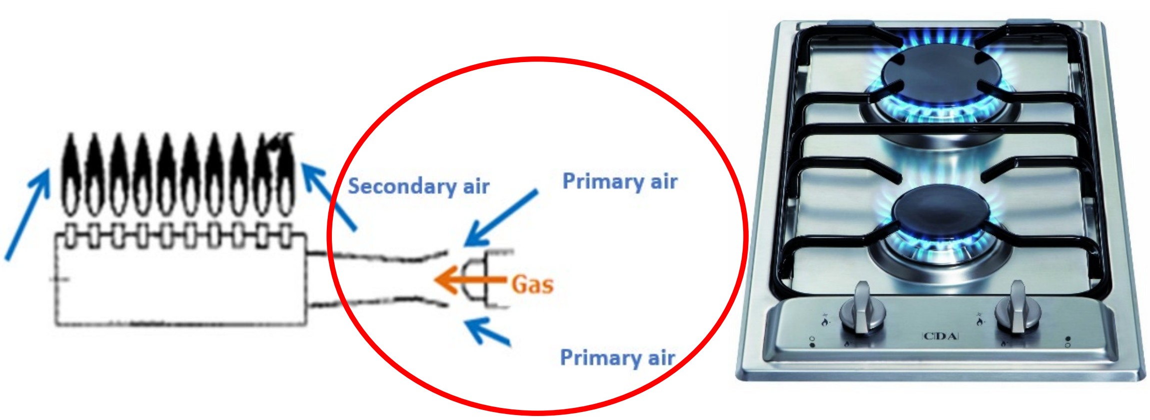

Figure 6-4: Principle of the partially premixed burner (Left) and example of its use in a stove top burner (Right)

6.2.1.1.5 Nozzle Mix Burner

In nozzle mix burners (also called non-premixed or diffusion burners), the air and natural gas are supplied separately, and mixing takes place downstream of the nozzle at the burner head as shown in Figure 6-5.

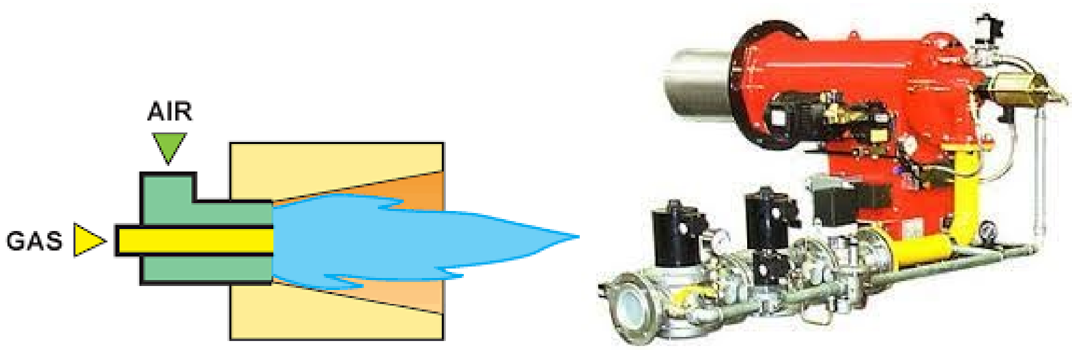

Figure 6-5: Nozzle mix burner (Left) and example of its use in a forced draught burner (Right)

Nozzle-mix burners eliminate the potential for flashback by keeping the fuel and air separate until they reach the burner nozzle. Air may be divided into multiple registers to control the mixing rate with fuel. Nozzle-mix burners supply the fuel and all or most of the combustion air through the burner. The air can be supplied using a fan, called forced draught, or via natural draught.

6.2.1.2 Typical Canadian Domestic Appliances and Burners

To assess the impact of hydrogen addition on the different appliance types, the appliances present in the Gazifère network were categorized based on their combustion principle. An inventory of the different appliances was performed, and the different burner types were mapped and categorized based on their combustion mode (non-premixed, partially premixed and fully premixed combustion). The inventory was performed based on the rental appliance list containing approximately 45,000 appliances. Furthermore, the list was supplemented with domestic gas appliances typically present in Canada.

6.2.1.2.1 Hot Water Heaters (present in Gazifère rental list)

[redacted] In these systems, presented in Figure 6-6, fuel and air are fully premixed at fuel-lean conditions (i.e., excess air). A fan is positioned upstream of the burner and forces the premixed combustion air and fuel through the burner of the hot water heater (i.e., forced draught).

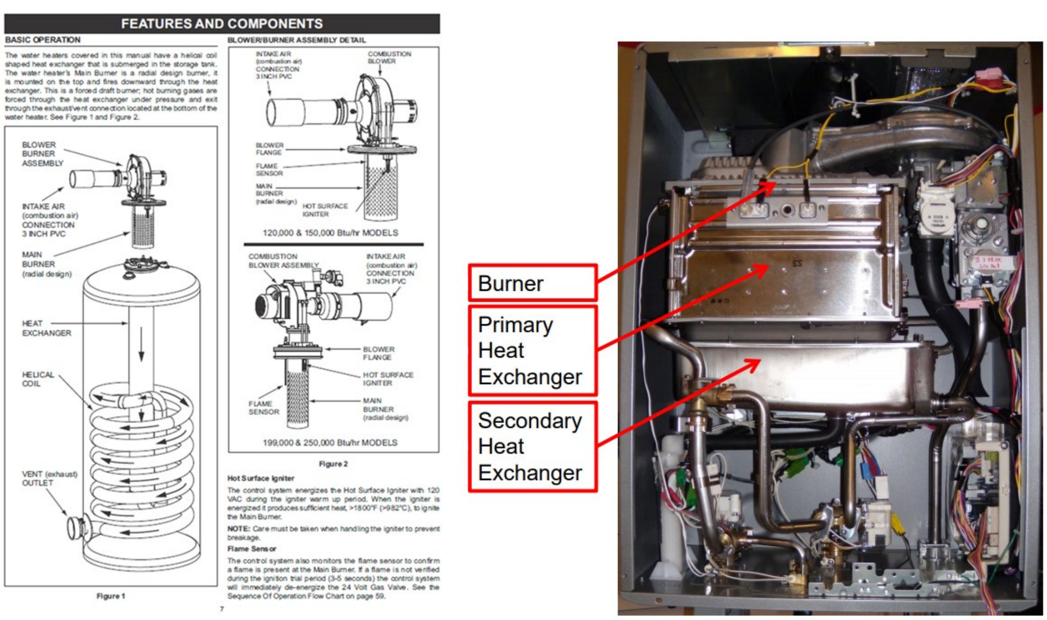

Figure 6-6: Typical fully premixed hot water heaters (fuel lean) with (Left) and without (Right) tank system

[redacted] The primary flame of these burners is fuel rich (i.e., excess of fuel) [redacted] These appliances often contain a different type of burner than fully premixed water heaters. The combustion air supply for these appliances can be divided into natural draught, induced draught, and forced draught. In natural draught hot water heaters, there is no fan present, and the air is supplied via draught created due to convection of the system and aspiration of the burner. The combustion air for induced draught appliances is supplied by a fan that is positioned in the exhaust while for a forced system the combustion air is supplied by the fan upstream of the burner system.

[redacted]

6.2.1.2.2 Partially Premixed Furnaces (present in the Gazifère rental list)

[redacted] Most of these appliances are induced draught, which means that a fan is present in the exhaust. An inventory of the burner types showed that these appliances are equipped with an in-shot burner, as shown in Figure 6-8 below and explained in the following section.

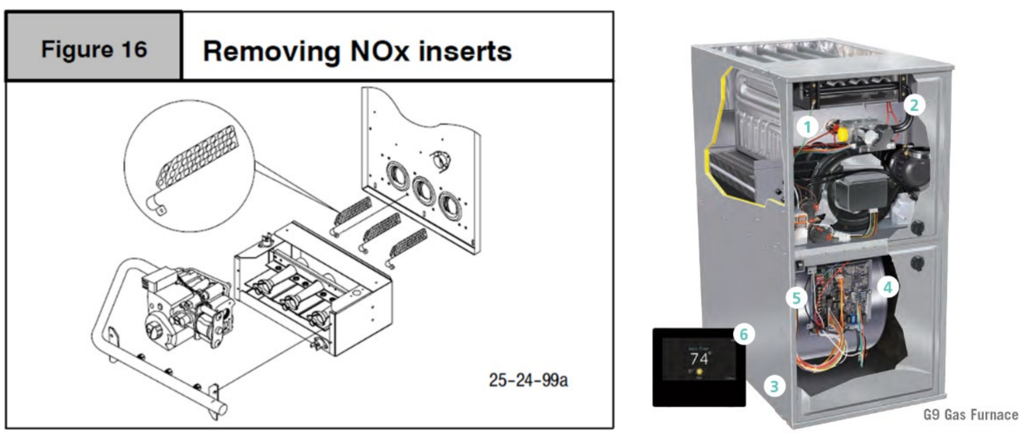

Figure 6-8: In-shot burners present in the Keeprite

6.2.1.2.3 Air Handlers (present in Gazifère rental list)

A rooftop air handler is a self-contained unit which is usually installed on the rooftop of a commercial building and used to provide cooling, heating, or a combination of both. The air handlers present in the rental list contain in-shot burners. In these burners, the gas jet is directed into a nozzle and then into the mixing tube with primary air (fuel rich). On top of the burner surface (Figure 6-9 right), a flame is created that burns inside the heat exchanger tube. These systems generally contain a fan in the exhaust that creates an under pressure in the heat exchanger tube. The under pressure allows secondary combustion air entering the tube to complete the combustion. These systems are induced draught, partially premixed systems.

Figure 6-9: In-shot burner in roof top air conditioner (Left, red circle) and in-shot burner (Right)

6.2.1.2.4 Boiler Appliances (present in Gazifère rental list)

A boiler provides both hot water and heating for a commercial building or residential home. These appliances may contain different types of burners, both partially premixed burners, such as the Laars HH 400 series, and fully premixed burners, such the Rinnai M series shown below.

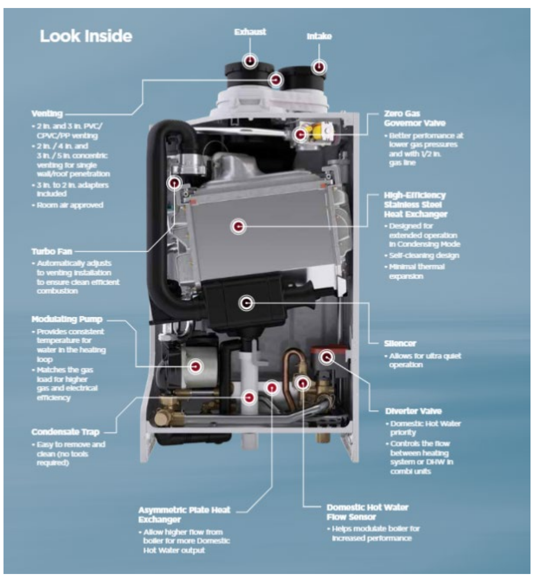

Figure 6-10: Rinnai M series

6.2.1.2.5 Gas Fireplaces (present in Gazifère rental list)

Gas fireplaces are partially premixed appliances that contain a venturi mixing tube creating a fuel rich, partially premixed mixture. The secondary combustion air is supplied via natural draught.

Figure 6-11: Gas fireplace

6.2.1.2.6 Ranges and Ovens (not present in Gazifère rental list)

Ranges, or stovetop burners, and ovens are partially premixed appliances. The gas jet is injected into a venturi tube creating a negative pressure that draws in the primary combustion air. In the venturi, natural gas and air are premixed under fuel-rich conditions and, to complete the combustion, secondary air is supplied from the surroundings.

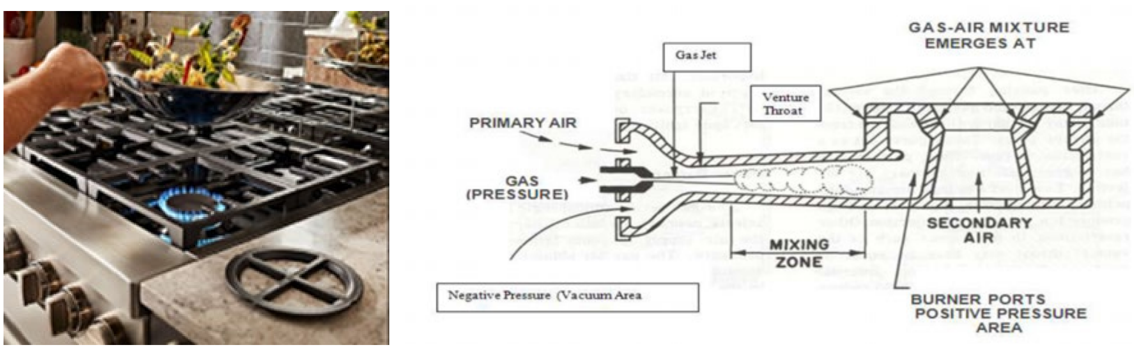

Figure 6-12: Range (Left) and basic principle of range/atmospheric gas burner (Right)

6.2.1.2.7 Fully Premixed Furnaces (not present in Gazifère rental list)

Modern furnaces are often fully premixed combustion systems to meet emission regulations. These appliances contain a fan upstream of the burner to allow for mixing fuel and air prior to combustion. To reduce NO_x emission, these appliances operate with an excess of air (fuel lean).

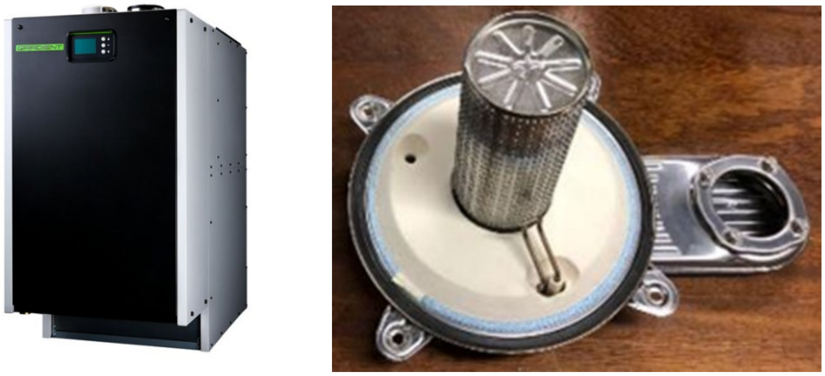

Figure 6-13: Fully premixed furnace (Left) and burner (Right)

6.2.1.2.8 Catalytic Burners (not present in Gazifère rental list)

Catalytic heaters are used in several applications such as instrument heating, building heat, and anti-freeze protection [44]. Because of the homogeneously distributed infrared radiation in the panels, catalytic heaters are beneficial for industrial applications where uniform distributed heat over a large area is required, such as in drying and curing processes. [redacted].

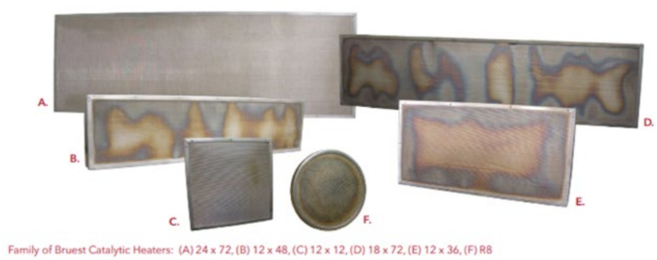

Figure 6-14: Catalytic heaters ([46])

6.2.1.2.9 Home Backup Generators (not present in Gazifère rental list)

Stationary engines are used throughout industrial, commercial, and institutional facilities for power generation, gas compression, and combined heat and power. Gas engines are sensitive to gas quality variations, such as H_2 or C_2^+ [5]. One of the issues of gas quality variations is the unwanted occurrence of engine knock. The knock resistance of a fuel gas is characterized by a methane number, which is analogous to the octane number used to qualify gasoline. All OEMs prescribe the minimum methane number allowed in their gas specification.

[5] C_2^+ means ethane and higher hydrocarbons such as propane, butane, and so on.

Figure 6-15: Home Backup Generator ([48])

6.2.1.2.10 Other Appliances (not present in Gazifère rental list)

Appliances such as fryers, BBQ grills, pool heaters, patio heaters, garage air heaters, radiant heaters and wok (jet) burners primarily contain partially premixed burners. Different burner styles are present in these types of equipment such as ribbon burners, line burners, in-shot burners, etc.

6.3 Gas Interchangeability Analysis

The current end-use equipment in Gazifère's network, as described in the previous section, is designed, tested, installed, and maintained for a given range of local distributed natural gas. The injection of hydrogen into the natural gas grid may have an impact on the physical and chemical combustion properties of the delivered gas, which can affect the performance of this equipment and chemical processes by taking the gas properties out of the range for which the end-use equipment or process was designed. Performance characteristics of appliances that could be affected include flashback (safety) and engine knock resistance.

As an alternative to expensive and time-consuming large-scale testing of end-use equipment, gas interchangeability analysis methods are applied to compare combustion performance of gases. The assessment comprises analyses of the performance and safety of end-use equipment when hydrogen is added to natural gas. For this assessment, DNV applies novel methods developed by DNV for comparing the combustion performance of gases (interchangeability methods) as an alternative to large-scale testing [47]. It is important to note that the impact of a given amount of hydrogen addition to natural gas can depend on the composition of the natural gas to which it is added. For example, if the natural gas to which hydrogen is added is already at the limit of the gas or equipment specification, then no hydrogen addition is allowed.

To determine if a new gas composition is allowed, the fundamental combustion properties of the "new" (blended) gas are calculated and compared with the combustion properties of the traditionally distributed gases, while also considering the physical changes that occur in the appliance when changing the gas quality, such as primary air ratio. In this way, the resulting gas interchangeability limitations are founded on the physics and chemistry of gas utilization, and not on the performance of individual appliances. For hydrogen/natural gas mixtures that are assessed to be outside the interchangeability envelope, these mixtures do not automatically result in failure of the installed equipment but do represent an increase in the risk of equipment failure; that is, there is an increased risk of failure as compared to the natural gases currently being supplied to the equipment. The studied gas interchangeability parameters are summarized in Table 6-2.

Table 6-2: End-use equipment categorization and failure modes

Category	Gas interchangeability parameter(s)	Failure modes
Fully premixed industrial, commercial & domestic appliances	Wobbe index, burning velocity	Flashback Burner overheating Thermal input
Partially premixed domestic appliances (e.g., ranges and hot water heaters)	Wobbe index, burning velocity	Flashback Burner overheating Thermal input
Non-premixed (Diffusion burners) industrial burners	Wobbe index	Burner overheating Thermal input
Gas engines (Home backup generators)	Methane number, Wobbe index	Engine knock Pollutant emissions

[redacted]

[redacted]

6.3.1 Changes in Thermal Input (Wobbe Index)

The addition of hydrogen to natural gas lowers the Wobbe index of the gas. Consequently, for equipment not having a control system to maintain the thermal input and/or fuel-to-air ratio control, the thermal input decreases and the excess air ratio increases upon hydrogen addition.

[redacted]

As shown in Figure 6-17 and Table 6-4, almost 27% hydrogen by volume can be added to the natural gas having the highest Wobbe index. If the selected natural gas has a Wobbe index at the lower end of the Wobbe range (47.50 MJ/m^3), no hydrogen addition is allowed since adding hydrogen would lower the Wobbe index below the lower legal Wobbe index limit.

Table 6-4: Maximum allowed hydrogen percentages based on three years of measured gas composition

Wobbe index Natural Gas, MJ/m^3	**Maximum H_2 in natural gas, vol%**
Distribution Maximum	26.8
Distribution Average	24.3
Distribution Minimum	21.7

6.3.2 Changes in Burning Velocity (Risk of Flashback)

One of the potential risks of hydrogen addition to partially premixed and fully premixed end-use equipment (cooking burners, hot-water heaters, many central heating burners, dryer burners, etc.) is the occurrence of flashback. This phenomenon occurs when the presence of hydrogen increases the laminar burning velocity to the point that the burning velocity is higher than the exit velocity of the cold fuel/air mixture[6]. As a result, the flame propagates back into the burner as illustrated in the Figure 6-18 (Right). Flashback can cause appliance failure, damage, and possible release of explosive mixture into the home and should be prevented.

[6] E.g., when switching from CH4 to H2 combustion the exit velocity increases with about a factor of three but the laminar burning velocity increases with a factor of 6 which may result in flame flash back

In this study, laminar burning velocity was numerically calculated for the natural gas and H_2 mixtures [50][7], including the shift in the primary equivalence ratio of the fuel/air mixture caused by the change in stoichiometric air factor upon hydrogen addition. This shift in equivalence ratio is illustrated in Figure 6-18; hydrogen addition to natural gas shifts the equivalence ratio to lower values for both fuel-rich (partially premixed, $\varphi>1$) and fuel-lean (lean-premixed, $\varphi<1$) situations. As shown, hydrogen addition on the fuel-rich side ($\varphi>1$) increases the burning velocity strongly when going from pure methane to methane having 23 vol% hydrogen, while the impact on the burning velocity is modest for fuel-lean combustion.

