



BSI Standards Publication

Gas infrastructure — Consequences of hydrogen in the gas infrastructure and identification of related standardisation need in the scope of CEN/TC 234

National foreword

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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Gas infrastructure - Consequences of hydrogen in the gas infrastructure and identification of related standardisation need in the scope of CEN/TC 234

Infrastructure gazière - Conséquences d'hydrogène dans l'infrastructure gazière et l'identification des besoins relatifs à la normalisation dans le domaine d'application de CEN/TC 234

Gasinfrastruktur - Auswirkungen von Wasserstoff in der Gasinfrastruktur und Identifikation des zugehörigen Normungsbedarfs im Zuständigkeitsbereich des CEN/TC 234

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European foreword

This document (CEN/TR 17797:2022) has been prepared by Technical Committee CEN/TC 234 “Gas infrastructure”, the secretariat of which is held by DIN.

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Introduction

The injection of hydrogen in natural gas infrastructures demands considerations with regard to the integrity, safety and performance of the systems facing increasing hydrogen levels, its fluctuation and variation.

There is extensive research on the use of hydrogen as an admixture with natural gas in various percentages or as pure hydrogen. Impact studies already completed or in progress are focusing on the use of existing gas networks but also of dedicated gas networks for hydrogen. They also include the impact of the introduction of hydrogen in various percentages into the gas infrastructure on all the existing technologies within the gas supply chain.

Accepting hydrogen into the natural gas network requires input from many gas TCs at CEN, i.e. CEN/TC 234 and particularly from the manufacturers of essential components, e.g. valves, gas pressure regulators, gas meters, safety control devices, leak detection devices, and many more (see Annex A). Many of these manufacturers are assessing the potential impact of hydrogen on existing components in natural gas service.

Co-operation with these other CEN and ISO/TCs for various essential components and applications will be necessary to ensure that projects to introduce hydrogen have all the essential elements of the gas chain fully co-ordinated into the plan. The positive co-operation of the component manufacturers will be particularly important.

In the transition scheme to hydrogen, there is a large body of knowledge and experience available from the hydrogen industry for gas production and use. The long-established safety requirements in this sector will aid the amendment of natural gas standards and codes of practice and the development of any new standards

This report is written for

- CEN/TC 234 as basis for definition of a TC roadmap for standardisation
- CEN/TC 234 WGs as a guideline for the standardisation work
- interested parties to get an insight in the decision process of CEN/TC 234's hydrogen standardisation.

NOTE This document has been elaborated in co-operation between the Working Group convenors, secretaries and experts, TC chair and secretariat of CEN/TC 234. Respecting different working group contributions, the way in which the content is presented and the level of details differs for the different topics. This is acceptable as the real technical work will take place in the dedicated working groups with co-ordination of the TC 234 Convenors/Secretaries group to ensure the final coherence of the resulting standardisation deliverables.

1 Scope

This document is written in preparation of future standardization and provides guidance on how injection of H₂ into the gas infrastructure can impact processes from the input of gas into the on-shore transmission network up to the inlet connection of gas appliances.

NOTE 1 Gas infrastructure includes gas installation pipework between the delivery point of the gas and the inlet connection to the gas appliance in buildings and on industrial sites.

The assessments refer to the concentrations of 2, 5, 10, 20 and up to 100 Vol.- % hydrogen in natural gas.

Furthermore, it identifies the expected revision need of the existing CEN/TC 234 standards as well as the need of further new standardisation deliverables.

It examines the effects on each part of the gas infrastructure in the scope of the CEN/TC 234 Working Groups 1 to 12 inclusive, based on available studies, reports and research. Due to several limitations at different hydrogen concentrations, the impacts are specified.

For some specific impacts, pre-standardization research is needed.

By convention, for this technical report, the injection of pure hydrogen, i. e. without trace and/or minor components is considered. Awareness is given that there is the need to consider trace and/or minor components and limits set on the gas quality on European and national level, too.

The information from this report is intended to define the CEN/TC 234 work program for the coverage of H₂NG in relation to the scope of the CEN/TC 234 and its WGs.

NOTE 2 Progress on hydrogen will develop over time. In principle this will be reflected in the standardisation process in CEN/TC 234.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviations

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

The International Gas Union glossary on Underground Gas Storage [1] can be useful too:

3.1 Terms and definitions

3.1.1

hydrogen embrittlement

HE

interaction of hydrogen atoms and steel can have a negative effect on the mechanical behaviour of steel.

Note 1 to entry: The general term for this degrading effect is called hydrogen embrittlement

3.2.2

explosive atmosphere

mixture with air, under atmospheric conditions, of flammable substances in the form of gases, vapours, mists or dusts in which, after ignition has occurred, combustion spreads to the entire unburned mixture

[SOURCE: EN 13723:2013, 3.28]

3.2.3

hazardous explosive atmosphere

explosive atmosphere present in such quantities that precautions against ignition are required

[SOURCE: IEC 61340-4-4:2018, 3.6]

3.2.4

hazardous area

area in which an explosive atmosphere is present, or can be expected to be present, in quantities such as to require special precautions for the construction, installation and use of equipment

[SOURCE: IEC 60079-0:2013]

3.2.5

explosion group

ranking of flammable gas-air mixtures with respect to the Maximum Experimental Safe Gap (MESG)

[SOURCE: EN ISO 16852:2016, 3.12.2]

3.2.6

temperature class

temperature range used for:

- classification of equipment, protective system for explosive atmospheres based on its maximum surface temperature; or
- classification of flammable gases and vapours based on their auto ignition

[SOURCE: EN 13237:2012, 3.63]

3.2.7

explosion pressure

highest pressure occurring in a closed vessel during the explosion of a specific mixture of flammable substances with air or air and inert gases determined under specified test conditions

[SOURCE: EN 15967:2011]

3.2.8

ignition temperature

lowest temperature (of a hot surface) at which under specified test conditions an ignition of a flammable gas or flammable vapour in mixture with air or air/inert gas occurs

[SOURCE: EN 14522:2005]

3.2.9**limiting oxygen concentration****LOC**

maximum oxygen concentration in a mixture of a flammable substance and air and an inert gas, in which an explosion will not occur, determined under specified test conditions

[SOURCE: EN 13237:2012, 3.49]

3.2.10**lower explosion limit****LEL**

lowest concentration of the explosion range at which an explosion can occur

[SOURCE: EN 13237:2012, 3.19.1]

3.2.11**maximum experimental safe gap****MESG**

maximum gap of the joint between the two parts of the interior chamber of a test apparatus which, when the internal gas mixture is ignited and under specified conditions, prevents ignition of the external gas mixture through a 25 mm long joint, for all concentrations of the tested gas or vapour in air

[SOURCE: EN 13237:2012, 3.51]

3.2.12**maximum explosion pressure**

maximum value of explosion pressure measured in the tests for explosion pressure when the content of the flammable substances in the mixture is varied

[SOURCE: EN 13237:2012, 3.2]

3.2.13**minimum ignition energy****MIE**

lowest electrical energy stored in a capacitor, which upon discharge is sufficient to effect ignition of the most ignitable atmosphere under specified test conditions

[SOURCE: EN 13237:2012, 3.54]

3.2.14**upper explosion limit****UEL**

highest concentration of the explosion range at which an explosion can occur

[SOURCE: EN 13237:2012, 3.19.2]

3.2.15

ventilation

movement of air and its replacement with fresh air due to the effects of wind, temperature gradients, or artificial means (for example, fans or extractors)

[SOURCE: IEC 60079-10-0:2015]

3.2 Symbols and abbreviations

Symbols and abbreviations should be selected from those already established in relevant ISO and/or CEN standards. New symbols and abbreviations should be defined only where there is no suitable alternative and recorded in CEN/TC 234 Doc N 776 (so called N 215).

The symbols and abbreviations used in this document are listed in Annex J.

4 Executive summary

Intention of the European gas industry is to enable the use of natural gas infrastructure for hydrogen.

For the use of hydrogen in the natural gas infrastructure it is reasonable to identify:

- the similarities (what is equal) and differences (what is different) between methane (natural gas) and hydrogen and – based on these
- the consequences or the impact of hydrogen on the gas system (e.g. materials, safety, maintenance).

NOTE 1 Acknowledging the impact of the similarities on applications, in this document only the impact on gas infrastructure is considered as in the scope of CEN/TC 234.

NOTE 2 Natural gas is a mixture of hydrocarbon gases and other gases (e.g. nitrogen). Its main component is methane.

The following similarities and differences of the properties of methane and hydrogen need consideration:

Table 1 gives common properties of hydrogen and natural gas whereas Table 2 shows differences in the nominal values of the common properties of hydrogen and methane.

Table 1 — Common properties of hydrogen and natural gas

Characteristic	Methane (natural gas)	Hydrogen
gaseous	yes	yes
colourless	yes	yes
odourless	yes	yes
toxic	no	no
flammable	yes	yes
explosive	yes	yes
corrosive	no	no

Table 2 — Properties of hydrogen and methane — differences

Parameter	Methane	Hydrogen
Relative density (air = 1)	0,55	0,07
Flammability limits [Mol.- %]	4,4–17	4,0–77
Ignition energy [mJ]	0,26	0,017
Combustion energy up/low) [MJ/m ³]	40/36	13/11
Wobbe number [MJ/m ³]	upper: 54 lower: 48	48–41
Gross calorific value [kJ/mol, at 20 °C]	891	286
Flame colour	blue	colourless
Molecular mass [g/mol]	16	2
Molecule size [pm]	220	75
Diffusion coefficient in air [10 ⁻⁴ m ² /s]	0,61	0,20
Infrared absorption	yes	no
Joule-Thomson coefficient [K/bar]	0,4	–0,03
Sound velocity [m/s]	388 ^a	1 203
NOTE 1 This Table is meant as indication of general differences between methane (CH ₄) and hydrogen (H ₂) without referring to the specific conditions.		
NOTE 2 More details related to mixtures of methane with hydrogen are given in Table B.1.		
^a High caloric natural gas		

In Clause 6, a detailed evaluation of technical safety and integrity and performance aspects is given per part of the natural gas infrastructure.

In Clause 7, the suitability of the different parts of the gas infrastructure for hydrogen and hydrogen admixtures are summarised in form of tables.

As a conclusion, the following aspects need specific attention:

1) materials

- embrittlement of steel (5.2.2)
- diffusion and/or permeation of the gas through materials
- deterioration of elastomers
- suitability of sealing materials
- ...

NOTE 3 Consideration should be given also to historic materials remaining in networks such as grey cast iron and ductile cast iron.

