Proceedings of the ASME 2020
International Pipeline Conference
IPC2020
September 28-October 2, 2020, Calgary, Al, Ca

IPC2020-9205

H2 IN AN EXISTING NATURAL GAS PIPELINE

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ABSTRACT

N.V. Nederlandse Gasunie (Gasunie) has converted an existing gas transmission line from transporting natural gas to transporting a mixture of gaseous hydrogen and 30% to 0% methane. To enable this, an assessment was carried out on technical safety, process safety, work safety and external safety.

The pipeline, with two valve stations and, was constructed in 1996 according to applicable Dutch regulations and actively managed in accordance with Gasunie company standards.

The pipeline was evaluated for hydrogen transportation and, based on the following measures, this was seen as being feasible:

- *The water dew point of the feed must not exceed -8° C;*
- *The pipeline must be separated from the natural gas transport system;*
- *Blowdown must be performed either at the site of the supplier or the user of the hydrogen;*
- *Gas measurement equipment, personal safety and leak detection must be suitable for hydrogen;*
- *Due to the assignment of hydrogen as a chemical agent, the safety contour was reduced by performing extra measures, such as additional communication to landowners, additional requirements for the pressure-regulating system and verification of additional settlement and stresses.*

The operational changes consist of a number of maintenance and management issues:

- *In- service welding and hot tapping are not allowed;*
- *Equipment suitable for use in gas group IIC (ATEX) must be used;*
- *Emergency and maintenance procedures must be updated to those applicable for pipeline and valve stations containing hydrogen.*

Keywords: Hydrogen, Operation, Methane to Hydrogen

1. INTRODUCTION

In autumn 2017, an interest was expressed by Dow Chemicals, Terneuzen, Netherlands and Yara Fertilizers, Sluiskil, Netherlands in a pipeline which was not used for regular natural gas transport, to transport hydrogen-rich gas from Dow to Yara. This was to reduce the flaring of gas from a naphtha cracker at Dow and to convert natural gas to hydrogen at Yara. This would result in a reduction in greenhouse gas emissions and, at the same time, a conversion of natural gas to hydrogen to produce fertilizer. The pipeline was used at that time as a back-up and filled with 40 bar natural gas. The potential for this change was studied by Gasunie and, based on the results, the company decided to convert the pipeline to hydrogen transport. The hydrogen content of the feed from Dow is around 80% and, the remaining content is methane. The pressure of the feed will be around 35 bar.

This paper discusses the assessment performed by Gasunie on this pipeline for its suitability to safely transport hydrogen. The items addressed in this paper are technical safety, process safety, work safety and external safety.

2. METHOD

Dutch pipeline regulation NEN 3650-1 [1], paragraph 10.5, contains the following regarding a change of fluid;

“Prior to a change in the function of the pipeline, such as a change in the transported substance and/or a change in process conditions such as pressure and temperature, extensive research must demonstrate that the design and integrity of the pipeline system is appropriate for the intended new application.

The investigation must be based on the current and complete pipeline file, maintained according to the PDCA cycle, the intended product and/or the intended process conditions. Particular attention must be given to welding procedures used, other connection methods, internal and external lining and to pipe materials, valves and other pipe components used."

In the assessment, a distinction is made between technical safety (integrity), process safety, work safety and external safety, including consequences for permits. The assessment used existing internal and external investigations. No new or experimental investigations were carried out for this assessment.

3. RESULTS AND DISCUSSION

Based on the method described above, a stepwise analysis was made of the relevant factors impacted by the transportation of hydrogen instead of natural gas in the line. In paragraphs 3.1 to 3.5 the pipeline properties are described. Paragraphs 3.6 to 3.22 discuss the impact on the pipeline of transporting hydrogen.

3.1 Line routing

The pipeline has a length of around 11 km (7 miles), see Figure 1. The year of construction is 1996, the line has a design pressure of 66.2 bar (o) (960 psi) and a nominal diameter of 400 mm (DN 400, 16"). The line contains three HDD crossings, one below the Gent-Terneuzen channel and two additional combined crossings. A railroad is crossed inside a casing. The pipe has connections for a pig trap at valve stations S-081 and S-728. The pipe is coated with a flowcoat on the inside, a polyethylene coating on the outside and has active cathodic protection.