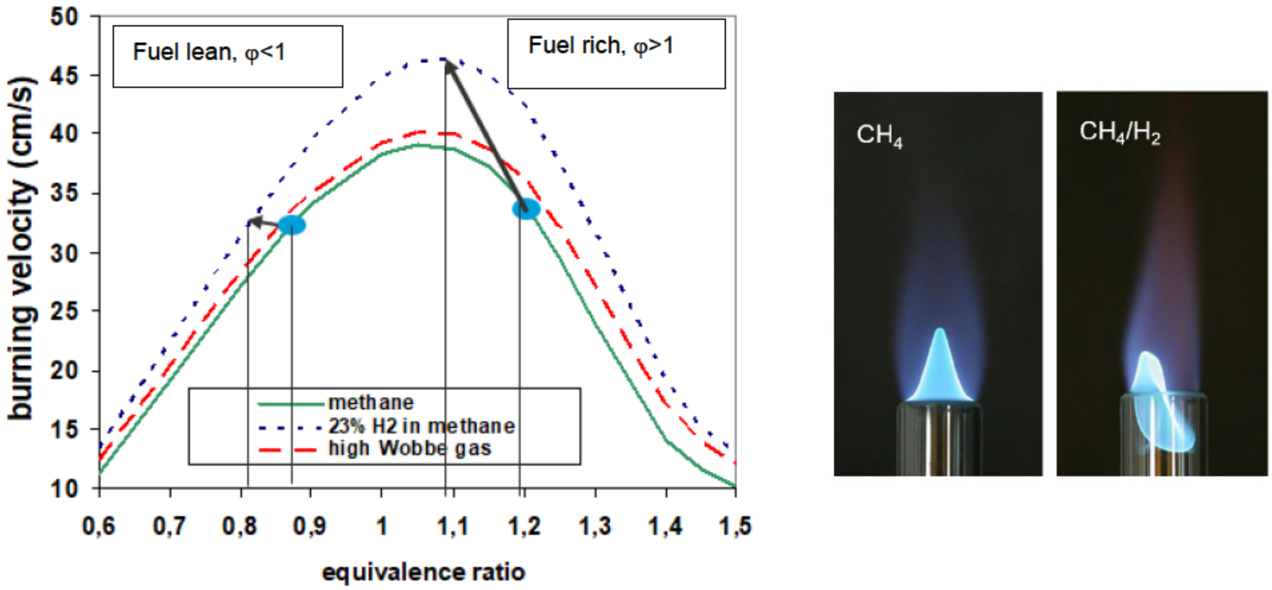

Figure 6-18: Illustration of effect of hydrogen addition to methane, including the shift in equivalence ratio caused by hydrogen addition (Left) and illustration of flashback (Right)

In the gas interchangeability analyses, the burning velocities for the natural gas/H_2 mixtures are then compared with that of defined limit gases. When the hydrogen content is such that the burning velocity of the natural gas/H_2 mixture becomes higher than that of the relevant limit gas, this content (and higher concentrations) represents an increase in the risk of flashback over that experienced by appliances when exposed to the normal range of distributed natural gases.

Partially premixed appliances

Partially premixed appliances, as noted previously, include ranges and conventional hot water heaters. In the analysis, hydrogen was added to the three distribution gases shown in Table 6-3, and the resulting burning velocity was compared to those of the distribution limit gases. The contractual natural gas with the lowest Wobbe Index is the limit gas (worst-case gas) since this gas has the highest burning velocity and, thus, the highest risk for the occurrence of flashback.

[7] In this study, the USC-Mech II reaction model was used to compute the laminar burning velocities.

[redacted]

From Figure 6-19 it can be seen that hydrogen addition results in a linear increase in the burning velocity. When adding hydrogen to the distribution gas with the highest Wobbe index, 9.6 vol% hydrogen admixture is allowed, while for the distribution gas with the lowest Wobbe index 8.0 vol% H_2 is allowed without materially increasing the risk of flashback. These results are summarized in Table 6-5 below.

Table 6-5: Maximum hydrogen admixture for different distribution gases, based on flashback in partially premixed appliances

	Flashback (vol% H_2 in natural gas)
Distribution Maximum	9.6
Distribution Average	8.4
Distribution Minimum	8.0

Fully premixed appliances

For fully premixed appliances, such as modern high efficiency furnaces and hot water heaters, the fuel and air are fully premixed before it is burned. These appliances are adjusted at an excess air ratio ($\varphi<1$) to reduce NO_x emissions. As illustrated in Figure 6-20, burning velocity calculations show that when adding hydrogen to the Distribution Maximum gas, there is no increased risk of flashback until high hydrogen fractions on the order of 30-40 vol% are added for fully premixed appliances.

[redacted]

Table 6-6: Maximum hydrogen admixture for different distribution gases, based on flashback in fully premixed appliances

	Flashback (vol% H_2 in natural gas)
Distribution Maximum	~30-40
Distribution Average	~30-40
Distribution Minimum	~30-40

6.3.3 Changes in Propensity for Gas Engine Knocking

Gas-fueled reciprocating internal combustion engines are known to be sensitive to variations in fuel composition because of the possible occurrence of engine knock [49], [50], [51], which can result in loss in performance and, in the worst case, engine damage. The effect of hydrogen addition on the knock resistance is calculated by using the PKI Methane number algorithm [51]. The methane number scale is a methane-hydrogen scale; pure methane is a knock-resistant fuel and is assigned a value of 100, while hydrogen is knock sensitive and is given the value of 0. In other words, a decrease in Methane number indicates a decrease in the knock resistance (and vice versa).

The composition of natural gas plays an important role in the amount of hydrogen that can be added. 'Lean' natural gas (low fraction of higher hydrocarbons, such as the Distribution Minimum gas (Table 6-3)) generally has a higher knock resistance than 'rich' natural gas (high fractions of higher hydrocarbons, such as the Distribution Maximum gas). Therefore, more hydrogen can be added to 'lean' natural gases in comparison to 'rich' natural gases.

Engine manufacturers often define fuel gas specifications for their engines to prevent the occurrence of engine knock. However, based on interviews with several OEMs that deliver home backup generators for the Canadian market, no specific details with regard to the minimum methane number specified were provided. The fuel specifications from Generac, one of the largest producers of home backup generators in North America, indicated that a maximum of 5% propane is allowed [51], which corresponds to a PKI methane number of 75. Based on this information, an equivalent methane number of 75 was taken as the minimum value allowed in gas engines for home backup generators.

[redacted] The addition of hydrogen lowers the methane number and the amount of hydrogen that can be added depends on the gas composition; about 18.9 vol% hydrogen can be added to the Distribution Minimum gas while 6.7 vol% hydrogen can be added to Distribution Maximum gas. Adding more hydrogen increases the risk of engine knock, but it does not mean that engine knock will actually occur.

Table 6-7: Maximum hydrogen admixture for different distribution gases to prevent increased risk of engine knock

	Engine knock (Vol% H_2 in natural gas)
Distr bution Maximum	6.7
Distr bution Average	14.6
Distr bution Minimum	18.9

6.3.4 Gas Interchangeability Analysis Summary

The maximum allowable fraction of hydrogen for the natural gas compositions studied in the interchangeability analyses is summarized in Table 6-8. The allowed percentage of hydrogen based on the interchangeability analysis is limited by gas engines (home backup generators) at the higher end of the Wobbe index (6.7 vol%) and by the partially premixed appliances at the lower end of the Wobbe index (8.0 vol%). As a result, the allowed fraction of hydrogen in natural gas depends on the composition of the natural gas ("gas quality") that flows through the point of hydrogen injection and the appliance types installed in the field.

Table 6-8: Maximum allowable hydrogen percentage based on the interchangeability analysis (Wobbe limit, flashback/burner overheating limit in fully and partially premixed appliances, minimum methane number (engine knock) in gas engines)

	Heat input (Wobbe), vol% H_2	**Flashback/ overheating partially premixed, vol% H_2**	**Flashback/ overheating fully premixed, vol% H_2**	**Engine knock, vol% H_2**
Distribution Maximum	26.8	9.6	~30-40	6.7
Distribution Minimum	21.7	8.0	~30-40	18.9
Distribution Average	24.3	8.4	~30-40	14.6

6.4 Domestic and Commercial End-Use Equipment Combustion Performance

The gas interchangeability analysis described above assesses whether there is an increased risk of the critical failure modes for end-user appliances upon hydrogen addition; however, it does not indicate whether issues will occur for individual appliances and is, therefore, considered a conservative approach. Gazifère's aim is to increase the hydrogen percentage in natural gas outside the gas interchangeability envelope. To provide insights into how the maximum percentages found in the gas interchangeability analyses relate to experimental data on appliances, DNV compared the results of the gas interchangeability analyses with publicly available experimental data from DNV's work and data found in literature. This assessment will provide insight into what extent the maximum hydrogen blending levels can be expanded and the types of appliances that should be investigated in more detail.

6.4.1 Literature Review on the Effect of Hydrogen on Equipment Performance

Impact of Hydrogen Admixture on Installed Gas Appliances (2012) [54]

Nitschke-Kowsky and Wessing [52] studied the impact of hydrogen addition to methane (up to 30 vol% hydrogen) for the following appliances:

- One fully premixed atmospheric boiler
- Two fully premixed condensing boilers without combustion control system
- Two fully premixed condensing boilers with combustion control system (Safety Combustion Technology or SCOT [55], to maintain the fuel-air ratio in the appliance)

The authors reported that the SCOT combustion control system was unable to keep the fuel-air ratio constant at increasing hydrogen fractions in natural gas. Instead of keeping the ratio constant, the ratio varied as if there was no control system installed. Similar failing of the control system was observed in a recent publication by others [55].

The NO_x emissions for all tested appliances were found to decrease upon hydrogen addition as expected for these fuel-lean operation appliances (see Table 6-9).

Table 6-9: Measured NO_x emission for three appliances with and without H_2 added to CH_4 **[54]**

Appliance	**NO_x emission (mg/kWh)**			
	CH_4 + 0 vol% H_2		**CH_4 + 30 vol% H_2**	
	Full load	**Partial load**	**Full load**	**Partial load**
Atmospheric boiler	70	35	31 (-56%)	25(-29%)
Condensing boiler w/o control	58	13	19 (-67%)	9 (-31%)
Condensing boiler with control	26	31	15 (-42%)	21 (-32%)

The measured CO emissions remained unchanged or slightly decreased for the condensing boilers studied (both with and without the SCOT control system). The CO emissions for the atmospheric boiler were found to vary, showing a tendency to flame instability [54]. Burner deck temperatures were not measured during the study, which makes it difficult to estimate the long-term effects on the burner surface integrity.

THyGA Project (2022) [56]

The THyGA project is an ongoing European project where several domestic appliances are currently being tested to observe how they react in the short term (few minutes to few hours) and long term (over several weeks) to different hydrogen-natural gas mixtures (up to 60 vol% hydrogen). The first results of the short-term tests were recently published [54]. The table below presents the appliances that have been tested thus far.

Table 6-10: Overview of appliances tested within the THyGA project [56]

Appliance category	Burner type	For range hobs: burner tested?	Modulating burner (Y/N)	Pressure regulator (Y/N)	Can the appliance be adjusted? (Y/N)	Combustion control (Y/N)	Max. power input (net) [kW]	Min. power input (net) [kW]
Boiler	Atmospheric		Y	Y	N	N	25.8	11.0
Boiler	Low NOx		Y	Y	Y	N	22.2	8.9
Boiler	Atmospheric		N	Y	Y	N	17.0	
Boiler	Low NOx		Y	Y	Y	Y	24.8	10.6
Boiler	Premixed		Y	Y	Y	Y	20.0	4.8
Boiler	Premixed		Y	Y	N	Y	24.0	6.9
Water heater	Atmospheric		N	N	N	N	10.5	5.3
Water heater	Atmospheric		N	N	N	N	10.5	5.3
Cooking hob	Atmospheric (*)	Large	N	N	N	N	3.0	0.8
Cooking hob	Atmospheric (*)	Small	N	N	N	N	1.0	0.5
Oven		Oven	N	N	N	N	2.5	1.0
Cooking hob	Atmospheric	Large	N	N	N	N	2.7	0.7
Cooking hob	Atmospheric	Small	N	N	N	N	0.9	0.3
Oven	Cavity burner	Oven	N	N	N	N	2.4	0.8
Oven + grill	Cavity burner	Oven	N	N	N	N	1.7	
Fryer	Premixed		Y	Y	Y	Y	31.0	16.0
Gas grill	Atmospheric		N	N	N	N	5.9	
Fire – convection heater	Atmospheric		Y	Y	N	N	5.8	3.1

(*) Atmospheric Partially Aerated Single Ring burner" (hob)

A safety assessment was performed by investigating the effect of hydrogen on different gas compositions (CH_4 and mixtures of CH_4 and N_2). The gas compositions were chosen to fall within the Wobbe specifications of the gases distributed within the EU (47.63-52.78 MJ/m^3 [15°C /15°C]). Several tests (including flashback test, cold/hot start, flame detectability, ignitability, and so on) are planned but have not all been performed. The report describes the results thus far and the following observations were made:

- Atmospheric burners are more sensitive to flashback with the addition of H_2 in natural gas. For the atmospheric appliances studied, signs of partial flashback (e.g., increase in combustion noise) were observed at 40 vol% H_2 and flashback was generally observed at 50-60 vol% H_2.
- The main problem identified with premixed boilers, identified through the tests, is not flashback but situations where appliances are adjusted for a low Wobbe index gas with some hydrogen and are later switched on to a high Wobbe index gas without hydrogen or with low levels of hydrogen. The main consequence is a very strong increase in CO emissions levels. The authors expect that this situation could become rather common in many places if hydrogen is injected in the grid.

As with the previously referenced study, burner deck temperatures were not measured to investigate the long-term effect of a higher burner deck temperature on the lifespan of the burner deck.

DOMHYDRO Project (2013-2015) [57]

Within the DOMHYDRO project [57], 30 appliances were tested for the effects of hydrogen addition to natural gas (up to 10 vol% and a cold start experiment with hydrogen up to 30 vol%). The tested appliances included fully and partially premixed boilers, an air heater, radiant heater, and two decorative gas fireplaces. The outcome of the project revealed that natural gas was judged “no problem” when containing 10 vol% hydrogen. Here too, burner deck temperatures were not measured.

Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner (2019) [58]

The effect of hydrogen addition on the combustion performance of a US cooktop burner (partially premixed) was experimentally investigated by Zhao et al. [58]. Without a cooking pot placed above the burner, flashback was observed at 75 vol% H_2 and the burner deck temperature was found to increase by 25°C. Interestingly, when heating a cooking pot flashback occurred at lower hydrogen levels (55 vol%) and the burner was destroyed within half a minute due to overheating of the burner. During cold start, flashback occurred at even lower levels of hydrogen (20 vol%). No significant cooking time or reduction in efficiency was observed (< 50 vol% H_2), however the hydrogen addition was found to lead to shorter ignition times. The combustion noise was found to increase upon hydrogen addition, and especially with volume percentages above 40 vol%. No significant changes in NO_x emissions were observed. Due to the flashback limit at cold start, the authors concluded that the cooktop burner can operate safely and efficiency with up to 20 vol% hydrogen added to natural gas.

Experimental assessment of the combustion performance of an oven burner operated on pipeline natural gas mixed with hydrogen (2019) [59]

Zhao et al. [59] also studied the effect of hydrogen addition to natural gas for a US partially premixed oven. Here too, hydrogen addition was found to decrease the ignition time. Under steady operation conditions, 55 vol% hydrogen could be added to natural gas without flashback. However, during ignition flashback was observed at 30 vol% hydrogen. The experiments were performed with steps of 5 vol% H_2 and since at 25 vol% H_2 no flash back was observed during (cold/hot) ignition, the flashback limit was set at 25 vol%. The burner temperature was found to increase upon hydrogen addition from 169°C (natural gas) to 273°C (natural gas + 10 vol% H_2). Adding more hydrogen resulted in a higher burner surface temperature (due to the flame being closer to the burner). The authors suggest that this increase in burner surface temperature may degrade the material and increase the risk of flashback. The CO emissions were found to decrease with increasing hydrogen content in natural gas, whereas the NO_x levels were unchanged.

Combustion performance of low-NOx and conventional storage water heaters operated on hydrogen enriched natural gas (2020) [60]

Choudhury et al. [60] studied the effect of hydrogen addition to natural gas on the combustion performance of a partially premixed conventional water heater having a pancake burner (similar to that presented in Figure 6-7) and a low-NO_x (fully premixed) hot water heater. Neither water heater showed substantial changes in combustion performance below 10 vol% hydrogen. The low- NO_x water heater showed a decrease in NO_x emission upon hydrogen addition, whereas the conventional water heater showed a slight increase in NO_x emission. At 10 vol% H_2 in natural gas, “a deflagration like event was observed for both the water heaters”. The authors note that “at 10% H_2 addition no issues with ignition from a cold start were observed, but during relight of the main burner after water draw, instability (flashback/ignition delay) was observed”. Therefore, the authors conclude that below 10 vol% H_2 in natural gas represents the safe operation range of both water heaters.

HyDeploy Project (2019) [61]

In the HyDeploy project [61], extensive laboratory work and tests on appliances installed on the Keele University gas network were undertaken and centred on understanding the implications of a 20 vol% hydrogen blend relative to natural gas. The report describes the laboratory tests where two ranges, four boilers, and two fireplaces were tested using mixtures of methane and hydrogen (up to 28.4 vol% H_2). The results of the tests revealed that the tested domestic appliances were capable of operating safely on hydrogen concentrations up to 28.4 vol%. The authors noted that the gas appliances sold in the UK are certified with a reference gas that contains 23 vol% H_2 (G222 [62]).

Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance (2022) [63]

In a recent study by Glanville et al. [61], the impact of 0-30 vol% hydrogen in natural gas on the performance of North American hot water heaters and furnaces was investigated. Table 6-11 shows an overview of the tested equipment. The water heaters and furnaces tested in this study did not show any flashback issues during cold and hot start-up or during normal operation. The burner surface temperature was also measured during the experiments. The burner surface temperature of the condensing furnace increased by 5°C up to 30 vol% H_2 in natural gas, while the burner surface of the non-condensing furnace slightly decreased in temperature (-2.5°C) for the same amount of hydrogen in natural gas. A significant shift in burner surface temperature was observed for the water heaters; the burner surface temperature of the ultra-low NO_x water heater decreased by a maximum of 40°C at 30 vol% H_2 in natural gas, while the burner surface temperature of the standard water heater increased by a maximum of 80°C at the same amount of hydrogen in natural gas. The authors do not further analyse the consequences of this change in burner surface temperature and to what extent this may affect the lifetime of the burner surface in the long run. The NO_x emissions from the measurements showed no change (standard water heater and condensing furnace) or a decrease (ultra-low NO_x water heater and non-condensing furnace) with increasing amounts of hydrogen in natural gas. No changes in CO emissions were observed for the studied appliances.

Table 6-11: Overview of appliances tested by Glanville et al. [63]

Equipment name	Burner type	Additional air supply
Standard water heater	Pancake burner (partially premixed)	Natural draught
Ultra-low NOx water heater	Radiant burner (premixed)	Natural draught
Non-condensing furnace	In-shot burner (partially premixed)	Induced draught
Condensing furnace	In-shot burner (partially premixed)	Induced draught

6.4.2 DNV Research on Domestic Appliances

At DNV, an investigation into the impact of hydrogen addition on a range was performed for Gasunie. Figure 6-22 shows that the flame length of the primary flame (inner cone) decreases upon hydrogen addition as a result of the stronger stabilization of the flame. Consequently, the temperature measured under the burner plate increases with increasing hydrogen content in natural gas as shown in Figure 6-22. As a result of the increase in flame temperature, the coating of the burner plate was damaged due to overheating.

This damage started to appear at approximately 40 vol% H_2 and worsened for higher percentages. As an example, the presence of 20 vol% hydrogen resulted in an increase of approximately 20°C in temperature, which is an increase of less than 10%. Increasing the hydrogen content led to flashback occurring at ~80 vol% H_2; however, DNV also performed experiments by rapidly reducing the power (rapid turn-down). Flashback during turn-down occurred at 50 vol% in the experiments. No measurements with a cooking pan on the burner, cold start, or reignition were performed during these experiments. Based on this research it is expected that up to 20 vol% hydrogen blends will pose no issues for the cooking ranges studied; however, burners with built-in bridle plates and wok (jet) burners are not known to have been studied.