2) safety aspects of hydrogen/, explosion prevention and protection

- ATEX requirements
- purging
- venting
- proof of gas tightness
- detection of hydrogen and admixtures
- odorization
- fire detection

3) technical system

- compression
- biochemical reactions in reservoirs and caverns
- metering
- gas preheating
- Joule-Thomson-Dehydration
- ...

4) Other aspects

- Volume in relation to energy content (5.3)
- Gas quality

The existing standards of CEN/TC 234 can be amended to cover natural gas infrastructure used for hydrogen services. For some aspects new CEN deliverables are needed.

The revision needs of the CEN/TC 234 standards respectively the need to elaborate additional standards is documented in Clause 8. The extent and timeframe of revision differs for the single aspects and for some aspects rely on further research results.

The involvement of the competent experts will be ensured by calls to the NSB, with the new work item proposals and beyond. Strong involvement of the sector is required.

NOTE 4 CEN/TC 234 intends to elaborate the related revisions in cooperation with the relevant TCs (e.g. CEN-CLC/JTC 6) and stakeholders. Preparations and first work items are already in process in the dedicated working groups.

5 General considerations for the entire gas infrastructure

5.1 Explosion protection and prevention

5.1.1 General principles

The general principles for the prevention of and protection against explosions are laid down in the European Directive 1999/92/EC (ATEX II). It addresses employers in order to protect workers and other persons from explosion hazards. The provisions given in this European Directive are detailed in national

regulations. However, operators of plants and equipment also apply the general principles given of Directive 1999/92/EC with regard to third party protection.

With a view to preventing and providing protection against explosions, technical and/or organizational measures need to be taken, in order of priority and in accordance with the following basic principles:

- prevention of the formation of explosive atmospheres, or where the nature of the activity does not allow that,
- avoidance of the ignition of explosive atmospheres, and
- mitigation of the detrimental effects of an explosion to ensure the health and safety of workers.

Safety measures of the gas industry include safe gas infrastructure as well as safe gas utilisation and does focus on the prevention of unsafe situations, as explosions, by preventing the formation of explosive atmosphere and avoidance of the ignition where the formation of hazardous explosive atmospheres cannot be safely excluded. For pipework in buildings, also prevention measures in case of external fire are required. These basic principles are applying equally to natural gas, hydrogen and any admixtures of these. Public and workers safety is the prime consideration.

5.1.2 Safety characteristics of natural gas-hydrogen mixtures and their impact on explosion prevention

5.1.2.1 General

The safety characteristics of natural gas and hydrogen are well known. In a detailed study the safety characteristics of natural gas – hydrogen mixtures were examined in order to determine possible risks relating to occupational safety and health for hydrogen concentrations of up to 10 Vol.-%. The results of the measurements are given in Annex B.

A safety design for hydrogen can fully be used for natural gas application. Gas detecting equipment needs special consideration as detailed in Annex C.

5.1.2.2 Prevention of the formation of explosive atmospheres

Basic requirement for the prevention of the formation of explosive atmospheres is the gas tightness of the gas system. Wherever possible, the gas bearing part of the gas infrastructure is designed and operated to be permanently technically gastight. The gas tightness of the gas system is proven by tightness tests.

On components of the system for natural gas tightness test are carried out with air. If components of the gas system are specified for higher contents of hydrogen the test gases for the tightness tests need to be specified to verify the gas tightness against hydrogen leakage. For existing systems, the gas tightness can be verified with operating gas after the overall gas tightness test with inert gas, e.g. nitrogen.

Gas releases from the gas system can occur e.g. from:

- shaft sealing systems of valves or rotating equipment
- joints (e.g. pipe joints)
- venting of block and bleed systems
- depressurization and opening of equipment for maintenance activities
- emergency shut down with depressurization
- equipment failure

Where the release of gas cannot safely be avoided, the gas needs to be vented to safe atmosphere, as already detailed in the applicable European standards.

The amount of gas escaping through any shaft sealing systems, e.g. for rotating equipment, compressors, can increase with increasing hydrogen content.

The lower density will support the dilution and venting of the gas mixture near gas leakages. The lower explosion limit (LEL) is about the same value for natural gas and hydrogen and any mixture of these gases.

The extent of hazardous areas at the apertures of venting lines and vent stacks was calculated with natural gas and natural gas with 10 Vol.-% H₂ [2] There was no significant difference between the results for pure natural gas and natural gas with 10 Vol.-% H₂. For H₂ contents above 10 Vol.-% the extent of hazardous areas is being investigated.

Flammable gases should be odorized for detection of gas in public areas and in buildings, depending on national legal and/or technical framework.

The UEL of natural gas-hydrogen mixtures increases with the increase of the hydrogen concentration. The MIE decreases significantly. However, this effect will be negligible up to 10 Vol.-%, but need consideration at higher H₂-concentrations. By purging with inert gas, the formation of hazardous explosive atmosphere can be avoided.

5.1.2.3 Avoidance of the ignition of explosive atmospheres

For equipment according to Directive 2014/34/EU the classification is made with regard to the ignition temperature and the explosion group related to the MESG.

The ignition temperature of pure hydrogen and natural gas is in the same order of magnitude. Therefore, the concentration of hydrogen in natural gas will have no significant effect on the possible ignition on hot surfaces and the temperature class of the equipment.

The value of MESG decreases with the increase of the hydrogen concentration in natural gas.

5.1.3 Consequences of H₂ and H₂NG in NG infrastructure for explosion protection related to identified H₂ concentrations

5.1.3.1 Hydrogen content up to 10 Vol.-%

The results given in Annex B indicate that up to 10 Vol.-% H₂ in natural gas the safety characteristics of gas mixture do not deviate from the safety characteristics of natural gas. None of the examined characteristics is affected significantly by the addition of up to 10 Vol.-% hydrogen. The explosion ranges are increased only slightly and the mixtures remain in explosion group IIA; as is pure natural gas.

The explosion hazard for pipework up to 100 mbar according to EN 1775 with H₂NG up to 20 Vol.-% was investigated in a DVGW research study (G 201615) [3] and no significant deviation from the safety concept according to EN 1775 was found.

Comparative calculations – based on gas dispersion calculations – to determine hazardous areas (explosion zones) for pure natural gas and natural gas-hydrogen mixtures with up to 10 Vol.-% hydrogen, also revealed only minor differences within the margin of error of the calculation methods.

In principle, gas detectors that are suitable for natural gas can be used for natural gas-hydrogen mixtures with a maximum of 10 Vol.-% hydrogen. However, this requires a separate safety assessment and, if necessary, a recalibration, see Annex C.

5.1.3.2 Hydrogen content above 10 Vol.-% up to full replacement of natural gas by hydrogen (100 % hydrogen)

For hydrogen concentrations above 10 Vol.-% up to 100 % a specific safety assessment is needed to assess the impact and possible modifications of the protection measures used for an existing natural gas system.

The explosion hazard for pipework up to 100 mbar according to EN 1775 with H₂NG up to 20 Vol.-% was investigated in a DVGW research study (G 201615) [3] and no significant deviation from the safety concept according to EN 1775 was found.

The explosion group of the equipment installed will be affected by the hydrogen concentration. Methane including natural gas is classified in explosion group IIA unless the hydrogen content exceeds 25 Vol.-% [EN ISO 80079-20-1]. For hydrogen contents above this limit in any part of the system, equipment complying with explosion group IIC is recommended. In Table B.1 the details of experiments are given. A detailed risk analysis should be carried out to adapt safety measures when reaching this hydrogen concentration.

For systems operated with hydrogen, ASME B 31.12 requires purging with inert gas prior to opening of the system, e.g. for maintenance work, and prior to commissioning.

For venting hydrogen to atmosphere or flaring of hydrogen, where permitted, specific precautions are given in EIGA IGC Doc 121/14 [4].

Since hydrogen is the more critical component in a natural gas–hydrogen mixture, a system design for 100 % hydrogen should be safe with regard to the extension of hazardous areas and the explosion group of the equipment used in these hazardous areas. However, a detailed, individual safety assessment is recommended.

5.2 N₂NG mixtures in contact with materials — Pressure integrity, gas tightness and functionality

5.2.1 General

5.2.1.1 Hydrogen tolerance of pipeline materials

Table 3 indicates the pipeline materials' tolerance of hydrogen concentrations in the admixture with natural gas up to 100 Vol.-% of hydrogen as resulted from various studies:

— Netbeheer Nederland/KIWA report Future proofed gas distribution networks [5]

NOTE A summary of the Netbeheer Nederland/Kiwa report is given in Annex H.

— further KIWA findings

— Kiwa report on hydrogen in natural gas on Ameland [6]

— GERG Report on admissible hydrogen concentration in natural gas systems [7]

— Additional information (based on presentations at Marcogaz/GERG EGATEC on 7 Nov. 2019)

— Findings from N.V. Nederlandse Gasunie and Open Grid Europe documented in the CEN/TC 234 WG 3 internal document N 795]

Table 3 — Hydrogen tolerance of piping material used in natural gas infrastructure

Pressure [bar g]	Materials	≤ 2 Vol.-%	≤ 5 Vol.-%	≤ 10 Vol.-%	Up to 100 Vol.-%
< 5,0	Steel	✓	✓	✓	✓ ^a
	Stainless steel	✓	✓	✓	✓
	Copper (alloys)	✓	✓	✓	—
	Multilayer/PEX	✓			
	PE	✓	✓	✓	✓
< 8,0	Steel	✓	✓	✓	—
	Stainless steel	✓	✓	✓	—
	Copper (alloys)	✓	—	—	—
	PE	✓	✓	✓	✓
< 10,0	Steel	✓	✓	✓	
	Stainless steel	✓	✓	✓	
	Copper (alloys)	✓			
	PE	✓			
< 60,0	Steel				
	Stainless steel				
	Copper (alloys)				
	PE				
Key ✓: No effect expected —: No short-term effect expected empty box: not part of the study findings at time when drafting this document					
^a till 20 Vol.-%					

NOTE Consideration should be given to historic materials remained in networks.

