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Leak tightness of PVC fittings with hydrogen

Partner for Progress

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Preface

This report is the result of a unique collaboration between PVC4Pipes, Netbeheer Nederland and Kiwa Technology. Both have asked Kiwa whether the PVC gas network used in the Netherlands is suitable for the transport of hydrogen gas. This joint assignment was carried out by Kiwa Technology by using old PVC pipe sections that have transported natural gas for many years. The pipes and joints were supplied by the Dutch Distribution System Operators whom we want to thank for their cooperation.

Summary

The PVC gas grid in the Netherlands is presumed to be suitable to transport hydrogen in the (near) future. To further support this concept, this additional study has been carried out.

Firstly, joints made of unplasticized PVC (PVC -U) and impact-resistant PVC (PVC-Hi) have been tested on their mechanical behaviour by deriving the maximum angle of deflection. This is done on joints taken from the natural gas distribution grid, which have been tested either without additional ageing or with ageing for 1000 hours at 60°C in an environment of hydrogen (inside the pipes).

The maximum angle of deflection obtained in this study ranges from 9° to 28° for old used PVC-U joints. The additionally with hydrogen aged PVC-U joints showed a maximum angle of deflection of 5°. PVC-Hi joints always show a maximum angle of deflection of more than 28° for both additional aged and non-aged joints.
Both tests show that the maximum angle of deflection, even after ageing, fulfils the requirements of the appropriate standard EN-ISO 13844 and NEN 7231 which covers PVC-Hi only.

The permeation rate for three PVC-U pipes has been determined. After correction for the pipe dimensions and applied hydrogen pressure, the permeation coefficient ranges between 87.3 [(ml·mm)/(m^2·day·bar)] and 115.3 [(ml·mm)/(m^2·day·bar)].
Similar the permeation coefficients for three PVC-Hi have been determined, ranging from 113.3 [(ml·mm)/(m^2·day·bar)] to 181.3 [(ml·mm)/(m^2·day·bar)]. As a reference, the permeation coefficient for polyethylene (PE100 RC) was reported to be 108 [(ml·mm)/(m^2·day·bar)] and 126.8 [(ml·mm)/(m^2·day·bar)].
The permeation coefficient is used to determine the permeation rate for different scenario's. For instance a PVC-U pipe Dn250, SDR 41, 12 meters in length and with a hydrogen pressure of 100 mbar will result in a permeation rate of less than 200 ml/day.

The permeation rate of four PVC joints (2x PVC-U and 2x PVC-Hi) has been determined at 200 mbar hydrogen. The permeation rate ranges from 6.5 ml/day to 7.5ml/day.
As a reference; For natural gas distributions, all leaks larger than 5 l/h are not allowed. The reported permeation rates are far below the 5 l/h and therefore no safety problems due to hydrogen permeation is expected.

Contents

1 Introduction

Both impact-resistant PVC (PVC-Hi) and unplasticized PVC (PVC-U) are widely used in the Dutch gas distribution network. These pipe materials with their connections have been used successfully since the 1960s. The total length of the PVC gas grid is more than 80,000 km (of which 20,000 km of PVC-U).
With the climate targets as agreed in the Paris climate agreement, the use of natural gas will be abandoned in the future. In order to be able to continue to use the existing network, which represents a considerable amount of capital, the application of hydrogen as an energy carrier is being investigated. An earlier study (Hermkens, Future proof gas distribution, 2018) concluded that PVC pipe systems were well suitable for the distribution of hydrogen. Because this was an overview of all knowledge that was available at that time, the white spots in knowledge were also identified. If the existing gas distribution network is to be used for the transport of hydrogen gas, the full behaviour should be known. This report describes the results of a study conducted by Kiwa Technology for PVC4Pipes in cooperation with Netbeheer Nederland filling in some parts of those white spots.
In this study straight joints have been artificial aged by exposition to hydrogen. At the same time a temperature of 60°C was applied. This is the maximum temperature PVC materials can resist. The aging time was set to 1000 hours which is an more often used duration for aging tests. After ageing the leak tightness under angular deflection, have been tested using air as the test medium. Both impact-resistant and unplasticized PVC joints have been used.
The pipe sections, including couplers, have been in service in the Dutch natural gas distribution grid for many years. (ranging from seven to over fifty years)
This report also includes results from angular deflection measurement of different types of joints which have been performed in the Netbeheer Nederland sponsored “Knowledge Centre Gas Distribution”-program (KCGD) as a reference. These tests have been performed on materials exposed to natural gas only.
Also the KCGD results of permeation measurements of both PVC-Hi and PVC-U pipes and couplers using hydrogen are included.

2 Test program and methods

2.1 PVC4Pipes part of the test program

This chapter explains the test programme of the maximum angle of deflection of used PVC joints after artificial ageing using hydrogen.

2.1.1 Ageing under hydrogen method

The joints used to measure the maximum angle of deflection were taken from the Dutch natural gas distribution grid. They have additionally been exposed to hydrogen at 60°C for 1000 hours. This exposure simulates the use of these already old joints for many additional years of use as a piping material servicing a hydrogen transporting grid. As the exact correlation between the exposure time and temperature to the real service time under practical conditions for hydrogen is unknown, an exact acceleration factor cannot be given. From earlier work of Roy Visser (Visser, 2009) it is known that the used temperature in this experiment corresponds with a time shift factor for PVC-U of 650 to 2500 when referring to 15 °C and 7 °C in air respectively.
A testing time of 1000 hours would then correspond with 74 to 285 years in practice. The acceleration factor for PVC-Hi is still unknown, but the presumption is that this factor is in the same order of magnitude, thus it will also exceed 50 years.

Four joints, which each consists of a socket, rubber ring (mostly NBR-type) and two PVC pipes, were artificially aged using a test chamber (with a temperature of 60°C) where the joints were stored for 1000 hours. The joints were pressurized using end caps (Georg Fischer) and 100% hydrogen as a medium. The pressure was about 30 mbar(g) (gauge pressure, which is measured against the ambient pressure and not the absolute pressure). In *figure 1* an overview of the installed joints including end caps in the test chamber is given. The caps were secured against shearing by means of orange straps.

After this ageing process at 60°C for 1000 hours under internal pressure with hydrogen, the joints including the pipes were cooled down to room temperature.

Figure 1 Ageing at 60°C of the four joints

2.1.2 *Maximum angle of deflection method*

After ageing of the four PVC joints, as described in the previous paragraph, a leak tightness test on each joint was performed, using air. To achieve this, a test rig was used as shown in figure 2.
On the left side the compressed air was reduced to approximately 115 mbar(g). This was fed into the measuring case shown on the right side of the image. In the measuring case the pressure was reduced to approximately 100 mbar(g) while the air flow was measured accurately. To measure the leak tightness of the samples, both pipe ends had to be closed. A gasbag (inflatable gas stopper) was used on either side of the joint to do this. The joint was pressurized using a gas bag with an internal line. If a joint is leak tight the flow will remain “0” when the pressure is kept constant.

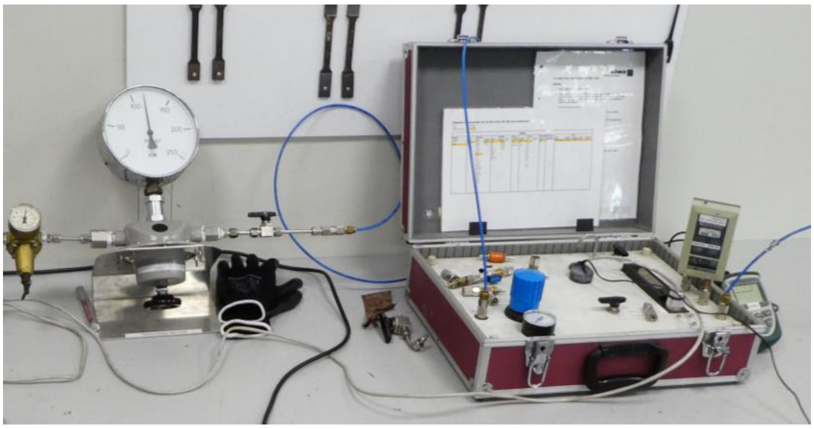

Figure 2 Leak tightness test rig

After ageing, the initial leak tightness test, an angular deflection was applied. During increase of the deflection the leak tightness was measured constantly. Once the joints started leaking, the angle of deflection at that moment was determined. To achieve this, the test rig as shown in figure 3 was used.

