HyDelta

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Executive summary

This report describes the execution and results of work package WP1F (testing valves in the transmission grid), which is a part of the HyDelta research programme. The research consists of measurements on the external leakages of ten ball valves with both natural gas and hydrogen at pressures above 16 bar. The internal leak tightness of twelve ball valves and the external leak tightness of seven plug valves in a natural gas grid were also measured.

The goal of measuring with both natural gas and hydrogen was to find a relationship or ratio between the leakage rates for the two gasses. Theoretically, it is possible to calculate that the ratio would be close to a factor of three. This factor could be used to identify if, with respect to leakages, existing valves are suitable for use in a hydrogen distribution network. In this research, there were insufficient leakages measured to confirm or disprove this ratio. With the ten valves for which measurements were carried out, it could be concluded that if no leak can be measured with natural gas, then there can also be no leak measured with hydrogen. Due to the limited number of measurements and the lack of leakages, this cannot be guaranteed for the entire population of valves. It is therefore recommended that if a pipeline will be assigned to transport hydrogen, all the valves connected to this pipeline should be inspected individually according to the measuring method described in this report.

From 37,000 valves installed in the national gas grid with a pressure rating above 16 bar, 12 ball valves and 4 plug valves were selected to represent the existing valves to the greatest degree possible. The selection criteria were based on the amounts and the most used brands/types installed in the grid. The measurements were divided between external leakages (from the valve to the environment) and internal leakages (from one side of the valve to the other). When a significant external leakage was detected using the "Leak Detection And Repair" (LDAR) method, an additional measurement was executed with a "Hi-flow sampler" (HFS) and/or a flow measurement. Two ball valves were found to have such a high level of internal leakage that the valve could not be filled with hydrogen. Therefore, out of the 12 ball valves, there were 10 measurements with hydrogen. It was not possible to measure one of the selected plug valves, and four extra plug valves were also measured. This brought the total number of valves used in the measurements to 19.

Plug valves were only tested on external leakages with natural gas. Performing any type of measurement with hydrogen proved unfeasible for plug valves. A comparison between hydrogen and natural gas could therefore not be made for these types of valves.

Summary of the measurements:

- Three of the twelve ball valves had a detectable amount of natural gas in the valve stem, all without a measurable flow.
- Four out of ten ball valves had a detectable amount of hydrogen in the valve stem, all without a measurable flow.
- No external leakage could be detected for either of the gasses with any of the ball valves. A leakage ratio could therefore not be determined.
- Five out of the twelve ball valves had a measurable internal leakage for natural gas, of which three were above the Gasunie rejection limit. The internal leak tests could not be performed with hydrogen.
- Two out of the seven plug valves had a measurable external leakage for natural gas. These tests could not be performed with hydrogen.

Besides the leakage measurements, other properties of the existing valves have been examined. A literature review indicated that no problems are expected with regard to the suitability of the materials used in valves for hydrogen, given the operating pressure and temperature. An enquiry was made among manufacturers about the suitability of valves with hydrogen. The general response was that no problems are expected if hydrogen is used with the newer valves.

Contents

Document summary 2

Executive summary 3

1. Rationale 6

2. Broad outline of aim and approach 7

  2.1 Objective 7

  2.2 Delivery 7

3. Method 8

  3.1 Selection of valves. 8

  3.2 Leak tightness measurements used: External leak tightness, ball and plug valves 9

  3.3 Leak tightness measurements used: Internal leak tightness, ball valves 11

4. Literature review and supplier enquiry 13

  4.1 Literature review 13

  4.2 Supplier enquiry 14

  4.3 Theoretical approach to the leakage factor 14

5. Results of field studies 15

  5.1 Measurements performed on ball valves 15

  5.2 Measurement results of external leakage for the ball valves 16

  5.3 Internal natural gas leakage measurements for ball valves 17

  5.4 Measurement results for external leakage, plug valves 18

  5.5 Interpretation and reflection on the results 19

6. Conclusions and recommendations 20

  6.1 General conclusions 20

  6.2 Ball valves 20

  6.3 Plug valves 20

  6.4 Recommendations 20

Bibliography 22

I. Details of the valves 23

II. Modelling of gas leaks. 24

III. Additional research into internal leakage of valves 28

1. Rationale

Using the existing gas transmission and distribution networks is a key element in minimising the social costs of rolling out hydrogen on a large scale. In this respect, it is important to know whether the existing natural gas transmission grid can be converted to hydrogen and what measures this would involve.

One of the unanswered questions concerns the suitability of the valves in the existing national transmission grid. Unlike the regional transmission grid, which is operated at pressures below 16 bar, the national transmission grid is operated at pressures above 16 bar. There are roughly 37,000 valves of various sizes, brands, types and ages in the national transmission grid. The variety of operating principles is limited, but when it comes to the use of sealing materials, the differences are greater.

The research described in this report involved conducting internal and external leak tightness measurements on the valves. The aim of the research is to determine the amount of leakage under both natural gas and hydrogen conditions. This is important in being able to make a conclusion about the expected amount of leakage under hydrogen conditions when taking measurements in the future under G-gas or H-gas conditions. An initial substantiated estimate can be made based on the leak tightness measurements carried out on a number of specifically selected valves.

In recent years, Kiwa has carried out internal and external leak tightness measurements on a number of valves taken from the transmission grid [1]. These valves were tested with hydrogen at a pressure of 66 bar. These tests revealed a mixed picture, with most valves proving (virtually) leak tight, but with a few valves also showing some leakage (the measured external leakage varied between 0 and 136 l/h, and the internal leakage between 0 and 411 l/h). These results called for further research to be conducted.

2. Broad outline of aim and approach

2.1 Objective

The aim of this work package is to increase knowledge about the suitability of valves for the application of hydrogen. For this research specifically, the intention is to examine whether a conclusion can be made with regard to the suitability of in-situ (operating) valves in relation to hydrogen.

The purpose of this research is to be able to answer the main question:
Can the existing/installed valves in the natural gas transmission grid be used safely for the transport of hydrogen?

The related sub-questions are as follows:

- What is the internal and external leak tightness (both with natural gas and hydrogen) of a selection of existing valve types that may be suitable for use in the hydrogen network?
- Are the materials (both steel and the sealing materials) in the valves suitable for use with hydrogen?
- How can the results of the measurements and the suitability of materials be translated into a conclusion about the suitability of valves in-situ?