5.2.1.2 Hydrogen tolerance of fitting materials

Table 4 indicates the fitting materials' tolerance of concentrations in the admixture with natural gas up to 100 Vol.-% of hydrogen based on Netbeheer Nederland/KIWA report [5] (Annex H)

Table 4 — Hydrogen tolerance of fitting materials used in natural gas infrastructure

Pressure [bar g]	Materials	≤ 2 Vol.-%	≤ 5 Vol.-%	≤ 10 Vol.-%	Up to 100 Vol.-%
< 0,1	Poly oxymethylene/ polyacetal (POM/PA-U)	✓	—	—	— ^a
	Teflon, polyvinylidene fluoride (PFTE)	✓			
	Poly tetra fluor ethylene (NBR)	✓	—	—	— ^a
	Styreen butadyene rubber (SBR)	✓	—	—	— ^a
	Silicon rubber (SR)	✓			
< 8,0	Poly oxymethylene/ polyacetal (POM/PA-U)	✓	—	—	— ^a
	Teflon, polyvinylidene fluoride (PFTE)	✓			
	Poly tetra fluor ethylene (NBR)	✓			
	Styreen Butadyene rubber (SBR)	✓			
	Silicon rubber (SR)	✓			
< 60,0	Poly oxymethylene/ polyacetal (POM/PA-U)				
	Teflon, polyvinylidene fluoride (PFTE)				
	Poly tetra fluor ethylene (NBR)				
	Styreen butadyene rubber (SBR)				
	Silicon rubber (SR)				
Key ✓: No effect expected —: No short term effect expected empty box: not part of the study findings at the time when drafting this document					
^a Till 62 Vol.-%					

NOTE Consideration should be given to historic fittings remained in networks.

5.2.2 Steel

5.2.2.1 General

In steel gas pipes and infrastructure employed in hydrogen service hydrogen embrittlement can lead to impact on the integrity of the steel used for gas pipeline systems. Measures can be taken to mitigate these effects.

The interaction of hydrogen atoms and steel can have a negative effect on the mechanical behaviour of steel. The general term for this degrading effect is hydrogen embrittlement. The degrading effect depends on, for example:

- the source of the absorbed hydrogen atoms: gas molecule H_2 or ion (H^+)
- the steel grade and the stress level
- the steel's microstructure
- the mechanical loading conditions: static, variable, dynamic
- the occurrence of continuous plastic straining
- the presence of crack-like defects
- the temperature
- the absence of an oxide layer (low temperature H_2 gas only)

Three examples of specific hydrogen embrittlement mechanisms – occurring with high temperatures ($> 150\text{ °C}$) or high hydrogen concentrations, larger than 50–500 atomic ppm – are hydrogen-induced cracking, high-temperature hydrogen attack and cold cracking due to welding:

- 1) HIC deals with recombination of hydrogen atoms to molecules within steel exerting high pressures. These pressures can be so high that cracks are created in the steel wall. HIC only occurs when the source of atoms is ionic, for example in the case of H_2S corrosion in relation to high hydrogen concentrations. Equivalent pressures are approximately 10 000 bar and higher (see 6.9.1).
- 2) HTHA occurs at high temperatures where hydrogen reacts with the carbon in the steel resulting in voids in the steel. Due to the voids, cohesion in the steel is lost.
- 3) Cold cracking occurs in weldments during or after welding. It is a combination of hardened microstructure and high water concentrations in the weld consumable. Typical hydrogen concentrations in the steel are significantly higher than the concentrations with hydrogen gas pressures.

NOTE 1 These conditions are not usual in gas infrastructure.

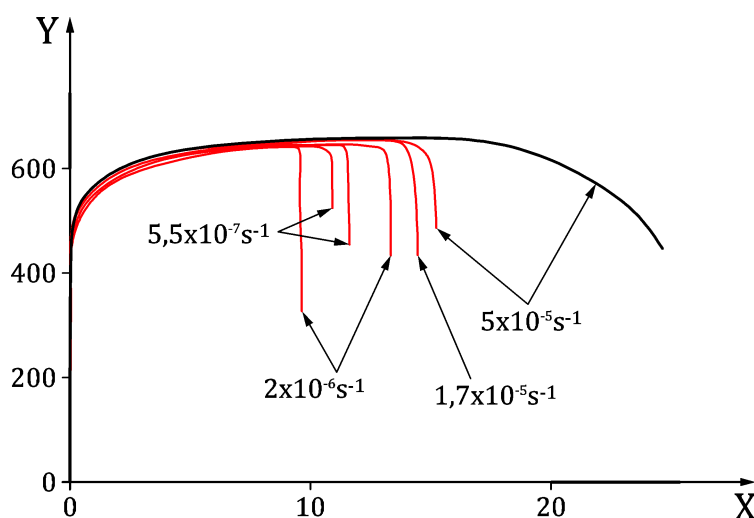
There is another hydrogen embrittlement mechanism which results from the dissociation of molecular hydrogen into atomic hydrogen due to the presence of steel. The effects of this mechanism could be relevant and will be described and also discussed in following clauses.

NOTE 2 The European project “Testing Hydrogen admixture for Gas Applications (THyGA)” also investigated embrittlement in the context of their studies on non-combustion related impact of hydrogen admixture on material compatibility (e.g. embrittlement). Results are described in the project deliverable [8].

5.2.2.2 Mechanical behaviour

Figures 1 to 3 illustrates the typical mechanical behaviour of (pipeline) steels in the presence of hydrogen. The actual steel yield strength ranges from 245 MPa to 650 MPa. Comparable results can be found in references [9], [10], [11], [12] and [13].

In the tensile test, the yield and tensile strength, elasticity and strain hardening are not affected. The fracture strain is affected and the effect becomes greater as the displacement rate in the test becomes smaller, see example in Figure 1



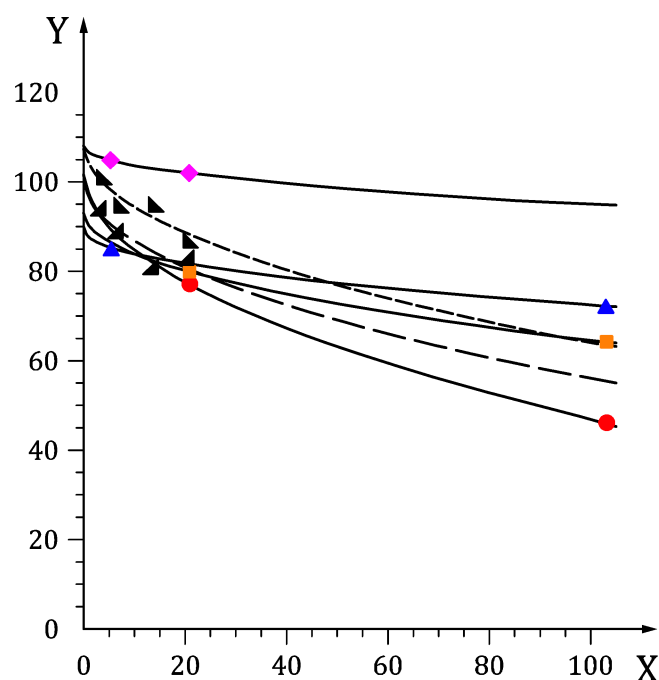
Key

Y	Yield strength (F/S_0 (MPa))
X	Strain (%)
■	30 MPa N ₂
■	30 MPa H ₂

NOTE The fracture strain is the strain where the curves end.

Figure 1 — Example: typical result of the tensile test in hydrogen gas: decrease of the fracture strain depending on the loading rate in H₂ gas (300 bar, steel X80 = L555) [Source: [14], Figure 4]

Fracture toughness testing is also affected by the displacement rate although there is a threshold. The decrease in toughness depends on the hydrogen pressure, see Figure 2.

**Key**

Y	Fracture resistance, K_{IH} (MPa m ^{1/2})
X	Hydrogen fugacity (MPa)
—▲—	X60 (heat D)
—◆—	X80 (heat B)
—●—	X80 (heat E)
—■—	X80 (heat F)
—▲—	Grade B (as rolled)
—■—	Grade B (normalised)

NOTE Up to around 15 MPa the fugacity is equivalent as the pressure.

Figure 2 — Example: effect of hydrogen gas pressure on fracture toughness for pipeline steels (Grade B = L245, X60 = L415, X80 = L555) [Source: [64]]

In tensile tests, smooth specimens are used. In contrast, specimens with a crack are used in fracture toughness and fatigue crack growth tests. This is a significant difference: intense plastic straining occurs in a small zone around the crack tip as the load on the specimen increases. In this situation the effect of hydrogen is significant.

With fatigue crack growth testing there can be a large effect on the growth rate. At low hydrogen pressures the effect can also be significant compared to the rate in air, see Figures 3 and 4. This effect is larger than expected from the tensile tests and fracture toughness tests. In addition to the fatigue crack growth rate, the threshold for the alternating stress intensity factor ΔK is also a parameter affected by hydrogen. Below the threshold ΔK_{th} , crack growth is so small that practically no crack growth occurs over a long time period.