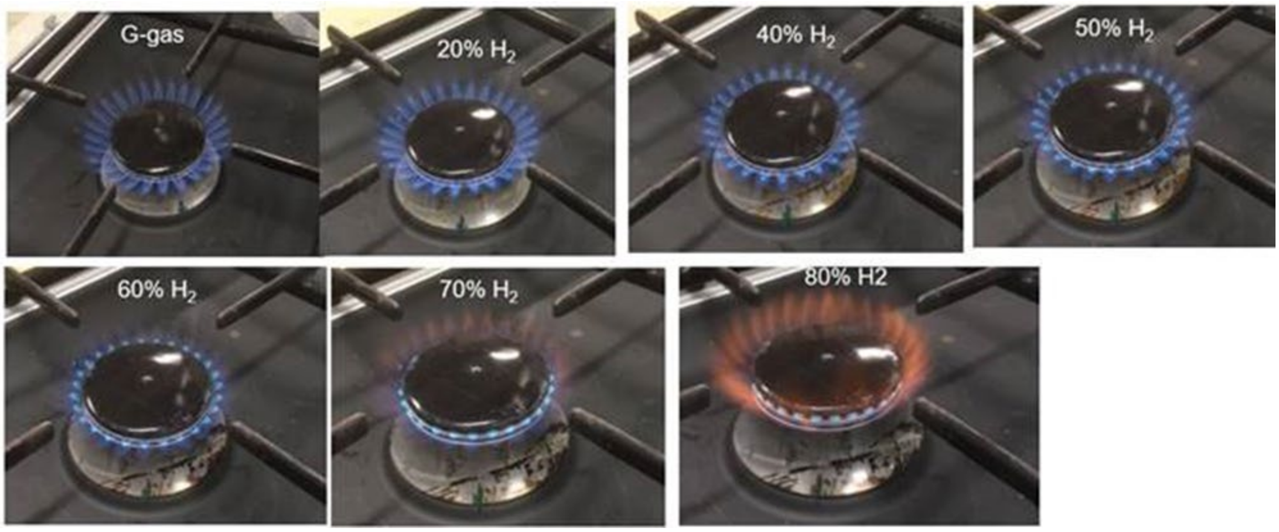

Figure 6-22: Changes in flame shape upon hydrogen addition for a range (partially premixed burner)

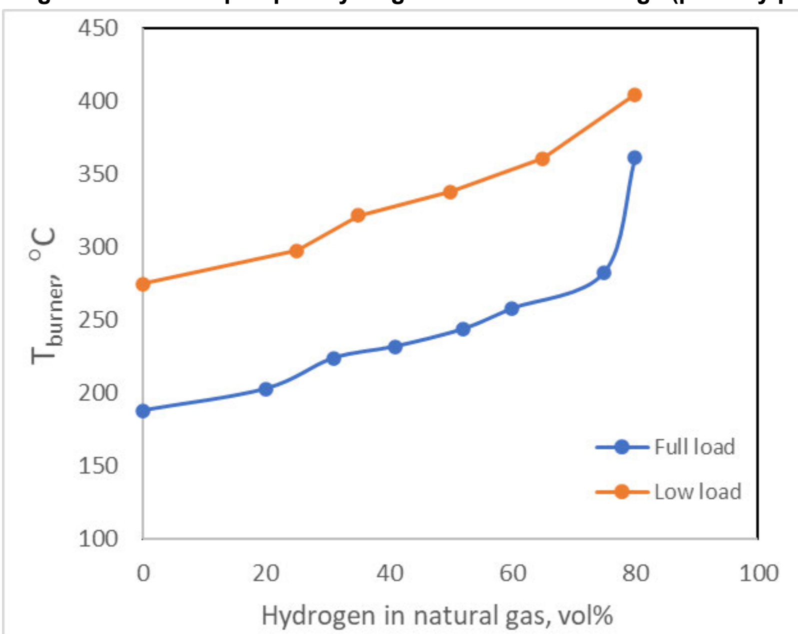

Figure 6-23: Temperature measured under the burner plate of a range for different hydrogen percentage in natural gas

Another study performed for Gasunie on the effect of hydrogen addition to Dutch natural gas[8] in two fully premixed condensing boilers with ceramic and stainless-steel burner decks revealed that the burner temperature of the ceramic burner deck decreased for up to 50 vol% hydrogen addition in natural gas. At hydrogen percentages above 50 vol%, the burner temperature increased, until flashback occurred at 70 vol% hydrogen in natural gas (indicated by the steep rise in temperature as can be seen in Figure 6-24 (left). The temperature of the stainless-steel burner deck remained constant up to 30 vol% hydrogen (Figure 6-24 (right)) but increased significantly for higher hydrogen fractions until flashback was observed at 70 vol% hydrogen in natural gas. In the experimental test program, no re-ignition or cold start experiments were performed.

[8] Dutch natural gas consists of roughly 82.0 vol% CH_4, 2.7 vol% C_2H_6, 0.4 vol% C_3H_8, 0 9 vol% CO_2 and 14.0 vol% N_2

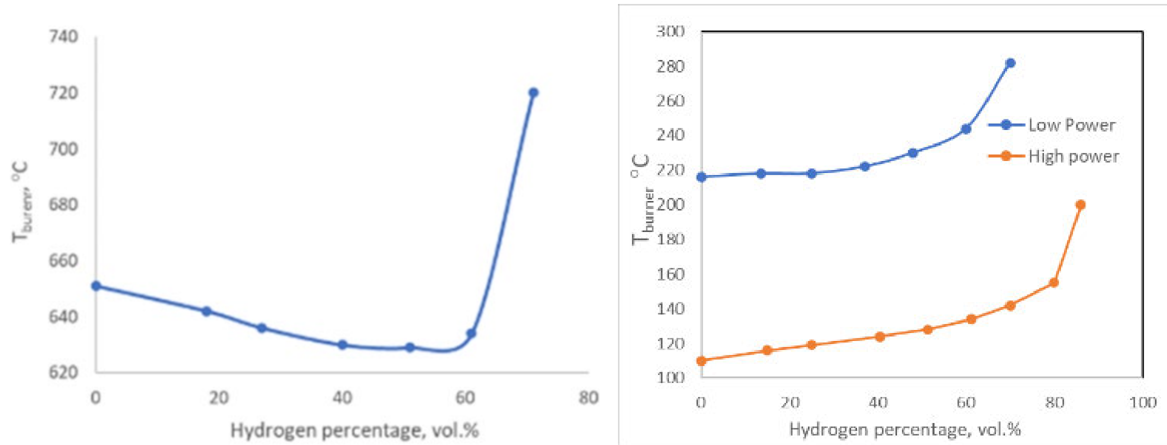

Figure 6-24: Temperature of burner deck as function of the hydrogen percentage in natural gas for high efficiency boilers: ceramic burner deck (Left), and stainless-steel burner deck (Right)

The premixed burners in the high efficiency boilers operate under fuel-lean conditions. As expected from these combustions systems, the addition of hydrogen resulted in a lower NOx emission (Figure 6-25 (left)) due to the shift in equivalence ratio to fuel leaner mixtures. Also, the CO emissions decreased substantially when adding hydrogen to natural gas for both tested appliances.

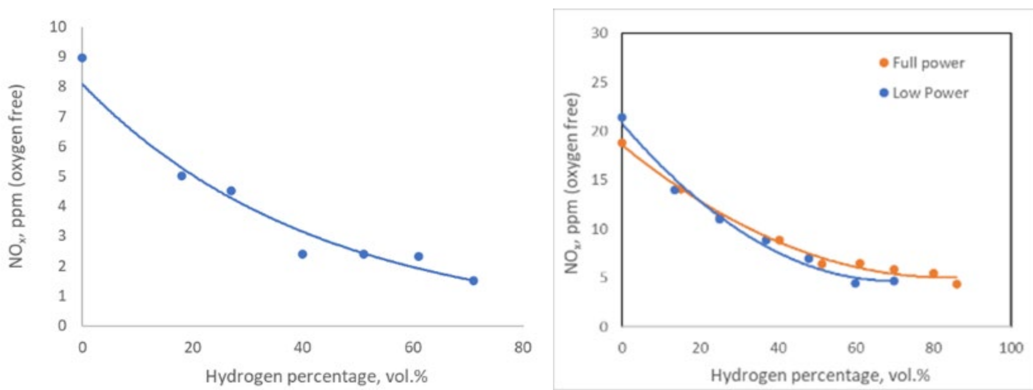

Figure 6-25: NO_x emission upon hydrogen addition for the boiler (fully premixed burner) with a ceramic burner deck (Left), and stainless-steel burner deck (Right)

In another study for Gasunie, DNV studied the effect of hydrogen addition to Dutch natural gas on the performance of a conventional hot water heater (partially premixed appliance). These appliances operate under fuel-rich conditions, which means that hydrogen addition results in a shift towards fuel-leaner (stoichiometric) conditions and higher burning velocities. Consequently, the flames tend to burn closer to the burner surface up to the point of flashback. This effect can be seen in the pictures below, where the addition of hydrogen leads to shorter flames that are located closer to the burner surface.

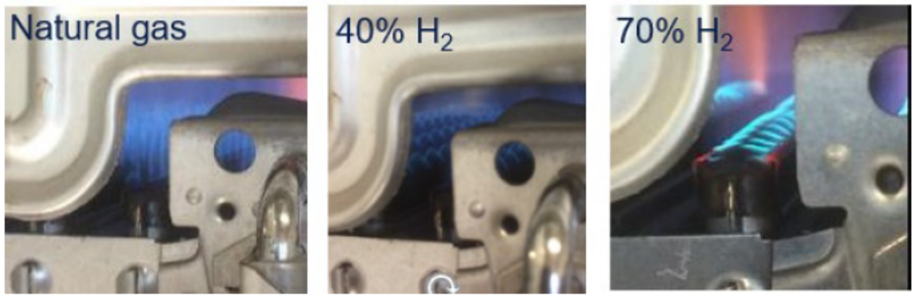

Figure 6-26: Flames shapes upon vol% hydrogen addition (hot water heater, partially premixed burner)

As the flame is located closer to the burner, its surface temperature increases as a result of more heat exchange between the flame and the surface. As can be seen in Figure 6-27, increasing the hydrogen content in the gas resulted in higher burner deck temperatures. Flashback was observed at ~70-80 vol% hydrogen in natural gas. Here DNV noted that no cold-start or reignition experiments were performed. As a result of the increased heat exchange between the flame and the burner surface, the flame temperature drops. Since the NO_x formation is temperature-dependent, the NO_x emissions decreased upon hydrogen addition as can be seen in the Figure below (right). The CO emissions (not shown) were reduced upon hydrogen addition, which is caused by the lower carbon content of the fuel and the decrease in equivalence ratio upon hydrogen addition (oxygen content available for combustion increases and reduces CO emissions).

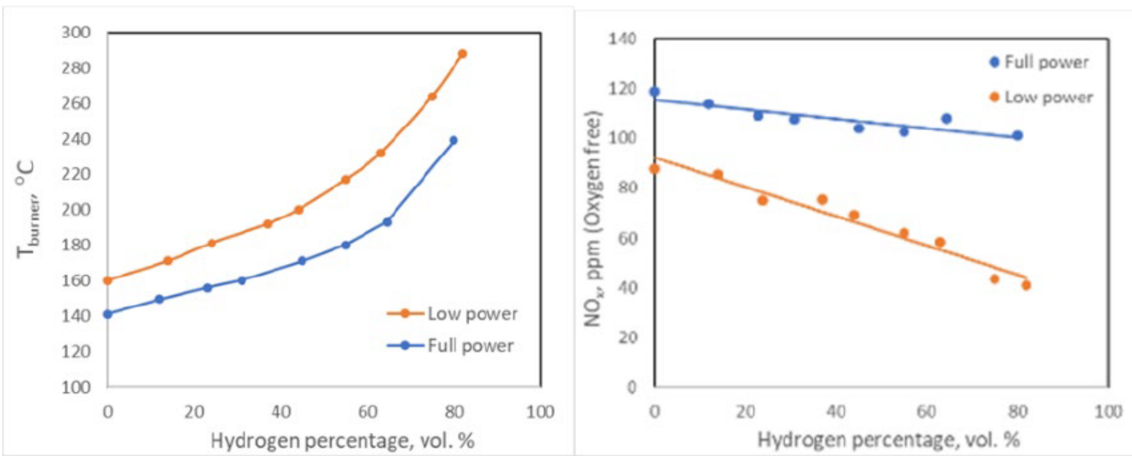

Figure 6-27: Temperature of burner deck for conventional hot water heater as function of the hydrogen percentage in natural gas (Left), and NO_x emissions upon hydrogen addition (Right)

6.4.3 Summary and Gap Analysis

The maximum allowed range of hydrogen blending found in the literature inventory is summarized in Table 6-12 together with the results from the gas interchangeability analyses from Section 6.3. The range of hydrogen blending in Table 6-12 is based on the lowest concentrations of hydrogen in natural gas at which the research observed issues. [redacted]

For the majority of the data found in literature, the gas interchangeability analyses identified a lower allowed hydrogen blending limit than the hydrogen blending percentages at which issues were experienced in the literature and observed in tests performed in the DNV combustion laboratory; however, for the fully premixed low NO_x storage water heater, an upper limit of 10 vol% hydrogen was experimentally observed in [60], while an upper blending limit between 30-40 vol% hydrogen was calculated in the gas interchangeability analysis. Other research performed on a similar fully premixed low NO_x storage water heater showed no issues within the tested range between 0-30 vol% H_2. Additionally, research performed at DNV on fully premixed appliances did not show issues up to approximately 40 vol% H_2. Tests on a conventional hot water storage heater with a pancake burner showed issues at 10 vol% hydrogen, which is similar to the maximum amount found in the gas interchangeability analyses. However, experiments performed in a recent study using a similar hot water heater showed no issues between the measured range of 0-30 vol% hydrogen [63]. These conflicting results were found in the literature for a number of different equipment types, which makes it difficult to draw general conclusions on the amount of hydrogen blending allowed.

Furthermore, in the majority of the studies found in the literature, not all potential failure modes were tested, such as flashback during steady-state operations, cold and hot ignition, measuring overheating of the burner surface, emission measurements, etc. Few studies present measured temperatures of the burner deck or demonstrate that the burner deck temperature can increase upon hydrogen addition. This increase in burner deck temperature can have a significant impact on the integrity of the equipment. For example, measurements on a conventional hot water heater with a pancake burner showed a substantial increase in the burner deck temperature from 450°C to 525°C when adding 30 vol% hydrogen to natural gas. It is unknown to what extent this temperature increase may affect the lifetime of the burner surface. An increase in the temperature may cause higher thermal stress and can ultimately result in damage such as crack formation on the burner surface. Cracks on the burner surface can be a potential source for fuel leakage and, consequently, an increase in CO emission due to incomplete combustion.

Table 6-12: Appliances presented and tested in literature; hydrogen limit for the major gas interchangeability failure modes

	Gas interchangeability, vol% H_2	**Literature inventory, upper H_2 limit**** Vol% H_2**	**Remarks**
Furnace (conventional, partially premixed)	10-11.5*	0-30	No issues but maximum limit tested is 30 vol% [63]
Furnace (fully premixed)	24-29**	0-15	Only one report with measurements up to 15 vol% H_2 in NG (no issues observed between 0-15 vol% H_2)
Hot water heater (conventional (partially premixed))	10-11.5*	0-10 (based on flashback)	Another study shows no issued up to 30 vol% H_2 [63]
Hot water heater (conventional (fully premixed))	10-11.5*	0-10 (based on flashback)	Another study shows no issued up to 30 vol% H_2 [63]
Ovens (partially premixed)	10-11.5*	0-10 (based on burner deck temperature) 0-25 (based on flashback)	Based on one single article [59]
Boilers (partially premixed)	10-11.5*	Up to 15-50 (depending on burner type)	The lower limit is of 15 vol% is based on a study in which no more than 15 vol% is added (no issues observed between 0-15 vol%)
Boilers (fully premixed)	24-29**	Up to 15-40 (depending on burner type)	The lower limit is of 15 vol% is based on a study in which no more than 15 vol% is added (no issues observed between 0-15 vol%)
cooking hubs (partially premixed)	10-11.5*	0-20 (based on flashback at cold start)	Varies limits found between different studied ranging from 20-40 vol% H_2
Gas fire(s) (partially premixed)	10-11.5*	0-28	Based on one UK study in which no details are provide, only statements. Unknown what the performance is above 28 vol%
Grill (partially premixed)	10-11.5*	0-40 (based on noise)	Based on a single study in EU
Fryer (partially premixed)	10-11.5*	0-23 (based on CO emission)	Based on a single study in EU. Unknown what the performance is above 23 vol%
Gas convection heater (partially premixed)	10-11.5*	0-50 (based on flashback)	Based on a single study in EU Present in Canada?
Garage heater (partially premixed)	10-11.5*	-	No information available
Catalytic heaters	-	-	No information available
Fire table, outdoor (partially premixed)	10-11.5*	-	No information available
BBQ/outdoor stoves	10-11.5* (Partially premixed) 24-29** (Fully premixed)	-	-
Home backup generators	6.5-19***	-	-
Pools, residential	10-11.5* (Partially premixed) 24-29** (fully premixed)	-	-

* Overheating and flashback are the limiting factors; the maximum H_2 allowed depends upon the natural gas composition at the H_2 injection point, see Section 6.3.

** Legal Wobbe index limits are the limiting factor; the maximum H_2 allowed depends upon the natural gas composition at the H_2 injection point, see Section 6.3.

*** Methane number is the limiting factor; the maximum H_2 allowed depends upon the natural gas composition at the H_2 injection point, see Section 6.3.

**** Based on the research that observed ‘issues’ with the lowest concentrations of hydrogen in natural gas.

As described above, the results of these studies are conflicting and are complicated by the fact that the studies performed do not all account for all major failure modes. In addition, the range of hydrogen blending tested varies among the different studies. [redacted] Other equipment not included in the rental list, but that is generally installed in Canada and may be present in the Gazifère area, is shown in Table 6-16. Based on the information in Table 6-13 to Table 6-16, it is apparent that information on the practical experience of hydrogen blending for Canadian appliances is limited, conflicting, or unavailable. Furthermore, for the majority of studies that are available, the maximum amount of hydrogen blending tested is 30 vol% H_2. Given the ambition of Gazifère to distribute maximum blends with hydrogen, it also necessary to investigate what happens above 30 vol% H_2 in appliances as well as determine safety margins to account for accidental overshoot in hydrogen blending and/or appliances that are not well adjusted or maintained.

Another important knowledge gap is the lack of information on the long-term effects of hydrogen addition on the performance and integrity of end-use equipment. As discussed above, the observed increase in burner deck temperature may cause long-term effects on burner deck integrity and ultimately result in damage (e.g., crack formation) within the lifetime of the burner when hydrogen blending is outside the gas interchangeability envelope.

The ultimate aim of Gazifère is to blend a maximum amount of hydrogen with natural gas in the entire network. To achieve this goal, the knowledge gaps should be identified and addressed prior to attempting this level of blending. DNV has developed a ranking of appliances to be tested, with the highest priority based on the information obtained in this study. A score from 0 (highest priority) to 4 (lowest priority) was assigned to each equipment type based on the availability of information and potential impact of hydrogen addition on the end-use equipment in Canada. The ranking was defined as follows:

- Sensitivity unknown; no data available.
- Sensitivity known; performance data limited, limited concentration range, and/or inconclusive data
- Sensitivity known and not sensitive up to 30 vol% H_2; unknown effect above 30 vol% H_2 and unknown long-term effects.
- Sensitivity unknown, but according to gas interchangeability analyses no issues up to ~30 vol% H_2 expected within the legal Wobbe index range as defined in the gas specifications.
- Data available; known sensitivity to H_2 addition but long-term effects are unknown.

6.4.3.1 Hot Water Heaters

The results presented in Table 6-13 summarize the data available for hot water heater types present in Canada. Some tests have been performed, but to DNV's knowledge none of the long-term effects have been studied for these appliances.

From the gas interchangeability analyses, the results indicate that fully premixed appliances are least sensitive to the presence of hydrogen and long-term issues are not expected with up to 30 vol% hydrogen. Therefore, the fully premixed appliances (number 3 and 6 in the table) are not a priority for testing (priority 3). Tests on the fully premixed appliance number 7 are reported in two studies with conflicting conclusions. Although DNV does not expect issues based on the gas interchangeability analyses, because of the conflicting results, this type of appliance has been given a priority 1.

For partially premixed hot water heaters, hydrogen blending outside the gas interchangeability envelope (>10 vol% H_2) results in an increased risk and practical information is needed to assess if hydrogen blending above 10 vol% H_2 results in performance issues. Based on the literature review, no information is available for partially premixed hot water heaters that contain tube burners or slit/slot burners (number 4 and 5 in the table) and, therefore, these two appliance types were assigned the highest priority for testing (priority 0). Appliance types 1 and 2 containing pancake burners have been tested up to 15 and

30 vol% hydrogen. No major issues were reported in one study, but in another study flashback at 10 vol% was reported. Given the conflicting information regarding the performance of these appliances they have been assigned a priority 1.

Table 6-13: Hot water heaters – available data and testing priorities

Type no	Combustion mode	Burner type	Air supply	Tested up to	Issues at vol% H2	Remarks	Recommendations	Priority for testing
1	Partially premixed, atmospheric vent	Pancake	Natural draught/ draught hood	30 vol% H_2	No issues up to 30 vol% H_2, but another study showed flash-back at 10 vol%	-	(long-term) testing >>30 vol% H_2	1
2	Partially premixed	Pancake	Induced draught	15 vol% H_2	-	CSA tested an induced draught hot water heater up to 15 vol% but burner type is unknown	(long-term) testing >>30 vol% H_2	1
3	Fully premixed	Cylindrical	Forced draught	-	-	Not tested, but we do not expect issues below 30 vol% H_2 in NG	-	3
4	Non mixed according to manufacturer; potentially premixed based on DNV knowledge	Tube burner	Natural draught/ draught hood	-	-	Not tested	(long-term) testing >>30 vol% H_2	0
5	Partially premixed	Slit/slot burner	Natural draught	-	-	Not tested	(long-term) testing >>30 vol% H_2	0
6	Fully premixed	Flat burner	Forced draught	-	-	Not tested, but DNV does not expect issues below 30 vol% H_2 in NG	-	3
7	Fully premixed	Radiant screen	Natural draught	30 vol% H_2	No issues up to 30vol% H_2, but another study showed flash-back at 10 vol%		(long-term) testing >>30 vol% H_2	1

6.4.3.2 Furnaces

Based on the gas interchangeability analyses, performance issues or long-term issues are not expected for blends up to 30 vol% hydrogen for fully premixed furnaces. These types of furnaces were, therefore, assigned a priority of 3 for testing. The partially premixed furnace that was tested did not exhibit any performance issues with up to 30 vol% hydrogen; however, how these appliances operate above 30 vol% H_2 is unknown, and they were assigned a priority of 2 as a result.