FIGURE 1: Routing of the pipeline (blue line)

3.2 Wall thickness, steel type, pipe type

The nominal wall thickness of the main length of the pipelineis 7.4 mm (0.3"). A length of 761 m (830 yd) has a nominal wall thickness of 6.2 mm (0.24"). The steel type of the pipe with a wall thickness of 7.4 mm is L415MB (X60M), the 6.2 mm pipe is made of St.E415.7 TM (X60M). These are the same steel types, but the pipes have been produced to different standards (EN 10208-2 and DIN 17125). But essentially these are the same since steel grade St.E 415.7 TM was converted to L415MB when EN 10208-2 was released in 1996. The pipes are welded with the high frequency induction (HFI) welding process. Available in Gasunie's archive are details of the pipe where inspected during production by Gasunie’s procurement inspection and all mill test reports. When looking at the requirements of DIN 17125, EN 10208-2 and comparing these with the current ISO 3183:2019, including annex A for European onshore gas pipelines, the requirements are identical. This results in the conclusion that the pipes meet the current standard. The flow and polyethylene coatings are factory-applied.

3.3 Design factor

The design factor is the ratio between the stress in the circumferential direction and the minimum specified yield strength. The design factor is calculated according to the simple calculation of NEN 3650-2 [1] for the two wall thicknesses and two pressures: the original design pressure and the set pressure of the safety at the hydrogen-producing unit. The calculation for wall thickness is the nominal wall thickness minus the tolerance of 0.35 mm. The results are given in Table 1.

Table 1 Overview of design factors

diameter [mm]	nominal wall thickness [mm]	calculation - wall thickness [mm]	pressure [bar (e)]	Stress [MPa]	SMYS [MPa]	design factor [-]
406.4	6.2	5.85	66.2	227	415	0.55
406.4	7.4	7.05	66.2	191	415	0.46
406.4	6.2	5.85	41.7	145	415	0.35
406.4	7.4	7.05	41.7	120	415	0.29

3.4 Girth welds

The girth welds are made with the cellulosic SMAW process in accordance with Gasunie Technical Standard CSW-01 from 1996. According to the welding method qualifications from the construction files, the hardness is around HV 200. All welds were examined with radiography. In addition to radiography, the tie-in welds have also been examined ultrasonically and magnetically. Before the tie-in welds were made the line was hydrostatically tested at a pressure of 88.1 bar (o) (1278 psi).

3.5 Integrity management

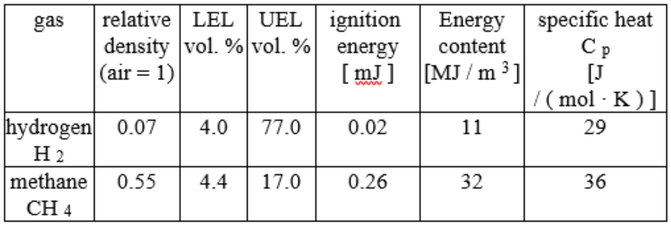
The pipeline was inspected by an MFL pig before being converted to hydrogen. The next inspection, based on the indications found, minor dents, metal loss and current knowledge of the external corrosion, was determined to be not later than 2047. The cathodic protection is functioning and there is no AC interference on the pipeline. In 2000 an incident of damage due to digging was recorded, but this led only to coating damage which was repaired.

3.6 Properties of hydrogen

Hydrogen (H_2) gas is lighter than air and natural gas, it has a choking effect and, as one of the smallest molecules on earth, it is one of the most difficult gases to prevent from leaking. When it expands under certain conditions, the temperature of hydrogen will increase (negative Joule-Thomson coefficient). It is highly flammable, has a low ignition energy and burns in air with a (pale) blue, nearly invisible flame [2]. Hydrogen has a wide range between the lower explosion limit (LEL) and upper explosion limit (UEL) compared to methane and natural gas.

Table 2 shows various data related to these properties of hydrogen and methane.

Table 2 Overview of physical and combustion properties of hydrogen, methane [3, 4]. For pressure and temperature, see references. Other references may contain different values.



gas	relative density (air = 1)	LEL vol. %	UEL vol. %	ignition energy [mJ]	Energy content [MJ / m ^{3}]	specific heat C_p [J / (mol · K)]
hydrogen H_2	0.07	4.0	77.0	0.02	11	29
methane CH_4	0.55	4.4	17.0	0.26	32	36

In the Naturalhy project, full-scale tests were carried out with 6" pipes where a rupture was simulated using an explosive [5]. One test contained a 22% vol. hydrogen-natural gas mixture and the other test 100% natural gas, both at a pressure of 71 bar (1029 psi). The natural gas-hydrogen mixture immediately caught fire after the explosion, while with the natural gas test no ignition took place. In References [5] and [6] the effects of hydrogen-natural gas fires were investigated. The heat radiation, overpressure and flame height are, for up to 20-25% vol. hydrogen-natural gas mixtures, not significantly different than for natural gas.