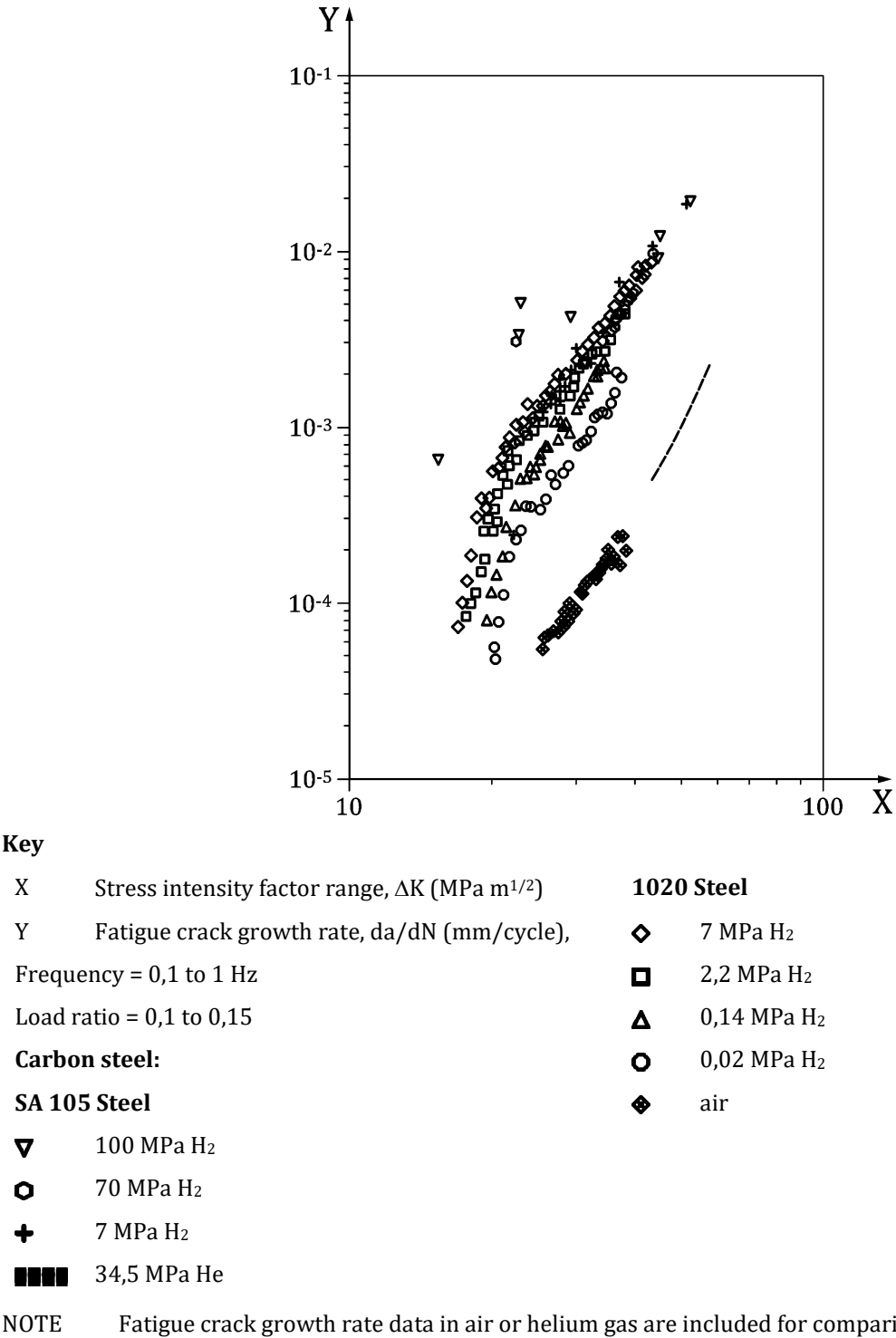
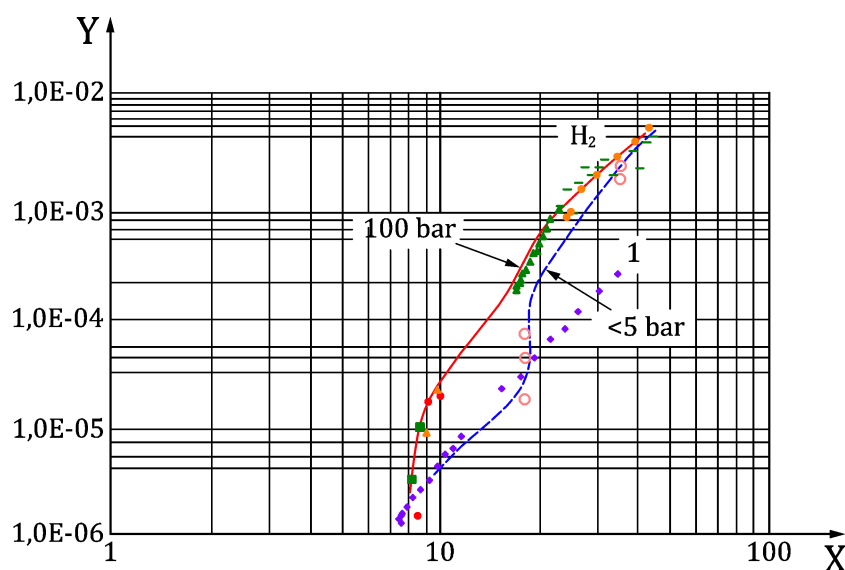


Figure 3 — Example: Effect of hydrogen gas pressure on fatigue crack growth rate for carbon steels (Steel SA 105 = L245, 1020 yield strength 350 MPa) [Source: [11], Figure 3.3.2.2]

**Key**

X Stress intensity factor range, ΔK (MPa m^{1/2})

Y Crack growth rate (mm/cycle),

1 Air

The test variables are:

- loading regime $R = 0,1$
- frequency used $f = 0,5$ Hz
- tested in air 100 bar H₂ and 5 bar H₂

Figure 4 — Example: Effect of hydrogen gas pressure on fatigue crack growth rate for carbon steels [15]

Fatigue crack growth in hydrogen depends on a variety of parameters:

- pressure cycle frequency,
- maximum stress,
- minimum stress,
- ratio between the minimum and maximum stress (R).

In the Naturalhy project, loading conditions derived from pipeline operations were used for the fatigue crack growth testing [10]. This resulted in fatigue crack growth curves and threshold ΔK_{th} values for pipeline steels see Figures 5 and 6. This threshold ΔK_{th} is set to 0,01 $\mu\text{m}/\text{cycle}$. If there is 1 cycle per day for 100 years, this means a crack growth 0,37 mm.

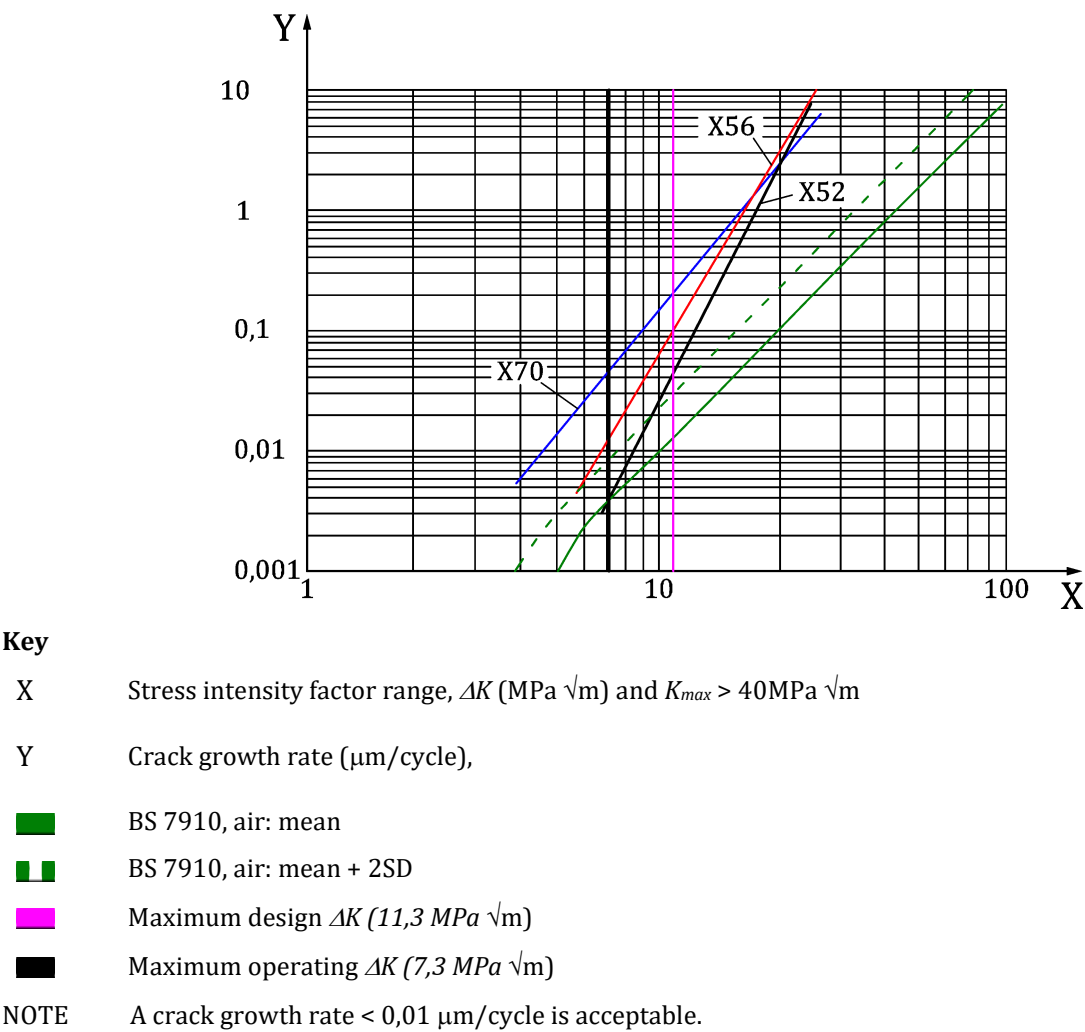
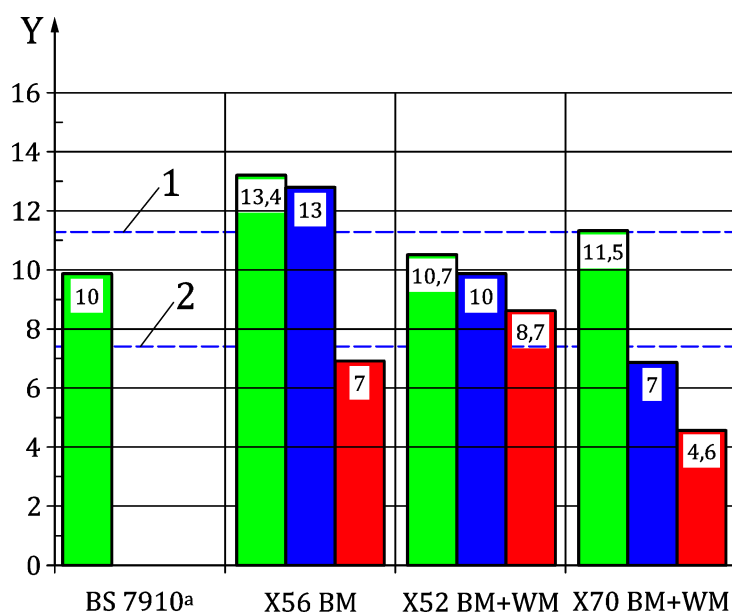


Figure 5 — Fatigue crack growth curves for three pipe steel grades in 100 % hydrogen at 66 bar (o) (steel X52 = L360, X56 = L390, X70 = L485) [Source: [10], Figure I]

**Key**

X Fatigue crack growth

Y $\Delta K_{threshold}$ in MPa√m

■ 100 % NG

■ 50 % H₂■ 100 % H₂1 Maximum design ΔK : 11,3 MPa√m2 Maximum operating ΔK : 7,3 MPa√m

Figure 6 — Threshold values for fatigue crack growth for three pipe steel grades in 50 % and 100 % hydrogen at 66 bar (o) (steel X52 = L360, X56 = L390, X70 = L485) [Source: [10], Figure J]

5.2.2.3 Welding of steel

Various studies on the effects of gaseous hydrogen on pipeline welds conclude that the main concern for the transportation of gaseous hydrogen is the decrease in toughness of the pipeline material and welds, see Annex F of this document. This decrease in toughness must be addressed in the design of the pipeline and therefore, if desired, additional testing of procedure qualification records (PQR) must be integrated in the construction requirements of the pipeline. When these additional tests are not available, or performed, the operator may choose an alternative method by selecting sufficiently conservative design parameters in order to evaluate the pipeline for the desired service.