Table 6-14: Furnaces – available data and testing priorities

Type no	Combustion mode	Burner type	Air supply	Tested up to	Issues at vol% H_2	Remarks	Recommendations	Priority for testing
1	Partially premixed (both condensing and non-condensing)	In-shot	Induced draught	30 vol% H_2	No issues		(long-term) testing >>30 vol% H_2	2
2	Fully premixed (modulating/ condensed)	Cylindrical	Forced draught	-	-	Not tested, but DNV does not expect issues below 30 vol% H_2 in NG	-	3

6.4.3.3 Boiler Systems

Although no Canadian fully premixed boilers have been tested, performance issues are not expected based on the gas interchangeability analyses and experience at DNV with fully premixed boilers. Therefore, fully premixed boilers have been ranked with priority of 3. To DNV's knowledge, no information is available for partially premixed boilers that have a tube burner. Since the gas interchangeability shows an increased risk above 10 vol% H_2 blending, it is strongly recommended that testing of this boiler type be completed and it is, therefore, ranked as a priority of 0.

Table 6-15: Boiler systems – available data and testing priorities

Type no	Combustion mode	Burner type	Air supply	Tested up to	Issues at vol% H_2	Remarks	Recommendations	Priority for testing
1	Partially Premixed	?	?	Up to 15 vol% H2	No issues	Burner details are missing	-	1
2	Fully premixed	Cylindrical	Forced draught	-	-	Not tested, but we do not expect issues below 30 vol% H_2 in NG	-	3
3	Partially premixed	Tube burner	Draught hood	-	-	-	(long-term) testing >>30 vol% H_2	0
4	Fully premixed	Flat burner	Forced draught	Up to 70 vol%	Flash back at 70 vol%	No increase in burner deck temperature below 30 vol% H_2	-	3

6.4.3.4 Other Equipment

Table 6-16 represents equipment that is not present in the rental list provided by Gazifère but is generally present in Canada. From Table 6-16, it can be seen that no information is available for the equipment type numbers 3, 6-10, and 14. For the equipment that was tested, no issues were observed up to 20 vol% hydrogen with the exception of the patio heater, which was only tested up to 15 vol% hydrogen in natural gas.

Table 6-16: Other equipment – available data and testing priorities

Type no	Other equipment	Combustion mode	Burner type	Air supply	Tested up to	Issues at vol% H_2	Remarks	Recommendations	Priority for testing
1	Ranges (small)	Partially premixed	Atmospheric cooking hob burner	Natural draught	Tested up to 70 vol% H_2	20 vol% H_2	Limit based on burner deck temperature	-	4
2	Ranges (large)	Partially premixed	Atmospheric cooking hob burner	Natural draught	Up to 75 vol% H_2	20 vol% H_2	Limit based on flash-back at cold start	-	4
3	Ranges (wok (jet) bridle plates)	Partially premixed	Atmospheric wok (jet) burners and bridle plates	Natural draught	-	-	-	(long-term) testing >>30 vol% H_2	0
4	Fryers	Partially premixed	Fryer burner	Induced draught	Up to 40 vol% H_2	23 vol% H_2	Limit based on CO emission, only one study available	(long-term) testing >>30 vol% H_2	1
5	Fireplaces	Partially premixed	Cylindrical	Forced draught	Up to 28 vol% H_2	No issues	No details of the tests provided only statements	(long-term) testing >>30 vol% H_2	1
6	Home backup generators	Fully premixed	Spark-ignited engine		-	-	-	(long-term) testing >>30 vol% H_2	0
7	Pool heaters	Partially premixed	Tube/line/r bbon burner	Natural draught	-	-	-	(long-term) testing >>30 vol% H_2	0
8	Catalytic heaters	Non-premixed	Catalytic burners	Forced draught	-	-	-	(long-term) testing >>30 vol% H_2	0
9	Dryers	Partially premixed	Tube and r bbon burners	Induced draught	-	-	-	(long-term) testing >>30 vol% H2	0
10	Rooftop air conditioners	Partially premixed	In-shot	Induced draught	-	-	-	(long-term) testing >>30 vol% H2	0
11	BBQ/grills	Partially premixed	Tube/line/r bbon burner	Natural draught	Up to 40 vol% H_2	40 vol% H_2	Based on noise at the injector, only one study available	(long-term) testing >>40 vol% H_2	1
12	Patio heaters	Fully and partially premixed	Flat and cylindrical burners	Natural draught	15 vol% H_2	No issues		(long-term) testing >>30 vol% H_2	1
13	Ovens	Partially premixed	Tube burner	Natural draught	Up to 55 vol% H_2	25 vol% H_2 flashback at cold start	Large temperature increase of burner above 10 vol% H_2	(long-term) testing >>30 vol% H_2	4
14	Garage heaters/ air heaters	Partially premixed	In-shot	Induced draught	-	-	-	(long-term) testing >>30 vol% H_2	0

6.4.4 Strategy to Fill Knowledge Gaps

The following strategy is proposed to fill the knowledge gaps in order to supply hydrogen percentages outside the gas interchangeability envelope:

- [redacted] Given the lack of information on the sensitivity of partially premixed appliances to hydrogen addition, it is recommended that a number of typical burners types and combustion modes shown in Table 6-13 to Table 6-15 be tested for hydrogen percentages above the targeted hydrogen blending (30 vol% H2); and the long-term effects be studied for a number of selected appliances that show the highest sensitivity toward hydrogen blending (e.g., show the largest increase in burner deck temperature). If experiments reveal that these appliances are limiting in terms of the maximum hydrogen that can added, then DNV proposes removal or replacement with appliances that are certified for 30 vol% H2 or higher. This requires the development of programs and regulations to support the development and certification of appliances that can handle 30 vol% H2. Furthermore, as a replacement strategy, partially premixed appliances that are limiting with regard to hydrogen blending can be replaced by fully premixed appliances.
- Currently it is unclear what the minimum methane number requirements are for home backup generators. It is therefore recommended that Gazifère discuss the methane number requirements for engines installed in the field with the OEMs in order to validate the maximum compatible limit for blended hydrogen service. It is also recommended that the performance of home backup generators be tested for hydrogen blends to determine the maximum amount of hydrogen allowed. If experiments reveal that these appliances are limiting in terms of the maximum hydrogen that can added, then DNV proposes removal or replacement with home backup generators that are certified for up to 30 vol% H2. This requires the development of programs and regulations to support the development and certification of new home backup generators that can handle 30 vol% H2. Additionally, if needed, it is recommended that a retrofit solution be developed for the existing equipment. For example, the compression ratio can be reduced, or the spark timing settings can be changed to avoid knock and increased wear and tear. Fuel adaptive engine control by, for example, spark timing adjustment can be applied to mitigate engine knock and increased NOx emissions.
- The presence of hydrogen may result in deterioration of the performance of equipment and the integrity of the appliance. For example, the presence of hydrogen can result in an increase in the burner deck temperature which can result in crack formation on the burner deck. This can result in, for example, an increase in the CO emissions. Inspection personnel should be aware of these aspects when doing maintenance and inspection of end-use equipment. Existing internal and industry training programs for maintenance and inspection personnel should be reviewed and recommendations for modifications should be provided. Furthermore, it is strongly recommended that CO sensors be installed in all households in the pilot area as a safety precaution. These sensors also detect hydrogen leakages below 10% of the explosion limit.

6.4.4.1 Recommended Appliance Testing Program

A recommended test program for appliances that were ranked with the highest priority ‘0’ is given in Appendix 11: Appliance Testing Program Methodology to address current knowledge gaps and increase hydrogen compatibility beyond interchangeability limits.

DNV is currently testing eight Canadian domestic (partially premixed) appliances for another natural gas grid operator using hydrogen blends >30 vol% hydrogen in natural gas. To avoid unnecessary testing of similar equipment for each natural gas grid operator or appliance manufacturer, DNV proposes a joint industry project (JIP). The aim of the JIP is to remove current knowledge gaps on Canadian appliance performance by experimentally determining the effect of hydrogen blending. The tested equipment will be based on the identified knowledge gaps and discussion with the partners. The insights gained in this JIP will provide a basis for developing a Canadian hydrogen standard for end-use equipment.

6.5 Industrial Equipment

In this section, a general overview of the effect of hydrogen is provided for industrial processes and equipment, including indirect heating, direct heating, catalytic heaters, and gas engines.

Industrial heating processes can be roughly divided into indirect and direct heating. Indirect heating is when the substance to be heated, referred to as the load, is separated from the combustion products, for example, by heating tubes through which water flows for hot water and steam production. In contrast, direct heating, often associated with high process temperatures, exposes the product directly to the flame and/or combustion products in an industrial kiln or furnace.

6.5.1 Indirect Heating Processes

In indirect heating processes, the flame and flue gases do not come in direct contact with the product to be heated. Examples of indirect heating processes include hot water and steam production for heating oil or other liquids (such as in distillation processes). Industrial gas-fired boilers are used for on-site process steam production and sometimes also to generate electricity in a Rankine cycle using a steam turbine. Most boiler systems for hot water and steam production contain forced draught burners (nozzle mix, non-premixed burners). Modern low-NO_x forced-draught gas burner designs are often used to minimize thermal NO_x by limiting the intensity of fuel/air mixing and, thus, limiting reaction rates to reduce peak flame temperature.

6.5.1.1 Radiant Tube Burners

To maintain integrity and life expectancy of radiant tube burners, the flame length (for higher temperature flames) is critical to prevent flame impingement on the radiant tube itself. To DNV's knowledge, the impact of hydrogen addition on the flame shape of radiant tube burners is unclear. According to API RP 535 *Burners for fired heaters in general refinery services* [62], hydrogen addition tends to produce a shorter and more stable flame, which makes flame impingement on tubes or other surfaces less likely; however, flame temperatures can be higher and, therefore, burner spacing may need to be adjusted. Leicher et al. [63] showed that the flame length did not change substantially upon hydrogen addition when keeping the power and the air factor constant. Tests on a forced-draught burner in an industrial hot water boiler at DNV also did not show significant changes in the flame shape upon hydrogen addition (0-100 vol% H_2) when keeping the air factor and thermal input constant. Based on available literature, DNV recommends investigating the impact of hydrogen addition on the flame shape and temperature distribution in burner systems where flame impingement might be an issue such as water tube boilers, steam methane reformers, oil heating furnaces, and radiant tube burners. During a hydrogen blending pilot project, it is recommended that the temperatures of the tubes be monitored to prevent overheating.

6.5.1.2 Condensing Boilers

In the commercial and industrial sectors, condensing boilers are occasionally used because of their high thermal efficiencies of up to 90%. In condensing boilers, the flue gas is used to heat recycled water in a heat exchanger, which is then fed to the boiler. For natural gas, the flue must be cooled below the dew point of 55.7°C for condensation to occur, which means the return water inlet temperature needs to be on the order of 50°C. It is possible to operate a condensing boiler in non-condensing mode if the return water temperature is too high. One of the concerns when blending hydrogen into natural gas for use in condensing boilers is the increase in water dew point (as seen in Table 6-17), causing condensation in the flue stack and resulting in potential corrosion issues. However, for low percentages of hydrogen in natural gas, no substantial changes in the water dew point are calculated; the presence of 20 vol% H_2 increases the dew point temperature from 55.7 to 56.8°C.

Table 6-17: Dew point of H_2/NG blends (Natural gas is Wobbe average gas) assuming 3% O_2 in the flue gas

H_2 in Natural Gas, vol%	Dew point, °C
0	55.7
2	55.8
5	56.0
10	56.2
15	56.5
20	56.8
25	57.2
30	57.5
50	59.3
70	62.0
100	70.2

6.5.1.3 Forced-Draught Burners

Leicher et al. [63] studied a forced-draught burner using different hydrogen blends (0%, 2.5%, 5%, 7.5%, 10%, 15%, 20%, 30%, and 50%) in natural gas. The results showed good burner performance over the entire range of mixtures studied. Without active fuel control, excess air increased, and power output of the burner reduced as a result of the decrease in Wobbe index. When using adaptive fuel control, excess air and power were kept constant upon hydrogen addition, resulting in a slight measured increase in NO_x emissions.

At DNV, the combustion performance of a 475 kW forced-draught burner [64] was studied for natural gas, hydrogen blends, and pure hydrogen. The results are presented in Figure 6-28 and Figure 6-29. When performing the tests with the original burner management system (BMS), a strong reduction in the burner load (thermal input) and an increase in the excess air, which consequently results in a reduction of the thermal efficiency, were observed. When applying adaptive fuel control [51], the thermal input and air factor were successfully kept constant.

Figure 6-28: 475 kw boiler equipped with a 475 kW forced-draught burner [64]

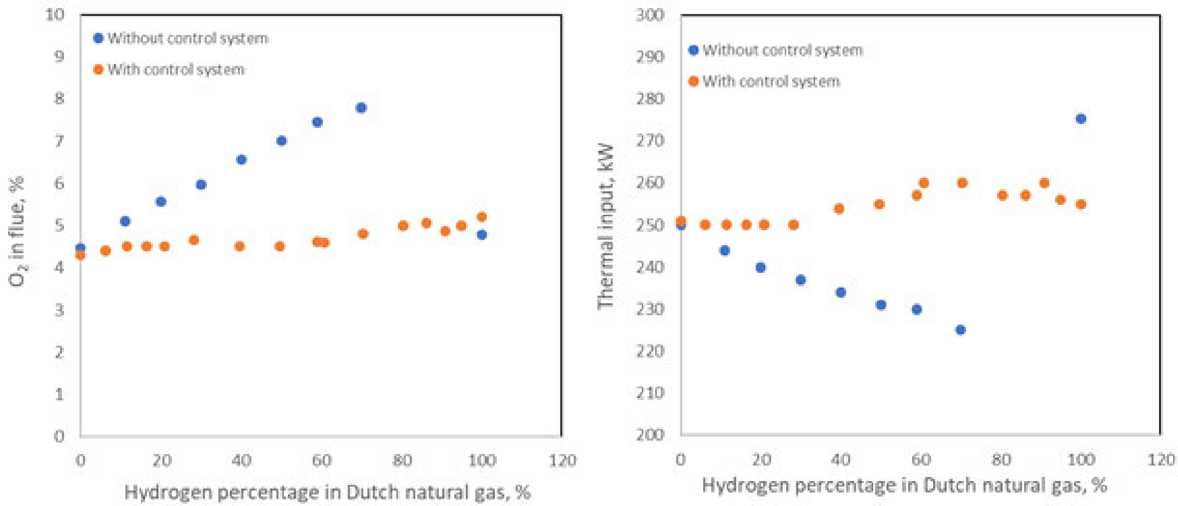

Figure 6-29: Effect of H_2 addition on oxygen percentage (Left) and on thermal input (Right) [64]

As shown in Figure 6-30 [64], switching from natural gas to pure hydrogen resulted in a significantly increased measurement in NO_x emissions as a result of the increase in the adiabatic flame temperature, which results in faster NO_x production mainly via the thermal NO_x mechanism. However, for blends up to 30 vol% hydrogen, only a slight increase in NO_x emissions was observed. Without the control system, NO_x emissions increased from approximately 70 to 80 mg/m^3 (3% O_2) at 30 vol% hydrogen. The increase in NO_x emissions was successfully mitigated by applying external flue recirculation [64], as can be seen in Figure 6-30 (Right). This burner concept is currently being tested in a large-scale pilot project at Nedmag [65], a salt mining company in the Netherlands, using a 2 MW forced-draught burner to heat oil. In the pilot project, hydrogen blends in natural gas ranging from 0-100 vol% H_2 will be used.

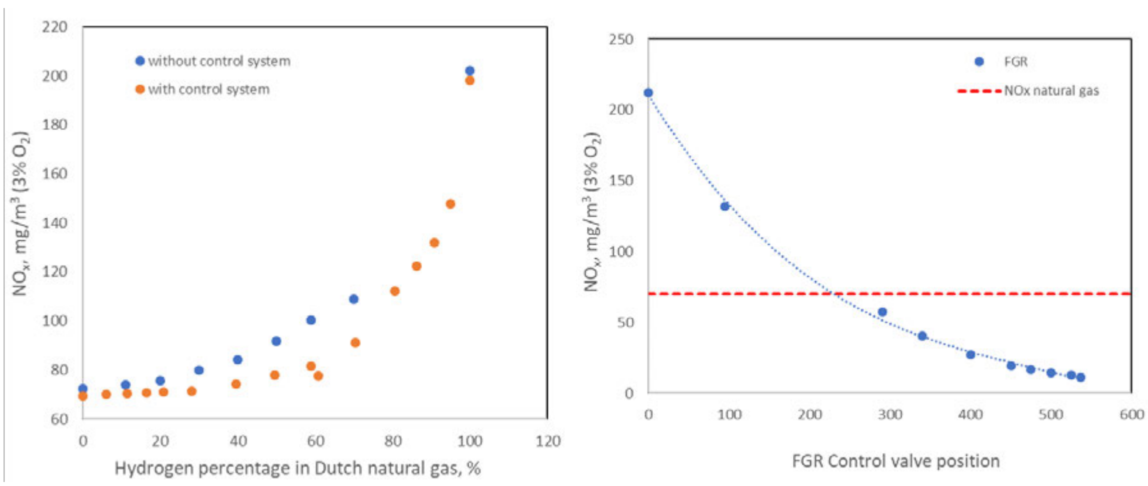

Figure 6-30: Effect of hydrogen addition to Dutch natural gas on the NO_x emissions, measured with (orange dots) and without (blue dots) the fuel adaptive control system [66]

At DNV, another 500 kW forced-draught burner was tested in the same boiler system as shown in Figure 6-28 using hydrogen blends up to 30 vol% in natural gas. The results (presented in Figure 6-31) show that NO_x emissions increased upon hydrogen addition. At 30 vol% hydrogen in natural gas, NO_x emissions increased from 50 to 60 mg/m^3. No performance issues were observed during the measurements.

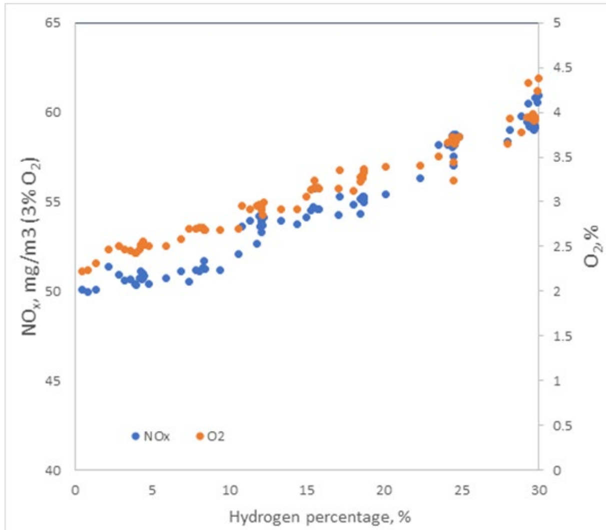

Figure 6-31: NO_x emissions from a power burner in a commercial heating boiler as a function of hydrogen fraction in natural gas

6.5.1.4 Fully Premixed Radiant Burners

Examples of commercially available premixed radiant burners include the LPMW burner from John Zink Hamworthy Combustion, which employs lean combustion in combination with fuel staging for NO_x control and can burn gases containing up to 75 vol% hydrogen without facing flashback issues. The Walrad burner, also by John Zink Hamworthy, can burn up to 60 vol% hydrogen [66]. The authors in [67] found that the radiant fully premixed burner tested was shut-off automatically for hydrogen percentages above 15 vol% due to too much oxygen in the flue gases. Applying adaptive fuel- control can mitigate this issue. However, adjustment by the control system to lower the oxygen concentration in the flue gas can increase risk of flashback. Based on experience within DNV, major issues are not expected for up to 20 vol% hydrogen for these radiant fully premixed burners.

6.5.1.5 Summary

From the results presented in the literature, DNV does not expect major performance issues with indirect heating processes for up to 20 vol% hydrogen in natural gas when the Wobbe index of the gas is within the specifications of the traditional distributed gases. For higher percentages, it is recommended that an adaptive fuel-control system be included to keep the power output and excess air constant. When the burner is already operating near the legal NO_x limit, a small amount of hydrogen addition can lead to exceedance of the NO_x limits. However, generally, major performance issues (including NO_x emissions) are not expected for percentages up to 20 vol% H_2. The results are summarized in Table 6-18 below.

Table 6-18: Hydrogen percentages and mitigating measures for indirect heating industrial burners

Burner type	Range H_2 (%)	Issues	Mitigating measures
Forced-draught burners (diffusion type) for, e.g., hot water, steam, and oil heating	0-30 vol% (gas interchangeability based on Wobbe shows an allowed range between 0-29 vol% H_2)	No issues, in case the Wobbe index and NO_x emission are within the defined Wobbe band and legal NO_x limits. Special attention is recommended to prevent flame impingement on the tubes (water, oil etc.) to be heated NO_x generally increases upon hydrogen and can exceed the legal NO_x limits	None, in case the Wobbe index, NO_x emission and flame length are within the defined Wobbe band and legal NOx limits and process requirements. When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is design for the installation of a new burner control system (load and efficiency) necessary. When the legal NO_x limits are exceeded, NO_x mitigating measures are needed, such as (external) flue gas recirculation Flame length can be controlled by for example changing the air factor or in the worst-case scenario adapting or replacing the burner is necessary
Radiant tube burners (diffusion burners)	0-x vol% (gas interchangeability based on Wobbe shows an allowed range between 0-29 vol% H_2)	Potential issue overheating of the burner tube due to change in heat distribution NO_x generally increases upon hydrogen and can exceed the legal NOx limits	Flame length can be controlled by, for example, changing the air factor. In the worst-case scenario, adapting or replacing the burner is necessary. When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is designed, the installation of a new burner control system (load and efficiency) is necessary. When the legal NO_x limits are exceeded, NO_x mitigating measures are needed, such as flue gas recirculation.
Radiant heater (premixed combustion)	0-20 vol% (gas interchangeability based on Wobbe shows an allowed range between 0-29 vol% H_2 and 30 vol% hydrogen based on overheating and flash-back)	Generally, no issues but increase of oxygen concentration in flue upon H_2 addition can result in shut-off by the safeguarding system. Readjustment to lower the oxygen concentration in the flue gas can increase risk of flash-back	When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is designed, the installation of a new burner control system (load and efficiency) is necessary.
Partially premixed burners	0-x vol% (gas interchangeability based flashback and overheating shows an allowed range between 0-11 vol% H_2)	Potential issue overheating of the burner tube due to change in heat distribution Flashback issues NO_x generally increases upon hydrogen and can exceed the legal NOx limits	When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is designed, the installation of a new burner control system (load and efficiency) is necessary. When the legal NO_x limits are exceeded, NO_x mitigating measures are needed, such as (external) flue gas recirculation. Overheating and flashback can be avoided by, for example, changing the air factor. In the worst-case scenario, adapting or replacing the burner is necessary.