In order to answer these questions, leak tightness measurements were carried out with natural gas as well as with hydrogen. In addition, the research examined whether this knowledge could be translated in such a way as to also be able to come to a conclusion about the suitability of in-situ valves for hydrogen. This would allow for a real-world assessment of the suitability of a valve (scheme) and any related potential risks.

2.2 Delivery

The delivery of this report concludes the work package. This report contains the following sections:

- The results of the inventory of materials used in the valves and the research into these materials.
- The measurement results and the interpretation of the internal and external leak tightness measurements carried out.
- A translation of the results to the in-situ situation.

3. Method

A literature review and field research were conducted in order to answer the main question from Chapter two. Here, the focus of this project was mainly on the field research. The approach and the results from the literature review are presented in Chapter 4. After that, the field research is discussed. The criteria used for selecting the valves are explained first. The measurement methods are then briefly described. As the field research was a continuous learning process, the measurements and measurement methods were adjusted as the measurements were being taken based on new insights. An effort has been made to present the measurements as straightforward as possible. Furthermore, although not all of the measurement data have been presented, this report attempts to represent the measurement data as accurately as possible.

3.1 Selection of valves.

An inventory was made of the most common valves in the existing Gasunie network of transport pipelines with a pressure higher than 16 bar.

The inventory was based on a number of properties. The most important valve properties are as follows:

- Function within the transmission grid (sectioning, station connections, etc.)
- ANSI class (up to what pressure is the valve designed to handle)
- Manufacturer/brand of the valve
- Dimensions of the connection (DN 900, DN 1200, etc.)
- Number in use
- Type (the most common types are ball, gate or plug valves)
- Age

The inventory showed that valves in the Gasunie transmission grid are used in roughly the following proportions [2]:

- 70% ball valves
- 22% plug valves
- 8% gate valves

The most common brands of ball valves in the Gasunie main transmission grid (DN 900 – DN 1200) are Cameron, Grove and RMA. Cameron and Grove were used until around 2000. Since that time, RMA ball valves have become the most common. The plug valves are from Christensen and AUDCO, with Christensen being the most frequently used. An inventory carried out by Gasunie shows that these valves are also common among the other European gas transmission grid operators.

The selection of valves was based on the frequency of occurrence of the valve types. As ball valves are the most commonly used type, the decision was made to use a selection of 75% ball valves and 25% plug valves.

The most common brands are Cameron, Grove and RMA. A selection was made from each of these brands of four valves in the diameter range DN 900 to DN 1200, ANSI 600 with a variety of ages. It is highly likely that these types are also currently installed in the intended national hydrogen network.

Plug valves are also widely used in the transmission grid; the most common brand (Christensen) was selected in the diameter DN 400, ANSI 600 with a variety of ages.

Four valves of each of the four brands/types were selected, bringing the total to sixteen, see Table 1. During the preparatory stage, it was assumed that twelve valves would be tested and a back-up valve would be selected for each brand. In the end, the decision was made to test all sixteen valves in order to gain better insight. One of the RMA valves was replaced by a Börsig valve for practical reasons. In addition, three extra plug valves were measured, bringing the total to nineteen measured valves.

For detailed information on the selected valves see Appendix I.

Table 1. Selected valves.

Producer	Type	DN series	Production year	Quantity	Leak tightness
Grove	Ball valve	900 – 1200	1963-1993	4	Internal and external
Cameron	Ball valve	900 – 1200	1974-2000	4	Internal and external
RMA	Ball valve	900 – 1200	2006-2011	4	Internal and external
Christensen	Plug valve	400	1975 - 2009	4	External

3.2 Leak tightness measurements used: External leak tightness, ball and plug valves

The description of the leak tightness measurements is described in detail in a measurement protocol [2]. This measurement protocol is not publicly available. Therefore, the most important aspects of the valve selection, the determination of the external and internal leak tightness, are briefly explained in the following paragraphs.

The external leak tightness test consisted of three steps, whereby each subsequent step was only carried out if the values in the previous step were significant:

1. LDAR measurements (natural gas and hydrogen)
2. Leakage rate measurements using a Hi-flow sampler (natural gas only)
3. Leakage rate measurements using a 'Brooks' rotameter (natural gas and hydrogen)

The ambient temperature was not recorded during the measurements. The effect of temperature on the measurements is minimal. In addition, the measurements were taken in the autumn when solar radiation is generally negligible. The most important points are explained below.

LDAR measurements (natural gas and hydrogen)

The measurements for all valves started with a LDAR measurement, similar to the one used by Gasunie. LDAR stands for Leak Detection And Repair campaign. This involves using a gas concentration meter to measure the vent opening of the valve's extension spindle for a certain period of time and recording the maximum value. The concentration of methane found with this method (in ppm) is not a determination of the actual leakage rate, but it can be used as an indicator of whether a repair is required. The box on the right contains the explanation of LDAR as given by Gasunie. The research described in this report diverges from Gasunie practice at two points: the limit value and the measurement time.

> Explanation of Gasunie leakage measurement (LDAR) areas – Code: LEK-001 – Department: EIWI (Gasunie):
>
> The measuring probe of the TVAxx measuring device should be moved slowly and as close as possible to the potential source of the leak. The maximum measurement value is important. Hold the probe around the position with the maximum measurement value for about five seconds and record this value if > 1000 ppm.

Gasunie uses a value of 1000 ppm as the limit value for repairing the leak detected. In view of the aim of this research - establishing a ratio between measurements in natural gas and hydrogen - different limit values have been used: 500 ppm for natural gas and 100 ppm for hydrogen. These values were chosen based on the measurement accuracy of the measuring equipment used.

Gasunie uses a measuring time of 5 seconds. For this research, concentration measurements were conducted for at least 1 minute, as the measured value fluctuates as the measurement is being taken. The maximum value measured is important and has been included in the tables. Measuring for a longer time increases the chance of measuring the maximum value.

For the gases used in this research, if no gas concentration was measured, it can be assumed that there was no (or a negligible) leak. If a gas concentration has been measured, this does not necessarily say anything about the size of the leak. A small leak can/will eventually lead to a high concentration in the protective tube. We therefore assume that when a methane concentration > 500 ppm is measured, that there is a possible measurable leak, after which the subsequent measurement is started.

