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MODERN PE PIPE ENABLES THE TRANSPORT OF HYDROGEN

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SHORT SUMMARY

To investigate the suitability of PE pipes for the transport of hydrogen on a specific industrial site, three topics were investigated. These topics are: the chemical resistance of PE to hydrogen, the permeation rate of hydrogen through PE and the electrofusion of PE pipes exposed to hydrogen. It can be concluded that the tested PE100-RC pipes on the premises of Groningen Seaport are suitable for the transport of hydrogen at pressures of up to 2 bar. However, during design and maintenance, the specific characteristics of hydrogen that distinguish it from methane need to be taken into account.

KEYWORDS

Polyethylene, PE100-RC, Hydrogen, Permeation, Electrofusion, Maintenance

ABSTRACT

At Groningen Seaports, hydrogen gas is produced as a by-product on a local chemical site. To encourage reuse of this kind of energy-rich waste, the hydrogen is used as a fuel for scheduled buses in the northern part of the Netherlands (Groningen).

A special pipeline is installed to transport the hydrogen from the production facility to the filling station where the buses are fueled with the hydrogen. It is important that the long-term safety and security of this pipeline can be guaranteed. Moreover, the construction and maintenance process must be carried out cost-effectively. Polyethylene with raised crack resistance (PE100-RC) was selected as a potential piping material. As there is little experience with the combination of this PE piping material and hydrogen gas, a study was carried out before construction work started. This study considered safety and material aspects, as well as maintenance issues for this particular pipeline at this specific location. Factors such as installation modes of the pipe and various possible maintenance activities during the operational phase were considered. A number of important material parameters, such as the permeation rate and the fusibility after prolonged exposure to hydrogen gas, were investigated for the selected PE100-RC material. The results of the study and additional insights into the construction of this pipeline are presented.

In the near future, the available volume of hydrogen gas is set to increase. This is especially so if the surplus renewable energy generated by photovoltaic cells or wind turbines is used to produce

hydrogen gas. This could result in additional opportunities beyond the new applications mentioned above. The existing natural gas network offers new and economically interesting opportunities to store and transport this excess renewable energy in the form of hydrogen gas. However, a possible drawback is the volume of hydrogen gas emitted from the oldest natural gas networks as a result of permeation, since this may prove to be higher than for modern PE materials. As such, permeation tests on these old (first-generation) PE pipes will also be investigated in the near future.

INTRODUCTION

The transition from energy from fossil sources to energy from renewable sources is the subject of increasing attention in the Netherlands. As part of this transition, hydrogen gas is being considered as an energy storage and transportation solution. At present, hydrogen is often produced on a small scale as a by-product of other industrial processes. However, in the near future the available volume is likely to increase. This is especially so because the surplus energy generated by photovoltaic cells and/or wind turbines can be used to produce hydrogen by electrolysis.

Polyethylene (PE) is the most widely-used pipeline material worldwide for networks used to distribute and transport natural gas at pressures of up to 10 bar. The main advantages of PE compared to steel are the relatively low installation costs and the ease of maintenance. If new and existing PE networks prove to be suitable for the distribution of hydrogen, this is likely to offer new and economically interesting opportunities to store and transport excess renewable energy. The currently-used PE100-RC was investigated in a specific case study to identify whether it is fit for purpose from a safety, material and maintenance perspective.

There are several issues to consider. For example, permeation may be a problem due to the economic loss and the environmental impact of lost gas. Permeated gas can also accumulate in unexpected places, leading to possible safety issues.

EXPERIMENTAL

Piping material

The investigated PE pipes are certified in accordance with EN 1555 (PE pipe systems for the transport of natural gas). They are sold as PE100-RC pipes, and are tested in accordance with PAS 1075.

Chemical and mechanical suitability

When transporting mediums such as fluids or gases via pipelines, it is important to understand the possible chemical interactions between the transported medium and the pipeline material in order to predict the lifetime of the pipeline system and any resulting risks.