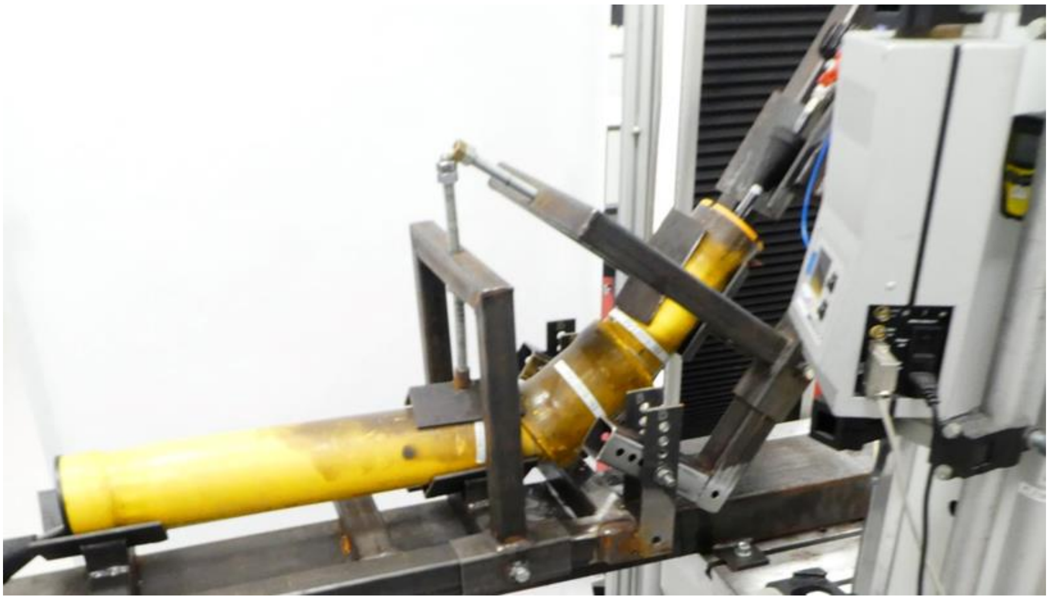

Figure 3 Angular deflection test rig (placed into a tensile test machine)

The test rig consist of two parts, which are connected with a bold. One end is fixed to a frame and the other part is able to move up or down. Depending on the diameter of the pipe and coupler the position of the bold can be adjusted in such a way that the middle of the joint is centred to the pivot point of the test rig. The pipes (with the coupler) are clamped onto the test rig, allowing the coupler to move. In this figure the test rig is placed in the universal tensile test machine. The universal tensile test machine was used to achieve a constant lift of the movable part of the test rig. At least every 30 seconds (most of the experiments every 10 seconds) a photograph is taken. By measuring the time between start of the angular deflection and the moment leakage started, the picture corresponding to the moment of leakage is selected. The measured angle of deflection in that photograph corresponds to the maximum angle of deflection before leakage occurs.

2.2 Knowledge Centre Gas Distribution test program

This report also gives some of the results of the running program funded by Netbeheer Nederland. It consists of:

- Permeation measurements of used, as-received PVC-Hi and PVC-U pipes, which were removed from the existing natural gas network, with hydrogen at 200 mbar(g).
- Leak or permeation measurements of used, as-received PVC-U and PVC-Hi straight joints tested with hydrogen at 200 mbar(g).
- Measurement of the maximum angular deflection of used, as received joints until leakage. In this case, the joints are tested with air at 100 mbar(g).

2.2.1 Permeation method for the pipes

Figure 4 Overview of the test set-up

Due to the pressure difference, hydrogen will permeate through the PVC pipe, where it eventually accumulates in the steel jacket pipe. The concentration of hydrogen in the jacket pipe is measured at specific times using a gas chromatograph (*Varian micro-GC CP-4900*). Before each measurement the system is calibrated using calibration gases with a known concentration of hydrogen.

Because multiple jacket pipes are used for this project the average dimensions are given in this report. For the calculations the exact dimensions of the jacket pipes are used. The steel jacket pipes have on average an internal diameter of 151 mm and a length of 601 mm. The average outer diameter of the PVC pipe is measured to be 110.4 mm. The total annular volume (the internal volume of the jacket pipe minus the external volume of the PVC pipe) is therefore 5038 ml.
For each measurement 5 ml of nitrogen and permeated hydrogen is removed from the jacket pipe. This is about 0.1% of the annular volume. It is therefore concluded that removing such a small amount from the accumulated hydrogen in the jacket pipe is negligible for the determination of the permeation rate.
The dimensions for each jacket pipe and each PVC segment is known very precisely. These values are actually used for calculating the permeation properties.

For the end caps multi/joint connections of GF piping systems are used. The end caps are outside the jacket pipe and do not influence the permeation measurement.

After an initial phase without any permeation (the breakthrough time or time-lag), hydrogen accumulation inside the steel jacket pipe starts. After some more time, a stationary permeation phase is reached, showing linear increase of the hydrogen accumulation with time. The slope of this part of the curve provides the permeation rate. The given volume is applicable at standard temperature and pressure (STP conditions).
For the pipe segments the permeation rate is calculated and corrected for the length of the pipe and the pressure in accordance with Henry's law (Moore, 1972) (in *ml* hydrogen per *day* per *metre* pipe length at 200 mbar(g) and at room temperature).

Due to the concentration increase of the accumulated gas in the steel jacket pipe, the absolute pressure difference (or driving force) between the inner and outer pipe wall will decrease. The results are corrected for this decrease in absolute pressure difference. Also the maximum concentration of hydrogen of the accumulated gas over all measurements is 5.7% which is sufficiently low .

For a monolayer pipe, the permeation coefficient (P_C) can be calculated using the thickness of the pipe (e), the median surface area (A), the partial pressure difference (p) and the flow of the permeant (Q, *in volume over time*), as follows (Scholten & Wolters, 2008), (van der Stok, Scholten, & Dalmolen, 2010):

$$P_C = \frac{Q \cdot e}{A \cdot p} \qquad (1)$$

Or written as the permeation rate (Q):

$$Q = P_C \cdot \frac{A \cdot p}{e} \qquad (2)$$

Formula (2) can be converted into more pipe related parameters following (Scholten & Wolters, 2008). Please note that a small but neglectable error is made in this conversion (van der Stok, Scholten, & Dalmolen, 2010):

$$Q = \frac{PC \cdot \pi \cdot (SDR-1) \cdot L \cdot p}{1000} \qquad (3)$$

Where L is the length of the pipe and the SDR is the ratio between the pipe diameter and the wall thickness.

This means that a thicker wall decreases the permeation rate and a larger surface area (larger diameter) and higher pressure will increase the permeation rate.
In this way, the permeation coefficient can be used to derive the permeation rate of other pipe dimensions.

2.2.2 *Leakage / Permeation method for the joints*

The exact same test set-up has been used for the joints (two pipes with a straight coupler in between) as for the pipes alone (see previous paragraph).