Leakage rate measurements using a Hi-flow sampler (natural gas only)

If a concentration > 500ppm was measured with the LDAR measurement method, then a measurement with a HFS (Hi-flow sampler) was conducted. With the HFS measurement, the amount of natural gas leaking from the vent opening is suctioned in and the measuring unit then determines the amount of leakage. Here, it is important for there to be a stable situation between the leak and the amount of ventilation in the protective tube. Because the need for a stable situation, HFS measurements are particularly useful for larger leaks.

The HFS is not suitable for hydrogen, as it only detects methane. If a quantity of natural gas has been measured with the HFS measurement, a flow rate determination is also carried out using a flow meter, if possible.

Leakage rate measurements using a 'Brooks' rotameter (natural gas and hydrogen)

The manifold is connected to the drain during the flow rate measurement for the ball valves (see Figure 3). The flow meter (see Figure 2) is connected to the manifold, which in turn is connected to the venting installation. The required pressure is then regulated by a needle valve. The quantity vented is equal to the quantity leaking through both seals. For plug valves, the flow meter is connected to the vent opening, where the leakage is measured through the opening. A more detailed description of the measuring method, as well as the specifications for the rotameter can be found in the measurement protocol [2].

3.3 Leak tightness measurements used: Internal leak tightness, ball valves

For this project, the internal leakage rate was only measured for ball valves as this has limited relevance for plug valves. Plug valves are used as wear valves for the purpose of dispersing large pressure differentials. For this reason, a certain degree of internal leakage is permitted for this type of valve.

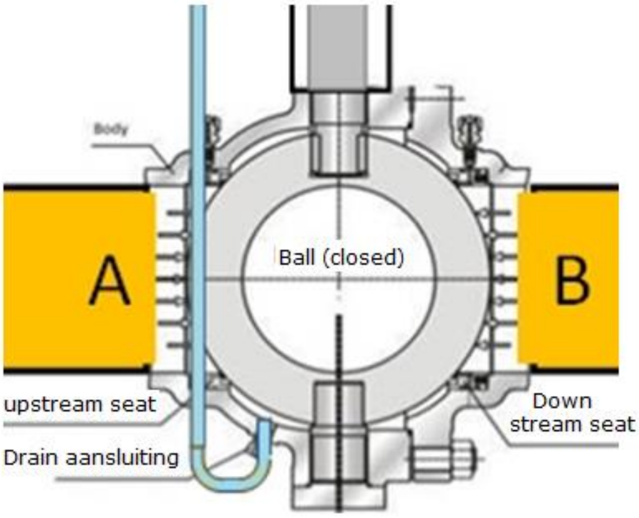

Figure 1 (left): Schematic representation of a ball valve.

Figure 2 (right): Set-up with flow meter (foreground) and venting installation (background).

During exploratory measurements it was concluded that from a practical point of view, it is not possible to determine the internal leak tightness for hydrogen. In all cases, the volume of the pipe sections at either side of the valve was too high for them to be completely filled with hydrogen. Even the shortest sealable pipe sections (e.g. in the case of scraper trap valves) have such a large volume that it is practically impossible to fill the section with hydrogen up to a pressure of 67 bar. The internal leak tightness measurements described here have therefore only been conducted with natural gas.

Figure 3: Above-ground configuration of a valve including control unit.

The internal leak tightness was determined at various pressure differentials over the seals. The pressure differentials were obtained by releasing pressure in the body, while the pressure in the through-pipe on both sides of the valve remained more or less the same. Once the desired pressure differential was reached, the pressure was kept constant by operating the needle valve in the direction of the flow meters. The flow rate was then read. The measured leakage is the total leakage of the two seals; the ratio of the leakage size between the two seals is unknown.

4. Literature review and supplier enquiry

Part of the research question relates to the suitability of materials. A literature review was carried out for this purpose, which is described in the section below. The second part of this chapter summarises the responses of manufacturers to the question of the suitability of existing valves in a hydrogen network. Afterwards, the theoretical approach to the leakage factor is discussed.

4.1 Literature review

In January 2021, Kiwa Technology completed research concerning the influence of hydrogen on soft materials [3]. The research included a literature review as well as experimental research. The aim of the research was to map out any potential shortcomings in soft materials that could interfere with the safe and reliable distribution of hydrogen. Soft materials are understood to be polymers: rubbers and plastics, lubricants (with oil as main ingredient), epoxy resins and glues. The research focused on the gas pressure regulation installations for distribution system operators (DSOs). The maximum pressure in the networks of the DSO is 8 bar, while for the national transmission system operator (TSO) it is up to 80 bar. It will be demonstrated later on that the conclusions from the report can also be used for the higher pressure found in the national transmission grid.

The literature review indicated that no material interactions with hydrogen are to be expected in DSO gas pressure control systems, as they do not contain high pressures of more than 900 bar or temperatures above 200 degrees Celsius. API RP941 [4] indicates that only such extreme conditions could result in a volume change and compression differences in the materials that could lead to their deterioration. It is therefore concluded that the effects of hydrogen on the degeneration of soft (and other) materials are negligible at the pressures and pressure differentials found in the Dutch distribution networks. Since the pressures in the Gasunie national transmission grid also remain well below 900 bar and the temperatures stay well below 200 degrees Celsius, no issues with the materials are to be expected in this regard. However, a possible increase in hydrogen permeation should be taken into account for materials where permeation plays a role. For this reason, older valves need to be inspected on an individual basis to determine whether they meet the material and construction requirements for safely transporting hydrogen.

Before 2006, valves were purchased without additional specifications for fugitive emissions. At the time, a German national directive, the TA-luft/VDI 2440 [5], with its corresponding test procedure, generally applied. This directive was established in 1964 and was the only recognised industry standard for valves that was used to classify fugitive emissions into the atmosphere until 2006. The directive specified how much a valve stem seal or gasket was permitted to leak, but it did not specify under what conditions. Instead, it was up to the manufacturer to test the components under - what they believed to be - the applicable conditions. This could be seen by many as haphazard, as it is then up to each individual manufacturer to decide under what conditions leak testing is carried out. TA-luft did not specify how many mechanical or thermal test cycles the valve had to undergo in order to pass the tests [6].