The investigated PE pipe was a DN90 SDR11 90x8.2 mm. Its chemical suitability was determined by weight measurement and mechanical tensile tests on PE rings, which were exposed to hydrogen for a period of 1,000 hours at 2 bar while subject to constant deformation. To limit changes in the material that may occur when preparing test specimens, only rings were cut from the received pipes. A reference material was also tested under the same conditions using air instead of hydrogen.

The deformation – and resulting stress – was applied to the rings by placing them in a U-clamp, which deformed the ring (see Figure 1 below). A strain of 1.9% was used for the DN90 SDR11 pipe. This initially corresponds to 50% of the upper yield strength, but this decreases over time.

The U-clamps with the rings were placed in a cylinder at a pressure of 2 bar (see Figure 2 below) for a period of 1,000 hours at room temperature.

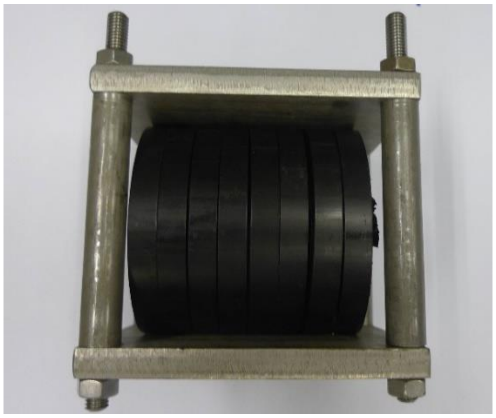

Figure 1: PE rings in a U-clamp

Figure 2: Cylinders filled with hydrogen at 2 bar

The mass was weighed before and after the exposure of the rings. The difference in weight results from a possible chemical attack caused by exposure to hydrogen while the rings are subject to deformation. After exposure, the rings underwent a tensile test to determine the yield stress and the elongation at break, among other effects. Because strain is not evenly distributed with rings, the displacement of the crosshead of the tensile tester was used to measure the elongation.

<u>Permeation</u>

The investigated PE pipe was a DN100 SDR 17.6 110x6.3 mm. Another pipe made from the same PE material was used for the permeation tests. This had a narrower wall thickness than the pipes used in the previously-mentioned chemical suitability and mechanical tests. The main advantage of using a pipe with a narrower wall thickness is that the test times for the permeation tests can be shortened. However, the results are applicable to both PE pipes, as the material is identical.

The permeation rate is dependent on several parameters. A detailed description of the displacement of gas molecules through pipe walls is given by Scholten and Wolters [1].

The relationship between the permeation rate and the Permeation Coefficient (PC) is linear, and is given by the following formula.

$$PC = \frac{Q_p \times e}{A \times \Delta p}$$

PC = permeation coefficient [ml mm m^{-2} $bara^{-1}$ day^{-1}]
Q_P = permeated volume [ml day^{-1}]
e = wall thickness [mm]
Δp = difference in partial pressure [bara]
A = area of the pipe [m^2] (the area is calculated by using the average of the inner and outer diameter, and the length of the pipe)

The PC of the material can be used to calculate the volume loss of the total pipe by permeation using the following formula:

$$Q_p = \frac{PC \times \pi \times (\mathrm{SDR} - 1) \times L \times \Delta p}{1000}$$

Q_P = permeated volume [ml day^{-1}]
PC = permeation coefficient [ml mm m^{-2} bara^{-1} day^{-1}]
SDR = ratio of the wall thickness to the diameter of the pipe
L = length of the pipe [m]
Δp = difference in partial pressure [bara]

The tested PE pipe was sealed with end caps and placed inside a jacket pipe as shown in Figure 3. As the operational pressure in this case is 2 bar, the permeation test was performed with a overpressure of 2 bar (2 bar(o)) resulting in an absolute pressure of 3 bar (3 bar(a)) with respect to air. The jacket pipe was filled with 100% nitrogen.


Figure 3: Permeation experimental setup in which the PE pipe (black with yellow stripes), the jacket pipe (grey) and the pressure gauge are visible

The permeation rate was identified by measuring the concentration of hydrogen in the nitrogen in the jacket pipe using a gas chromatograph. Over time, the hydrogen will permeate the PE pipe wall and reach a steady state. The PC can then be calculated using this information.
The experiment was performed at room temperature.