6.5.2 Direct Heating Processes

6.5.2.1 Burner Performance

In many direct heating processes, the flame shape must be considered when designing process burners for different fuels. For the refractory material in furnaces and boilers, hot spots and flame impingement must be avoided to prevent increased degradation of the expensive refractory lifetime. Leicher et al. [63] found that the flame length did not change substantially upon hydrogen addition when keeping the power and the air factor constant. Tests at DNV have shown no burner overheating upon hydrogen addition for industrial swirl burners studied. However, during experiments the hot flame zone was observed to shift closer to the burner upon hydrogen addition. For burners that contain a ceramic tube on top of the burner, this can result in higher temperature of the ceramic tube and the burner block.

Experiments performed by Leicher [68] with different hydrogen/natural gas blends (0, 10, 30, 50, and 100 vol% H_2) in a glass melt furnace using a typical nozzle-mix glass burner with pre-heated air (1150°C) showed an increase in NO_x emissions from 400 ppm with natural gas to 700 ppm at 30 vol% hydrogen. Further increase of the hydrogen percentage did not significantly change the NO_x emissions for this burner. The NO_x emissions from a high-velocity nozzle-mix burner used in the ceramic, steel, and aluminium industry were measured in an industrial batch furnace by Slim et al. [69] using different hydrogen blends. The results (presented in Figure 6-32) show that the NO_x emissions strongly increased upon hydrogen addition. The strongest increase was observed at the lowest furnace temperature. Measured CO emissions decreased strongly upon hydrogen addition.

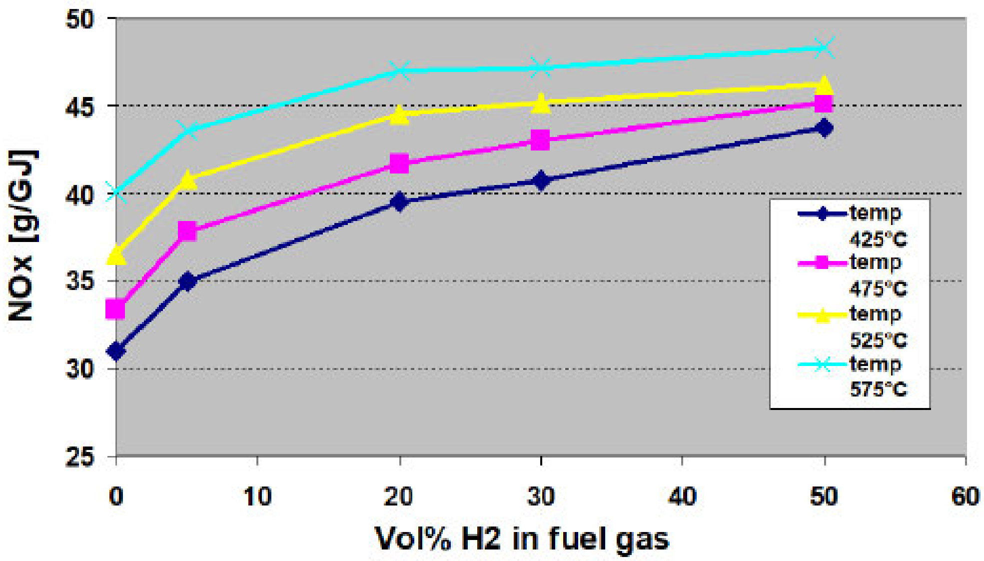

Figure 6-32: Measured NO_x emissions from a high-velocity burner at different furnace temperatures and hydrogen percentages in natural gas in an industrial furnace [69]

A study by the IGF in Germany [72] describes testing of a low-NO_x nozzle-mix burner used in the metals industry, which can be adapted to different fuels by mounting different burner heads. These heads differ in the arrangement of nozzles and the amount of swirl applied to combustion air. The tests were run at up to 50 vol% hydrogen at constant air flow rate and then at constant excess oxygen. A slight increase in NO_x emissions was observed with increasing hydrogen content. Emissions of CO remained low throughout. The test was run with the burner outside the furnace, i.e., it did not account for any changes the fuel blend might have on the process.

Burner performance tests were performed at the combustion laboratory of DNV using a Honeywell Maxon Kinedizer burner [71] using hydrogen/natural gas blends ranging from 0-100% H_2 in natural gas. The burner (shown in Figure 6-33 below) has a design that is close to that of one of the Maxon burners installed at the Kruger paper mill plant on the Gazifère network. The burner tests were performed using a 500-kW furnace and results (shown in Figure 6-34) showed no substantial increase in the NO_x emissions up to 20 vol% hydrogen but a linear increase from 20 to 100 vol% hydrogen.

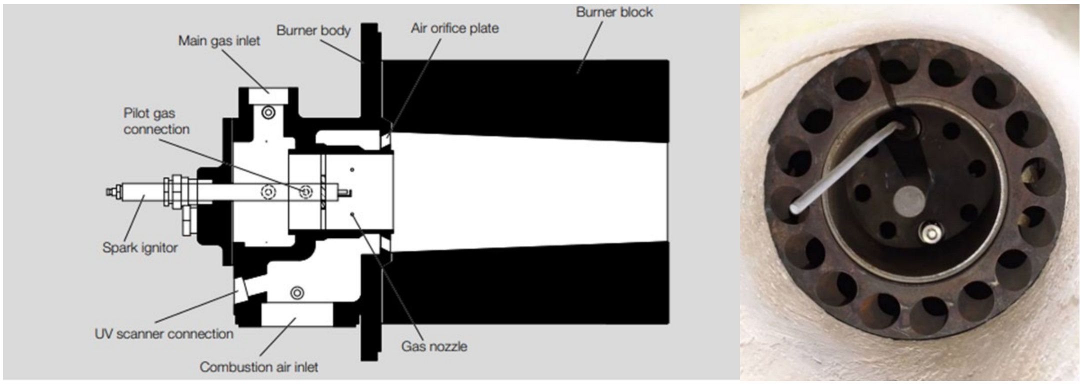

Figure 6-33: Honeywell Maxon Kinedizer burner

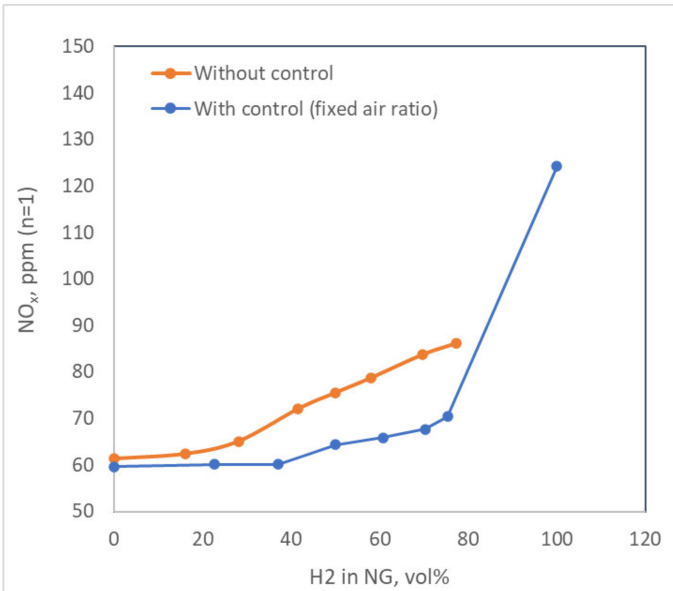

Figure 6-34: Measured NOx emissions from an Maxon Kinedizer burner at different hydrogen percentages in natural gas in an industrial furnace [73]

Radiant burners (described in the previous section) are also used for direct heating processes. As discussed above, control issues may occur upon hydrogen addition above 15 vol% hydrogen in natural gas due to the increase in oxygen in the flue gas. This can be solved by applying fuel adaptive control, but flashback may be an issue. Based on the gas interchangeability analyses, we do not expect issues between 0-13 vol% hydrogen for partially premixed radiant burners. For fully premixed radiant burners, we expect no issues up to 20 vol% hydrogen when applying fuel adaptive control; however, an increase in the burner surface temperature may impact the lifetime. More research is recommended for higher percentages of hydrogen to prevent overheating and flashback.

Summary

To summarize, the results described in the literature show that different burner types exhibit different combustion performance upon hydrogen addition to natural gas. However, hydrogen blending experience is only available for a limited number of burner types, which makes it difficult to draw general conclusions for all of the different types of burners installed. For the burners studied, the main concerns are the change in burner load, air factor, heat transfer, increase in the NO_x emissions, changes in flame length, and the shift of the hot flame zone closer to the burner surface upon hydrogen addition. For burners that operate close to the legal NO_x limit, hydrogen addition can lead to an exceedance of the NO_x limits. To mitigate the NO_x emissions, external flue gas recirculation can be applied, small amounts of inert gases can be added to the fuel to reduce the flame temperature, or the burner configuration can be adapted to create more internal flue gas recirculation to cool the hot flame zone in order to supress the thermal NO_x mechanism. Where the NO_x emissions from the installed natural gas burners are far below the legal NO_x limits, DNV does not expect major performance issues with up to 20 vol% hydrogen for the burners studied. However, fuel adaptive control is recommended to keep the power output and the air factor at the desired level. Above these percentages, additional research is recommended. The results are summarized in Table 6-19.

Table 6-19: Hydrogen percentages and mitigating measures for burners used in direct heating processes

Burner type	Range H2 (%)	Issues	Mitigating measures
Nozzle mix burners (swirl burner, high speed burner, etc.)	0-30 vol% (gas interchangeability based on Wobbe shows an allowed range between 0-32 vol% H_2)	No issues, in case the Wobbe index and NO_x emission are within the defined Wobbe band and legal NO_x limits. Change in heat distribution may result in overheating refractory and burner which can result in burner adjustments above ~10 vol%. NO_x generally increases upon hydrogen and can exceed the legal NO_x limits	None, in case the Wobbe index and NOx emission are within the defined Wobbe band and legal NO_x limits. When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is designed, the installation of a new burner control system (load and efficiency) is necessary. When the legal NO_x limits are exceeded, NO_x mitigating measures are needed, such as flue gas recirculation. Changing air factor to prevent overheating burner system.
Radiant heater (fully premixed burner)	0-20 vol% (gas interchangeability based on Wobbe shows an allowed range between 0-32 vol% H_2 and 40 vol% hydrogen based on overheating and flash-back)	Generally, no issues but increase of oxygen concentration in flue upon H_2 addition can result in shut-off by the safeguarding system. When controlling the air factor, the risk of flash-back increases	When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is designed, the installation of a new burner control system (load and efficiency) is necessary. Changing air factor to prevent overheating burner system.
Premixed forehearth burner (glass industry)	0-x vol% (gas interchangeability based on Wobbe shows an allowed range between 0-32 vol% H_2 and 40 vol% hydrogen for fully premix burners and 0-13vol% for partially premixed burners based on overheating and flash-back when not controlling air the factor)	Issue, potential flash-back however no information available for H_2/NG. Gas interchangeability analyses show no large impact but when controlling the air factor, the risk of flash-back increases	When the Wobbe range is outside the Wobbe bandwidth for which the burner control system is designed, the installation of a new burner control system (load and efficiency) necessary. Flash-back can be prevented by changing the air factor (higher excess of air).

6.5.2.2 Potential Impact to Product Quality

A computational study by Leicher et al. [74] analysed the impact of variable natural gas quality on the operation of a regenerative glass furnace. The model was calibrated for optimum performance with a reference fuel. Variations in gas density and heating value were studied assuming that the control either maintains constant stoichiometry and gas flow rate (the common control strategy) or adjusts both air and fuel flow rates depending on the fuel quality information from a gas chromatograph. The first scenario resulted in significant changes in heat transfer patterns negatively affecting product quality. In the second scenario with more sophisticated controls, these changes were mitigated. It can be concluded from this study that variable gas composition with hydrogen may increase the requirements placed on plant instrumentation and controls. Other research indicates that the expected increase in water vapor atmosphere upon hydrogen addition can result in more foam formation in the glass melt [75]. Furthermore, in [75] the authors indicate that the change in the kiln atmosphere (flue gas composition and temperature) can impact the glass quality and the lifetime of the refractory material. As described above, other direct heating processes such as drying processes, asphalt, and paper mills require stable process conditions such as constant temperature, thermal input, flue gas composition, and flue gas flow rate to guarantee constant product quality. It is known that hydrogen blending results in a change to the water vapour content, oxygen content, temperature, and the flue gas flow rate. These changes can have a negative effect on the drying process. To our knowledge, not much information is available regarding the quantitative effect of hydrogen addition to natural gas on the product quality. It is therefore strongly recommended that projects be initiated to further investigate the impact of hydrogen blending on the product quality.

To gain general insights into the changes of the oven atmosphere for different hydrogen blends, the changes in adiabatic flame temperature, flue gas composition, excess air, and flue gas flow were calculated using the Gazifère distribution gas maximum gas (see Table 6-3) as a reference. The results are illustrated in Figure 6-35 to Figure 6-37 below.

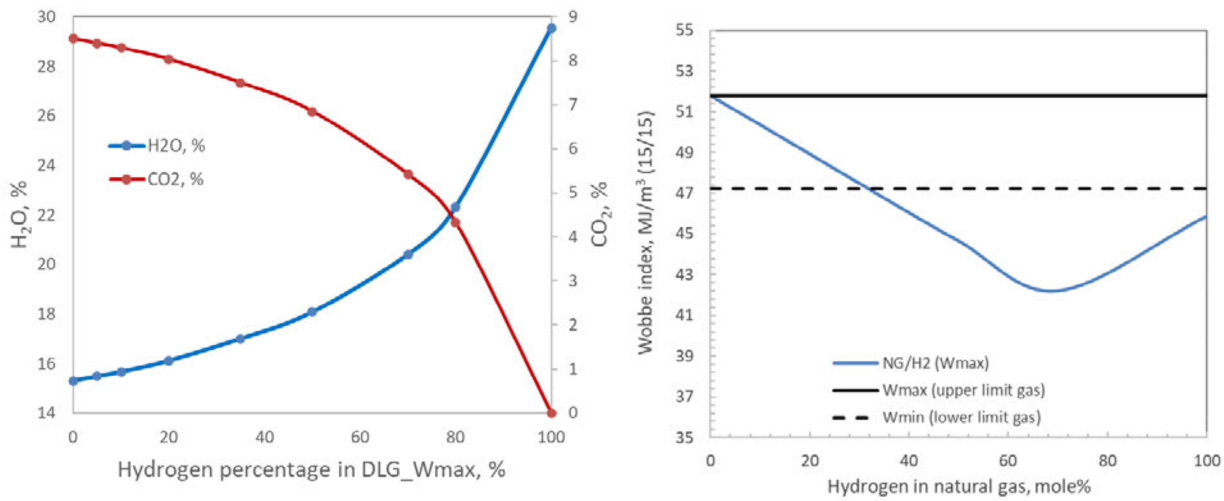

Figure 6-35: Flue gas composition for different hydrogen blends (vol %) in Gazifère distribution gas maximum gas (see Table 6-3)

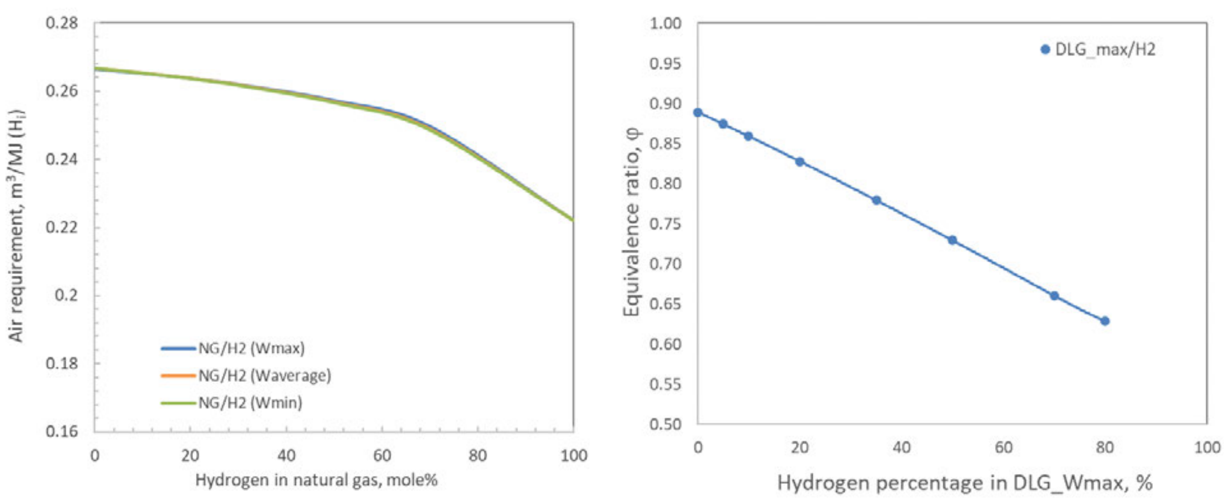

Figure 6-36: Air requirement (Left) and equivalence ratio (Right) for different hydrogen blends natural gases distributed in the Gazifère network

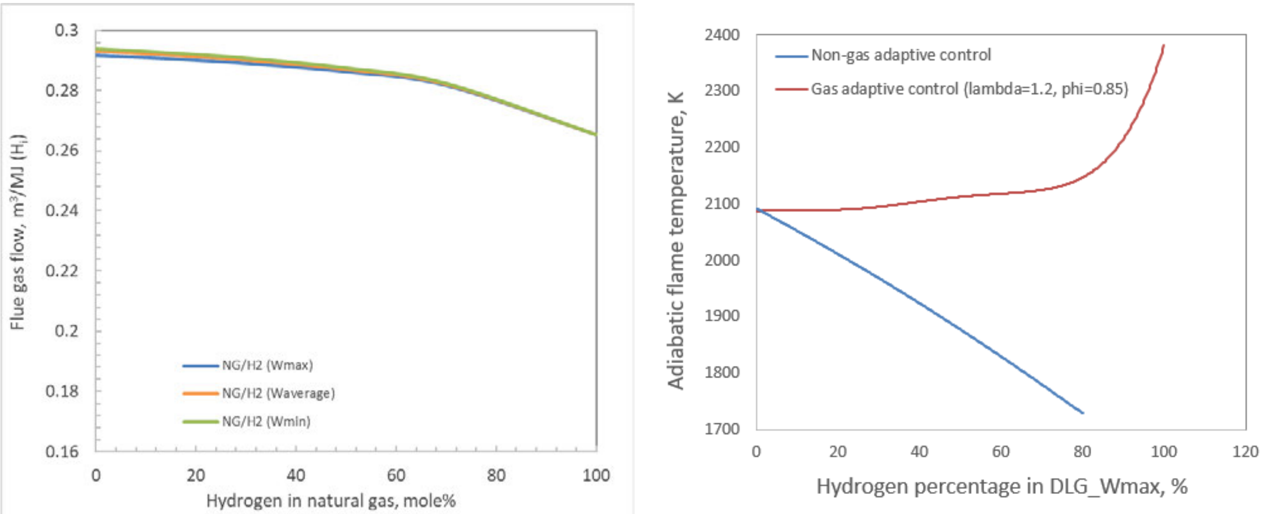

Figure 6-37: Flue gas flow (Left) and adiabatic temperature (Right) for different hydrogen blends natural gases distributed in the Gazifère network

The calculations show a large shift in equivalence ratio (Figure 6-36) and Wobbe index (Figure 6-35) upon hydrogen addition. Consequently, for processes without fuel adaptive control, these changes will cause a reduction in burner load, a reduction in oxygen concentration in the flue gas, and a change in the flue gas temperature (Figure 6-37). These changes can affect the heat transfer in the furnace and the product quality. To mitigate these changes, it is strongly recommended that fuel adaptive control be applied to keep the burner load and excess air at the desired values. When applying fuel adaptive control, the power output and the equivalence ratio can be kept constant upon hydrogen addition. As a result, the amount of oxygen in the flue gas is kept 'constant'[9] resulting in only minor changes in the adiabatic flame temperature as illustrated in Figure 6-37. It is noted that for nozzle mix burners, the local temperatures in the flame zone can still change upon hydrogen addition due to the changes in flame speed and gas velocity [65].

As shown in Figure 6-35, the water vapor concentration increases and the CO_2 amount decreases upon hydrogen addition, which can impact the radiation flux. Moreover, the change in water vapor concentration can affect drying processes and can interact with the product for direct heating processes, such as affecting the foaming in the glass melt as described above. However, based on the calculations, for low hydrogen percentages in natural gas the increase in water content is minor. For example, when 20 vol% hydrogen is present, the water percentage in the flue gas increases from 15.3 % to 16.1%, which is an increase of approximately 5%. Furthermore, we see only minor changes in the flue gas flow for low hydrogen percentages; the flue gas flow lowers from 0.294 to 0.292 m^3(n)/GJ when 20 vol% hydrogen is present. This means that at fixed burner load, the flue gas flow decreases by 0.5% when 20 vol% hydrogen is present. When the hydrogen percentage is lower than 5 vol%, the changes in the physical and combustion properties are negligible. It is strongly recommended that Gazifère discuss these changes with the relevant connected industries to determine how these changes in physical and chemical properties may affect their processes.