The international standard ISO 15848-1, Annex B has been in force since 2006. The lack of a harmonised standard for verifying and classifying the environmental impact of leakage from valves into the atmosphere was the main driver. Unlike TA-luft, the ISO 15848-1 clearly specifies the test conditions. Testing may be carried out in three different classes where temperature and pressure are varied between the room temperature and test temperature, and between atmospheric pressure and test pressure respectively. Many believe that the test procedure for this standard is a better indication of the overall performance of the valve, as all valves are tested in exactly the same way.

4.2 Supplier enquiry

The manufacturers of the valves were asked whether the valves were compatible with hydrogen. Below is a quote of the response from each manufacturer.

RMA: Valves are suitable for use with hydrogen.

GROVE: Would like to discuss the possibilities.

Cameron: Cameron ball valves seem to be resistant to hydrogen.

Christensen: Older valves have not been tested in accordance with the current standard and for that reason may not meet the current emission requirements. The new designs do fall within the current standard.

Based on the literature review as well as the response from suppliers and Gasunie, no problems are anticipated with the soft (polymers) or hard (carbon steel) parts in the valves. These aspects were therefore not a criterion for selecting the valves in the experiments for this research.

4.3 Theoretical approach to the leakage factor

Appendix II contains a theoretical derivation for the expected ratio between the flow rate of natural gas and the flow rate of hydrogen passing through an identical outlet opening. Models of gas flowing through a small hole were used to determine the leakage factor between natural gas and hydrogen. The conclusion based on this theoretical analysis is that the expected leakage of hydrogen will be roughly three times greater in volume than that of natural gas, given a constant area of leakage.

Sub-question 124 of the HyDelta work package 1C looks in more detail at the leakage factor between natural gas and hydrogen, the results of which can be found in the report D1C_D1C.2.

5. Results of field studies

The results of the measurements are described in this chapter. The results for the ball valves are presented first, followed by the results for the plug valves. In the last paragraph, a brief reflection is provided on the interpretation of the measurement results.

5.1 Measurements performed on ball valves

Table 2 contains the measurements that were carried out on the ball valves. The manufacturer and location are indicated on the left side and the measurements carried out are indicated on the right side (in green).

Table 2: Measurements taken for the ball valves.

Fabrikant	Locatie	Aardgas				Waterstof	
		uitwendig	uitwendig	uitwendig	inwendig	uitwendig	uitwendig
		LDAR	HFS	Debiet	Debiet	LDAR	Debiet
Grove	Montfort	ja	nee	nee	nee	nee	nee
Grove	Nieuwstadt Zuid	ja	nee	nee	ja	ja	nee
RMA	Angerlo	ja	nee	nee	ja	ja	nee
Cameron	Spijk	ja	ja	ja	deels	ja	ja
Grove	Noordbroek	ja	nee	nee	ja	ja	nee
Borsig	Nieuwediep	ja	nee	nee	ja	ja	nee
Cameron	Nieuw Balinge	ja	nee	nee	ja	ja	nee
Cameron	Beltrum	ja	ja	nee	nee	nee	nee
Grove	Kielwindveer	ja	nee	nee	ja	ja	nee
RMA	Workum	ja	nee	nee	ja	ja	ja
RMA	Workum	ja	ja	nee	ja	ja	ja
Cameron	Anjum	ja	ja	nee	ja	ja	ja

Explanation of the table:

- External (uitwendig) leak tightness:
  Each valve was measured using an LDAR measurement. An HFS measurement was only applied if the LDAR detected a concentration of natural gas of 500 ppm or more.

- Internal (inwendig) leak tightness:
  A flow rate measurement was only applied if the HFS measurement indicated a significant value. For the measurements with hydrogen, this was done if the LDAR measurement showed an concentration > 100 ppm.
- The sequence was determined by the date and time of the measurement. Increased insight allowed measurements to be carried out more efficiently. Also, with the last measurements, an HFS and/or a flow rate measurement were applied more frequently to validate the LDAR measurement.

5.2 Measurement results of external leakage for the ball valves

Table 3 shows the measured values of the ball valves. On the left, the sequence number in the order that measurements were carried out, the manufacturer, and the location are indicated. After that, it is divided into measurements with natural gas (yellow) and hydrogen (blue). All flow rate indications in this report are in normal cubic metres per hour or in normal litres per hour.

Table 3: Measured values, ball valves.

Nummer	Fabrikant	Locatie	LDAR	HFS	Uitwendig debiet	LDAR		Uitwendig debiet
			Aardgas			Waterstof		
			ppm	m3/h	m3/h	ppm	max druk (bar)	m3/h
1	Grove	Montfort	< 500	-	-	-	-	-
2	Grove	Nieuwstadt Zuid	< 500	-	-	<100	30	-
3	RMA	Angerlo	< 500	-	-	<100	46	-
4	Cameron	Spijk	500	0	0	150	62	0
5	Grove	Noordbroek	< 500	-	-	<100	39	-
6	Borsig	Nieuwediep	< 500	-	-	<100	59	-
7	Cameron	Nieuw Balinge	< 500	-	-	<100	60	-
8	Cameron	Beltrum	2.000	0	-	-	-	-
9	Grove	Windeweer	< 500	-	-	<100	60	-
10	RMA	Workum	< 500	-	-	>12.000	60	0
11	RMA	Workum	700	0	-	>12.000	62	0
12	Cameron	Anjum	< 500	0	-	2500	64	0

Explanation of Table 3:

- Light yellow indicates a significant increase.
- During the measurements in Workum (valves 10 and 11) and Anjum (valve 12) a significant hydrogen concentration was measured with LDAR. A different meter was used for this measurement. For verification, additional measurements were carried out for both natural gas and hydrogen. It later emerged that the meter showed a cross-sensitivity to methane, as

a result of which these values do not provide a reliable picture and the flow rate measurements in particular should be noted.

- The pressure at which the tests were carried out with hydrogen was not always the same as the grid pressure. In two cases (valves 1 and 8), it was not possible to test with hydrogen because there was too much internal leakage. In the other cases (valves 2, 3 and 5), the grid pressure could not be achieved due to a limited supply of hydrogen available for transport.
- The valve in Spijk (number 4) had a high internal leakage of natural gas, although less than the set limit of 70 m^3/h. As a result, when filling up with hydrogen, a composition of natural gas and hydrogen was created in which only hydrogen was measured for the external leakage (these are the measurements for H2, i.e. in the blue column). This may have resulted in the lower than expected measured value for hydrogen.