<u>Repair and maintenance</u>

The most common method of repairing PE pipes is pipe replacement combined with electrofusion jointing. The ability to carry out electrofusion on PE pipes after prolonged exposure to hydrogen is therefore an effective measure of the ability to perform repair and maintenance in the future.

The investigated PE pipe was a DN90 SDR11 90x8.2 mm. Two PE pipes were exposed to hydrogen for a period of 1,000 hours at a pressure of 2 bar at room temperature. Electrofusion joints were made in accordance with NTA 8828:2016 [2], which is a strict Dutch technical agreement that specifies the procedure for carrying out electrofusion jointing on pipes.
To examine the possible effects of hydrogen on the jointing of PE pipes, the joints were visually examined and tested using the peel test in accordance with ISO 13954 [3] (see Figure 4 and Figure 5).

Figure 4: Execution of the peel test

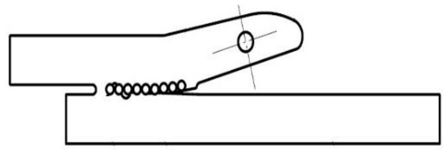

Figure 5: Schematic of the peel test [3]

The visual test was carried out to reveal any cavities in the jointed surface. In the peel test, four bars from the electrofusion joint were taken from each side of the joints (see Figure 6 and Figure 7Figure 6 below).

Figure 6: The electrofusion joint with the position of a tensile bar

Figure 7: The tensile bars from both sides of the electrofusion joint

RESULTS AND DISCUSSION

<u>Chemical resistance</u>

The results of the weighing of the PE ring samples are shown in the graph below in Figure 8.

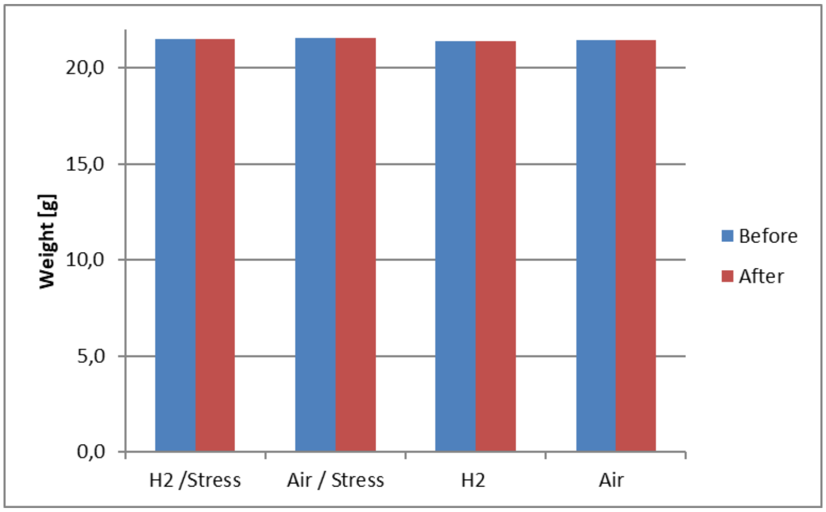

Figure 8: Outcomes of the weighing of the PE rings exposed to hydrogen or air with (8 rings) and without (6 rings) an applied stress

As can be seen in the graph and the table below (Table 1), the differences in weight are minimal. In none of the cases did the difference in weight exceed 0.1%.

Table 1: Weight measurement statistics

	Weights [g]			
	With applied stress		*Without applied stress*	
Hydrogen	Before [g]	21.492	Before [g]	21.406
	After [g]	21.498	After [g]	21.415
	Difference [g]	-0.003	Difference [g]	0.013
	Difference [%]	-0.015	Difference [%]	0.061
Air	Before [g]	21.527	Before [g]	21.434
	After [g]	21.536	After [g]	21.446
	Difference [g]	0.009	Difference [g]	0.018
	Difference [%]	0.040	Difference [%]	0.086

The outcome of the ring tensile test is shown in Figure 9.