3.7 Hydrogen degradation of metals

Hydrogen atoms in metals, especially in steel, can lead to hydrogen embrittlement. This term includes a number of degradation mechanisms such as: hydrogen-induced cracking (HIC), hydrogen stress cracking (HSC), hydrogen blistering, hydrogen attack, etc. For all mechanisms, hydrogen atoms must be dissolved in the metal matrix to have this effect. Hydrogen molecules cannot be absorped in metal, see for example Chapter 7 of Reference [7]. The temperature and partial hydrogen pressure (concentration) have a major influence on all these mechanisms. The temperature determines, among other things, the reaction rates, not just of the adsorption and absorption of hydrogen, but also the concentration and transport in the metals. The hydrogen pressure ultimately determines the amount of hydrogen absorbed into metals.

Hydrogen atoms are required for all low-temperature degradation mechanisms. Hydrogen ions (H^+) can easily enter the steel matrix, for example, H_2S gas in water will partly decompose into H^+ and HS^- ions. Hydrogen molecules will not split when in liquid water. So even if water is present in a pipeline, no hydrogen atoms will be formed. In a steel pipeline, hydrogen molecules can only split on a clean steel surface, that is without an oxide layer. These surfaces are not common in a finished pipeline, since after hydrotesting and commissioning all internal surfaces are either coated or have an oxide layer either from hydrotesting or exposure to air before the line is put into service.

The degrading effect of hydrogen depends on:

- 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 flaws
- the temperature
- the presence of an oxide layer (low temperature H_2 gas only)

Three examples of specific hydrogen embrittlement mechanisms are hydrogen-induced cracking (HIC), high-temperature hydrogen attack (HTHA) and cold cracking due to welding.

HIC deals with recombination of hydrogen atoms to molecules within steel resulting in high internal pressures in the steel matrix. These pressures can become so high cracks will be created in the steel. HIC only occurs when the source of atoms is ionic, for example in the case of H_2S corrosion. Equivalent pressures reached within the steel matrix are approximately 10,000 bar (145 ksi) and over.

HTHA occurs at high temperatures where hydrogen reacts with the carbon in the steel resulting in voids in the steel matrix. Due to these voids the cohesion and subsequently the strength of the steel is lost.

Cold cracking occurs in weldments during or after welding. It is a combination of hardened microstructure and high moisture concentrations in the welding consumable. Typical hydrogen concentrations in welds are significantly higher compared to concentrations occurring from hydrogen gas pressures.

The above three HE mechanisms are not relevant since they require high temperatures (> 150°C) or high hydrogen concentrations, over 50 – 500 atomic ppm. This compared to a hydrogen pressure of 101 bar which will result in around 0.5 atomic ppm or less in the steel based on a clean oxide-free steel surface.

The precise mechanism of hydrogen embrittlement at low temperature [8] is still unknown, also a certain degree of plastic deformation must occur. Under static hydrogen pressure, the suitability for a carbon steel for HTHA can be determined with so-called Nelson curves. The curve is shown in Figure 2. The design criteria for the Gasunie transmission network are indicated in this figure. These are well below the Nelson curve.

Figures 3 to 5 illustrate the typical mechanical behavior of pipeline steel in the presence of hydrogen. Comparable results can be found in References 9 to 12. In a tensile test, yield, tensile strength, elasticity and strain hardening are not affected. The fracture strain is affected and this effect increases with a decreasing displacement rate. Fracture toughness testing is also affected by the displacement rate although there is a threshold related to the amount of stress variation. The decrease in toughness depends on the hydrogen pressure, see Figure 4.

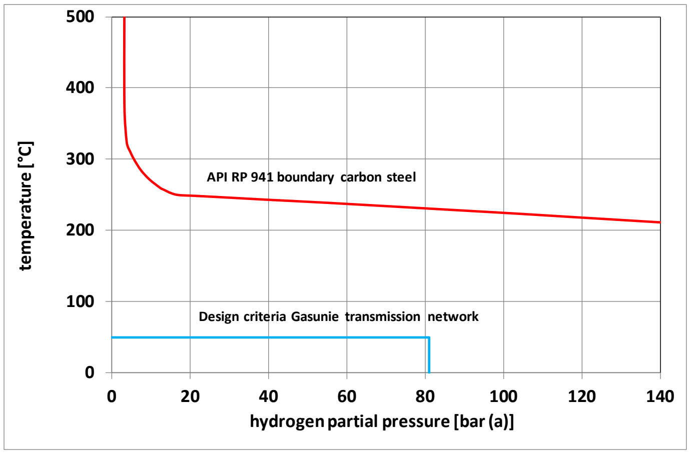


FIGURE 2: Permissible hydrogen partial pressures and temperatures for welded carbon steel [13] and the criteria for Gasunie's transmission network.