5.3 Internal natural gas leakage measurements for ball valves

The internal leakage was measured at different pressure differentials, the results of which are presented in Table 4.

Table 4: The internal leakage as a function of the pressure differential across the seals.

Nummer	Fabrikant	Locatie	Inwendige lekkage bij ΔP van ...				
			16 bar (m3/h)	25 bar (m3/h)	40 bar (m3/h)	ΔP max (m3/h)	ΔP max (bar)
1	Grove	Montfort	> 70	-	-	-	-
2	Grove	Nieuwstadt Zuid	30,0	38,3	42,2	33,8	54
3	RMA	Angerlo	28,8	18,8	7,5	4,9	56
4	Cameron	Spijk	~ 62	-	-	-	-
5	Grove	Noordbroek	-	-	-	2,6	64
6	Christensen	Nieuwediep	-	-	-	23,0	59
7	Cameron	Nieuw Balinge	1,36	0,78	1,66	0,56	60
8	Cameron	Beltrum	-	-	-	> 70	-
9	Grove	Windeweer	7,5	4,3	7,0	4,2	60
10	RMA	Workum (36)	13,5	7,5	1,35	0,31	59
11	RMA	Workum (04)	7,5	8,4	5,8	6,2	59
12	Cameron	Anjum	10,5	6,4	3,4	1,54	64

A large internal leak was detected when no significant drop in pressure was measured while venting the natural gas in the body. It was not possible to fill the valve with hydrogen due to these large internal leaks. In this case, the natural gas flowed so quickly into the body that it was practically impossible to get enough hydrogen into the body within the short amount of time available with the current set-up. The leakage rate for hydrogen in the case of large internal leaks for natural gas could therefore not be concluded based on these measurements. However, this is also less relevant because the permissible internal leakage, as specified by Gasunie for the valves with dimensions between DN 750 and DN 1200, is 60 m^3/h. The leaks are so large that these valves would also be rejected for natural gas. One ball valve (number 4) is borderline for rejection at 62 m^3/h. The measurement on this valve should be regarded as indicative, as the measurement was interrupted due to a clogged filter in the measuring unit as a result of contamination in the natural gas network. These three valves are marked in dark yellow in Table 4. Two valves were leaking significantly but were not over the rejection threshold, these are marked in light yellow. These internal leakage measurements indicated that the results of the measurements were dependent on the operating state of the ball. The measured internal leakage rate changed when the valve was operated and reset, causing the ball to rotate relative to the seals.

For valves measured with multiple pressure differentials, in most cases (five of the seven ball valves), the lowest internal leakage was obtained at the highest pressure differential. In three of the twelve ball valves tested, the internal leakage was greater than 60 m^3/h, therefore deviating from the limit set by Gasunie. In seven of the twelve ball valves tested, the internal leakage was < 10 m^3/h. For two of the twelve ball valves tested, the internal leakage rate at the highest pressure differential was between 10 and 60 m^3/h. Several tests show that the leakage rate increases with a smaller pressure differential across the seals.

5.4 Measurement results for external leakage, plug valves

Table 5 contains the measurements carried out and the related results for the plug valves.

Table 5: The measurements carried out and the results for plug valves.

Nummer	Fabrikant	Locatie	LDAR	HFS	Uitwendig debiet
			Aardgas		
			ppm	l/h	l/h
1	Christensen	Nieuwediep	< 500	-	-
2	Audco	Nieuw Balinge	>50000	135	280
3	Christensen	Beltrum	< 500	-	-
4	Audco	Beltrum	< 500	-	-
5	Christensen	Windeweer	< 500	-	-
6	Audco	Windeweer	>50000	32	-
7	Christensen	Workum	< 500	-	-

Explanation of Table 5:

- The measurements are shown on the right. There were two plug valves that had a measurable (> 500 ppm) leak (dark yellow).
- The values measured with the LDAR method were higher than the maximum value measured with the ball valves.

- More plug valves were measured than were in the selection process in order to gain additional insight.
- In Windeweer (number 6), an extra plug valve was measured because it was known to be leaking. No flow rate measurement was carried out because the HFS measurement was considered to adequately represent the measurements at the time it was taken.
- The leakage rate measured in plug valve 2 was of the same range in both measurements. In both cases, the measurement value fluctuated, which made a direct comparison difficult. In addition, the HFS measurement measures methane, while the flow rate measurement measures the total flow rate. Therefore, the measurement values of the flow rate measurement will generally be higher.

5.5 Interpretation and reflection on the results

The LDAR measurement was carried out with natural gas for all the valves. For six valves (four ball valves and two plug valves), the HFS measurement with natural gas was also performed. These six measurements were taken at five valves where a significant concentration was measured during the LDAR measurement; additionally, a control measurement was taken at one valve (number 12). This shows that the previous assumption (see paragraph 3.2) that a measured gas concentration of <500 ppm indicates a very small leakage, is sound. Leakages where a concentration of 2000 ppm or less is measured do not appear to provide a measurable value with the HFS for these valves.

For two plug valves, a leakage rate was determined using the HFS measurement. For one of these valves, a flow rate measurement was also carried out. This flow rate measurement showed a leakage rate that was in the same range as the one determined by the HFS measurement.

It is worth noting that for the majority of the valves, no external leakage was detected for natural gas and/or hydrogen. For ball valves where an external hydrogen leakage was observed using the LDAR methods, no leakage rates were subsequently found. In addition, it was found that particularly for hydrogen, the measured value during the LDAR measurement fluctuated more over time. This is not surprising, considering the dynamics of a gas leak. The fluctuating value confirms that the LDAR method is only suitable for determining whether there is a leak, but not how large the leak is.

In order to reduce internal leakages, decreasing/increasing the pressure as soon as possible would be advisable in view of the results in Table 4. It can also be concluded from the results in Table 4 that lowering the network pressure in order to reduce (internal and external) leakages actually results in a larger internal leakage rate across the valve. These situations occur, for example, during work activities where a pipe has to be depressurised.

The measurements were dependent on the operating state of the ball or plug. When the valve was being operated, the measured leakage changed. Each valve is also unique – based on the selected and measured valves, no correlation can be found between brand and production year.