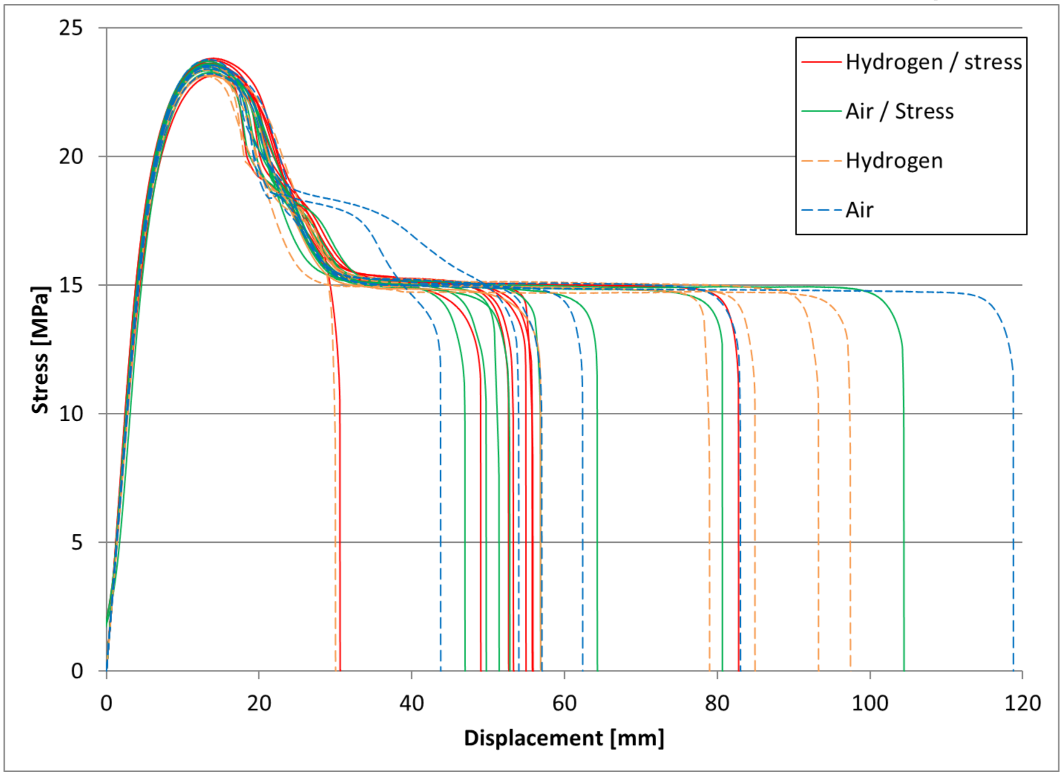

Figure 9: Ring tensile test. The horizontal axis shows the displacement [mm], the vertical axis shows the stress [MPa]. Red indicates hydrogen with applied stress, green indicates air with applied stress, orange indicates hydrogen without applied stress, and blue indicates air without applied stress.

For all tested rings, the upper yield stress lay within 1 MPa. This indicates that hydrogen has no negative effect on the PE material. The average values are summarized in the table below (Table 2).

Table 2: Upper yield stress statistics

	Upper yield stress [MPa]			
	With applied stress		*Without applied stress*	
Hydrogen	Median	23.610	Median	23.280
	Average	23.581	Average	23.303
	Standard deviation	0.197	Standard deviation	0.164
	[%]	0.836	[%]	0.702
Air	Median	23.500	Median	23.510
	Average	23.489	Average	23.495
	Standard deviation	0.146	Standard deviation	0.183
	[%]	0.622	[%]	0.777

The displacement of the rings tested during the ring tensile test resulted in a larger spread in outcomes. This can be seen in the table below (Table 3).

Table 3: Displacement at break statistics

Displacement at break [mm]	
With applied stress	*Without applied stress*

Hydrogen	Median	56.5	Median	82.0
	Average	55.1	Average	73.7
	Standard deviation	14.2	Standard deviation	25.7
	[%]	25.8	[%]	34.9
Air	Median	57.0	Median	59.5
	Average	64.0	Average	69.8
	Standard deviation	19.7	Standard deviation	27.3
	[%]	30.8	[%]	39.1

Due to the large spread, all the measurements are presented in a Whisker-Box plot as shown in Figure 10. The Whisker-Box plot shows the measured extremes and median. All other measured values are combined in the grey blocks.