In this case the permeation rate is measure as *ml* hydrogen per *day* at 200 mbar(g) at room temperature. The permeation rate, cannot be used to calculate the permeation rate for other joint dimensions. Because the joints consists of multiple components (two pipes, the socket, two rubber rings) and the exact contribution of each component cannot be determined in the current set-up.

2.2.3 *Maximum angle of deflection method*

The maximum angle of deflection was measured using the exact same method as described in paragraph **Fout! Verwijzingsbron niet gevonden.**. Please note: in this case the joints were tested as-received. This means that they were not additionally aged following paragraph 2.1.1.

3 Test samples

All PVC joints and pipes used in this study are excavated from the Dutch natural gas distribution grid by Dutch Distribution System Operators (DSOs) and delivered to the laboratory of Kiwa Technology. The excavated pipe segments were all in good condition and could be used for several more years. They were excavated due to planned maintenance and not because of problems with the pipe section. Without this planned maintenance these pipes and joints would have still been in the gas grid. The pipes were typically used at 100 mbar(g) with an absolute maximum pressure of 200 mbar(g). All pipe segments had an outer diameter of 110 mm.

3.1 Materials used in the PVC4Pipes program

The four joints that are used in this program, have also been used in the Knowledge Centre Gas Distribution program. As only the leakage / permeation was measured in the latter program, the joints were still usable for leak tightness and maximum angle of deflection measurements. The specifications of the four joints (all ø110 mm) are stated in table 1. Photographs of all four joints are shown in figure 5 to figure 8.

Table 1. PVC pipe joints used in the PVC4Pipes test program.

Kiwa reference #	Type of PVC	Component	Service life [years]
PVC 2011-088	PVC-U	Injection-moulded socket fitting including two pipes	unknown
PVC 2018-022	PVC-Hi	Thermoformed socket fitting including two pipes	42
PVC 2016-064	PVC-U	Thermoformed socket fitting including two pipes	56
PVC 2019-163	PVC-Hi	Injection-moulded socket fitting including two pipes	31

Figure 5 PVC 2011-088; PVC-U injection moulded coupler and PVC-U pipes

Figure 6 PVC 2018-022; PVC-Hi thermo formed coupler and PVC-Hi pipes

Figure 7 PVC 2016-064; PVC-U thermo formed coupler and PVC-U pipes

Figure 8 PVC 2019-163; PVC-Hi injection moulded coupler and PVC-Hi pipes

3.2 Materials used in the Knowledge Centre Gas Distribution program

Six PVC pipes (both PVC-U and PVC-Hi) are tested for permeation. The specifications are given in table 2 and a photograph of four of the six pipe segments is shown in figure 9.

As stated before, the four joints as shown in table 1 and figure 5 to figure 8 are also tested for permeation/leakage in the KCGD program.

Four different joints (one PVC-Hi and three PVC-U) are tested for leakage and maximum angle of deflection without additional ageing. The joints are specified in table 3.

All PVC pipes and joints have been in service for many years and were excavated for maintenance reasons as mentioned in the paragraph before.

Table 2. PVC pipe segments used for determination of the permeation rate in the KCGD test program.

Kiwa reference #	**Type PVC**	**Diameter [mm]**	**Wall thickness [mm]**	**Service life [years]**
PVC 2017-020	PVC-U	111,08	3,02	53
PVC 2018-086	PVC-U	110,23	3,44	46
PVC 2019-033#06	PVC-U	110,30	2,94	14
PVC 2019-003	PVC-Hi	110,43	2,95	27
PVC 2016-116	PVC-Hi	110,38	3,08	7
PVC 2017-108	PVC-Hi	110,45	2,99	27

Figure 9 Four of the six tested PVC pipe segments

Table 3. PVC pipe joints used in maximum angle of deflection measurements for the KCGD test program.

Kiwa reference #	Type of PVC	Component	Diameter [mm]	Service life [year]
PVC 2018-069	PVC-U	Injection-moulded socket fitting including two pipes	160	53
PVC 2011-067	PVC-Hi	Thermoformed socket fitting including two pipes	110	unknown
PVC 2012-064	PVC-U	Injection-moulded socket fitting including two pipes	110	44
PVC 2017-045	PVC-U	Injection-moulded socketfitting including two pipes	110	46

4 Results

4.1 Results of the PVC4Pipes test program

4.1.1 Maximum angle of deflection after ageing

After 1000 hours of exposure to hydrogen the samples including the end caps were installed in the test rig for the angular deflection. The flow during testing was measured (see figure 10). In this example during the first two minutes the flow is high. This is the time the sample is pressurized up to 100 mbar(g). After the pressurization the flow drops to zero, indicating that the sample is leak tight. After this initial leak tightness test, the angle of deflection is increased until leakage occurs. In this example of PVC 2016 -064, this is after approximately 1070 seconds. As photos are taken frequently, the photo corresponding to this moment of leakage is selected. The different photos corresponding tot the moment of leakage of all four samples are shown in figure 11 till figure 14.

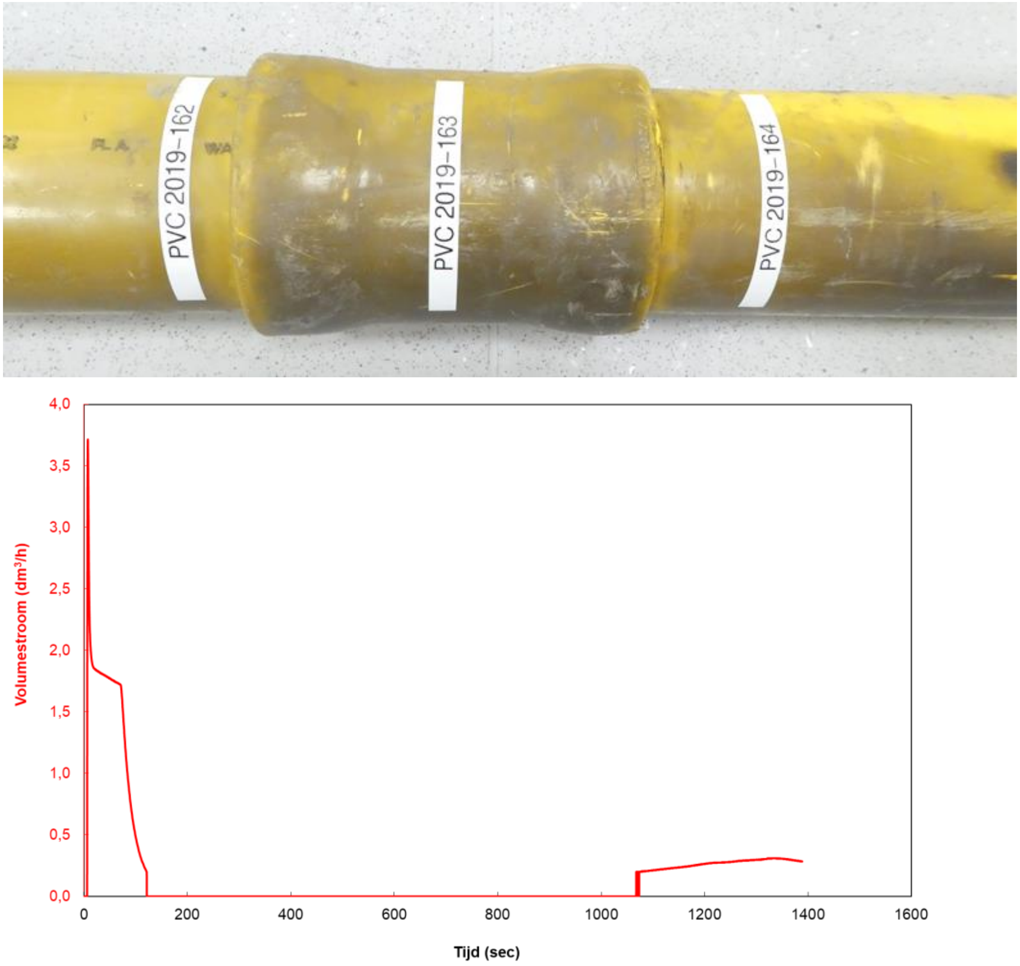

Figure 10 Typical measurement of air flow during the experiments, in this case of PVC 2016-064