If follow-up measurements are carried out by Gasunie or Kiwa, a number of issues need to be taken into account. The LDAR method proved to be less useful for hydrogen due to the considerable fluctuation of the measured value. A different measurement method is recommended to avoid having to carry out flow rate measurements unnecessarily. Because the HFS measurement is not suitable for hydrogen, and the measured values for natural gas corresponded to the flow rate measurement, the HFS measurement could be omitted for leak measurements in valves.

6. Conclusions and recommendations

6.1 General conclusions

The external leakages detected with LDAR for the tested ball valves are so small both with natural gas and with hydrogen that they cannot be traced back to a measurable leakage rate. In the case of the plug valves, the two external leakages detected (measured with natural gas) can be traced back to a measurable leakage rate. However, this did not provide an unambiguous answer to the research question. An insufficient number of leaks were found in order to establish a proper relationship between natural gas leaks and hydrogen leaks in plug valves. Based on the selected and measured valves, no correlation could be found between brand and production year. Based on the literature review and enquiries with manufacturers, there are no obstacles in terms of material use that are expected to prevent the valves from being used for hydrogen.

6.2 Ball valves

External leak tightness, natural gas

The external leakage measurements with natural gas indicated an increased concentration of natural gas in the protective tube for three of the twelve ball valves tested. After additional Hi-flow sampler (HFS) measurements, there appeared to be no measurable leakage rate. In the remaining nine ball valves tested, the concentration of natural gas in the protective tube was less than 500 ppm.

External leak tightness, hydrogen

In the measurements of the external leaks, a higher concentration of hydrogen was measured in three situations as compared to the concentration of natural gas. However, these increased concentrations of hydrogen do not yet represent a measurable leak. Based on the results obtained, it is not possible to establish an unambiguous relationship between the ratio of the leakage rate of natural gas and the leakage rate of hydrogen. This is due to the fact that the measured leakage rates were almost zero.

Internal leak tightness, natural gas

Not all valves were adequately sealed internally. Three of the twelve exceeded the 60 m^3/h limit. Since it can be assumed that internal leakage from these valves with hydrogen increases by a factor of 2.3 (see Appendix III) to a maximum of 3 (see Appendix II), it is recommended not to use these valves in new hydrogen networks. Before using an existing installed valve in a hydrogen network, it is advisable to determine the internal leakage. The fact that this occurs with natural gas is not an issue if the above factor is taken into account.

6.3 Plug valves

Two of the seven plug valves tested had a clearly measurable concentration of natural gas. A leakage rate of 135 and 30 litres per hour was measured. One of the valves had already been identified by Gasunie as having an external leak. External leakage rate measurements with hydrogen were not possible with plug valves. Internal leak tightness tests with natural gas are less relevant for this type of valve as they are used as wear valves.

6.4 Recommendations

Not enough leaks were found with the ball valves to obtain a good ratio between natural gas leaks and hydrogen leaks. If it is important to obtain a good factor for this with values measured in practice, it is advisable to carry out more measurements. It should be noted here that the assumption is that by measuring more valves, more valves with a leakage will be found. The set of valves discussed in this report, however, has not demonstrated that this is actually the case. The results of the measurements described in Appendix III can be used as a starting point.

The measured values for the LDAR method fluctuated during the measurement, especially during the measurements with hydrogen. In order to obtain a more reliable value, it is recommended to automatically save the fluctuating measuring values and to analyse them. This will give more reliable measurements that can be verified afterwards and that will provide more insight into the measurement value fluctuations. Combining these measurements with flow rate measurements would also provide more insight into the limit values that can be used as well as a possible adjustment of the Gasunie measurement protocol. In this respect, it is recommended that a new Gasunie repair standard should be made for hydrogen.

Performing the measurements described in this report requires a relatively low investment in comparison to the costs of purchasing a valve. Therefore, once it is clear which valves may be reused for hydrogen, it is advisable to determine the internal and external leak tightness with natural gas for each of them according to the measurement method used in the research. This will be a relatively easy way of providing useful information about the condition of the valve.

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I. Details of the valves

The table below shows the valves that were selected prior to the measurements and which were actually measured for this research.

Nummer	Type	Producent	Bouwjaar	DN	Locatie	Functieplaats	Bemeten	Geselecteerd
1	Kogelafsluiter	Cameron	1974	900	Spijk	S-471-901-GV-85	Ja	Ja
2	Kogelafsluiter	Cameron	1990	900	Beltrum	S-254-GV-03	Ja	Ja
3	Kogelafsluiter	Cameron	1996	900	Anjum	S-721-GV-31	Ja	Ja
4	Kogelafsluiter	Cameron	2000	1200	Nieuw Balinge	S-221-GV-02	Ja	Ja
5	Kogelafsluiter	Grove	1963	900	Windeweer	S-008-GV-01	Ja	Ja
6	Kogelafsluiter	Grove	1965	1050	Montfort	S-054-901-GV-02	Ja	Ja
7	Kogelafsluiter	Grove	1993	1200	Nieuwstadt Zuid	S-687-901-GV-01	Ja	Ja
8	Kogelafsluiter	Grove	1993	1050	Noordbroek	S-263-GV-034	Ja	Ja
9	Kogelafsluiter	RMA	2006	900	Workum	S-344-GV-04	Ja	Ja
10	Kogelafsluiter	RMA	2008	1200	Nieuwediep	S-214-901-GV-04	Nee	Ja
11	Kogelafsluiter	RMA	2009	1050	Angerlo	S-032-901-GV-66	Ja	Ja
12	Kogelafsluiter	RMA	2011	1200	Workum	S-344-GV-36	Ja	Ja
13	Kogelafsluiter	Borsig	1991	1200	Nieuwediep	S-214-GV-03	Ja	Nee
14	Plugafsluiter	Christensen	1992	400	Beltrum	S-254-HV-23	Nee	Ja
15	Plugafsluiter	Christensen	1975	400	Windeweer	S-002-901-HV-31	Nee	Ja
16	Plugafsluiter	Christensen	2009	400	Nieuwediep	S-214-HV-26	Ja	Ja
17	Plugafsluiter	Christensen	2009	400	Workum	S-344-HV-28	Ja	Ja
18	Plugafsluiter	Audco	1971	400	Nieuw Balinge	S-221-HV-22	Ja	Nee
19	Plugafsluiter	Audco	1972	400	Beltrum	S-254-HV-24	Ja	Nee
20	Plugafsluiter	Christensen	1986	400	Windeweer	S-008-HV-26	Ja	Nee
21	Plugafsluiter	Audco	1986	400	Windeweer	S-008-EV-22 *	Ja	Nee

II. Modelling of gas leaks.

The theoretical approach to leak size is discussed in more detail in the following section.