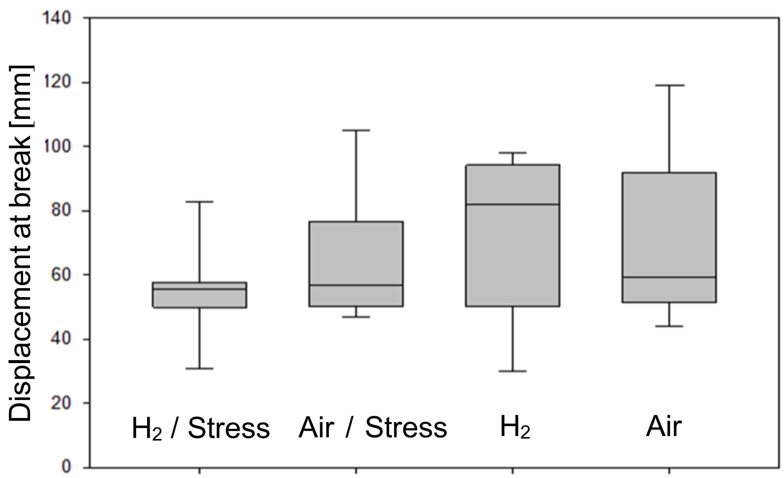

Figure 10: Whisker plot of the displacement at break. The measured extremes and median are given in the plot, while the other measured values are combined in the grey blocks.

As can be seen in the plot, there is a large spread in the measured values. However, the results are statistically comparable.

The large spread has three possible causes, which are explained below.

1. The influence of the gas on the material.
2. The material itself.
3. The test method.

As can be seen in Figure 10, the spread and standard deviation are large for both the PE rings exposed to air and those exposed to hydrogen. This indicates that the environment, in this case hydrogen, is probably not the cause. This is also in line with the outcome of the weighing measurements and the measurements of the upper yield stress.

The large spread may also be caused by the material itself. However, there is a lack of reference values available for the ring tensile test of PE100-RC compared to PE100. The PE100-RC material used in this case also fulfills all the requirements of EN 1555 for PE100. The spread in elongation at break values for PE100-RC is therefore assumed to be comparable to that of PE100.

The spread in values for the elongation at break is probably caused by the test method. A further analysis of the results indicates two very low displacement values of 30 mm. Both of these rings were exposed to hydrogen, one with stress and one without stress. Analyses of the rings revealed an atypical failure type, in which the ring had yielded and broken on one side. All the other rings failed with yielding on both sides and a break on one side. It is probable that these two rings failed differently as a result of ring displacement during the test.

Differences in the displacement of the rings during the tests is the most likely reason for the high scatter in the elongation values. This is confirmed by the lack of differences in weight before and after exposure to hydrogen.

Permeation

The permeation behavior of one of the pipes is given in the figure below. The vertical axis shows the measured accumulation of the hydrogen in ppm (parts per million) in the jacket pipe. The horizontal axes indicates the time in days, with the measured values indicated with red filled and open marks. The dotted line is the linear regression curve for the red filled values (nine values in total). The open marks were not used to calculate the regression, as the open marks in the lower timescale and the open marks in the higher timescale are indicative of non-linear behavior.