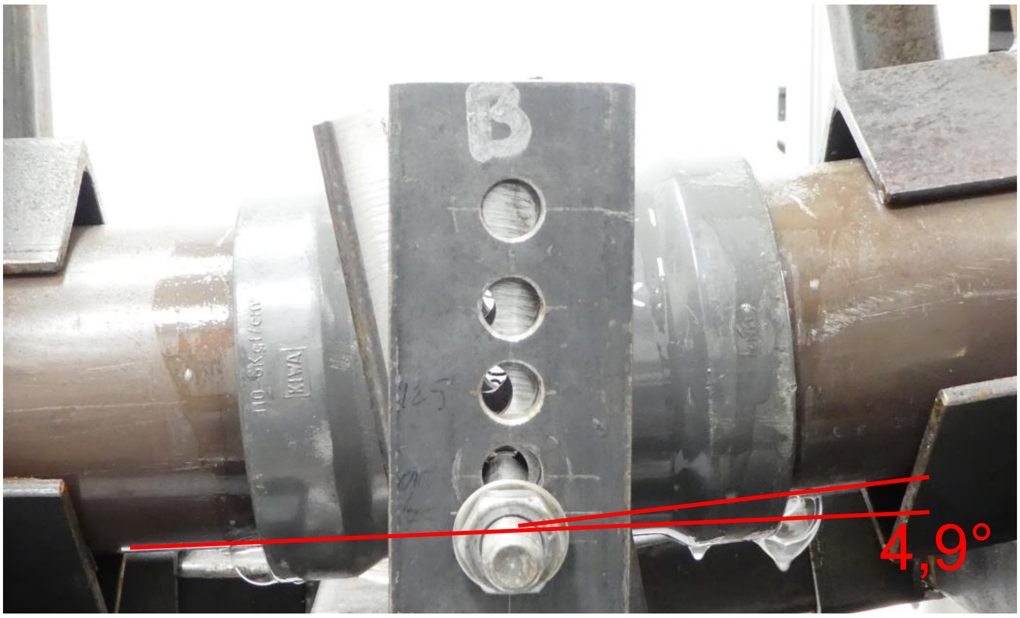

Figure 11 Angle of deflection at the moment of leakage of PVC 2011-088 (to make the leak visible, leak detection spray was used)

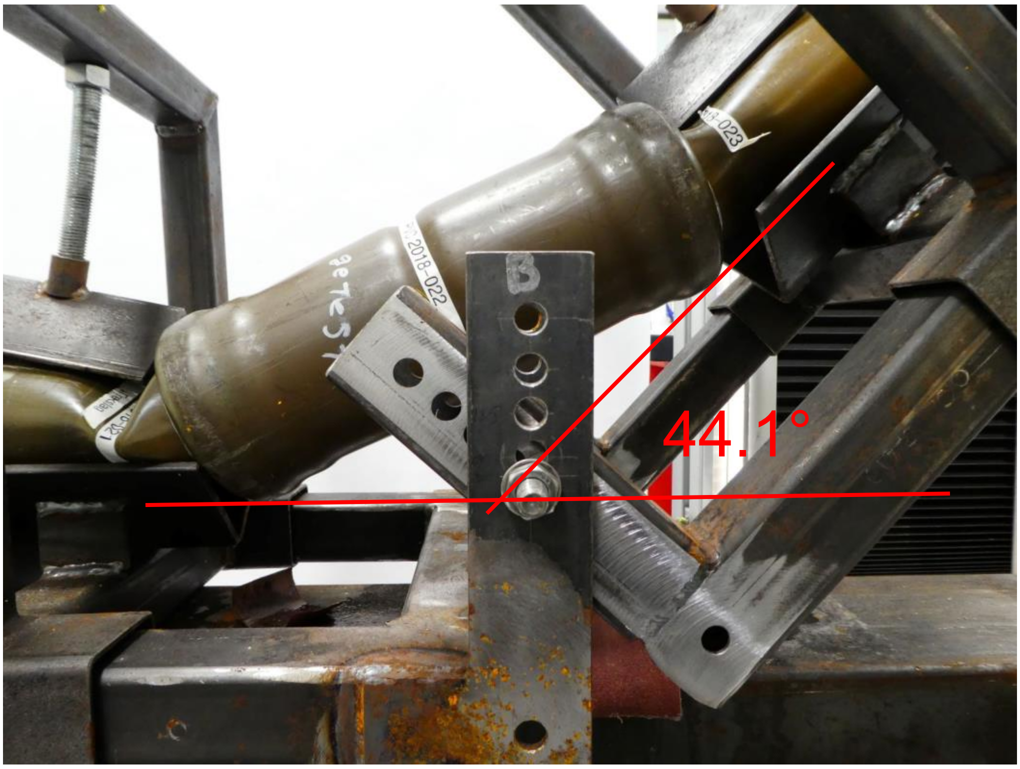

Figure 12 Maximum angle of deflection of the test rig reached (PVC 2018-022). No leakage occurred.