In the event of the accidental release of gas into an open space, the flow can be characterised as a high momentum gas jet which will mix with the air around the gas leak. In order to understand this phenomena, an assessment can be performed by reviewing a one-dimensional gas flow through a nozzle (or orifice) where the gas expansion is considered to be frictionless (or thermodynamically reversible) as well as adiabatic.

The shape of the leak itself is likely to have an effect on the resulting gas dispersion in the circumference of the leak. For now, the overall cross sectional area will only be considered to simplify the approach.

The most important parameter in defining the source of a gas leak is its mass release rate. This mass release rate is dependent on the pressure and temperature of the gas in the pressurised confined space which could be a pipeline, a valve housing or an isolated gas station releasing gas to the surroundings. Schematically, a generic sketch of a gas release in an open space can be defined as follows;

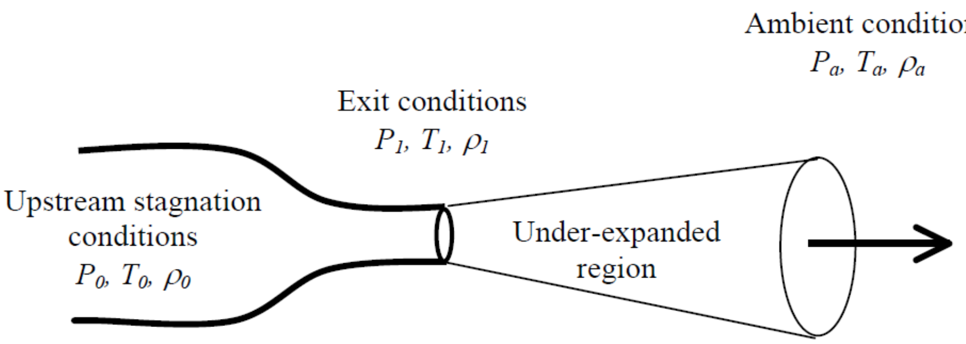

Figure II.1: Schematic overview of a gas release in an open space

The method to calculate the characteristics of a gas release is dependent on specific conditions during the release of gas. Depending on the pressure and temperature in the confined space (the stagnation conditions) and the nature of the gas, a gas release can be either subsonic or sonic.

Both the released as well as the ambient gas conditions can be described using the ideal gas low where the density of the gas can be defined as;

$$\rho = \frac{PM_w}{RT}$$

Where P is the pressure (in Pa), R is the universal gas constant in (J/kg.K), Mw is the molecular weight (in kg/kmol) and T is the temperature (in K). The local speed of sound is a function of the gas' thermodynamic properties which can written as;

$$a = \sqrt{\frac{\gamma RT}{M_w}}$$

Where g is the ratio of specific heat of the isentropic expansion factor, defined as;

$$\gamma = \frac{C_P}{C_V}$$

The release of gas through a restricted opening (a gas leak) will be either sonic or subsonic depending on the stagnation pressure. The transition between these criteria is defined in the critical pressure ratio defined as;

$$\frac{P_*}{P_0} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}}$$

Where P* is the critical pressure (the critical pressure ratio is a property of the gas only). If the pressure ratio is less than the critical pressure ratio, the flow is considered to be choked, sonic or critical and the Mach number at the exit is unity (M1 = 1). For natural gas (Mw = 18.6 kg/ kmol and g = 1.315), the critical pressure ratio is 0.543 which means that the release is sonic if the stagnation pressure exceeds 0.85 barg.

<u>Subsonic (lower pressure drops)</u>

In the case of a subsonic gas release, the pressure ratio Pa/P0 is more than the critical pressure ratio and the Mach number at the exit can be calculated from the following equations (meaning the Mach number will be less than 1);

$$\frac{P_0}{P_1} = \left(1 + \frac{\gamma - 1}{2} \cdot M_1^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{T_0}{T_1} = 1 + \frac{\gamma - 1}{2} \cdot M_1^2$$

$$\frac{\rho_0}{\rho_1} = \left(1 + \frac{\gamma - 1}{2} \cdot M_1^2\right)^{\frac{1}{\gamma-1}}$$

Subsequently, the mass velocity (G = Fm/A) where Fm is the mass flow rate and A is the nozzle exit area, at the nozzle exit is given by;

$$G = P_0 \sqrt{\frac{\gamma M_w}{RT_0}} \cdot \frac{M_1}{\left(1 + \frac{\gamma - 1}{2} \cdot M_1^2\right)^{(\gamma+1)/(2(\gamma-1))}}$$

<u>Sonic (higher pressure drops)</u>

If the pressure ratio Pa/P0 is less than the critical pressure ratio, the flow is considered to be choked, sonic or critical and the Mach number at the exit is unity (M1 = 1). In this case, the pressure at the exit is far greater than the pressure of the surrounding in which the gas will discharge. This discharge is characterised by a series of depressuration shocks which are highly non-isentropic. Such a flow condition is denoted with an asterisk and thus M1 is denoted as M1*. Since the Mach number is consistently considered as unity for sonic conditions, the following equations are simplified to;

$$\frac{P_*}{P_o} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{T_*}{T_o} = \frac{2}{\gamma + 1}$$

$$\frac{\rho_*}{\rho_o} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}}$$

Subsequently, the mass velocity (G* = Fm/A) where Fm is the mass flow rate and A is the nozzle exit area, at the nozzle exit is given by;

$$G^* = P_0 \sqrt{\frac{\gamma M_w}{R T_0}} \cdot \left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/(\gamma-1)}$$

Under choked conditions, the exit velocity is a function of the local temperature T* where the exit velocity is also scaled accordingly as;

$$a^* = \sqrt{\frac{\gamma R T^*}{M_w}}$$

Where g is again the ratio of specific heat of the isentropic expansion factor. During choked conditions while expansion is taking place, the gas will experience a significant pressure drop where internal energy will be converted to kinetic energy. Recovery of initial enthalpy will occur as the discharging gas jet decelerates.