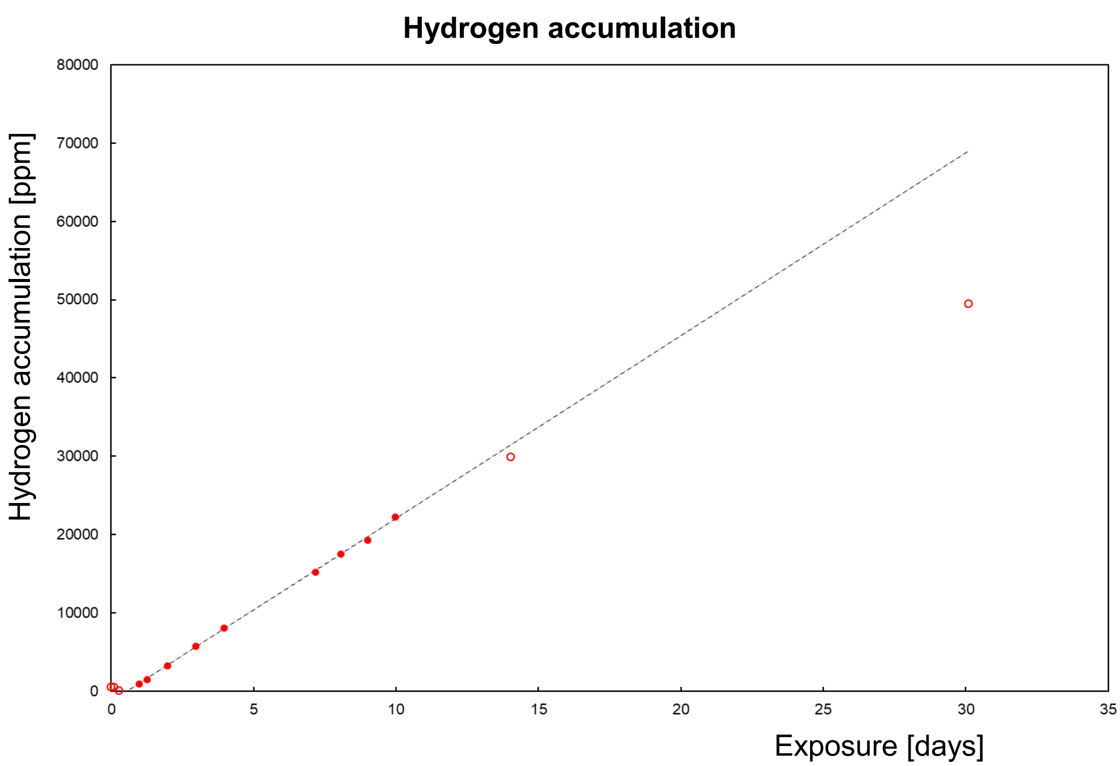

Figure 11: The horizontal axis indicates the exposure of the pipe to hydrogen in days, the vertical axis indicates the accumulation of hydrogen in the jacket pipe in ppm.

In the graph (Figure 11), it can be seen that the breakthrough time of the hydrogen is about one day. A steady state condition is then reached. The Permeation Coefficient (PC) can be calculated by using linear regression. Linear regression is performed using nine data points. The first three points are in the breakthrough period. The last two points are ignored as they are excessively influenced by a higher partial concentration of hydrogen in the jacket pipe.

$$PC = 126.8\ \frac{\mathrm{ml} \times \mathrm{mm}}{\mathrm{m}^2 \times \mathrm{day} \times \mathrm{bara}}$$

By using the PC, the permeated volume of hydrogen for the total length of the pipeline can be calculated if the length, pressure and SDR of the pipe are known. In this specific case, an SDR11 pipeline with a length of 1,000 meters, operated at a pressure of 2 bar, will emit 4,360 liters of hydrogen per year. This equates to 4.36 m^3 of hydrogen per year.

The PC for methane is 56 $\mathrm{ml{\cdot}mm{\cdot}m^{-2}{\cdot}bara^{-1}{\cdot}day^{-1}}$, which results in 1.93 m^3 methane per kilometer of pipeline per year.

This calculation was performed for a pipeline at room temperature. As the permeation increases with elevated temperatures, the permeation of hydrogen for a buried PE pipe in practice will be even lower.

<u>Repair and maintenance</u>

The electrofusion jointing procedure was followed without any noteworthy issues being encountered. No cavities were found in any of the test bars. The peel test also resulted in breakage of the pipes. No failure of the joint area was observed. The results are shown in the photographs below in Figure 12 and Figure 13.