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 when the load on the specimen increases. In this situation the effect of hydrogen is significant.

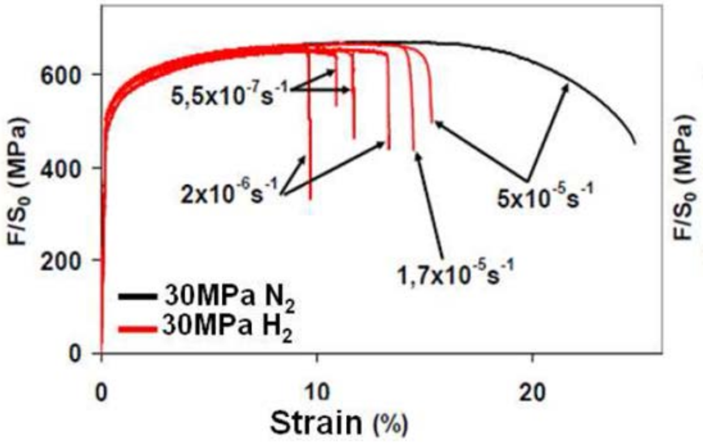


FIGURE 3: Example: typical result of the tensile test in hydrogen gas: decrease of the fracture strain depending on the loading rate (L555, X80) in H_2 gas (300 bar) [14]. The fracture strain is the strain where the curves end.

The only way hydrogen atoms can be formed is when a hydrogen molecule comes to a clean steel surface, this means without the oxide or rust layer which is usually present in a steel pipeline. Clean surfaces can only be created in steel pipeline when fatigue loading creates flaws in the steel surface. When, at that moment, no oxygen is present, an oxide film will not be formed on the newly formed surface caused by fatigue. Hydrogen molecules can then dissociate at the clean fatigue crack surface and enter the steel matrix as an atom. This mechanism is called 'hydrogen-enhanced fatigue'.

The conditions for hydrogen embrittlement by hydrogen at low temperature are:

1. presence of sufficient hydrogen atoms;
2. presence of clean surface flaws in contact with hydrogen gas;
3. fatigue loading;
4. absence of oxygen.

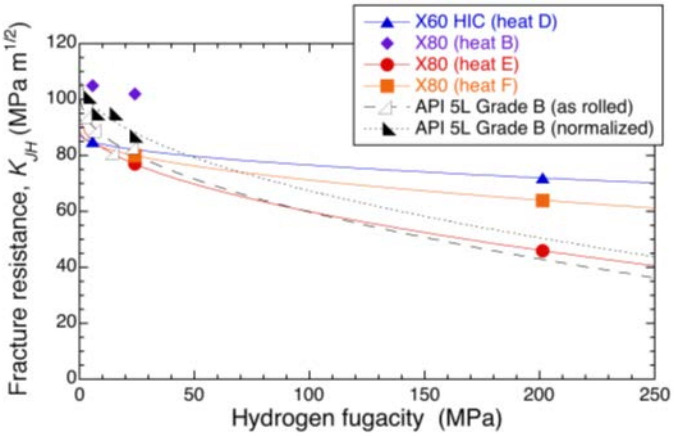


FIGURE 4: Example: effect of hydrogen gas pressure on fracture toughness for pipeline steels [11]

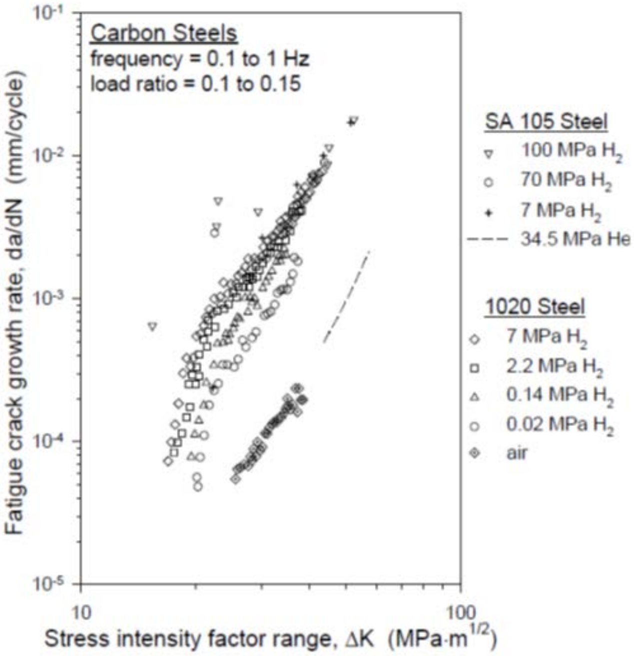


FIGURE 5: effect of hydrogen gas pressure on fatigue crack growth rate for carbon steels [11].