6.5.3 Catalytic Heaters

Practical information on the effect of using hydrogen or natural gas/hydrogen blends in catalytic heaters is scarce. Below is a summary of the few sources found in literature.

In catalytic heaters, the catalyst is preheated to ensure catalytic combustion of hydrocarbons. The minimum ignition energy of methane is 0.3 MJ and catalytic combustion occurs between 300-450°C. Hydrogen requires much less ignition energy (0.02

[9] The oxygen content upon hydrogen in natural gas in the flue gas slightly changes at constant equivalence ratio

MJ) and burns catalytically at lower temperatures (150-200°C) [76]. Because of this low combustion temperature, the lifetime of the catalyst support material present in the equipment may be extended when operating on hydrogen as compared to operating on natural gas [76].

In 1991, Pyle et al. [77] investigated a commercially available catalytic domestic space heater intended for use with natural gas and propane (Platinum CAT) for conversion to hydrogen combustion. The heater was installed in a living room and fuelled with hydrogen from high pressure gas cylinders. The following observations were made when the catalytic heater was fuelled with hydrogen:

- The hot wire starter for natural gas operation was unnecessary for initiation of hydrogen-air catalytic combustion.
- Overheating of the surface was not observed.
- An even combustion pattern was observed (visually), glowing dull orange in a dark room.

Another numerical study by Zhang et al. [78] suggested that the presence of water may lead to adsorption of water blocking the CH_4 oxidation on the platinum catalyst. The increase of hydrogen in natural gas leads to a higher water content in the fuel gas, which can not only increase the moisture in the heated room but may also affect the catalyst performance. In Table 6-20 below, preliminary calculations of the CO_2 and H_2O content in the flue gases for hydrogen methane mixtures are shown. The results show that the increase in water vapor is modest up to 30 vol% H_2 blending.

Because of the lack of information on the effect of hydrogen blends and pure hydrogen on the performance of these heaters, it is recommended that these heaters be further experimentally investigated to determine their tolerance to hydrogen.

Table 6-20: Calculated H_2O and CO_2 content in flue gases for different hydrogen fractions in methane (assuming complete combustion, ϕ=1)

CH_4 (vol%)	H_2 (vol%)	CO_2 (vol%) [exhaust]	H_2O (vol%) [exhaust]
100	0	9.48	18.78
98	2	9.43	18.86
95	5	9.35	19.00
90	10	9.20	19.22
80	20	8.88	19.75
70	30	8.49	20.38
0	100	0.00	34.10

6.5.4 Gas Engines

Stationary gas engines installed in the industry and at compressor stations are equipped with a power control. This control maintains a desired constant power, for example, in response to changes in the calorific value of the gaseous fuel due to hydrogen admixture. Gas quality variations that are too fast or too large may lead to disrupted engine service and even an engine stop [79]. Furthermore, in some cases, the control range of the power control is not sufficient to accommodate a large change in calorific value due to hydrogen admixture. In the latter case, the control system will shut the engine down.

Generally, there are two common types of lambda control used in gas engines: 1) lambda-sensor-based AFR (Air Fuel Ratio) controller, and 2) speed-density AFR control. The first type (lambda control) is dominant in older-generation gas engines. Modern gas engines are usually equipped with a variant of a speed-density AFR control. In response to hydrogen admixture, the AFR control based on a lambda sensor was found to maintain a virtually constant gas-air ratio. Figure 6-38 below shows that with 20% hydrogen in the gas this leads to an increase of approximately 10% in the peak pressure. This increase in mechanical load is undesirable because of the increase in wear-and-tear of critical engine parts such as bearings and piston rings, resulting in shorter maintenance intervals. Additionally, the increase in the in-cylinder temperature (see figure below) results in a substantial increase in the NO_x emissions [80], [81], [51], [52], [53].

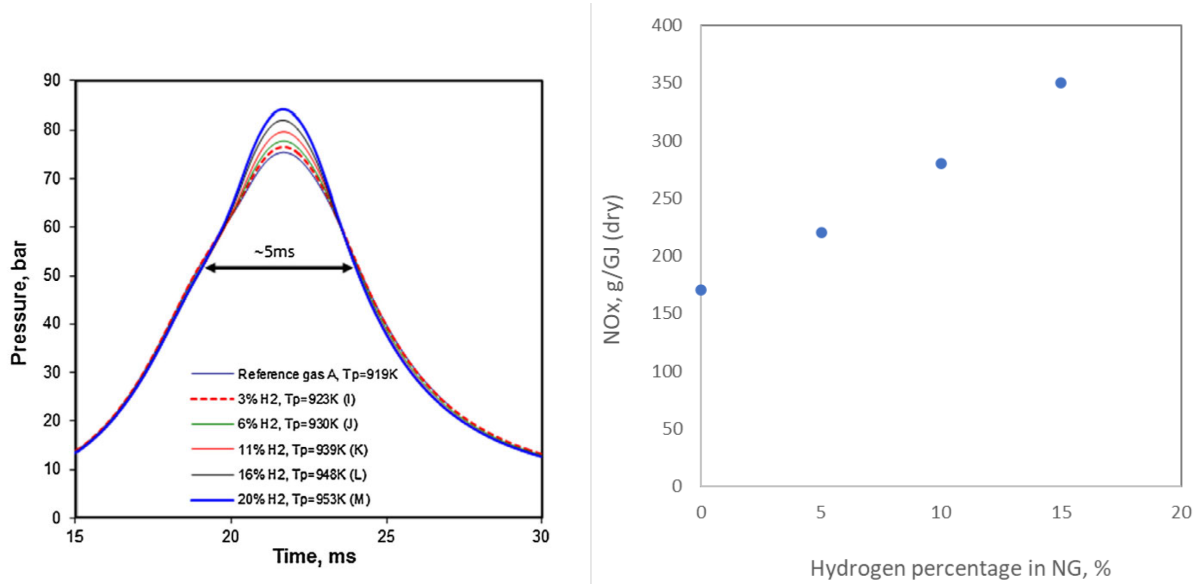

Figure 6-38: Measured pressure profiles for natural gas/hydrogen mixtures control based on a lambda sensor [82] (Left) and measured NO_x emission in the same gas engine (Right)

Several gas engines studies [83], [51], [52], [53] have confirmed that hydrogen admixture leads to a lower knock resistance of the fuel gas. The knock resistance of a fuel gas is characterized by a methane number. All OEMs prescribe the minimum methane number allowed in their gas specification. Consultations with gas engine manufacturers by DNV in the past have indicated that there is not yet much experience in the market with natural gas-hydrogen mixtures. Based on the currently known fuel gas specifications, engine manufacturers generally allow a maximum of between 0 and 5% hydrogen in the fuel gas for gas engines installed in the field. In some cases, OEMs indicated that their gas engines optimized for high efficiency are suited for hydrogen contents of around 10 – 15 vol% without derating. However, they note that the amount of hydrogen strongly depends on the current engine setting and on the methane number of the natural gas to which hydrogen is added.

For hydrogen percentages between 15-25%, potential issues according to OEMs include insufficient lambda control range, power loss, increased NO_x emissions, misfire, and engine knock. Above 25 vol%, complete retrofitting or replacement of the engine is often needed. The gas interchangeability analyses completed by DNV indicated that 0-22 vol% hydrogen does not result in an increased risk of the occurrence of engine knock, which is a broader range than suggested by the OEMs interviewed. It is noted that owners of gas engine equipment often have guarantee agreements with the manufacturer. Operation outside the fuel specification can lead to loss of guarantee, with costly consequences for both repair of gas engine damage and non-delivery of power. In this respect, we advise consulting the manufacturers when considering supplying gas engines with hydrogen-containing natural gas, and if necessary, discussing possible mitigating measures to increase the percentage of hydrogen in natural gas.

Mitigating measures for gas engines

There are several options to mitigate the risk of knock in the installed base of gas engines within the Gazifère network when adding hydrogen to the supplied natural gas. A summary of options is presented in Table 6-21.

The first potential mitigating measure is to readjust all critical engines such that they can accommodate the worst-case hydrogen-containing fuel and remain free of knock. Typically, this would involve a structural de-rate in power output. A rule of thumb is that engines require 1% power de-rate per methane number point below their methane number requirement. The disadvantage of derating is the structural loss in engine power output, possibly affecting the utility of the gas engine for its purpose. Moreover, fuel efficiency will typically also be reduced. Another option to prevent the occurrence of engine knock is to reduce the compression ratio of a given engine series by installing other pistons, allowing the normal power output to be retained, but still at the cost of a lower fuel efficiency.

An interesting alternative would be to have critical gas engines equipped with a feed-forward, fuel-adaptive engine control system, which is currently being researched. Using a gas composition sensor combined with a knock prediction model, this system provides real-time engine performance optimization in response to changes in fuel composition, allowing the engine to constantly deliver best-possible engine performance for the actual fuel gas quality. This approach avoids the need power derating and generates significant fuel cost savings as compared to derating or lowering the compression ratio.

To remain NO_x emission compliant, engines having lambda controllers need to be re-adjusted, i.e., have the lambda setpoint set fuel-leaner to accommodate hydrogen admixture. In the case of variable hydrogen admixture, the re-adjustment would need to be done for the maximum fraction of hydrogen expected. An alternative to re-adjustment would be to replace the lambda-sensor AFR control with an aftermarket AFR control of the speed-density type. The results are summarized in Table 6-21.

Table 6-21: Hydrogen percentages and mitigating measures for gas engines

Range H_2 (%)*	Issues	Mitigating measures
0-5%	No	No
5- 15%	Knock (shutting down, engine damage, increased wear and tear)	De-rating (efficiency and power loss) Lowering compression ratio (efficiency loss) Applying fuel flexible control
15-25%	Insufficient lambda control range (power loss, increase emissions, misfire, knock, etc.)	De-rating (efficiency and power loss) Lowering compression ratio (efficiency loss) Applying fuel flexible control Redesign gas engine (including fuel system and engine management system)
>25%	Insufficient lambda control range (power loss, increase emissions, misfire, knock, etc.)	Replacing gas engine

*The gas interchangeability analyses indicated that 0-6.7 vol% hydrogen is allowed based on methane number calculations for Gazifère's distribution gases (based on risk of engine knock). Therefore, it is recommended that Gazifère discuss with the OEMs whether a range of 0-15 vol% hydrogen is allowed.

6.6 Material Inventory Downstream of the Meter

In the Gazifère network, different types of end-users are present such as domestic, commercial, and industrial end-users. All these end-users have different types of material (piping, valves, etc.) installed through which the natural gas/hydrogen mixture will flow. The question is if hydrogen addition will impact the integrity of the materials downstream of the utility termination point compared to the situation in which only natural gas is distributed.

In general, end-users' equipment for natural gas meets requirements in the ASME Boiler & Pressure Vessel Code, which is the standard that regulates the design, development, and construction of boilers and pressure vessels utilized in a variety of industries. However, the ASME standard lacks information about natural gas/hydrogen mixtures. Therefore, a literature study was performed to investigate which materials are suitable.

Limited details of the specific materials and components downstream of the utility were provided by Gazifère. An inventory of materials used 'behind the gas meter' infrastructure and end-use equipment was made. Lists of (typical) materials used downstream of the utility termination point are presented in Table 6-22 (metals) and Table 6-23 (non-metals). [redacted]

The materials indicated in orange or red are affected by hydrogen. These materials do not experience failure ad hoc or at short-term usage, but rather have a decreased fracture resistance. This implies that the lifespan of the components decreases, and the integrity is no longer guaranteed in the long term. These materials are mostly affected by hydrogen embrittlement which decreases the fracture toughness. It is difficult to estimate how the lifetime of these components is affected. It will depend on material, shape, and thickness. Although the literature suggests that some materials are more prone to failure, this does not mean that failure will occur in reality. Thus far, DNV has not experienced component failure in practice when using hydrogen blends.

As illustrated in Table 6-22, the majority of the steel grades used in the gas infrastructure and end-use equipment in the industry and domestic market operating at pressures below 8 bar can handle up to 10 vol% hydrogen. The partial hydrogen pressures in the domestic market are much lower than pressures used in the industry, inducing relatively low-stress levels. Therefore, apart from cast iron, there are no issues expected with hydrogen blending (0-30 vol%) for the domestic market. For industry, when hydrogen percentages are above 10 vol% it is recommended to perform a more detailed assessment of the materials present in the industry.

As demonstrated in Table 6-23, non-metallic materials do not generally experience any interaction with hydrogen. Therefore, most non-metallic materials can be used when in contact with natural gas – hydrogen blends. Only silicone rubber shows a significant reaction with the hydrogen and is, therefore, not recommended for hydrogen use.

Table 6-22: Typical metallic materials downstream of the utility (Colours indicate suitability for hydrogen: Green suitable, Orange is maybe allowed, Red is not suited, Gray is not relevant, and Blue is unknown to our knowledge)

			Industrial, max 8 bar					Domestic, max ~1 bar				
		Hydrogen vol%	2%	5%	10%	20%	30%	2%	5%	10%	20%	30%
		Partial pressure H_2, bar	0.16	0.4	0.8	1.6	2.4	0.02	0.05	0.1	0.2	0.3
	Metal group	**Typical alloys**										
Ferrous alloys	Carbon steel YS<360 N/mm2	AISI 102, Grade A, B, X42, X52 and X70	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Ferrous alloys	Carbon steel YS=360 - 480 N/mm2		Green	Green	Green	Orange	Orange	Green	Green	Green	Green	Green
Ferrous alloys	Stainless steels	Austenitic: 304(L) and 316(L) Note: 316 preferred!	Blue	Blue	Blue	Blue	Blue	Gray	Gray	Gray	Gray	Gray
Ferrous alloys	Stainless steels	Ferritic: 409 and 444	Green	Green	Green	Red	Red	Gray	Gray	Gray	Gray	Gray
Ferrous alloys	Stainless steels	Martensitic: 410	Green	Green	Green	Red	Red	Gray	Gray	Gray	Gray	Gray
Ferrous alloys	Stainless steels	Precipitation hardening: 17-4PH	Green	Green	Green	Red	Red	Gray	Gray	Gray	Gray	Gray
Ferrous alloys	Stainless steels	Duplex: 2205 and 2507	Green	Orange	Orange	Orange	Orange	Gray	Gray	Gray	Gray	Gray
Ferrous alloys	Cast iron	ASTM A48/ ASTM A47	Blue	Blue	Blue	Blue	Blue	Green	Green	Green	Orange	Orange
Ferrous alloys	High strength steel (bolts)	Steel quality 8.8, 10.9 Not in contact with H2?	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Al	Aluminium (-alloys)	Aluminium (Al), AL 99,5, AL 99,8	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Cu	Copper (-alloys)	Copper (Cu), bronze, messing	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Other metals	Zinc plating	Zinc plated steel, zinc plated brass	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Other metals	Nickel (-alloys/plating)	Hastelloy C, Inconel, Alloy C-276	Green	Green	Green	Red	Red	Gray	Gray	Gray	Gray	Gray
Other metals	Transition metals	Platinum	Green	Green	Green	Green	Green	Gray	Gray	Gray	Gray	Gray
Other metals	Transition metals	Tantalum	Green	Green	Green	Red	Red	Gray	Gray	Gray	Gray	Gray
Other metals	Stellite	Stellite F	Orange	Orange	Orange	Orange	Orange	Gray	Gray	Gray	Gray	Gray
Other metals	Cobalt (super)alloys	X40, X45 FSX414	Orange	Orange	Orange	Red	Red	Gray	Gray	Gray	Gray	Gray
Other metals	Nickel (super)alloys	Hastelloy X, Alloy 706, Alloy 718	Orange	Orange	Orange	Red	Red	Gray	Gray	Gray	Gray	Gray
Other metals	Titanium alloys		Green	Green	Green	Orange	Orange	Gray	Gray	Gray	Gray	Gray

Table 6-23: Typical non-metals materials downstream of the utility (Colours indicate suitability for hydrogen: Green suitable, Orange is maybe allowed, Red is not suited, Gray is not relevant, and Blue is unknown to our knowledge)

					Industrial, max 8 bar				
				Hydrogen, vol%	2%	5%	10%	20%	30%
				Partial pressure H_2, bar	0.16	0.4	0.8	1.6	2.4
	Cat.	Polar?	Material group	Typical example(s)					
Polymers	Thermoplastic	No	Polytetrafluorethylene	Teflon, PTFE					
			Polyethylene	PE					
		Yes	Chlorotrifluoroethylene	CTFE					
			Polyethylene terephtalate	Dacron, Valox, PET					
			Polyamide based polymers	Vessel					
			Nylon	PA6.6					
			Polyether ether ketone	PEEK					
			Aramid						
			Polyvinylchloride	PVC					
	Tset	Yes	Epoxy						
	Rubber	No	Silicone rubber	highly permeable					
			Ethylene propylene	EPDM/EPR					
			Nitrile rubber	Buna-N, NBR					
			Chloroprene rubber	Neoprene					
			Fluor elastomers	FDM, FKM, Viton					
N-m			Lubricant	Dow corning Molykote 55 grease					
			Asbestos						
			Graphite						

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A list with examples of end-user components (provided by Gazifère) was analysed for hydrogen blending and results are illustrated in Table 6-24. The material properties of most components remain intact with hydrogen blending. The list also contains components with a black coating, such as the black pipe and the black pipe nipple. It is unknown what kind of coating is used for these pipes; therefore, it is impossible to estimate the compatibility with hydrogen blends. For some other components, detailed information on the type of steel used is lacking, therefore, it is difficult to estimate if they are suitable for hydrogen blending.

Besides the components shown in Table 6-24, other end-user components (like gas controllers for gas appliances) were investigated. These components are made of unspecified materials and most manufacturers are not keen on sharing detailed specifications of the used materials. Therefore, it is difficult to predict the integrity of such products when hydrogen is blended. One manufacturer of such components did reveal that the materials used in their gas regulators are suitable for hydrogen use:

> *Concerning our gas controllers: our most used gas valves are tested and certified for 100% hydrogen use and therefore also for natural gas – hydrogen mixtures. This means that all materials used in our gas controllers and valves are compatible with hydrogen without any adverse effects on the safety-, integrity or functional properties. Since the current European standards do not consider hydrogen applications (currently under development), there is*

no official CE approval. Instead, an inspection body issues a certificate for the relevant component stating it is suitable for hydrogen applications.

Most materials, piping, and components are compatible with hydrogen blending. A remaining uncertainty in this regard is the maximum temperature and the type of steel components in the fuel supply of gas turbines or engines, as well as piping and components with hardness above 237 HB [66]. It is recommended to study hydrogen blending above 30 vol% for future purposes. Furthermore, it would be of great value to perform practical experiments with materials, piping, or components that are affected by hydrogen. By cycling pressures slightly above the consumer (or industrial) deviations, the resistance against fracture can be investigated and the lifetime of these components can be determined.

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8.2 Mitigation Measures

8.2.1 Leak Detection

In the UK, the gas distribution networks identified early on in their research that the existing gas detection equipment that is used for first emergency response are cross sensitive to hydrogen. This relates to the CO element of the detector which activates when hydrogen is introduced to the gas mix. [120] Furthermore, the thermal catalytic and thermal conductivity sensors in the detectors produced a wide variability when exposed to 20% H2 blend. On average the lower explosion limit (LEL) and v/v readings were on average over reading 1.2 to 1.5 more. To overcome this issue for the UK blending trials, the gas distribution networks purchased two variants of gas detection equipment: one for CO and one for monitoring natural gas flammable ranges. [121] The trials identified the following two detectors as the most suitable:

- **GMI GS 700 flammable gas detector** – infrared device which does not contain a CO sensor. The presence of hydrogen for infrared devices is directly proportional to the hydrogen that is in the gas mix. Therefore, the project did a simple recalibration using the worst-case assumption that there would be a 20% blend. Whilst this meant the readings were on the conservative side for a blend lower than 20%, it allowed the gas distribution networks to maintain their current limits for leak detection action levels.
- **Drager X-am 5000 compensated CO detector -** The CO detectors in the gas distribution networks' existing gas detectors cannot be compensated to take into account the hydrogen content, which is why they alarm when exposed to H_2. The compensated detectors can be adjusted to take into account the additional signal of the hydrogen when a blend is introduced.

A defined number of the above detectors, based on the number of properties and historic publicly reported escapes in the trial areas were procured and stored in a location near to the trial area. First emergency responders were required to collect a pair of the detectors prior to investigating the public reported escape.

A combined CO and flammable gas detector which is not affected by the introduction of H2 has been developed by GMI and is currently be trialled.

8.2.2 Odorization

[redacted]

A recent study in the Netherlands [122] has shown that 100% TetraHydroThiopheen (THT), the standard odorant in the Netherlands, does not need any adaption of the dose in any blending case of hydrogen up to 100%. The same concentration of THT (18 mg/Nm^3) can be applied as for the natural gas reference system.

Within the UK gas distribution network, a two-part odorant known as Odorant NB is used, comprised of 78% TBM and 22% DMS. Research by DNV [123], looking specifically at blends up to 20%, identified that introducing hydrogen with natural gas can dilute odorant concentration, but does not cause a safety issue. Recommendations from this report identified that monitoring downstream of the injection point should be carried out using rhinology testing and a gas chromatograph to measure levels of odour intensity. Analysis of the increased odorant sampling validated the lab results where no 'noticeable' change in odour concentration was identified. These findings allowed the gas distribution networks in the UK to justify to the Health and Safety Executive (HSE – UK safety regulator) that no increased monitoring was required for Phase 2 of HyDeploy in the public network.