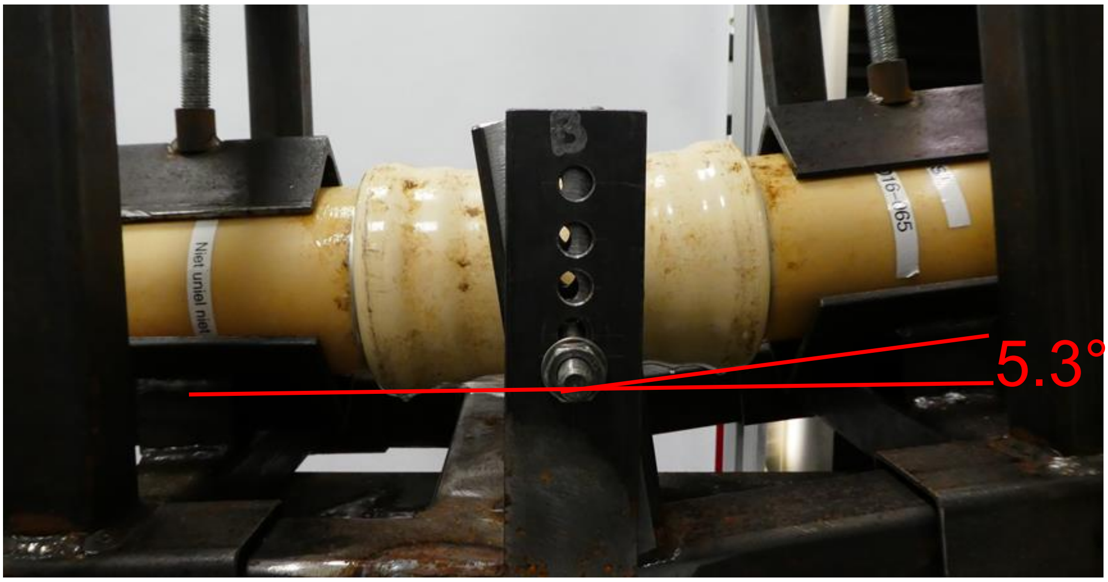

Figure 13 Angle of deflection at the moment of leakage of sample PVC 2016-064

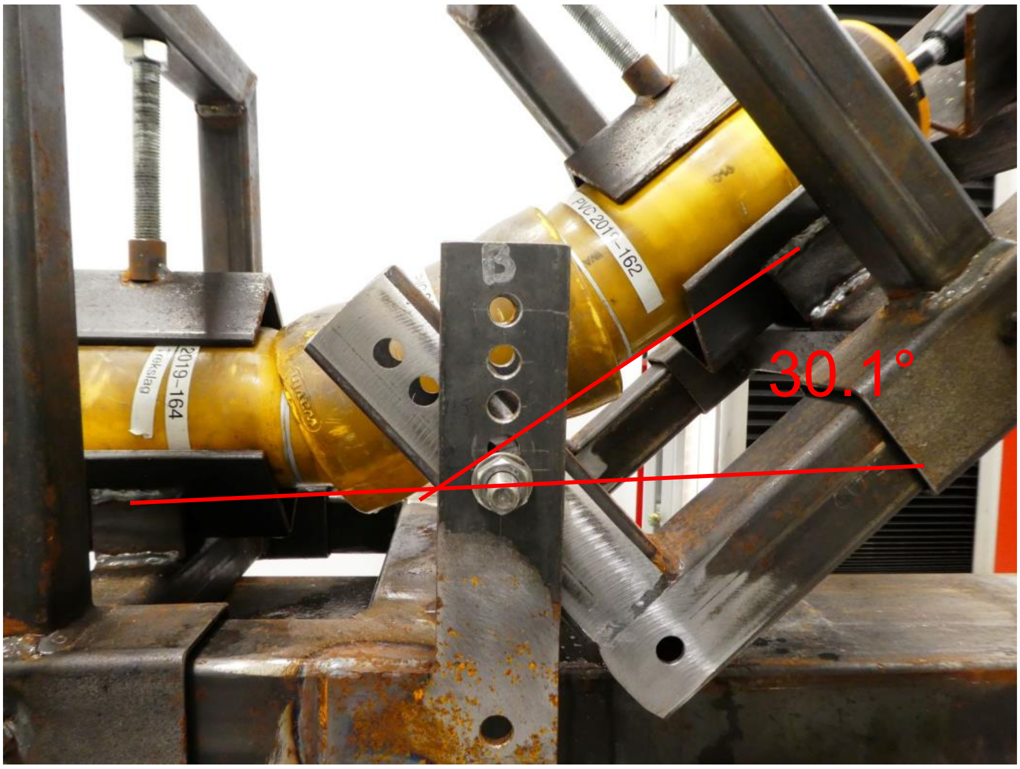

Figure 14 Maximum angle of deflection of the test rig reached (PVC 2019-163). No leakage occurred.

These results show a maximum angle of deflection of approximately 5° for PVC -U joints after ageing with hydrogen.
The angle of deflection of the PVC-Hi joints could not be measured as the test rig reached its maximum capability. The maximum angle of deflection is therefore greater than 30° after ageing with hydrogen.

4.2 Results of the Knowledge Centre Gas Distribution test program

4.2.1 Permeation of the pipes and permeation / leakage of the joints

The accumulated hydrogen in the jacket pipe over time is shown in figure 15 for the PVC pipes and figure 16 for the PVC joints. Because the PVC pipes can be considered homogeneous, the slope of the steady state is corrected for the length of the tested pipe, hence the accumulation is shown in millilitre per metre pipe. The initiation phase (breakthrough time) has not been observed for both the pipes and the joints. This is not uncommon for relatively thin plastic materials. This indicates that the steady state permeation is reached within one day. The slope of the steady state is shown in table 4 for the PVC pipes and table 5 for the PVC joints. Also the square of the Pearson product moment correlation coefficient (RSQ) is given in both tables. The RSQ of all slopes is favourably high (very close to the maximum of 1, which indicates a perfect correlation).

The slope of the accumulated hydrogen in the jacket pipe over time is corrected for both the diameter and the wall thickness of the pipe, and the change in actual pressure (which decreased as a result of permeation and the accumulation in the jacket pipe) following formulae (2) in paragraph 2.2.1. This results in the permeation coefficient for each PVC material, are shown in table 4. Please note that the PVC joints cannot be considered homogeneous due to the various components. Therefore, the permeation rates only apply for DN 110 systems at 200 mbar(g) at room temperature. All tested joints had a length of 610 mm (includes both the socket and both pipe ends).

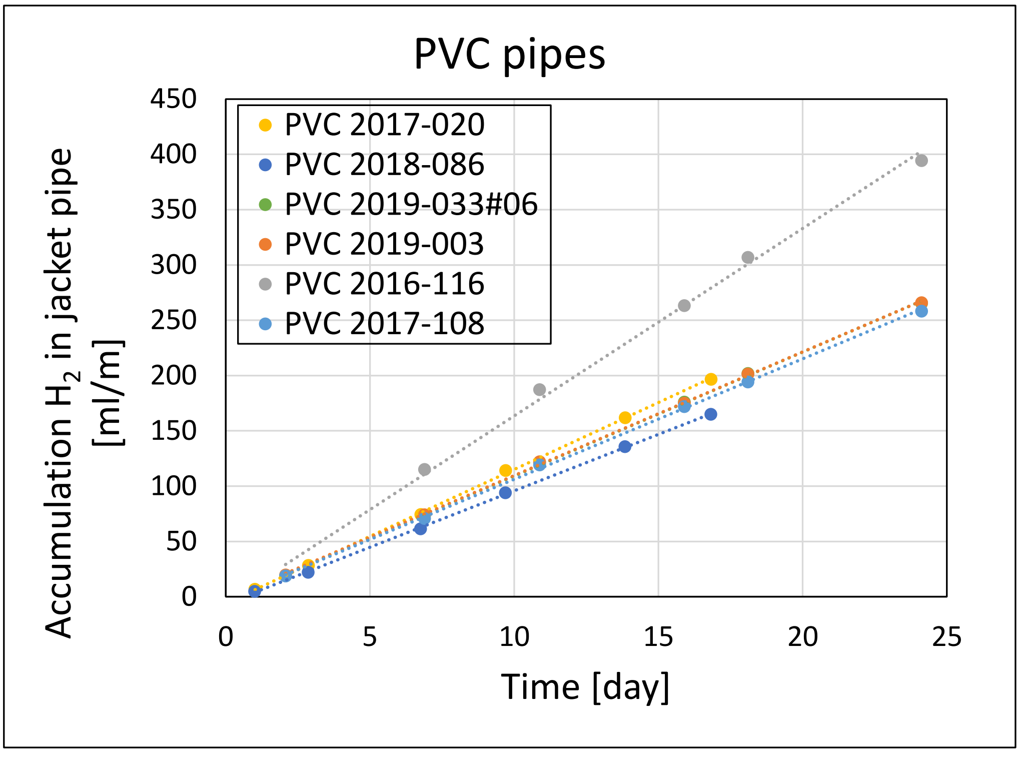

Figure 15 The accumulated hydrogen in the metal jacket pipes over time. The dashed lines are a linear regression over the measured points

Table 4. The permeation rate, the RSQ, and the permeation coefficient of the different PVC pipes.