3.8 Degradation scenario

Translated to the gas transport system, hydrogen can be absorbed, in the case of weld or other flaws, on the inside of circular seams and longitudinal seams. Whether these flaws will actually grow and whether they will then accelerate to grow in hydrogen in relation to the growth in natural gas has been the research objective of the EET and Naturalhy projects

[10, 15]. In the EET and Naturalhy research project, test pieces containing a crack were tested under a fatigue load in various hydrogen-natural gas mixtures. The results are shown in a graph where the vertical axis represents the crack growth rate and the horizontal axis the variable stress intensity factor ΔK, see Figure 6. By using the variable ΔK, both the crack length and the varying mechanical load are included. ΔK is to be considered as the cracking driving force. From Figure 6 it can be seen that there is some influence of the steel type on the crack propagation rate. The steels in this figure are representative of the steels used in Gasunie’s transportation grid.

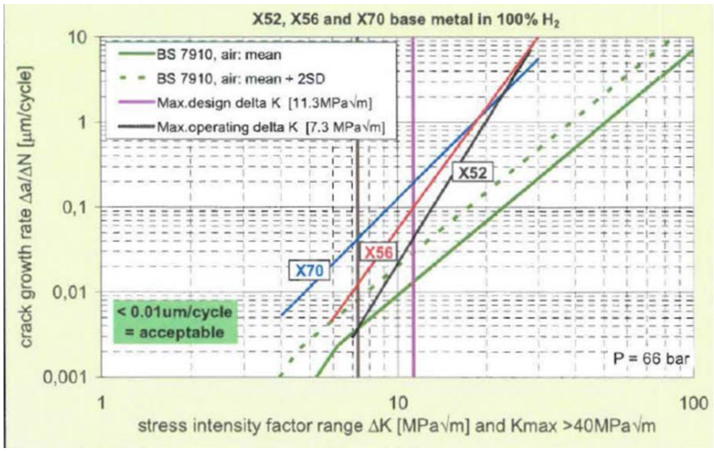


FIGURE 6: Fatigue crack growth of 3 steels for pipes in 100% hydrogen at 66 bar (o) [10]. X52 = L360, X56 = L390, X70 = L485

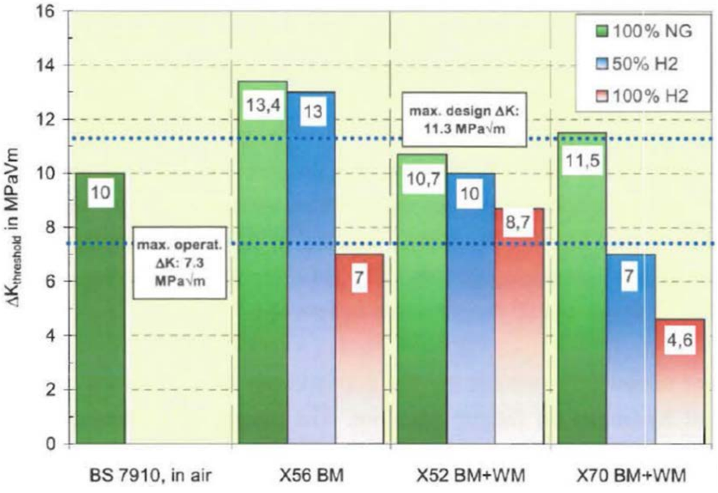


FIGURE 7: Threshold value for ΔK for three pipeline steels in 100% hydrogen at 66 bar (o). Steel type X52 = L360, X56 = L390, X70 = L485

The research also shows that the crack growth rate in natural gas for weld and base metal for the three steels are the same as in air. This means that the crack growth rate in natural gas is between the green lines of Figure 6. Whether a crack will grow and at what speed depends on the ΔK. Below a certain ΔK, the threshold ΔK_{th}, a crack will not grow. This threshold value has been determined in the Naturalhy project, see Figure 7.

3.9 Polymers

In general, hydrogen has no influence on the integrity of the polymers used in the gas transport system. Certain plastics are known to swell. For the polymers and plastics used within the gas transport system, it has been established that hydrogen has no adverse effects on the integrity and applications of these materials [16].