On the topic of hardness, a study by The Welding Institute in the UK, [16] has been published on the potential impact of hydrogen on welded joints. This study confirms that the weld region in steel gas pipes is unlikely to be a problem during service with hydrogen but depending on the operating conditions. Reference to the Nelson curves suggests the hydrogen service for carbon steel pipes below 250 °C, the hydrogen partial pressure does not matter above 6,9 MPa absolute (69 bar). Below that pressure, there can be scope for higher operating temperatures. However, the Nelson curves were designed to consider high temperature hydrogen attack, rather than hydrogen embrittlement. For carbon steels, it is difficult to introduce sufficient diffusible hydrogen during non-corrosive service, as the absorption of hydrogen into steel requires atomic hydrogen to be adsorbed on the surface of the steel – the energy for dissociation of hydrogen gas to allow this adsorption makes this kinetically unfavourable in most cases.

Some design documents such as the industry guideline EIGA IGC Doc 121/14 [4] and the standard ASME B 31.12, give a limitation on the hardness of weldments but do not disclose the technical reasoning behind these hardness limits.

The Annex D of the EIGA document gives a general HV 250 maximum, this maximum hardness originates from sour gas specifications.

The ASME B 31.12 gives limits for the PQR testing but these are specified for post weld heated condition, but for other situations the limits are to be based on the material specification and/or the engineering design. For production weld testing, a number of prerequisites for if and where hardness testing is required are in place. As an example, if a girth weld is welded in the field with an electrode containing less than 1,6 % Mn (which is most pipeline electrodes) and not post weld heat treated no hardness testing is required.

The only direct link between hardness of pipeline materials and hydrogen embrittlement comes from H₂S service. But since the hydrogen concentration in gaseous hydrogen service differs from sour service, the use of sour gas specifications, e.g. EN ISO 15156-2 cannot be directly transferred into H₂ specifications [17]. Sour gas (H₂S) corrosion results in very large atomic hydrogen concentrations compared with hydrogen gas. E.g. 0,02 bar H₂S in water results in approximately 90 atomic ppm while 101 bar H₂ results (if dissociation of H₂ molecule can occur) approximately 0,3 at. ppm which is a factor 300 lower, see Table 5 for pressure versus concentration from various hydrogen sources.

Table 5 — Estimated hydrogen concentration in steel at 20 °C

Source of hydrogen	Concentration H atoms [atomic ppm]	Equivalent pressure [bar (a)]
3 ml H₂/100 g Welding electrode	150	15 000
81 bar H₂	0,25	81
0,01 bar H₂S [18]	14	7 100
active CP [19]	56	11 000
1 bar H₂S [20]	185	16 000
Cathodic charged [20]	650	21 000

Sour gas specification EN ISO 15156-2 does not require a hardness requirement when the H₂S pressure is less than 0,003 bar (0,3 kPa). This H₂S pressure will still result in a hydrogen of around 5 ppm in steel [21], this is considerably higher than obtained with hydrogen gas. This is supported by research in the Naturalhy project, when weldments with hardness 350–375 HV were tested in hydrogen gas. No cracking was found [10].

So, the hardness requirement is only relevant with very high hydrogen pressure, much higher than design pressure of existing gas pipelines.

For welding, where atomic hydrogen is present in the welding arc itself, this results in diffusible hydrogen entry into the steel. However, this hydrogen is then diffusing away after welding, such that for a 10 mm wall thickness weld, welded with cellulosic electrodes, all hydrogen is expected to have escaped by three weeks after completion of welding at ambient temperatures from –5 °C to 20 °C. As there is usually a longer delay between completion of welding and service, the potential limitation of diffusing hydrogen is not usually going to be a consideration. The situation changes with the use of cladding or dissimilar metal joints, but again, there usually must be atomic hydrogen from a corrosion reaction in order to cause significant problems.

Conclusion: with respect to welding there is no significant difference in the welding procedures for H₂ application in comparison to NG.

5.2.3 PE and PA-U

For details on PE, and PA-U, pipe systems in gas pipelines with MOP up to and including 16 bar for all concentrations see 6.7.1 and Annex G.

6.7.1 also refers to the assessment of steel pipes operating at the lower pressure range and ensuring electrical safety.

5.2.4 Alloys

Pipes in alloys of copper, nickel, stainless steel and cobalt might be relevant for purposes, e.g. in instrumentation and/or fittings.

For detailed more information, reference is made to the hydrogen compatibility research results of Sandia National Laboratories' [22] - and for the use of copper for hydrogen technical and laboratory gases - to the study DK1 I 164 [23].

5.2.5 Information on deterioration and chemical aggression of elastomers

The effect of deterioration and influences of elastomers should be looked at for each application.

5.2.6 Others

Further research is necessary regarding flexible hoses for MOP greater than 16 bar.

NOTE Further research is necessary regarding materials other than steel for pressures above 16 bar. In particular, further research is needed for composite pipes made from RTP, GRP, GRE etc.

Other pipe and fitting materials in historic use, e.g. such as PVC, grey cast iron and/or ductile cast iron, will need to be assessed separately to ensure safety during hydrogen service.

5.3 Volume in relation to energy content — consequences for the capacity and function of the gas transportation, underground gas storage and distribution system

Beside integrity aspects, the effect of hydrogen admixtures on the performance of gas compression, storage, transport and distribution has to be assessed.

It has to be noted that an increasing concentration of hydrogen will reduce energy transport and storage capacity of existing infrastructures. This is because H_2 is carrying around three times less energy per volume and an eight times lower density compared to natural gas. This can result in larger gas throughput volumes and consequently flow velocities, which need to be compressed to meet current energy transport capacities requirements.

The calorific storage capacity and performance of underground gas storage systems will be reduced dependent on the hydrogen content. Additional infrastructure can be required to overcome the capacity issue.

With the admixture of hydrogen, a potential increase in noise emissions at gas pressure regulating stations (higher flows) can occur. Reference is made to Marcogaz publication related to conversion of m^3 to kWh [24].

6 Technical considerations per topic applicable for the different parts of the gas infrastructure (along chain)

6.1 General

Additionally, to the explanations in Clause 5, which are relevant for all parts of the gas chain or several parts, in the following, a specific view is given on the technical considerations per part of the gas chain and in relation to the existing CEN/TC 234 standards.

NOTE The CEN/TC 234 WG responsibilities for each of the parts of infrastructure is listed in the informative Annex I.

6.2 Gas quality

6.2.1 Scope of considerations — Gas quality — EN 16726

In general, the injection of hydrogen in the natural gas can harm the minimum and/or the maximum limits of the gas quality parameters listed in the standard EN 16726:2015+A1:2018. It is identified that the physical properties of hydrogen differ from those of natural gas. This means that the gas quality parameters need to be checked for consistency.

NOTE EN 16726 and the statements in this clause refer mainly to H-gas. For L-gas slightly different percentage might apply. NL has the intention to document the composition of L-gas admixtures with hydrogen.

CEN/TC 234 WG 11 deals with the parameters as given in EN 16726:2015+A1:2018 for H-Gas, such as:

- relative density
- methane number
- hydrocarbon dew point
- water dew point.

More information related to the standardisation need is given in 8.2.

The following parameters need similar attention and are part of the pre-normative studies of CEN SFG GQS (TF1 WI and TF3 O_2):

- Wobbe Index (not covered by EN 16726+A1:2018)
- GCV (not covered by EN 16726+A1:2018)

— Oxygen.

The following parameters and issues need additional attention, hence affected by hydrogen addition. However, they are not yet subject to EN 16726:2015+A1:2018 and need cooperation with other TCs involved (i.e. TCs in the field of utilisation):

- flame speed
- flame stability
- flame detection
- variation of gas composition

Regarding test procedures for applications burning gases that contain hydrogen, reference is made to EN 437. Complementary tests, including specified test gases (reference gases and limit gases), need to be developed in addition to existing tests defined in EN 437.

For the revision need of EN 16276 and the need of additional standardisation see Clause 8.

6.2.2 Technical considerations — Identified H₂NG

6.2.2.1 Relative density

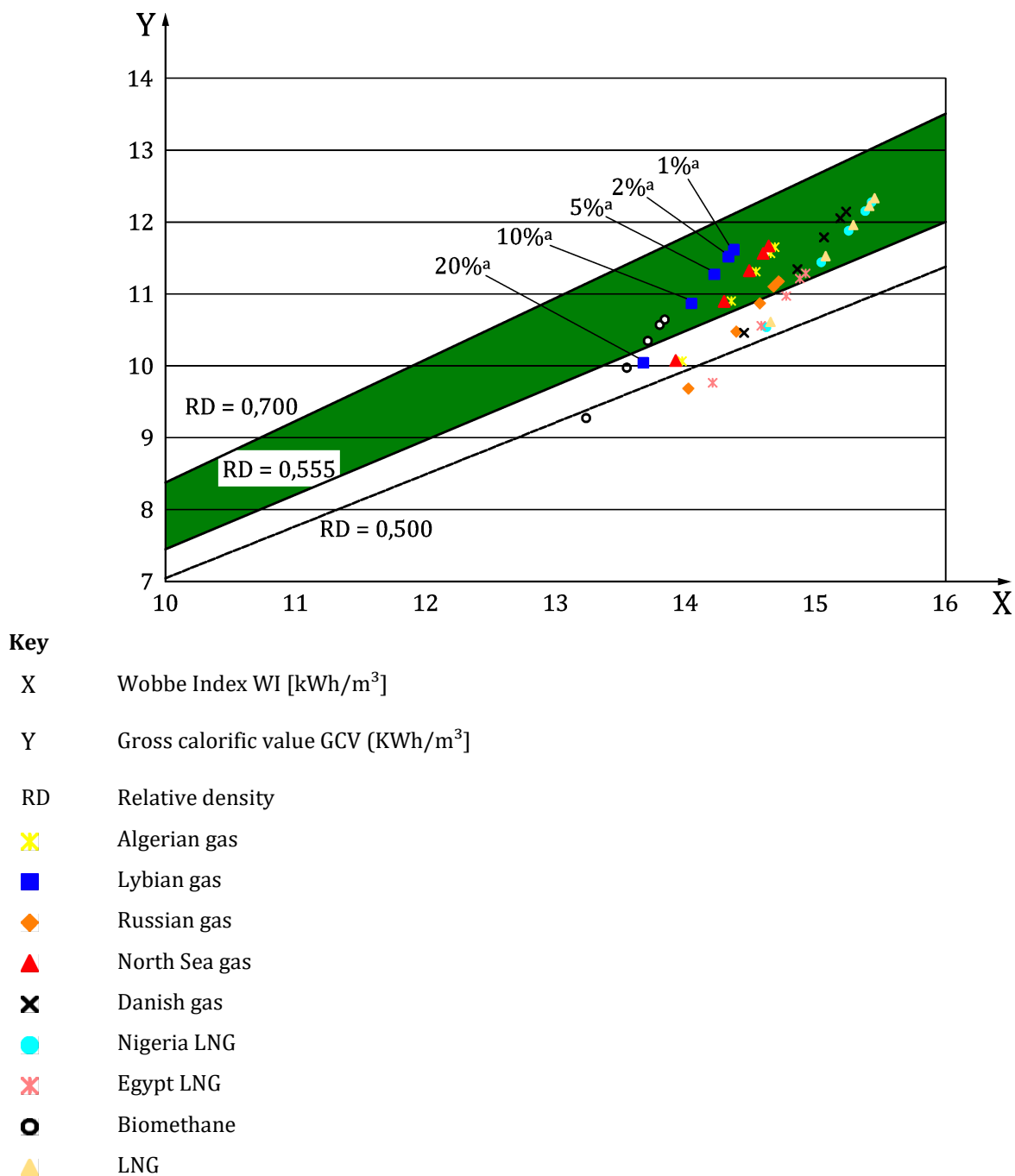
According to EN 16726:2015+A1:2018, relative density is limited to 0,555–0,7. The lower limit is of greater importance when it comes to hydrogen injection into the natural gas network due to the lower density of hydrogen compared to methane. The source for the lower limit is the density ratio between methane and air at reference conditions (see ISO/TR 29922):