As part of further work for the H100 project [124], a range of odorants were assessed for their suitability within a 100% hydrogen network. Amongst these odorants, Odorant NB most closely matches Spotleak 1420 (with an injection rate of 6 mg/m^3) and TBM(79%)+IPM(15%)+NPM(6%) most closely matches Spotleak 1009 (with an injection rate of 16 mg/m^3). Both odorants were found to be suitable for the gas distribution network and end-use appliances for 100% hydrogen. However, it was noted in the report that both are unsuitable for use in fuel cell applications and, as such, further work is needed to consider any additional purification needed for fuel cells.

8.2.3 Purging

As part of Hy4Heat [125], the purge standards for UK domestic installations were reviewed to assess the validity of the standards following the introduction of blends or pure hydrogen into the domestic environment. The density difference between hydrogen and air is much greater than between natural gas and air. This may result in increased pocketing and stratification of the gas. This may be avoided by using higher purge velocities; however, due to the higher flame speed and wider flammability limits, there may be an increased risk in flame burn-back. Therefore, attempting to light the purged gas as a means of detecting the gas should be avoided.

8.3 Public Awareness

8.3.1 HyDeploy Project

Keele University commissioned social science research to understand public perception to hydrogen blends and what barriers if any there might be for adoption as part of the HyDeploy project. During Phase 1 the research was focused at Keele University (comprising 100 homes and 30 university buildings) and during Phase 2 at Winlaton (comprising 668 homes, a school, several small businesses, and a church). Consumers were engaged throughout the project, through a variety of in person and virtual methods. Although the demographic areas were very different, the findings were very similar, and it has been suggested by Keele University that the findings may be generalised for the whole of the UK [126]. The overall findings of the research are outlined below:

- High levels of acceptance of both hydrogen blends and new technologies to support climate change.
- Consumers shared their ‘pride’ at supporting a world first. This highlighted that a similar attachment could be present if blended hydrogen is rolled out to new locations.
- Low levels of understanding of hydrogen and the impacts or differences to natural gas.
- Public acceptance of hydrogen blending will be affected by cost. There is limited tolerance for an increase in cost to reduce household emissions.

Building on the work conducted by Keele, Newcastle University [127] conducted some research to help shape the consumer engagement of the trial area in Winlaton. The University developed a bank of questions which were used during face to face and online surveys of people from a similar demographic to the trial area. The research concluded that:

- The more informed people were with regards to the history of hydrogen rich towns gas being used as recently as the 1970’s and the fact that new gas appliances in the UK are tested with hydrogen and natural gas blends, the more amenable they would be to have the H2 blend in their home.
- Participants would be unwilling or unable to pay more for hydrogen blends if the costs were more expensive.

- 70% believed that blending hydrogen would have a positive impact on the environment.

8.3.2 H21 Project

Leeds Beckett University, along with members of the H21 team, conducted some research to investigate how communities and individuals would respond to the prospect of a 100% hydrogen conversion of the gas network. [128] A range of people of all ages, genders and socio-economic backgrounds in Leeds, Birmingham and Monmouthshire were interviewed to inform the questions within an online survey completed by respondents across the UK. This was followed by workshops in different locations with both members of the public and hydrogen experts. The key finding from this research was that generally there is support of a hydrogen conversion provided issues around the environmental benefits, safety, cost and disruption to the public are addressed.

9 SYSTEM WIDE MAXIMUM HYDROGEN BLENDING CONCLUSIONS

This section provides an overview of the results and recommendations from each area of analysis including, where applicable, identified maximum allowable hydrogen blending percentages based on the different areas of analysis.

Hydraulic Analysis of Gazifère Gas Distribution Network

Based on a 15 nominal vol% hydrogen blend, the total natural gas supply flow rate is decreased by 5.3%. The addition of hydrogen does not create any new local or global bottlenecks. [redacted] As a result, the amount of hydrogen received by each customer will vary from the defined level of blending.

Conceptual Design of Hydrogen Injection Facilities

[redacted] The design can be potentially applied across multiple locations if required, subject to minimal load differentials at the respective locations.

Assessment of Network Equipment, Components, and Materials

Table 9-1 summarizes the concerns for pipe of various pressure classes with varying amounts of hydrogen addition. The envisioned range of hydrogen blends (initially not greater than 20 vol% hydrogen) is likely to result in minimal integrity management concerns for steel pipe in the low-pressure class, and the associated PE pipe is also unlikely to be significantly mechanically affected. The effects on nonmetallic components other than PE pipe, such as leakage and increased wear, are likely to be more dramatic as hydrogen partial pressure increases.

The greatest susceptibility to hydrogen-related cracking is believed to be at crack-susceptible microstructures associated with hard fabrication welds and ERW seams. Guidance is provided in this report on prioritization of pipe sample collection and testing to determine if high risk metallurgical features are present. In addition, some alloys used in valves and other ancillary equipment (e.g., some stainless steels and high strength-low alloy steels) may be present in heat-treated conditions that make them susceptible to hydrogen embrittlement and cracking. Components that meet the requirements of NACE MR0175 or similar industry standards applicable to materials used in hydrogen sulfide service would be suitable (and conservative) for the envisioned hydrogen-blended natural gas service conditions. [redacted]

With regards to other materials present in the system, the acceptability of black malleable iron (BMI) in hydrogen-blended natural gas service varies by standard. It is considered prudent to replace these components with equivalent components using other materials noted as acceptable, prioritizing components in extra high pressure systems or components at higher risk of strikes or in areas of land movement. Components with a high potential to be under bending or other supplementary stresses, such as elbows or tees, are at a higher risk compared to those without these stresses, such as caps and plugs.

Table 9-1: Summary of Integrity Management Concerns for Various Combinations of Pipe Pressure and Hydrogen Content

Hydrogen Content in Gas (Vol%)	MOP, kPa (psi)			
	3.5 (0.5)	440 (64)	1207 (175)	3206 (465)
<5%	No concern	No concern	No concern	Note 2
5%	No concern	No concern	No concern	Note 3
10%	No concern	No concern	Note 3	Note 4
15%	No concern	Note 1	Note 3	Note 4
20%	No concern	Note 1	Note 3	Note 4
30%	No concern	Note 2	Note 4	Note 4
50%	No concern	Note 3	Note 4	Note 5
75%	No concern	Note 3	Note 4	Note 5
100%	No concern	Note 3	Note 5	Note 5

Note 1: Some potential for minor embrittlement, likely less than 20-30% reduction of fracture toughness. Some related reduction in critical flaw size for failure of crack-l ke flaws. Flawed, hard seams and weld zones are most at risk of failure. Low operating stresses minimize the l kelihood of rupture.

Note 2: Potential for minor reduction of fracture toughness. Possibly some minor related reduction in critical flaw size for failure of crack-like flaws. Flawed, hard seams and weld zones are most at risk of failure.

Note 3: Potential for up to about 30% reduction of fracture toughness, but low operating stresses minimize the likelihood of long ruptures. Flawed, hard seams and weld zones are most at risk of failure.

Note 4: Potential for up to about 30% reduction of fracture toughness. Some related reduction in critical flaw size for failure of crack-like flaws. Hard seams and weld zones are most at risk of failure. Minimal likelihood of long rupture for pipe stressed to less than 20% SMYS. Very long flaws are required for rupture of piping that operates between 20% and 30% SMYS. Greater suscept bility to accelerated FCGR compared to pipe at lower stress levels. Some small potential for failure of embrittled, crack-susceptible microstructures that are highly stressed by external forces, especially if planar flaws are also present.

Note 5: Same as note 4 except that toughness could be reduced by up to about 50% for some steels.

Assessment of End Use Equipment

Table 9-2 summarizes the maximum allowable hydrogen percentage based on the gas interchangeability analysis performed for the categories of appliances identified in the Gazifère system. To provide insights into how the maximum percentages found in the gas interchangeability analyses relate to experimental data on appliances, DNV compared the results of the gas interchangeability analyses with publicly available experimental data from DNV's work and data found in literature. This review highlighted that the results of available studies are conflicting and are complicated by the fact that the studies performed do not all account for all major failure modes (including long term effects). In addition, the range of hydrogen blending tested varies among the different studies. As a result, DNV has recommended a priority ranking of domestic and commercial appliances to be tested based on the availability of information and the potential impact of hydrogen addition on the end-use equipment (see Section 6.4.3).

Table 9-2: Maximum allowable hydrogen percentage based on the interchangeability analysis

	Heat input (Wobbe), vol% H_2	Flashback/ overheating partially premixed, vol% H_2	Flashback/ overheating fully premixed, vol% H_2	Engine knock, vol% H_2
Distribution Maximum	26.8	9.6	~30-40	6.7
Distribution Minimum	21.7	8.0	~30-40	18.9
Distribution Average	24.3	8.4	~30-40	14.6

For the industrial processes a differentiation is made between indirect (e.g., steam and hot water production) and direct (e.g., glass melting) processes. For indirect heating processes, DNV does not expect major performance issues for up to 20 vol% hydrogen in natural gas when the Wobbe index of the gas is within the specifications of the traditional distributed gases. For higher percentages, addition research is recommended to prevent overheating of the burner deck, flash back and increase in NOx emission. To keep the power output and the air factor constant upon hydrogen addition an adaptive fuel-control system is recommended. Furthermore, we recommend applying (external) flue gas recirculation to mitigate the effect of hydrogen addition on NOx emissions.

For direct heating processes, the main concerns are the change in burner load, air factor, heat transfer, increase in the NO_x emissions, changes in flame length, and the shift of the hot flame zone closer to the burner surface upon hydrogen addition. Where the NO_x emissions from the installed natural gas burners are far below the legal NO_x limits, DNV does not expect major performance issues with up to 20 vol% hydrogen for the burners studied.

Hydrogen Blending Risk Assessment – Sample Calculations

For the base case reviewed, the change in location specific risk (LSR) and Individual Specific Individual Risk (ISIR) following the introduction of hydrogen is small in comparison to the difference in risk due to the pipe material; the risk is highest when the property is located close to the main. In addition, the following results were obtained:

- The risk of fires decreases, and the risk of explosions increases with increasing hydrogen blend. For larger diameter pipes, this decrease in fire risk outweighs the increase in explosion risk resulting in an overall decrease in risk as a result of introducing hydrogen.
- The change in risk due to pipe material outweighs any change in risk as a result of introducing hydrogen.
- Increasing the operating pressure increases the risk for both natural gas and hydrogen blends.
- The semi-detached house and multi-attached building show the largest increases in risk when changing from natural gas to 10 vol% or 20 vol% hydrogen blend due to the additional risk from explosions occurring within the attached dwelling(s), increasing the explosion risk level experienced by the house being analysed.
- In order of highest risk to lowest risk, the dwelling types are ranked from multi-attached building, semi-detached house, detached house, and finally bungalow.
- The finished basement shows the largest increases in risk when changing from natural gas to 10 vol% or 20 vol% hydrogen blend. Furthermore, the overall risk is greater for the finished basement than the unfinished basement. This is due to the unfinished basement essentially being one unoccupied large room, whereas the finished basement consists of a number of smaller occupied rooms.

Additional Risk and Safety Considerations

Hydrogen blending in natural gas pipelines leads to a number of additional risk and safety considerations due to the physical behaviour of hydrogen, limitations of existing procedures and equipment, and public awareness considerations.

Due to the physical behaviour of hydrogen, the addition of hydrogen results in a lower mass flow rate but a higher volumetric flow rate in the case of a leak. This will produce a larger flammable cloud outdoors or reach a flammable concentration within a building more quickly. Using a correlation based on the pressure within the pipe and the square of the diameter of the hole the ignition probability for both blends and pure hydrogen will be higher than for an equivalent natural gas pipeline.

Based on previous experiments, immediate ignition following the rupture of a high pressure pipeline transporting blends or pure hydrogen would result in thermal incident radiation levels with distances similar to those experienced for equivalent natural gas releases. Limited experimental data indicates that for hydrogen, the potential for significant overpressures to be generated by delayed ignition of the unconfined gas cloud is greater than for natural gas. However, the impact of this on the level of risk is uncertain and part of ongoing experimental programmes on the ignition behaviour of hydrogen following a release.

Consideration should be given to the potential impacts of hydrogen blends on leak detection, odorization, purging, and public awareness. Existing gas detection equipment is cross sensitive to hydrogen, so consideration must be given to equipment compatibility with hydrogen blends. A number of odorants have been found to be suitable for the gas distribution network and end-use appliances up to 100% hydrogen, which should be compared against the odorants currently in use.

Summary

Table 9-3 below provides an overview of the main areas of concern for system wide hydrogen blending within the Gazifère network, along with a summary of the main recommendations from each area of analysis to reach 15 vol% hydrogen blending.

Table 9-3: Areas of Concern and Recommendations to Reach 15 vol% Hydrogen Blending

Area of Analysis	Areas of Concern	Recommendations
3 Hydraulic Analysis of Gazifère Gas Distribution Network	A non-uniform level of hydrogen blending will occur throughout the network in the high demand operational scenario due to injection hydrogen at only one of two natural gas supply locations. As a result, the amount of hydrogen received by each customer will vary from the defined level of blending.	• Update modelling if blends above 15 vol% H2 are targeted • Develop means to ensure hydrogen uniformity if required
4 Conceptual Design of Hydrogen Injection Facilities	• DNV has produced a single conceptual design that can be potentially applied across multiple locations on the network. If, however, there are significant load differentials requirements within the network, then this will require revaluation to assure the applicability of this design. [redacted] • The conceptual design scope of work excludes the following items, which should be included for the proposed site at a later stage: o Environmental Assessments such as Geotechnical Assessments, Ground Movement Assessments, Archaeological, Mining, SSI's, Topographical survey data reviews, etc, for the proposed site to be used. o Routing of pipelines and identification of potential location(s) for the Hydrogen Blending, Injection and Control Station (HBICS), including evaluation of Building Proximity Distances (BPD), Area Classifications and Safety Distances.	• Assessment of Location of HBICS considering BPD, Area Classifications and Safety Distances • Assessment of Civil Engineering Requirements for the proposed HBICS Site • Environmental Assessments including Geotechnical Assessments, Ground Movement Assessments, Archaeological, Mining, SSI's, Topographical survey data reviews, etc., for the proposed site to be used

Area of Analysis	Areas of Concern	Recommendations
	○ All requirements related to the Civil engineering discipline including foundations, earthworks, ground conditions, fencing, etc. ○ Equipment/component sizing for the storage of hydrogen within the blend site.	
5 Assessment of Network Equipment, Components, and Materials	• Reduction of fracture toughness occurs in steel pipelines at varying levels of blending depending on the operating pressure. • There is uncertainty concerning the potential presence of high risk metallurgical features (such as crack-suscept ble microstructures associated with hard fabrication welds and ERW seams) and anomalies (such as gouges and cracks). • Presence of black malleable iron. • There is the potential for hydrogen leakage at threaded connections and mechanical seals; however, this will be comparable to natural gas leakage at less than 20 vol% hydrogen. • Turbine, rotary, and ultrasonic flow meters require calibration for blending up to 20 vol% hydrogen. • Valve energy flow capacity decreases with increasing hydrogen blending.	• Pipe sample collection and testing [redacted] • Removal of black malleable iron in highly stressed locations • Consider network conditions and impact of valve energy flow capacity decrease
6 Assessment of End-Use Equipment	• There is a blending limit of 6.7 vol% hydrogen for home backup generators and 8.0% for pre-mixed appliances based on the gas interchangeability analysis. • There is contradicting or missing information from literature to justify operation outside of the gas interchangeability envelope. There is also a lack of information regarding the long term effects of hydrogen blending on appliance integrity. [redacted] • There is uncertainty around the effects of hydrogen on select materials that appear downstream of the meter, including steels with a hardness above 237 HB.	• Appliance testing program • Industrial burner pilot test • Further investigation of the effect of hydrogen on materials downstream of the meter where impact is unknown
7 Hydrogen Blending Risk Assessment	Location specific risk, although slightly higher due to hydrogen addition, is more greatly impacted by pipe material and distance of the main from buildings than hydrogen blending percentage (up to 20 vol%).	Conduct a detailed risk assessment specific to the Gazifère system.
8 Additional Technical and Safety Considerations	Limited experimental data indicates that for hydrogen, the potential for significant overpressures to be generated by delayed ignition of the unconfined gas cloud is greater than for natural gas. The impact of this on the level of risk is uncertain and part of ongoing experimental programmes on the ignition behaviour of hydrogen following a release.	Consideration should be given to the potential impacts of hydrogen blends on leak detection, odorization, purging, and public awareness.

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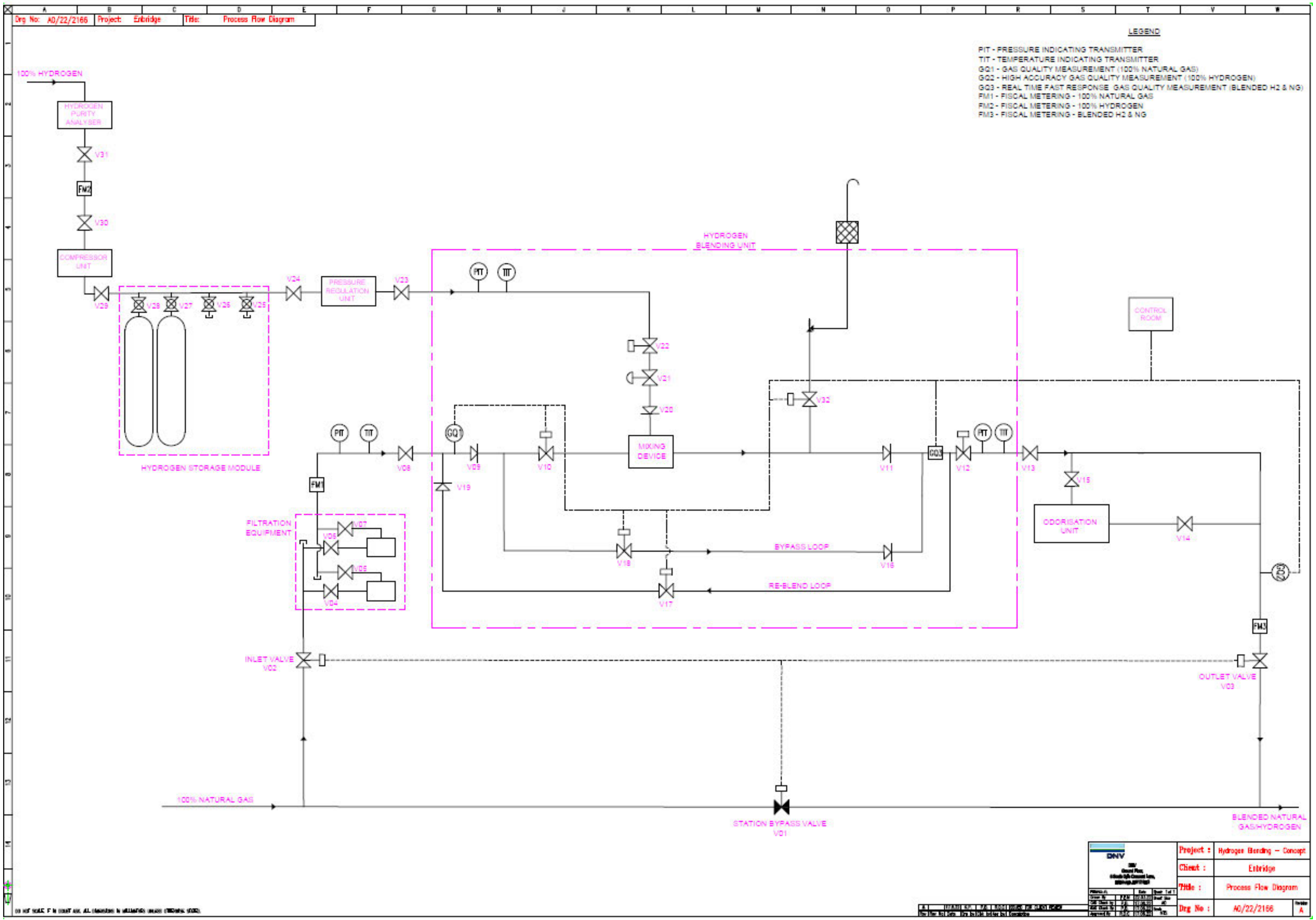
APPENDIX 4: HBICS PFD AND GENERAL ARRANGEMENT DRAWING