Kiwa reference #	Type of PVC	Permeation rate [ml/(m·day)]	RSQ of the slope [-]	Permeation coefficient [(ml·mm)/(m²·day·bar)]
PVC 2017-020	PVC-U	12.1	0.9996	90.9
PVC 2018-086	PVC-U	10.2	0.9997	87.3
PVC 2019-033#06	PVC-U	11.2	0.9996	115.3
PVC 2019-003	PVC-Hi	11.2	0.9996	117.2
PVC 2016-116	PVC-Hi	17.0	0.9967	181.3
PVC 2017-108	PVC-Hi	10.9	0.9994	113.3

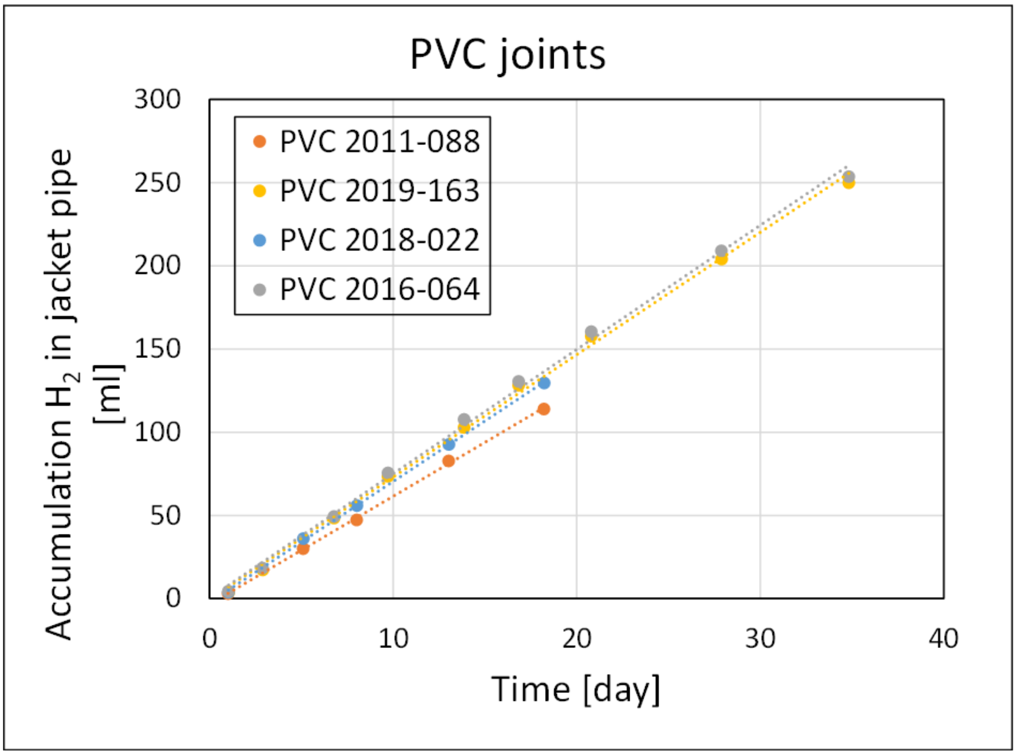

Figure 16 The accumulated hydrogen in the metal jacket pipes over time. The dashed lines are a linear regression over the measured points

Table 5. The permeation rate and the RSQ of the different PVC joints.

Kiwa reference #	Type of PVC	Permeation rate [ml/day]	RSQ of the slope [-]
PVC 2011-088	PVC-U	6.5	0.9993
PVC 2018-022	PVC-Hi	7.3	0.9997
PVC 2016-064	PVC-U	7.5	0.9976
PVC 2019-163	PVC-Hi	7.4	0.9979

4.2.2 *Maximum angle of deflection*

The maximum angle of deflection was measured using samples as received, without additional ageing with hydrogen.
The results of these measurements are shown in figure 17 to figure 20.
During some of these tests also the limitation of the test rig was reached. In those cases an answer to the maximum angle of deflection could not be given.

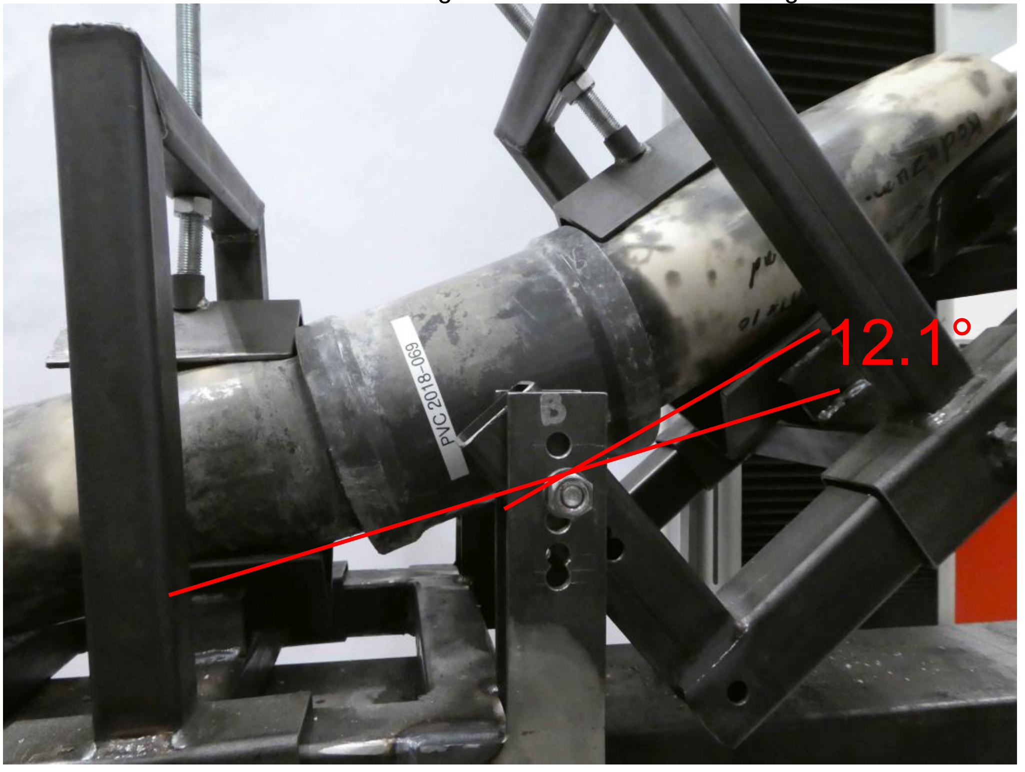

Figure 17 Angle of deflection at the moment of leakage of unaged PVC 2018-069

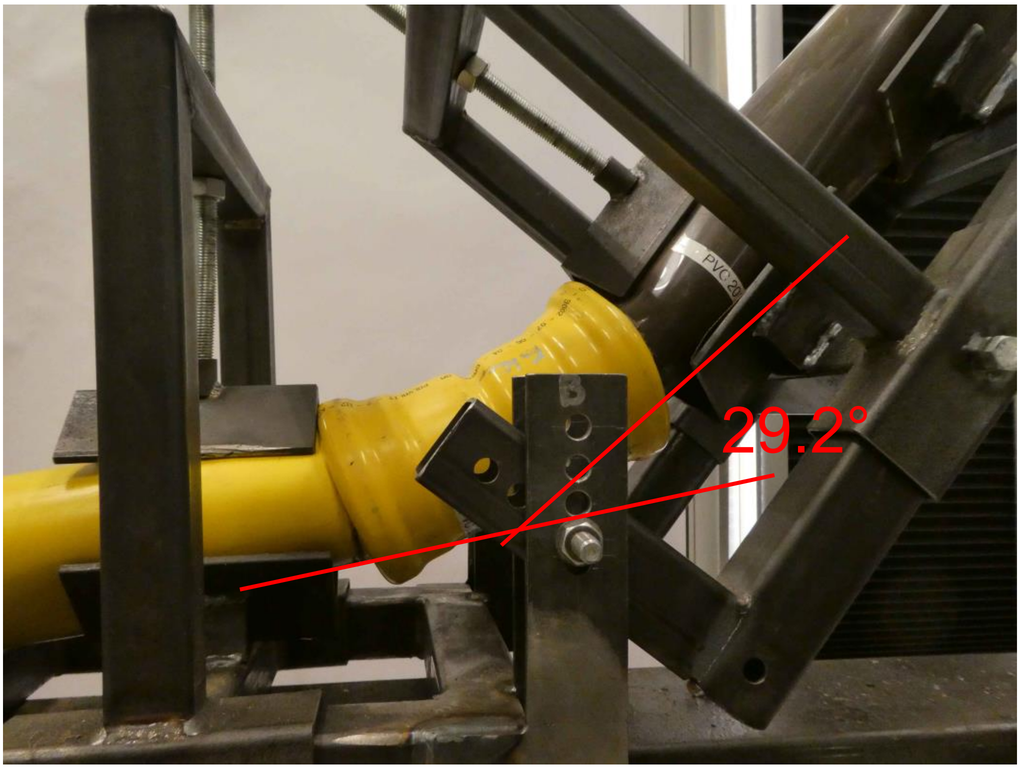

Figure 18 Maximum angel of deflection of test rig reached (PVC 2011-067). No leakage occurred