$$\frac{\rho_{\text{methane}}}{\rho_{\text{air}}} = \frac{0,717\,5\text{ kg kmol}^{-1}}{1,293\,1\text{ kg kmol}^{-1}} = 0,554\,9$$

An existing lower limit of 0,555 restricts the amount of hydrogen in natural gas. Restriction of hydrogen addition is strongly dependent on gas composition. The existing limit restricts hydrogen to around 3,8 Vol.-% (Russia), e.g. according to the typical gas composition given in Table A.2 of the DVGW Arbeitsblatt G 260 [25] respectively 13,0 Vol.-% (North Sea); see Figure 7.

In order to determine a lower limit than the existing 0,555, further investigation is required. To lower the limit to 0,45 would allow up to 20 Vol.-% hydrogen in biomethane, Russian and North Sea H-gas [26] and even in several LNGs.

Test gas G 222 is a limit gas for short-time stress testing on flame flashback, as given by EN 437, contains 23 % H₂ in methane and therefore has a relative density of 0,443. This gives no indication about the long-term performance of appliances if subjected to G 222.



[Source: Gas compositions by E.ON, SNAM and Enagás]

Figure 7 — Typical natural gas compositions with hydrogen addition and a lowered limit of the relative density of 0,5 [27]

As a measure of gas density relative to air at reference conditions, relative density is used for gas interchangeability together with Wobbe Index [28].

The upper limit of relative density restricts the content of the number of higher hydrocarbons in the natural gas, as well as the upper limits of GCV, WI and hydrocarbon dew point’.

The higher hydrocarbon content can be restricted using the upper limit of relative density; therefore, it is still an important parameter. Nevertheless, the lower limit needs an overhaul to allow for more hydrogen addition.

As an alternative, the lower limit of relative density can be waived and be replaced by a maximum hydrogen content. Other properties might limit the hydrogen content as well.

Compatibility testing will need to be performed e.g. within the field’s gas usage (engines, turbine) as well as metering and gas pressure regulation, storage, installation and distribution.

6.2.2.2 Water dew point

The variation of the water dew point of a natural gas (H-Gas, North Sea) when blended with pure and therefore water-free hydrogen was reckoned using the calculation method of moisture content described in EN ISO 18453 and is depicted in Figure 8. The water content or water dew point of the unblended gas was advantageously set to 40 mg/m³ or –8 °C at 70 bar(a), respectively. Expectedly, the water dew point declines almost linearly with the addition of hydrogen and hence the blending of any natural gas in accordance with EN 16726:2015+A1:2018 does not result in a deterioration of its properties.

NOTE EN ISO 18453 is applicable for admixtures with a certain H₂-content only. However, for higher proportions of hydrogen, the standard can be applied in principle.

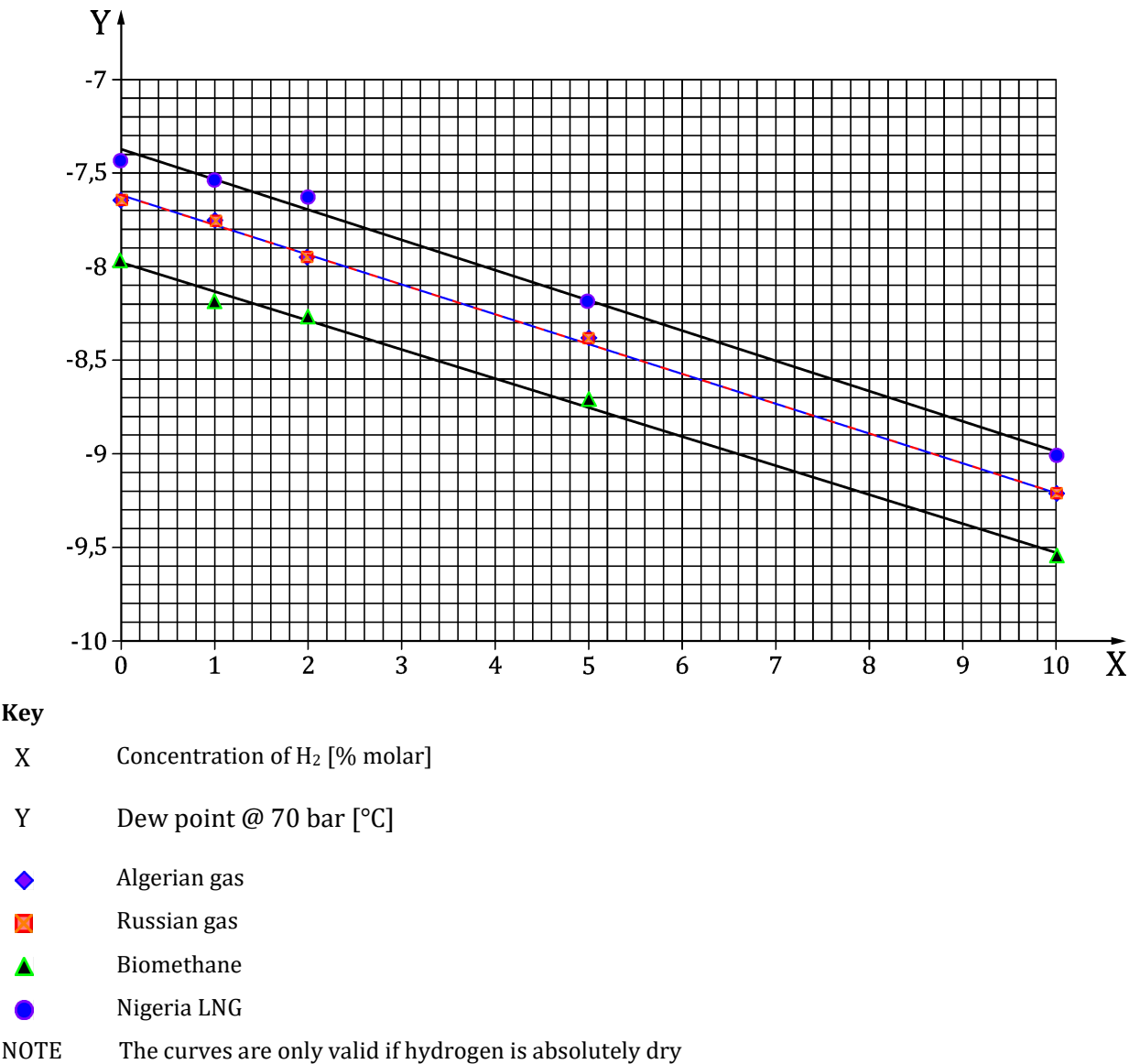


Figure 8 — Water dew point at 70 bar(a) as a function of hydrogen content

6.2.2.3 Hydrocarbon dew point

Figures 9 and 10 show the influence of different hydrogen additions on the phase transition curve of a high-calorific natural gas from Russia.

NOTE For purposes of the calculations, gas analyses of up to C20 representative natural gases, the product data from the AspenHysys program [29] package and the Peng-Robinson state equation have been used.

It is to be anticipated that the phase transition curve of natural gases is not accessible by measurement [30]. However, the calculated curves provide an impression of the pressure and temperature conditions at which condensate can be formed. The phase transition curves do not indicate the expected volume of condensate [30].

In practice, hydrocarbon dew point measuring instruments are used for online measurement of the hydrocarbon dew point at delivery points. These instruments are generally operated with ex works settings. The detection limit of these instruments is generally between 5 mg and 50 mg of condensate per standard cubic meter of natural gas, reference is made to ISO/TR 12148, [31], [32], [33], [34] and [35]. The quality curves are shown in Figures 8, 9 and 10. Using measuring instruments with a detection limit of 5 mg/m³ or 50 mg/m³, these curves occur with the gas depicted in Figure 9.