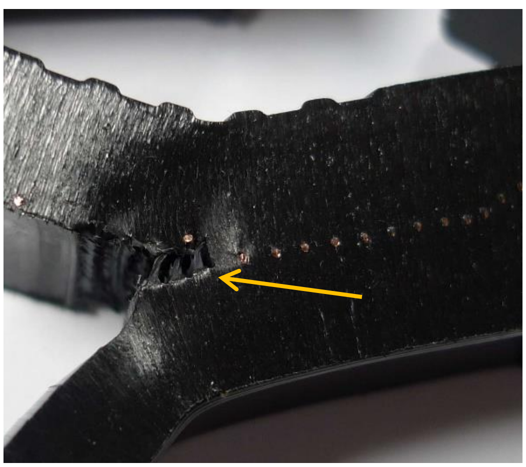

Figure 12: The yellow arrow shows the ductile failure of the joint area

Figure 13: The visual examination showed no cavitation, which indicates a good quality joint

The permeation test demonstrated that the pipe wall is almost saturated with hydrogen after 1,000 hours. However, this did not result in visible voids or mechanical weak spots in the fusion zone. The temperature during jointing was higher than the melting temperature of PE. This probably led to depletion of the dissolved hydrogen during the jointing process.

When maintaining a PE pipe system, a leak survey is one of the most important techniques used to monitor the tightness of the system. While standard leak survey methods equivalent to those used for natural gas pipelines may be used, special attention should be paid to the detector type.

The aspects of the behavior of hydrogen that distinguish it from methane (ignition energy, energy content and density) should be taken into account when adapting work procedures and safety instructions.

<u>Design and construction</u>

During design and construction of the PE pipeline on the premises of Groningen Seaport, the specific characteristics of hydrogen that distinguish it from methane were taken into account. During the design process, it is important to be aware of the above-ground and underground structures close to the hydrogen pipeline that could lead to the accumulation of permeated hydrogen. In addition, the commissioning and decommissioning of pipes containing hydrogen requires the adaption of work instructions to take the explosion limits of hydrogen into account.

CONCLUSIONS

To answer the question of whether PE pipe is fit for purpose for the transportation of hydrogen on the premises of Groningen Seaport, the interaction between PE and hydrogen and the effects of maintenance and repair on safe usage were investigated.

In order to investigate the vulnerability of PE exposed to hydrogen, the PE pipe material was exposed to 100% hydrogen for 1,000 hours at 2 bar at room temperature. The results of the experiments for the chemical interaction showed no significant differences between pipes exposed to air and those exposed to hydrogen. From a material integrity perspective, no negative effects were found.

When using PE pipes to transport gases, permeation may be a safety issue. As hydrogen molecules are very small, the permeation of hydrogen is expected to exceed that of methane. Permeation measurements revealed a permeation coefficient of 126.8 $ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$ for hydrogen, compared to 56 $ml \cdot mm \cdot m^{-2} \cdot bara^{-1} \cdot day^{-1}$ for methane. Our expert opinion is that the risks are comparable, due to the limited difference in the permeation coefficient and the differences in physical behavior of hydrogen in air compared to methane.

The combined conclusion is therefore that PE material may be used at the premises of Groningen Seaport for pipes used to transport hydrogen. To permit the conclusion that this PE material is fit for the purpose of transporting hydrogen at a pressure of 2 bar in this specific case, repair and maintenance should also be possible. The most common repair method for PE pipes is pipe replacement combined with electrofusion jointing. To test this, PE pipe material was exposed to 100% hydrogen (1,000 hours, room temperature, 2 bar). After exposure, the pipes were jointed using the standard electrofusion technique. The diffusion of hydrogen in the wall of the pipe had no effect on the electrofusion jointing process or the quality of the joint.

During design and construction, the specific characteristics of hydrogen that distinguish it from methane were taken into account. In this specific case, the design and construction were commissioned and approved by Kiwa Technology.

It may be concluded that the examined PE100-RC pipeline on the premises of Groningen Seaport is fit for the purpose of transporting hydrogen at pressures up to 2 bar. More generally, it can be concluded that PE pipes permit the transport and distribution of hydrogen in a safe and reliable way.

ACKNOWLEDGMENTS

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