Hydrogen molecules have a smaller size compared to methane molecules, so there will be a higher permeation rate. This can lead to more emissions at flange connections, insulation couplings, valves and possibly membranes in pressure control equipment.

From a physics point of view, it can be argued that, as long as hydrogen occurs as a molecule in the gas transport system and does not dissociate into hydrogen atoms or hydrogen ions, hydrogen can be considered relatively inert/non-reactive.

3.10 Internal corrosion

Like natural gas, hydrogen is not corrosive. However, it is recommended that hydrogen or hydrogen-rich gas should be free of water. In order to prevent internal corrosion, the water dew point of the gas must be lower than the minimum expected gas temperature. For the Gasunie grid this means -20°C (-4°F) for aboveground piping and 5°C (41°F) for underground pipes. Gasunie uses the criterion that the water dew point at pipeline entry must be below -8°C (18°F) at 70 bar (a) (1015 psi).

3.11 External corrosion

Changing the content from natural gas to hydrogen-rich gas or hydrogen has no effect on the external corrosion. No change is needed in the cathodic protection of the pipeline.

3.12 Fracture propagation

Due to hydrogen being lighter than methane, the rate of decompression will increase by adding hydrogen to methane. If the hydrogen-gas mixture is released, the pressure reduction will be faster. This results in a lower crack driving force. As a result, no additional requirements are necessary with regard to limitation of running fractures.

3.13 Hydrogen enhanced fatigue

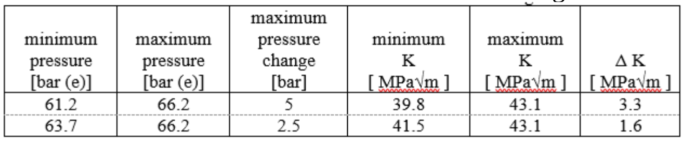
For the static situation, based on the gas conditions, temperature and hydrogen pressure, the possible hydrogen concentration in the steel will be at such a low level that no negative effect (see Figure 2) is to be expected. This applies to all used steel components in the pipeline and the valve stations.

When considering the fatigue load due to pressure variations, additional assessment has to be made compared to a natural gas pipeline.

For comparing the approach in the EET and Naturalhy studies [10], the threshold ΔK must be calculated. Starting from a conservative flaw of 3 mm by 50 mm, the ΔK is calculated at the design pressure of the line with two ranges of pressure changes. The K-calculation is based on BS7910:2005. The results of these calculations are shown in Table 3. From this table it is evident that the ΔK for the flaw in the longitudinal seam is a factor 4 larger than for the same flaw in the girth weld. Under normal circumstances, the axial load due to the internal pressure, acting on the circumferential crack, is around 30% of the stress in the circumferential direction.

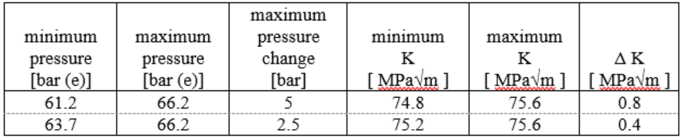
In all cases with a hydrogen pressure of 66.2 bar(e) (960 psi), the ΔK is lower than the lowest threshold ΔK in Figure 7. This results in the conclusion that even this conservative flaw will not increase in height leading to leakage or rupture. This is due to the fact that the pressure variation is too small to initiate crack growth.

Table 3a Stress intensity factor K and ΔK , axial flaw of 3 mm by 50 mm in the longitudinal seam without residual stresses due to the normalization treatment after HFI welding



minimum pressure [bar (e)]	maximum pressure [bar (e)]	maximum pressure change [bar]	minimum K [MPa√m]	maximum K [MPa√m]	Δ K [MPa√m]
61.2	66.2	5	39.8	43.1	3.3
63.7	66.2	2.5	41.5	43.1	1.6

Table 3b Stress intensity factor K and ΔK, circumferential flaw of 3 mm by 50 mm in the girth weld seam with residual stresses



minimum pressure [bar (e)]	maximum pressure [bar (e)]	maximum pressure change [bar]	minimum K [MPa√m]	maximum K [MPa√m]	Δ K [MPa√m]
61.2	66.2	5	74.8	75.6	0.8
63.7	66.2	2.5	75.2	75.6	0.4

3.14 External leakage

Hydrogen molecules are smaller than methane molecules. Due to this difference, the permeation through polymeric seals and membranes, such as in valves, flange connections and insulating couplings, can increase. In open areas, this leakage is not a problem given the low molecular weight of hydrogen. However, a flammable environment could arise in confined spaces. Additionally, when small spaces containing a mixture of hydrogen and methane are leaking hydrogen by permeation, the remaining mixture in this space will gradually change to a 100% methane gas.