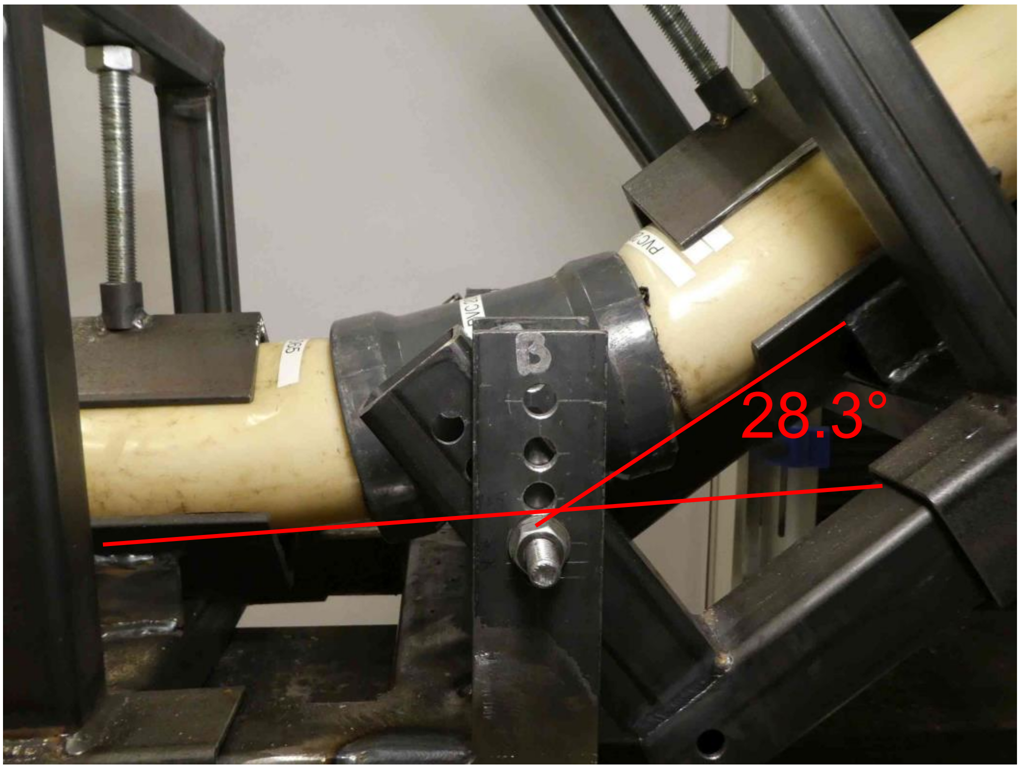

Figure 19 Angle of deflection at the moment of leakage of unaged PVC 2012-064

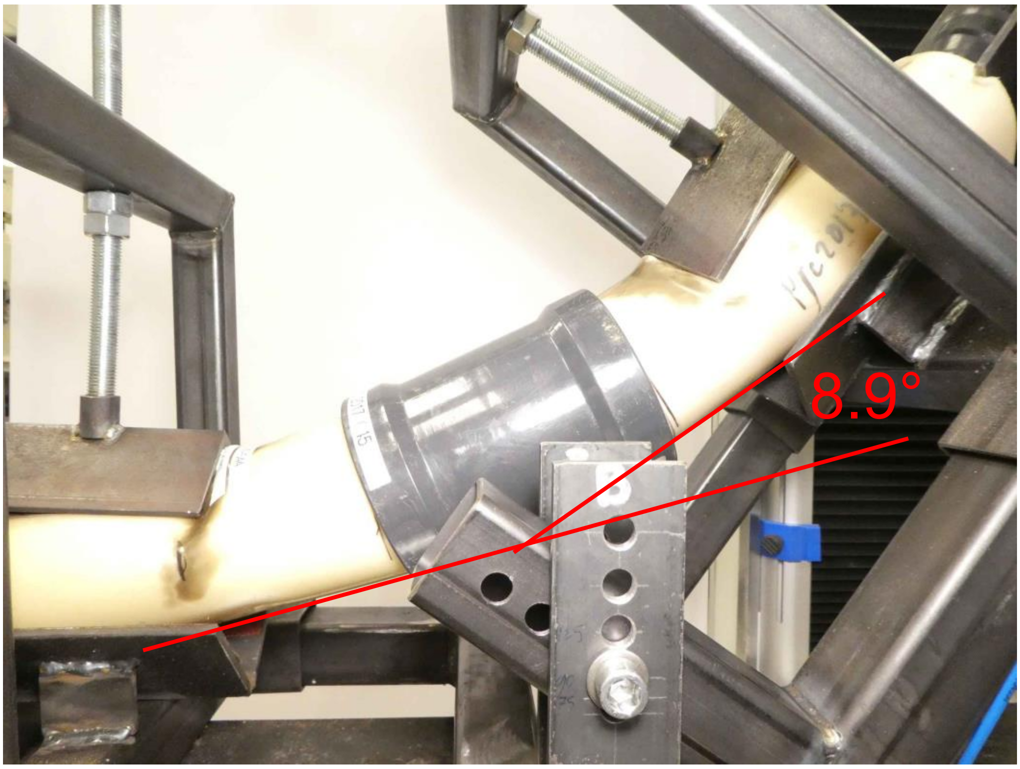

Figure 20 Maximum angle of deflection of test rig reached (PVC 2017-045). No leakage occurred

These results show a range of maximum angles of deflection of approximately >9° to 28° for DN 110 mm and 12° for DN 160 mm PVC -U joints without ageing
The maximum angel of deflection of PVC-Hi joint is not derived as the test rig reached its maximum capability. The maximum angle of deflection without additional ageing is therefore greater than 29°

5 Discussion

5.1 Maximum angle of deflection

The minimum angle of deflection for new PVC straight couplers/sockets according to (EN-ISO 13844 Plastics piping systems - Elastomeric-sealing-ring-type socket joints for use with plastic pressure pipes - Test method for leaktightness under negative pressure, angular deflection and deformation , 2015) is at least 2°. This means that the angle of deflection as measured in this report for new samples should at least be 4°.

In the Dutch standard (NEN 7231:2020 Plastics piping systems for gas supply- fittings of modified polyvinyl chloride, 2020) the maximum angle of deflection defined at a distance of 10 times the diameter is 13°. In our case, the distance between the applied deformation and the coupling is very small. This ensures that the angular deflection in our test is much more extreme than that prescribed in the standard. If we adhere to the value from the standard, an angle of 26° applies to new PVC-Hi couplers.

The measured values for PVC-U samples before and after ageing for 1000 hours at 60°C and an internal pressure of 30 mbar(g) of hydrogen both fulfil the criteria of 4°. As ageing is assumed to be equal to at least 50 additional years in practice of distributing low pressure hydrogen, these results are promising.