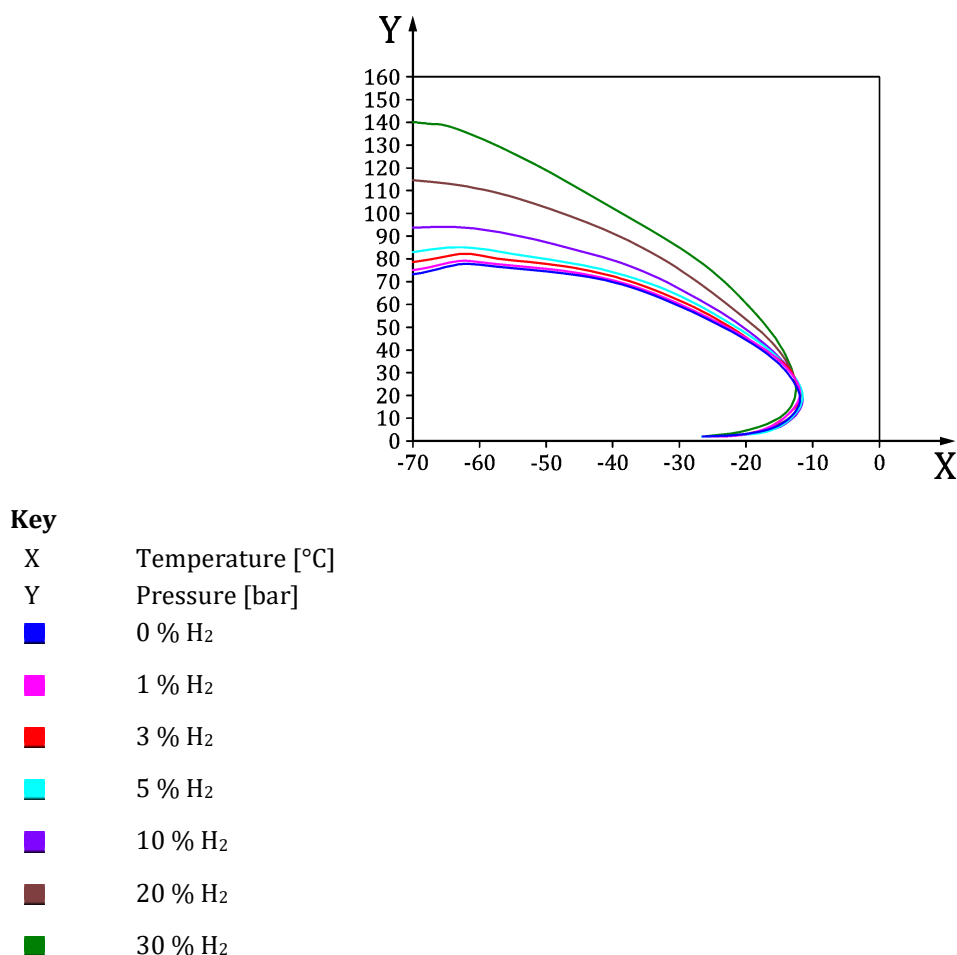


Figure 9 — Influence of hydrogen additions on the phase transition curve of a high-calorific natural gas from Russia

The curves in Figure 10 occur when a measuring instrument with a detection limit of 5 (50) mg/m³ is used.

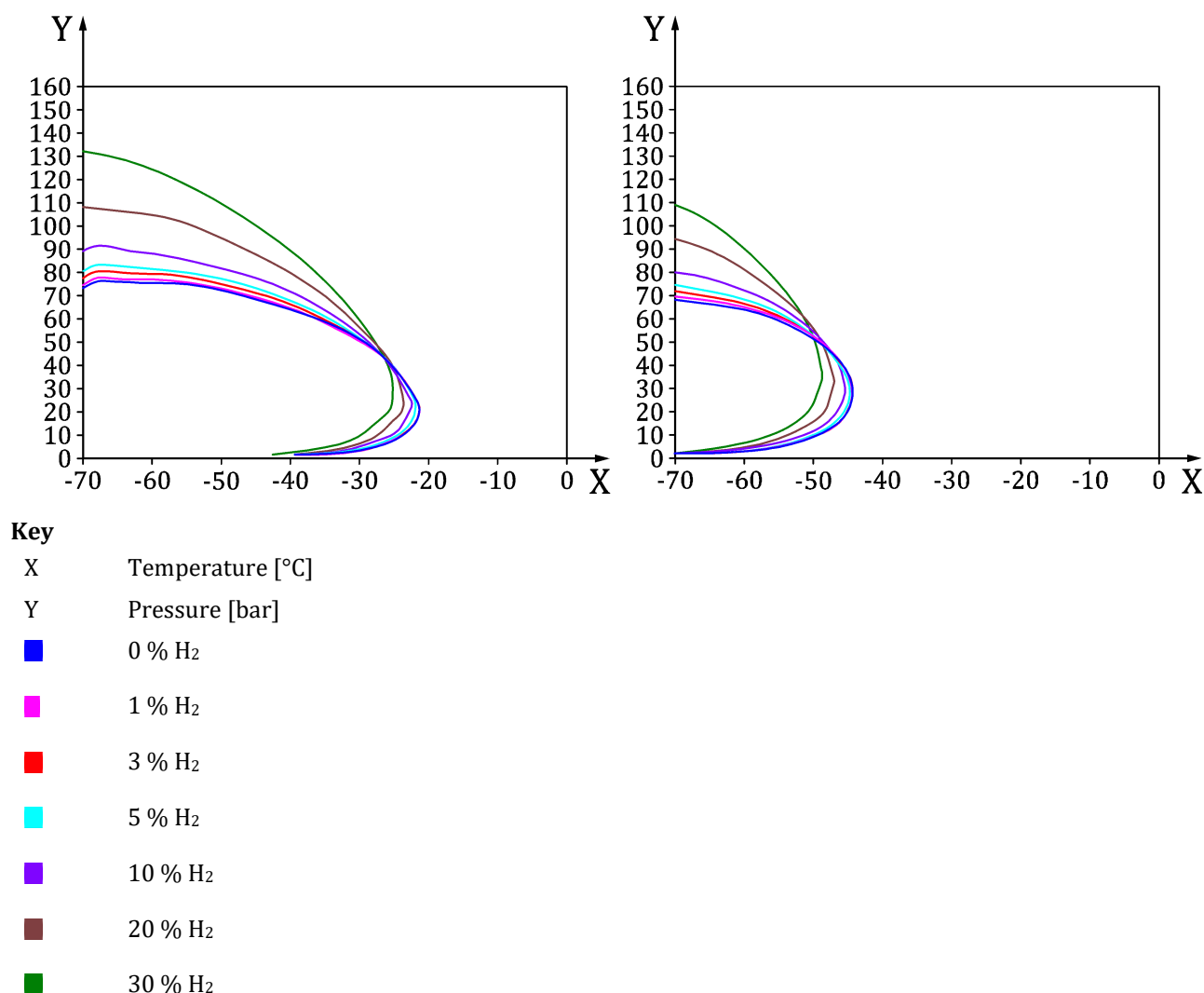


Figure 10 — 5 mg/m³ (left) and 50 mg/m³ (right) quality curves with different volumes of added hydrogen in a high-calorific natural gas from Russia

6.2.2.4 Methane number

Natural gas has a high knock resistance compared with petrol and LPG. This generally results in a high fuel energy to mechanical/electrical energy conversion with reciprocating gas engines. The knock resistance of gaseous fuels is expressed in the Methane Number (MN). Pure methane has a MN of 100 and hydrogen a MN of 0. Hydrogen has much lower auto-ignition temperature than methane.

Adding hydrogen to natural gas, LNG and to biogas/biomethane lowers the knock resistance of the resulting mixture. The extent of this lowering depends on the composition of the natural gas into which the hydrogen is injected. A natural gas with a relatively high fraction of higher hydrocarbons (C₂+) has a much lower knock resistance than methane. Carbon dioxide (CO₂) in a gas mixture tends to increase the knock resistance. That is why biomethane has a slightly higher knock resistance than methane. In this clause,

- biomethane is used to illustrate the effect of hydrogen addition/injection on gases with a high MN and
- Heavy LNG e.g. from some sources in North Africa is used to illustrate the effect of hydrogen addition/injection on gases with a MN around the minimum limit

When adding hydrogen to pure methane or biomethane, the MN decreases linearly with the fraction of hydrogen. However, when adding hydrogen to LNG, a non-linear effect on the MN occurs. Both phenomena are illustrated in the following Figure 11.

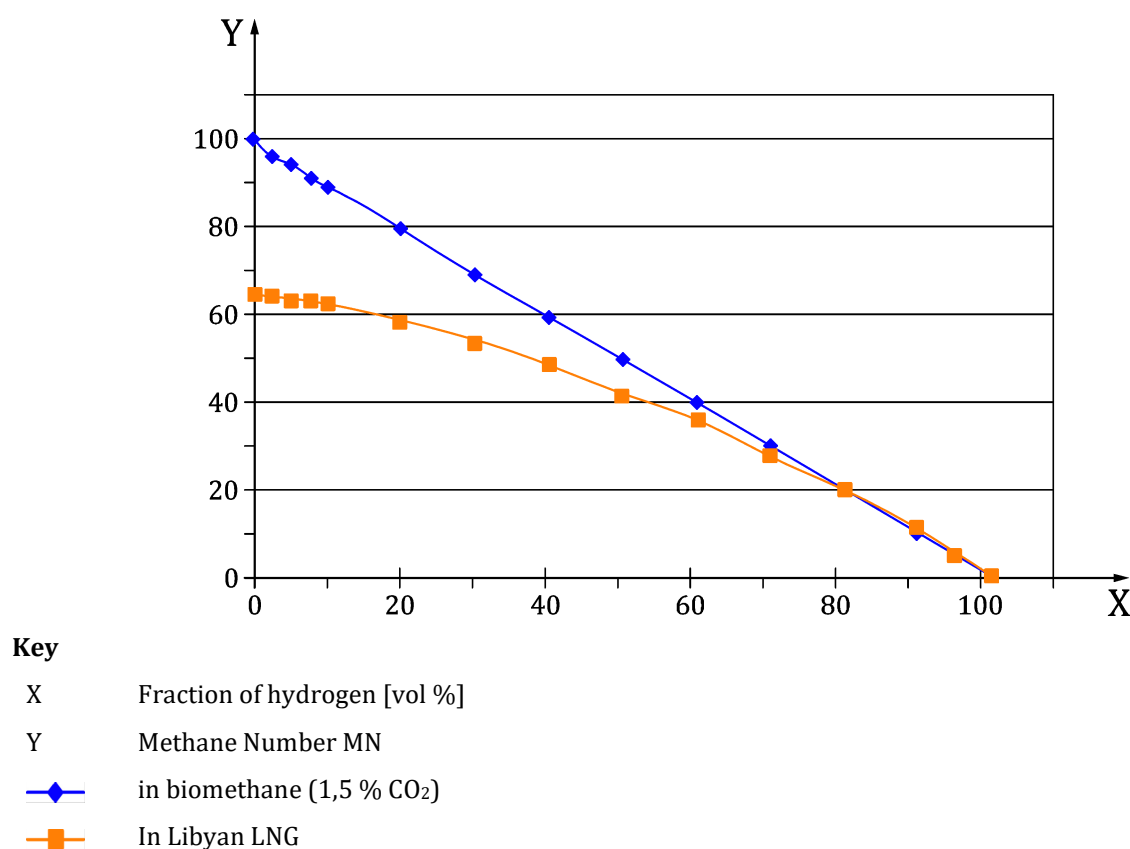


Figure 11 —Decrease in MN with the fraction of hydrogen in admixture with biomethane and Libyan LNG (example)

Because this LNG has itself a low MN, the lowering of the MN up to a hydrogen fraction of 30 % is limited. Nevertheless, even a small fraction of hydrogen will decrease the MN to below 65. At a level of 70 % of hydrogen in Libyan LNG, the MN is roughly the same as for 70 % of hydrogen is injected in biomethane.