3.15 Internal leakage

The smaller molecular size of hydrogen may lead to more leakage at valves. This should be taken into account when shutdown of the line is to be performed. In order to avoid issues due to any unforeseen leakages or incompatibility of valve materials, the decision to replace the existing valves of both valve stations with so-called H_2 compliant valves was taken at an early stage. Later analysis revealed that the design of the valves was identical to the original valves except for the thickness of the body to reduce the peak stresses in the body. In the past year one of the valve stations which was replaced was tested under 66.2 bar(e) (960 psi) hydrogen. This included leak tests, seat tests and blowdown operations at the valve station, no significant issues were found. It is also notable that, during all the blowdown tests performed at this valve station, over 20, the released hydrogen never ignited. Based on that experience it was concluded that existing valve stations can be used for 100% hydrogen. Pressure control equipment can use polymeric membranes. It is unclear to what extent increased permeation of hydrogen influences the functioning of this pressure regulation equipment.

3.16 Explosion limits

Hydrogen has a lower ignition energy and a wider explosion band than methane and natural gas. With hydrogen in natural gas, the explosion band will become larger and the ignition energy will be lower. With the empirical rule of Le Chatelier, the LEL [17] of a gas mixture can be determined:

$$LEL_{meng} = \frac{1}{\sum_{i=1}^{n} \frac{X_i}{LEL_i}}$$

where n is the number of combustible components, X_i is the mole fraction of the flammable component i and LELi the lower explosion limit of component i. The LEL is calculated according to this rule for H_2 with methane. Comparison with experimental values [17] indicates that the mixing rule of Le Chatelier is indeed applicable for the calculation of the LEL and UEL of hydrogen-methane mixtures. For example, an LEL of 4% and a UEL of 32% are found experimentally with a mixture of 60% hydrogen and 40% methane. Based on this calculation, it is concluded that the LEL of the hydrogen methane mixture is hardly affected by hydrogen. With the mixing rule from Le Chatelier, an LEL of 4.2% and UEL of 32% are calculated for the initial mixture to be transported of 70% hydrogen and 30% methane .

3.17 Work safety

Employees working at Gasunie locations must wear an 'LEL meter'. This meter is calibrated on pure methane and sounds an alarm at 10% of the LEL of methane. In the previous section it has already been determined that the LEL does not change significantly with hydrogen. Internal testing from Gasunie has established a cross sensitivity to hydrogen for this Crowcon gasman meter. This means no additional measures were required for the personal gas metering

Devices based on infrared absorption should not be used when hydrogen is to be measured. Hydrogen does not absorb infrared radiation and is therefore not detected by these type of devices.

3.18 Explosion category

In Europe and therefore also in the Netherlands, equipment used with pressure equipment containing combustible gas mixtures must comply with EN-IEC 60079-14. EN-IEC 60079-20-1 indicates the gas group of explosive gas mixtures. There are two main gas groups: gases in mines (I) and others (II); group II is subdivided into the categories IIA, IIB, IIC. The categories are based on the minimum igniting current ratio (MIC ratio) or the maximum experimental safe gap (MESG).

Gas group IIA is the lowest category and IIC the highest. Natural gas and methane fall into category IIA and hydrogen into category IIC. This means the change of content from natural gas to hydrogen resulted in a need to verify whether the electrical equipment met the higher ATEX category. Where this was not the case the equipment was replaced. The temperature class of the fluid also requires verification. But the temperature class for natural gas, methane and hydrogen is T1 (lightest category) because the auto-ignition temperature of these gases is over 450°C (842°F).

3.19 In-service welding

Due to the high temperatures during welding, the absorption of hydrogen atoms in the pipe wall can increase considerably. Cold cracks may occur during cooling. This scenario is probably highly dependent on the welding process conditions to be applied, the wall thickness and the sensitivity of the steel to cold cracks. Since we do not yet have any experience in this regard, in-service welding is currently not allowed on Gasunie’s hydrogen-containing pipeline.

3.20 Blowing down

Venting takes place for certain activities in the transport system: for emptying liquid trap facilities and control blocks, maintenance of valves, replacement of components etc. As long as this is done through small diameter blowdown piping and concerns small quantities for a short duration, blowoff of hydrogen or hydrogen-rich gas is seen as acceptable.

In general, the assumption is: high-pressure hydrogen lines will almost always ignite if the gas is released. Although, as with natural gas, there is no clarity about the ignition mechanism, it can be stated with certainty that released hydrogen ignites spontaneously at much lower pressures/quantities compared to natural gas [18].