As relative big differences in angles of deflection are measured between PVC-U joints, some additional investigations have been made. Especially the shape of the rubber sealing rings could be of importance. It is known that in rare cases only O-rings are used, whereas normally a lip-ring is used. Due to the shape, the lip-ring is expected to have a better resistance against angular deflection. To see whether the lip-ring was used two PVC-U joints aged with hydrogen were cut in the axial direction. The result of PVC 2016-064 is shown in figure 21. On the pipe, which was originally inserted in the socket, the impress of the rubber sealant ring is visible (lower part of the photograph). It clearly shows that the sealant ring is of the lip-type, but also that the lip is torn-off of the body of the ring. It is unclear if this is caused by the experiment that is performed or if this was already the case before the executing of the test. The second joint investigated is PVC 2011-088. This ring is also of the lip-type. This lip-ring is fully intact. The measured relative low angle of deflection is probably not correlated to the poor quality of the lip-ring from sample PVC 2016-064.

Figure 21 De-mounted joint PVC 2016-064 after testing

A remark about the ageing process used has to be made. It is unknown if the differences in results of the angle of deflection measurements before and after ageing are the result of the quality of the original installation of the pipes in the socket or if they are the result of the exposition to hydrogen during ageing or the result from the ageing process itself (1000 hrs at 60°C). Even combinations cannot be excluded. It is therefore not clear where the differences originate from.

5.2 Deriving the permeation rate for hypothethical real life scenarios

By using the values of table 4 and table 5 and formulae (2), the permeation rate of hydrogen of various designs of the PVC system can be calculated. For each calculation the highest value of a certain PVC material, as given in the tables, is used.

EXAMPLE 1

One pipe segment of 12 metre of unplasticized PVC pipe DN250, SDR 41 (A = 9.19 m^2, e = 6.10mm) at a pressure of 100 mbar(g) (1.1 bar absolute pressure p). Over one year 70 litre hydrogen will permeate over the full length.

$$115.3 \cdot \frac{9.19 \cdot 1.1}{6.10} \cdot \frac{365}{1000} = 70\ litre/year$$

EXAMPLE 2

One kilometre of impact modified PVC pipe DN110 SDR 41 (A = 320 m^2, corrected for the pipe ends which were still present inside the joint during testing, e = 2.68mm) containing a joint every 12 metre at a pressure of 200 mbar(g) (1.2 bar absolute pressure p). Over one year 9697 litre hydrogen will permeate over the full length.

$$\left(181.3 \cdot \frac{320 \cdot 1.2}{2.68} + \frac{1000}{12} \cdot 7.4\right) \cdot \frac{365}{1000} = 9697\ litre/year$$

EXAMPLE 3 - reference

One pipe segment of 12 metre of PE100 RC DN250, SDR 17 (A = 8.87 m^2, e = 14.7mm) at a pressure of 100 mbar(g) (1.1 bar absolute pressure p). Over one year 31 litre hydrogen will permeate over the full length.

$$126.8 \cdot \frac{8.87 \cdot 1.1}{14.7} \cdot \frac{365}{1000} = 31\ litre/year$$

Please note that the SDR-class for polyethylene pipe differ from the values used for the PVC-U calculation in Example 1. This has been done because the application of PVC-pipes differ form the application of PE-pipes in the Dutch natural gas distribution grid. We selected a common field of application. For the calculation the permeation coefficient of 126.8 [(ml·mm)/(m^2·day·bar)] as reported by (Hermkens, Colmer, & Ophoff, Modern PE pipe enables the transport of hydrogen, 2019) are used.

An example for PVC using methane cannot be given. The reason is that there is only one reference available in literature with a permeation value that differs to much from the values Kiwa expects.

5.3 Permeation compared to leakage

For gas distribution the leak tightness is measured according to EN 12327. For impact modified PVC pipe systems the maximum allowable leakage rate according to the Dutch standard NEN 7244-5 is 5 l/h at maximum operating pressure. To put the measured permeation rate in perspective, the permeated hydrogen in l/h can be compared to the limiting values for a distribution leak (based on methane). The exact allowable leakage rates for hydrogen are still unknown. If the maximum allowable leakage rate is presumed to be in the same order of magnitude it is safe to work for the time being with a maximum leakage rate of 1 l/h.
The highest permeated volume of the PVC pipes is 17.0 ml/(m·day) at 0.2 bar(g) or 0.71 ml/(m·h), which is over 1400 times lower than 1 l/h for every metre of pipe. Moreover, permeated hydrogen is not concentrated at one location, but distributed over the 1 metre pipe.

Therefore, the permeation of hydrogen though a PVC pipe is much smaller than a leak.

Permeation of hydrogen will lead to the loss of energy. 0,71ml/(m.h) will lead to an energy loss of approximately 0,0025 Wh (9 Joule) per meter pipe per hour. The value of an allowable leak in a natural gas distribution grid is approximately 49 Wh (176 kJ) per hour.
The energy loss due to permeation of hydrogen of a kilometre of PVC pipe is therefore approximately 19 times lower than the energy loss due to leakage from one allowable leak in a natural gas grid.

6 Conclusion

6.1 Maximum angle of deflection

The maximum angle of deflection of eight PVC joints (both PVC-U and PVC-Hi) is derived. These eight samples have been divided into two groups of joints. One group is tested as-received and one group is tested after an additional ageing of 1000 hours at 60 °C with an internal pressure of 30 mbar(g) of hydrogen.

The results of the angle of deflection measurements for PVC joint are:

Kiwa reference #	Type of PVC	Aged (60°C, 1000 hrs, hydrogen)	Maximum angle of deflection [°]
PVC 2011-088	PVC-U	yes	4.9
PVC 2018-022	PVC-Hi	yes	>44
PVC 2016-064	PVC-U	yes	5.3
PVC 2019-163	PVC-Hi	yes	>30
PVC 2018-069	PVC-U	no	12.1
PVC 2011-067	PVC-Hi	no	>29
PVC 2012-064	PVC-U	no	28.3
PVC 2011-045	PVC-U	no	>8.9

All tests show that the maximum angle of deflection, even after ageing, fulfils the requirements of the appropriate standard EN-ISO 13844.

6.2 Permeation

The permeation rate of six PVC pipes and four PVC joints (both PVC-U and PVC-Hi) is derived. For the PVC pipe materials also the permeation coefficient is derived. These permeation coefficients can be used to calculate the permeation rate of PVC pipes of other dimensions. The test results are stated in the tables below:

PVC pipes

Kiwa reference #	Type of PVC	Permeation rate [ml/(m·day)]	Permeation coefficient [(ml·mm)/(m^2·day·bar)]
PVC 2017-020	PVC-U	12.1	90.9
PVC 2018-086	PVC-U	10.2	87.3
PVC 2019-033#06	PVC-U	11.2	115.3
PVC 2019-003	PVC-CPE	11.2	117.2
PVCSL 2016-116	PVC-A	17.0	181.3
PVCSL 2017-108	PVC-CPE	10.9	113.3

PVC joints

Kiwa reference #	Type of PVC	Permeation rate [ml/day]
PVC 2011-088 (087, 089)	PVC-U	6.5
PVC 2018-022 (021, 023)	PVC-Hi	7.3
PVC 2016-064 (063, 065)	PVC-U	7.5
PVC 2019-163 (162, 164)	PVC-Hi	7.4

The permeation rate is over 1400 times lower than 1 l/h, which is a worst-case scenario for hydrogen based on the maximum allowable leak rates for natural gas in a gas distribution system. This means that the amount of hydrogen permeating through the pipe walls is rather small and does not lead to safety issues. The measured permeation of the joints is comparable to the permeation of less than 1 metre of pipe.

The overall conclusion is that both unplasticized PVC and impact resistant PVC systems used in the Netherlands show a good behaviour of angular deflection and a good behaviour on permeation of hydrogen through the pipe wall and rubber sealed socket couplers. The good behaviour of angular deflection even after additional ageing equal to more than 50 years, meet the requirements mentioned in the relevant standards for new couplers. This shows that slight ground movements even if hydrogen will be transported in future can be assimilated by the joints.

7 References

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