Drg. No: A0/22/2166
Project: Enbridge
Title: Process Flow Diagram
LEGEND
PIT - PRESSURE INDICATING TRANSMITTER
TIT - TEMPERATURE INDICATING TRANSMITTER
GQ1 - GAS QUALITY MEASUREMENT (100% NATURAL GAS)
GQ2 - HIGH ACCURACY GAS QUALITY MEASUREMENT (100% HYDROGEN)
GQ3 - REAL TIME FAST RESPONSE GAS QUALITY MEASUREMENT (BLENDED H2 & NG)
FM1 - FISCAL METERING - 100% NATURAL GAS
FM2 - FISCAL METERING - 100% HYDROGEN
FM3 - FISCAL METERING - BLENDED H2 & NG
100% HYDROGEN
HYDROGEN PURITY ANALYSER
V31
FM2
V30
COMPRESSOR UNIT
V29
V28
V27
V26
V25
HYDROGEN STORAGE MODULE
V24
PRESSURE REGULATION UNIT
V23
HYDROGEN BLENDING UNIT
PIT
TIT
V22
V21
V20
MIXING DEVICE
GQ1
V08
V09
V10
V19
FM1
V32
V11
GQ3
V12
V13
V15
CONTROL ROOM
ODORISATION UNIT
V14
FILTRATION EQUIPMENT
V07
V06
V05
V04
V18
BYPASS LOOP
V16
V17
RE-BLEND LOOP
GQ2
FM3
INLET VALVE V02
OUTLET VALVE V03
100% NATURAL GAS
STATION BYPASS VALVE V01
BLENDED NATURAL GAS/HYDROGEN
Project : Hydrogen Blending – Concept
Client : Enbridge
Title : Process Flow Diagram
Drg No : A0/22/2166
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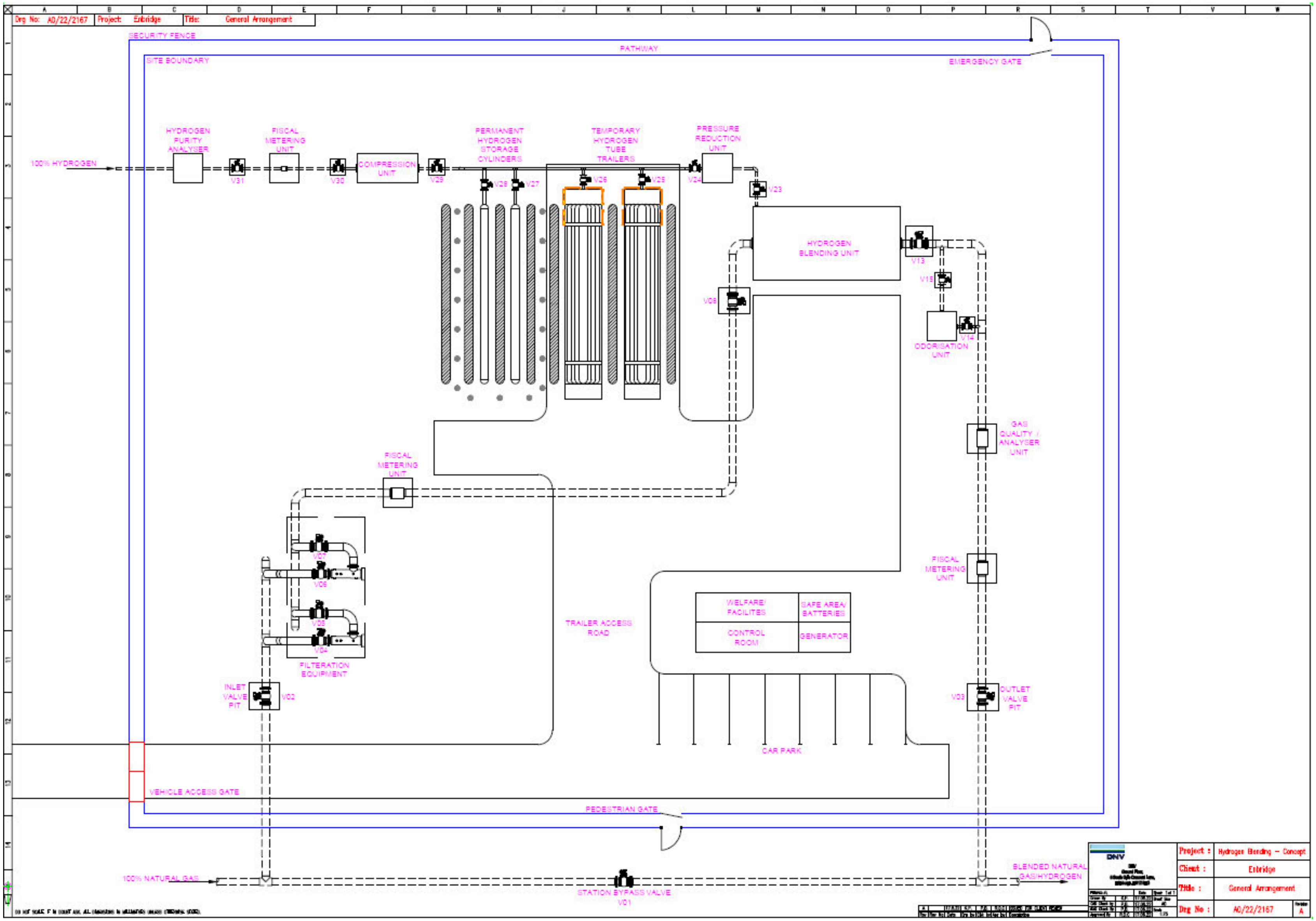

Drg No: A0/22/2167
Project: Enbridge
Title: General Arrangement
SECURITY FENCE
PATHWAY
SITE BOUNDARY
EMERGENCY GATE
100% HYDROGEN
HYDROGEN PURITY ANALYSER
V31
FISCAL METERING UNIT
V30
COMPRESSION UNIT
V29
PERMANENT HYDROGEN STORAGE CYLINDERS
V28
V27
TEMPORARY HYDROGEN TUBE TRAILERS
V26
V25
PRESSURE REDUCTION UNIT
V24
V23
HYDROGEN BLENDING UNIT
V13
V15
V08
V14
ODORISATION UNIT
GAS QUALITY / ANALYSER UNIT
FISCAL METERING UNIT
V07
V06
V05
V04
FILTERATION EQUIPMENT
INLET VALVE PIT
V02
TRAILER ACCESS ROAD
WELFARE/ FACILITIES
SAFE AREA/ BATTERIES
CONTROL ROOM
GENERATOR
V03
OUTLET VALVE PIT
CAR PARK
VEHICLE ACCESS GATE
PEDESTRIAN GATE
100% NATURAL GAS
STATION BYPASS VALVE V01
BLENDED NATURAL GAS/HYDROGEN
DNV
Project : Hydrogen Blending – Concept
Client : Enbridge
Title : General Arrangement
Drg No : A0/22/2167
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APPENDIX 5: PIPE SAMPLE COLLECTION AND TESTING GUIDANCE

Pipe Sample Collection and Testing Guidance (Note 1)

Type of Sample	Test	Test Procedure	Required/Optional
Any pipe with design pressure >1000 kPa and hoop stress >10% SMYS at MOP	Metallographic cross section through seam	Note 2	Required
	Hardness test on cross section	Note 3	Required
	Charpy impact	Note 4	Required
	Chemical analysis	Note 6	Required
	Tensile test	Per CSA Z245.1 section 7 and 8 requirements	Note 7
	Fracture toughness (CTOD or SENT) testing	Per ASTM E1820	Optional (mainly useful for H2 contents well above 5%)
Any pipe sample containing welded repairs, welded hot taps, or any other weld made while the piping was in-service	Overall photographs showing joint configuration and dimensions and weld workmanship	None	Required
	Metallographic cross section	Note 8	Required
	Hardness tests on cross section	Note 8	Required
Any pipe sample containing a girth weld made during construction	Metallographic cross section	Note 9	Required
	Hardness test on cross section	Note 10	Required
	Charpy impact	Note 11	Note 12
	Fracture toughness (CTOD or SENT) testing	Per ASTM E1820	Optional (mainly useful for H2 contents well above 5%)
Pipe suspected of having CW seams	Seam flattening test	Note 13	Required
	Metallographic cross section	Note 14	Optional

Note 1: The priority is on collection and testing of samples from pipelines operating at greater than 20% SMYS (i.e., XHP pressure class piping). However, if those samples are unavailable then similar pipe from lower pressure areas of the system can be substituted if they are believed to be representative of XHP class piping (i.e., having similar age, grade, and seam type)

Note 2: Polished and etched (Nital etch) with the following photographic images:

- Overall macro showing entire cross section of seam area
- 100X of seam fusion line near OD and near ID
- 300 to 400x of fusion line and coarse grained heat affected zone adjacent to fusion line near OD and near ID

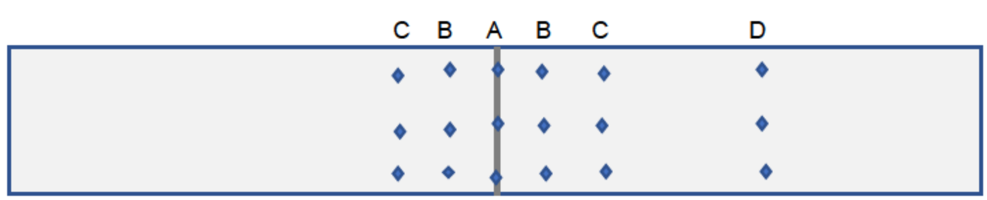
Note 3: 10 kg Vickers at locations shown here:

Location A: seam fusion line at midwall and at 1.5 mm from ID and OID surfaces

Location B: 0.75 mm from seam fusion line at midwall and at 1.5 mm from ID and OD surfaces

Location C: 1.5mm from fusion line at midwall and at 1.5 mm from ID and OD surfaces

Location D: Outside of visible heat affected zone at midwall and at 1.5 mm from ID and OD surfaces



Note 4: Transverse Charpy test specimens tested at design temperature, normal operating temperature, and operating temperature + 55 deg. C. 2 specimens at each temperature. Report Charpy specimen, size, measured energy (J) and %shear. Notch to be located at fusion line if ERW seam is present, with additional set of impact specimens in base metal remote from seam HAZ. Replicate specimens also tested in base metal remote from seam.

Note 5: Determined on a case-by-case basis depending upon the results of metallographic images and hardness test results

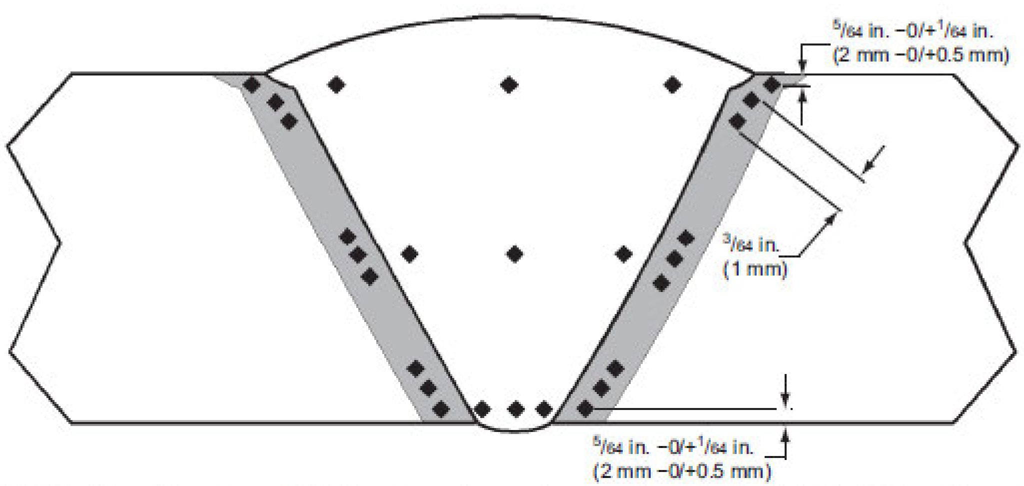
Note 6: Chemical analysis for C, Mn, Si, S, P, Ni, Cr, Mo, Cu, V, Ti, Nb, Al, B, reported to nearest 0.001% and measured after removal of at least 0.25 mm (0.01 in.) from the surface on which measurements will be made. Note whether measurements are made on an ID or OD surface vs. being made on a cross sectional view.

Note 7: Base metal tensile test. Required, for Grade X52 or higher. Optional for other grades

Note 8: To be determined based on specific sample configuration

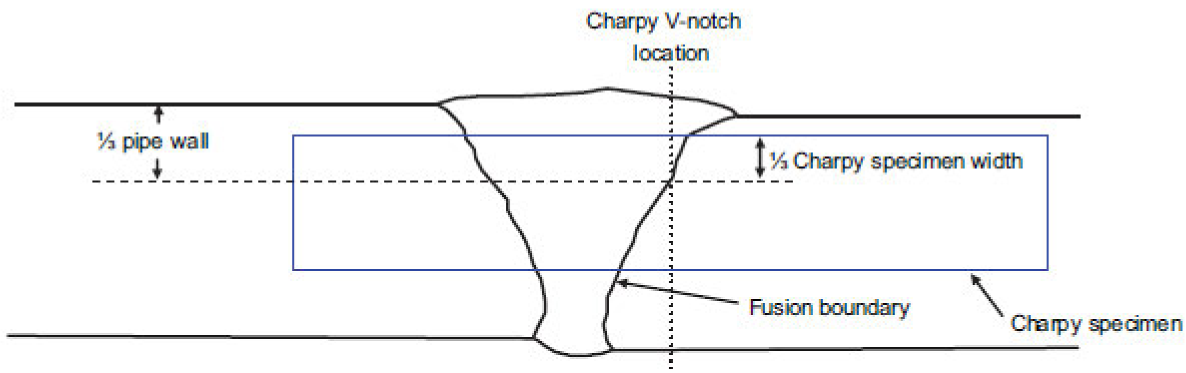
Note 9: Photomacrograph showing overall cross-sectional view to illustrate weld zone dimensions and workmanship. The preferred circumferential location of the cross sections is at 3:00 (or 9:00) and near 6:00. Of these two locations, 3:00 (or 9:00) is required and 6:00 is optional.

Note 10: 10 kg Vickers hardness on each cross section with measurements located as shown below.



NOTE Heat-affected zone (HAZ) hardness impressions must be entirely within the HAZ and located as close as possible to the fusion boundary (between the weld metal and HAZ).

Note 11: Longitudinal Charpy impact specimens with notches located at weld deposit centreline and, as shown below, at coarse-grained Heat Affected Zone



Note 12: Required for some samples. Applicability to be determined based upon pipe diameter, pressure, and steel composition

Note 13: Flattening tests do not normally apply to butt weld (CW) pipe but can be useful indicators of weld seam quality. Perform the test per CSA Z245.1, but after examining the pipe at 50% of original diameter, continue flattening until completely flat and reinspect for evidence of seam flaws. Photograph flaws to show dimensions.

Note 14: Nital etch with the following images:

1) Overall macro showing entire cross section of seam area

2) 100X of seam fusion line near OD and near ID

APPENDIX 6: EXAMPLES OF BURNERS PRESENT IN ‘OTHER’ EQUIPMENT IN CANADA

Pool burner 1

Pool burner 2

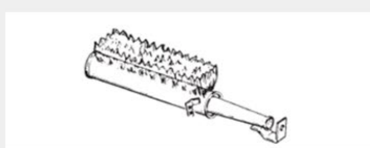
Fryer burner 1

Commercial laundry dryer

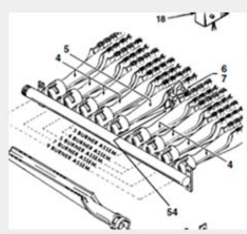
BBQ burners (tube/line/ribbon burners)

Patio heater burner (round type)

Pancake burner



Tube burner



Slit/slot burner

In-shot burner

Salamander grill

Napoleon radiant burner

Space heater

Furnace

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APPENDIX 9: DISTRIBUTION GAS COMPOSITIONS USED IN GAS INTERCHANGEABILITY ANALYSIS

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APPENDIX 11: APPLIANCE TESTING PROGRAM METHODOLOGY

Partially premixed appliances (containing tube and slit/slot burners)

As illustrated in Figure 6-17 and Figure A1, the Wobbe index changes upon hydrogen addition, decreasing for hydrogen percentages up to 70-80 vol%. Since the thermal input to a gas appliance is directly proportional to the Wobbe index, the thermal input will also decrease for the same range of hydrogen addition to natural gas. Another result of the addition of hydrogen to natural gas is the increase in the excess air. At hydrogen percentages above 75-85 vol%, the Wobbe index increases, resulting in an increase in the thermal input.

Hydrogen blending outside the legal Wobbe index limits is not realistic. Therefore, two tests are proposed: 1) hydrogen blending to methane resulting in a change in the Wobbe index and 2) hydrogen blending at the lower end of the legal Wobbe limit (W=47.24 MJ/m^3) while keeping the Wobbe Index constant, which is worst case for partially premixed appliances.

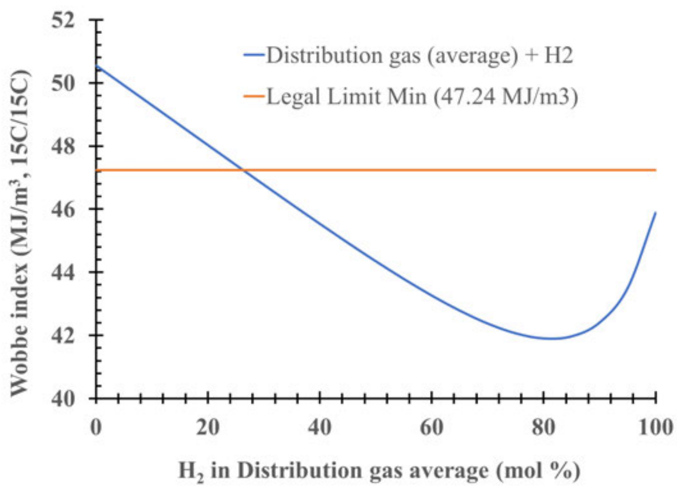

Figure A11-0-1: Effect of hydrogen addition to distribution gas (average) on the Wobbe index

During the experiments, hydrogen will be gradually added to natural gas until malfunctioning of the equipment occurs (e.g., flashback or (visual) deterioration of the burner deck, etc.). If no issues occur, blending will be performed up to approximately 90 vol% hydrogen in natural gas.

The following tests are recommended:

- Blending in hydrogen at 'steady state' condition (gradually increasing the hydrogen percentage with steps of 5-10 vol% hydrogen).
- Fast/abrupt changes in hydrogen percentage.
- Cold start and reignition with a high percentage (e.g., 50 vol%) hydrogen in natural gas.

During cold start experiments, DNV performs the tests with a parallel burner in operation connected to the same fuel supply line as the appliances studied to guarantee that the fuel in supply line is flowing (refreshed) and that the correct blend is used during the cold start experiments. The natural gas/hydrogen percentage is controlled with calibrated flow meter controllers and is checked with a calibrated GC.

It is recommended that the following performance parameters be studied:

- Burner deck temperatures

- Emissions: monitoring CH_4, H_2, O_2, NO_x, and CO in the flue gas
- Flame detection system: flame ionization measurements and/or voltage thermopile
- Visualization of flame structure
- Radiation flux measurements (in the case where a gas fireplace will be studied)

Home Backup Generators

The backup generators present in Canada contain gas engines. Since no experimental information is available for the impact of hydrogen addition on home backup generators, it is recommended that the performance of home backup generators outside the gas interchangeability envelope be tested.

Gas engines are known to be sensitive to unwanted engine knock, which is spontaneous autoignition of the unburned, compressed fuel/air mixture during the engine cycle. Hydrogen addition is known to lower the knock resistance and, thus, increases the risk of the occurrence of engine knock. It is recommended that hydrogen blending tests be performed with different natural gas blends, including a rich natural gas (high fractions of higher hydrocarbons) having the lowest knock resistance (worst case) and a lean natural gas having a high knock resistance (best case).

During experiments, hydrogen should be gradually added to natural gas until malfunctioning of the gas engine. The following tests are recommended:

- Blending in hydrogen at 'steady state' condition (gradually increasing the hydrogen percentage with steps of 5-10 vol% hydrogen).
- Fast/abrupt changes in hydrogen percentage.
- Engine start and stop using high blending ratios, for example 50 vol% hydrogen in natural gas.

It is recommended that the following parameters be tested:

- Peak pressure during hydrogen blending
- The engine knock limit
- Power output
- Emissions (NO_x, CO, C_xH_y, H_2)
- Effect of increased water content in the combustion products on lubrication oil. The lube oil degradation is studied by analysis of the chemical composition of oil samples taken over a long time period. The analysis also reveals any changes in wear-and-tear of the engine as a result of hydrogen admixing (high temperature and pressure inside the cylinder) as compared to an engine running on natural gas only.
- Crank case safety, by analysing gas samples from the crank case. The presence of hydrogen in the crank case may lead to increased risk of crank case explosions.
- Possible fuel efficiency gains when using hydrogen.

Test Program for Long Term Performance and Integrity

Data obtained in the literature show that hydrogen addition can result in an increase in the burner deck temperature for partially premixed appliances such as conventional hot water heaters and furnaces, gas fireplaces, and ranges. The increase in burner deck temperature may cause higher thermal stress and can ultimately result in damage (e.g., crack formation) within the lifetime of the burner. The results show that the temperature increase strongly depends upon the type of appliance studied and several papers indicate that the increase in burner temperature can impact the lifetime of the burner; however, no quantitative information is given.

To gain insight into the long-term effects of the increased burner deck temperatures, it is recommended that the long-term effects of hydrogen blending be studied for the equipment types that have been shown to be most sensitive to hydrogen blending. The selection of the appliances should be based on the information from the literature review and the data obtained in the test program described above.

The test program for long term performance and integrity aims to assess the impact of 30 vol% hydrogen blending on the appliance performance within the appliance lifetime of ~15-20 years. Based on DNVs experience with long term appliance testing for biomethane, DNV proposes a test period of 6 months during which the appliance is tested with a fixed hydrogen percentage (>30 vol% H_2; value to be determined) to allow extrapolation of the data to 15 years of operation. During the tests, the burner deck temperature should be monitored, emissions should be measured, and the burner deck should be visually inspected and compared with a reference test using natural gas (without hydrogen).

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About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analyzing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

Driven by its purpose, to safeguard life, property, and the environment, DNV helps tackle the challenges and global transformations facing its customers and the world today and is a trusted voice for many of the world's most successful and forward-thinking companies.