It is concluded that the effect of the addition/injection of hydrogen to natural gas and biomethane on the knock resistance depends to a large extent on the (initial) composition (fraction of higher hydrocarbons/CO₂) of the gas.

6.3 Gas compression

6.3.1 Scope of consideration — Gas compression

To transport gas through the transmission grid, compressor stations are needed to build up the required pressure. Compressor stations are typically placed every 100–250 km on the pipeline network. Gas turbines, fuelled with gas from the pipeline, are often used to power centrifugal compressors.

The main objective of this clause is to describe the technical effects of hydrogen admixtures on natural gas compressor stations in function of an increasing level of hydrogen in natural gas composition (≤ 1 Vol.-% and > 1 Vol.-% up to 10 Vol.-%) and give recommendations to operators to set up an appropriate asset integrity policy. For different hydrogen compositions different components of existing compressor stations have to be individually assessed. For detail refer to Table 10. For compressor units

any changes in concentration outside the design limits needs to be individually assessed. Assessments will include safety, reliability and performance.

This subclause focusses exclusively on the effect of hydrogen on those items specific for compressor stations (i.e. compressors, drivers, auxiliaries, filters and gas coolers), their H₂ compatibility and influence on safety, functionality and performance. Accessory items such as pipework, gas regulating components and analysers are part of the scope and assessment of other CEN/TC 234/WGs and of CEN/TCs in CEN/SFG-I.

The assessment of the equipment is based on available knowledge mainly of the members of CEN/TC 234/WG 7 for compression systems and is based on the evaluation of different studies such as NaturalHy and other literature. Various studies have shown that most parts of the natural gas system can cope with a limited hydrogen addition, with no adverse effects.

6.3.2 Technical considerations — Identified H₂NG aspects — Gas compression

Compared to natural gas, hydrogen is lower in density, energy content and ignition energy. When changing the medium to be transported, other degradation, failure mechanisms and suitability issues need to be taken into account. Blends with higher percentages of hydrogen face more challenging issues and restrictions across the whole grid, including pipeline materials and modifications required for compressors, sealing, meters, etc. Special attention has to be paid for leakages (density), ignition energy, flammability ranges and material integrity (embrittlement).

The effects of hydrogen on the components of compressor stations will be outlined in 7.3 in relation to the H₂NG concentrations and following the structure of the EN 12583 document. Focus is given primarily to those components, which are exclusively in use in compressor stations.

6.4 Gas pipelines with MOP over 16 bar — Gas transmission

6.4.1 Scope of consideration — Gas transmission — EN 1594

This approach shows a way on how hydrogen gas can be transported in existing natural gas pipelines. On a practical basis it is more or less limited to:

- welded pipelines made from low carbon steel pipes typical with yield strengths up to 555 MPa (X80);
- weldments, seamless and welded pipes, bends, reducers, flanges, valves, isolation couplings;
- hydrogen gas pressures up to around 100 bar (o).

6.4.2 Hydrogen piping and pipelines — ASME B31.12

6.4.2.1 General

ASME first published the Standard B31.12 Hydrogen Piping and Pipelines in 2008. With this standard the use of materials with unlimited yield strength is possible. The design pressure of pipelines instead is limited to a maximum of 200 bar.

ASME B31.12 provides a comprehensive approach to design, build and operate a hydrogen pipeline system. It describes several aspects about welding, inspection, service requirements for piping components and joints as well as design, installation, and testing of components. The code also specifies engineering requirements deemed necessary for safe design, construction, operation, and maintenance of pressure piping.

6.4.2.2 Fracture mechanics of hydrogen transporting pipelines

ASME B31.12 Part PL of this code sets forth requirements for:

- materials,
- components,
- design,
- fabrication,
- assembly,
- erection,
- inspection,
- examination,
- testing,
- operation, and
- maintenance of hydrogen pipelines.

There are also some exclusions. These are:

- design and manufacture of pressure vessels covered by the ASME Boiler and Pressure Vessel Code (BPVC),
- pipeline systems with temperatures above 232 °C or below –62 °C,
- pipeline systems with a moisture content greater than 20 ppm.
- pipeline systems with pressures above 21 MPa and a hydrogen content less than 10 % by volume.

NOTE This document also takes into account that a hydrogen content less than 10 % by volume is excluded. It can be assumed that this exclusion is caused by lack of knowledge about the effects of smaller portions of hydrogen less than 10 %. In section 5.2.2 of this document, it is shown that for steel pipelines having lower concentrations of hydrogen than 10 % by volume will lead to similar results as higher concentrations.

ASME B31.12, part PL-3.7 “Steel pipeline, steel piping systems design” contains important information about mechanical behaviour of steel pipelines which are exposed to hydrogen.

With this document the material performance factor of steel can be applied for existing natural gas transport pipelines.

6.4.2.3 Requalifying existing pipelines for hydrogen service

Requirements to allow an operator of a pipeline - previously used for service not covered by ASME B31.12 to qualify that pipeline for service under that code are set out in part PL-3.21 Steel Pipeline Service Conversions. Only the initial conversion to hydrogen service requires qualification testing. A comprehensive procedure to be followed is given. It is not defined in detail how the tests must be set up.

6.4.3 Technical considerations — Identified H₂NG aspect — Gas transmission

6.4.3.1 Hydrogen-enhanced fatigue of pipelines

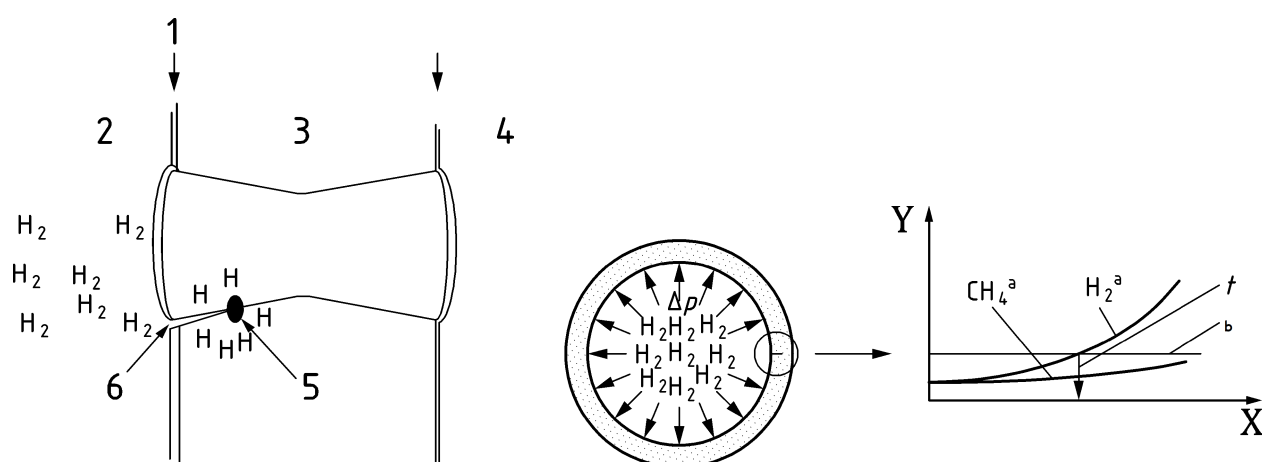
For general considerations of consequences of hydrogen on steel pipelines, see 5.2.

A comparison of the mechanical behaviour of the steel in the tests with the behaviour of the gas pipelines is carried out. Gas pipelines are usually designed so that stresses are below the specified minimum yield strength and fatigue loading is also usually not relevant considering the gas compressibility. This situation can be compared with the tensile test, where no hydrogen effects are to be expected as stresses are below the yield strength. The effect of hydrogen on the fracture strain is not relevant.

Gas pipelines are welded structures and weldments can contain a variety of defects, including crack-like defects. In this situation, a fracture toughness test might be relevant. However, this test involves a constantly increasing load, meaning continuous plastic straining at the crack tip in the presence of hydrogen. Newly built pipelines might be stressed increasingly by settlements and this is taken into account in the design. Existing pipelines are settled, therefore will not be stressed increasingly. Fatigue loading due to daily demand differences in combination with crack-like defects is a situation comparable to the fatigue crack growth tests.

So, where hydrogen gas is transported in pipelines at ambient temperatures and moderate pressures, the relevant HE mechanism is hydrogen-enhanced fatigue crack growth: existing crack-like defects in a pipeline, most likely weld defects, can grow faster in hydrogen gas than in natural gas under a fatigue loading.

At newly created steel surfaces, hydrogen molecules dissociate and are absorbed in the steel. Around the plastic zone of a growing crack-like defect, hydrogen atoms interact with the steel enhancing the crack growth compared with methane, see Figure 12.



Key

1	oxyde layer
2	inner
3	steel pipe wall
4	longitudinal pipe weld
5	hydrogen interaction with iron atoms and/or plasticity at the defect tip
6	defect $H_2 \rightarrow 2[H]$
X	number pressure variations N
Y	crack depth
a	defect in ...
b	acceptable
t	100 years

NOTE 1 Around the plastic zone of a growing crack-like defect, hydrogen atoms interact with the steel enhancing the crack growth compared with methane

NOTE 2 At newly created steel surfaces, hydrogen molecules dissociate and are absorbed in the steel.

Figure 12 — Illustration of the hydrogen-enhanced fatigue crack growth in pipelines

6.4.3.2 Approach for fit for purpose of existing natural gas pipelines with respect to hydrogen

According to ASME B31.12 there are two possible options (Option A and Option B) regarding the design of pipelines. According to Option A, a material performance factor has been taken into account for the effect of hydrogen gas on the mechanical properties of hydrogen steels. The material performance factor H_f is given in ASME B.31.12, Table IX 5A, and it equals 1,0 in the case of the yield strength of X52 or lower.

Pipelines made of steel with yield strength up to 360 MPa can therefore be used for transporting up to 100 % hydrogen without changing design pressure or design temperature. For steel grades with yield strength higher 360 MPa the performance factor leads to a reduction of the pressure and/or increasing of the wall-thickness.

A further possibility to design a pipeline is given by Option B of ASME B 31.12. Option B is based on fracture mechanics' approach. When using Option B, the material performance factor (H_f) needs to be 1,0. One possible basis for the fracture mechanics approach is the knowledge of the crack growth behaviour of the used material. To achieve this fracture mechanics testing of the used material can be applied. In lieu of measuring fatigue crack growth rate properties, the material constants for fatigue crack growth rates given in ASME B 31.12, Table PL-3.7.1-5, can be used for calculating the crack growth rate in combination with the given equation.