Calculations

Assumptions

Check GasUnie approach
Frictionless, adiabatic expansion
Speed of sound as function of dT https://nl.m.wikipedia.org/wiki/Geluidssnelheid
The shape of the leak is not taken into account
Rule of thumb; temperature drops with 0,5ºC per bar actual pressure

Input

		NG (G-gas)	H2
Mw	kg/kmole	18,60	2,02
Density	kg/m3	0,833	0,09
Critical pressure ratio	[-]	0,543	0,527
Isentropic coefficient (k)	[-]	1,315	1,41
Leak Area	m2	1,00E-06	
Leak Area	mm2	1	
Leak Diameter	mm	1,1284	

SUBSONIC

Case 1 (subsonic)				Case 2 (subsonic)			
		0,03 bar(g)				0,1 bar(g)	
Upstream Pressure (P0)	bar(g)	0,03		Upstream Pressure (P0)	bar(g)	0,1	
Upstream temperature (T0)	ºC	10		Upstream temperature (T0)	ºC	10	
Downstream Pressure (P2)	bar(g)	0		Downstream Pressure (P2)	bar(g)	0	
Pressure Ratio (P0/P2)	[-]	1,03		Pressure Ratio (P0/P2)	[-]	1,10	
Critical Pressure ratio (P2/P0)	[-]	0,971		Critical Pressure ratio (P2/P0)	[-]	0,910	
Upstream density	kg/m3	0,824	0,089	Upstream density	kg/m3	0,880	0,095
Isentropic coefficient (k)	[-]	1,315	1,41	Isentropic coefficient (k)	[-]	1,315	1,41
Factor (k-1)/k	[-]	0,240	0,291	Factor (k-1)/k	[-]	0,240	0,291
Mach number		0,211	0,204	Mach number		0,380	0,368
Subsonic/ sonic		Subsonic	Subsonic	Subsonic/ sonic		Subsonic	Subsonic
Valid statement		VALID	VALID	Valid statement		VALID	VALID
Isentropic/ Mach factor		1,007	1,009	Isentropic/ Mach factor		1,023	1,028
Critical pressure (P1)	[bar(g)]	0,00	0,00	Critical pressure (P1)	[bar(g)]	0,00	0,00
Critical temperature (T1)	[C]	11,99	12,41	Critical temperature (T1)	[C]	16,46	17,86
Speed of sound (@ P1, T1)	[m/s]	409,390	1288,605	Speed of sound (@ P1, T1)	[m/s]	412,587	1300,830
Gas velocity (@ P1, T1)	[m/s]	86,4	262,7	Gas velocity (@ P1, T1)	[m/s]	157,0	478,6
Mass flow	[kg/h]	0,249	0,082	Mass flow	[kg/h]	0,452	0,149
Volume flow	[m3/h(n)]	0,299	0,912	Volume flow	[m3/h(n)]	0,543	1,661
Ratio's between natural gas and hydrogen				Ratio's between natural gas and hydrogen			
Velocity ratio (@ P1, T1)	[-]	0,329		Velocity ratio (@ P1, T1)	[-]	0,328	
Mass flow ratio	[-]	0,330		Mass flow ratio	[-]	0,330	
Volume flow ratio	[-]	3,051		Volume flow ratio	[-]	3,058	

SONIC

Case 3 (sonic)				Case 4 (sonic)			
		39 bar(g)				66 bar(g)	
Upstream Pressure (P0)	bar(g)	39		Upstream Pressure (P0)	bar(g)	66	
Upstream temperature (T0)	ºC	10		Upstream temperature (T0)	ºC	10	
Downstream Pressure (P2)	bar(g)	0		Downstream Pressure (P2)	bar(g)	0	
Pressure Ratio (P0/P2)	[-]	39,49		Pressure Ratio (P0/P2)	[-]	66,14	
Critical Pressure ratio (P2/P0)	[-]	0,025		Critical Pressure ratio (P2/P0)	[-]	0,015	
Upstream density	kg/m3	31,615	3,427	Upstream density	kg/m3	52,948	5,739
Isentropic coefficient (k)	[-]	1,315	1,41	Isentropic coefficient (k)	[-]	1,315	1,41
Factor (k-1)/k	[-]	0,240	0,291	Factor (k-1)/k	[-]	0,240	0,291
Mach number		1,000	1,000	Mach number		1,000	1,000
Subsonic/ sonic		Sonic	Sonic	Subsonic/ sonic		Sonic	Sonic
Valid statement		VALID	VALID	Valid statement		VALID	VALID
Isentropic/ Mach factor		1,158	1,205	Isentropic/ Mach factor		1,158	1,205
Critical pressure (P1)	[bar(g)]	21,7	21,1	Critical pressure (P1)	[bar(g)]	36,4	35,3
Critical temperature (T1)	[C]	-28,53	-38,17	Critical temperature (T1)	[C]	-28,53	-38,17
Speed of sound (@ P1, T1)	[m/s]	379,192	1168,918	Speed of sound (@ P1, T1)	[m/s]	379,192	1168,918
Gas velocity (@ P1, T1)	[m/s]	379,2	1168,9	Gas velocity (@ P1, T1)	[m/s]	379,2	1168,9
Mass flow	[kg/h]	27,127	9,150	Mass flow	[kg/h]	45,431	15,324
Volume flow	[m3/h(n)]	32,565	101,668	Volume flow	[m3/h(n)]	54,539	170,270
Ratio's between natural gas and hydrogen				Ratio's between natural gas and hydrogen			
Velocity ratio (@ P1, T1)	[-]	0,324		Velocity ratio (@ P1, T1)	[-]	0,324	
Mass flow ratio	[-]	0,337		Mass flow ratio	[-]	0,337	
Volume flow ratio	[-]	3,122		Volume flow ratio	[-]	3,122	

III. Additional research into internal leakage of valves

After the measurements for this research were completed, internal leakage measurements were carried out on a DN 100 ball valve in additional to ref [1] in January 2022. These density measurements at 16, 25, 40 and 67 bar show an internal leakage of methane of 350 to 1445 l/h and an internal leakage of hydrogen of 840 to 3275 l/h. At 67 bar, the internal leakage of hydrogen is 2.3 times higher than the internal leakage of methane; at 40 bar this is a factor of 2.2, at 25 bar a factor of 2.3, and at 16 bar a factor of 2.4. On average, the internal leakage of hydrogen is a factor of 2.3 times higher than the internal leakage of methane. This average is based on 10 measurements per test pressure for each medium. The report describing these measurements is expected to be delivered in mid-February 2022.