During blowdown, the operator in methane operation has no additional protection, apart from his standard work apparel, against heat radiation. During the blowdown of natural gas, it is trusted the gas will not ignite when there are no apparent sources of ignition. This approach is not possible when performing blowdown with high-pressure hydrogen, because hydrogen will almost always ignite from high-pressure outflows from a large opening. For mixtures of hydrogen with methane it is highly likely that the risk of ignition is significantly increased. If the hydrogen-methane mixture ignites, the heat radiation will be roughly equal to heat radiation from natural gas, in contrast to a fire of pure hydrogen which has less heat radiation compared to natural gas.

Based on the above, it is Gasunie’s policy not to blow down lines with hydrogen-rich gas. This applies to both planned work and emergencies (paragraph 3.21). Measures to avoid blowdown for planned work are:

- Planned work: displace the hydrogen-rich gas with natural gas or nitrogen and then blow down the line in accordance with the normal procedure;
- Flare the line by flaring with Dow Chemicals

3.21 Incidents and emergencies

At the moment hydrogen cannot be vented in the event of an incident or disaster. However, it must be possible to reduce the pressure in the event of pipe damage. The procedure must be adjusted accordingly. Currently the feed can be stopped at Dow Chemicals and flaring will be used to blow down the line in an emergency. External safety is about the safety of the public and local residents, where the risk is determined by:

1. The probability (frequency) with which the pipe leaks and ignites the outflowing gas;
2. The effects of the torch fire on the public and local residents.

The external safety policy of the Dutch government sets standards for this risk [19,20].

3.22 Risk calculations

Quantitative risk calculations were performed by DNV GL for site-specific risk (PR) and group risk (GR) [21]. The calculations were performed in accordance with the guidelines for carrying out risk analysis on underground gas transport pipelines with hydrogen, as established by the Dutch government. For this a standardized software package is used, Safeti-NL. Hydrogen modeling is described in a Risk Calculation Guideline (Decree on external safety of pipelines), Module D - Chemical pipelines, section 2.5.1 [22] . This modeling has been followed. To be able to assess the line it was verified that the pipeline met the current state of technique. This assessment consisted of the following elements:

- The use of an effective safety management system, in accordance with Article 4(1) of the External Safety Pipeline Decree (Bevb) and NEN3650 with the NTA-8000 pipeline safety management system.
- Damage by third parties. Clearly indicated aboveground markings of the pipeline that can be seen from every viewpoint.
- Periodic communication with landowners to make them aware of the presence of the pipeline.
- Implemented KLIC/WION system with active recall (mandatory reporting of digging activities)
- Internal corrosion management system consisting of:
  - determination of product corrosivity;
  - application of design measures based on corrosivity; (for example, corrosion surcharge on wall thickness, applying corrosion inhibition, applying corrosion-resistant steel alloy of the pipe wall and any internal coating/liner);
  - effective monitoring program (for example, monitoring product quality through sampling, chemical injection, sampling on metal release).
- External corrosion mitigated by application of suitable coating and cathodic protection in accordance with NEN 3654. Effective monitoring program of cathodic protection and of coating.
- Operational and other causes of failure

- o Specified working area regarding flow, pressure, temperature, trip settings.
- o Automated process monitoring and process protection.
- o Monitoring of relevant DCS or SCADA data to continue operating within this working area.
- o Change of work area only permitted through established procedures, such as with changes (Management of Change).

The Bevb manual uses a failure frequency of $3.7 \cdot 10^{-5}$/(km/year) for standard technology for chemical pipes. This can be reduced by additional depth coverage, active recall on digging calls, increased reliability of pressure-limiting devices and having a non-corrosive fluid in the pipe. When combining all these measures, the risk of a fatality at the location of the pipeline was calculated at being less than $1 \cdot 10^{-6}$ per year.

4. CONCLUSION

N.V. Nederlandse Gasunie has converted an existing 16" transmission line from natural gas to a hydrogen-methane mixture based on verification for mixtures up to 100% hydrogen. The operational impact is limited but the personnel involved have to use adjusted procedures. This requires the use of suitable equipment when performing gas measurement, using spark-free tools, no blowdown from the main line. The external risks are managed by the additional measures on contact with landowners, additional requirements for pressure-limiting devices and the higher than minimum required Gasunie management system. The hydrogen-enhanced fatigue crack growth is checked by taking a conservative flaw, it was calculated that this flaw did not result in a ΔK high enough to initiate crack growth.

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