HyDelta

WP 1B Gas stations

D1B.3a Ventilation

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Document summary

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Dissemination level

Dissemination level		
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R1	Restricted to • Partners including Expert Assessment Group • Other participants of the project including Sounding Board • External entity specified by the consortium (please specify)	
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Document assessment

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Executive summary

As part of the national HyDelta research programme, specific research has been conducted in order to assess the role of ventilation in gas cabinets which are placed over gas pressure reducing and metering stations. As described in this report, this research is part of the work package 1B "Gas stations" and involves research question 212/ D1B.3a. This is formulated as follows: Is the safety level for a gas cabinet (in relation to ventilation) the same for natural gas as it is for hydrogen and to what extent are modifications required?

The goal of this research is to examine whether standard gas cabinets used to house gas pressure reducing and metering stations that are currently applied in the urban environment are also suitable if these would be applied for hydrogen. This research question was examined by measuring the gas concentrations that would arise if a predefined leak was introduced in two different gas cabinets. For this purpose, two different gas cabinet configurations (½ m^3 and 4 m^3 gas cabinets) were made available by Enexis (on behalf of the DSOs). In both configurations, the gas pressure reducing and metering station was positioned to mimic the situation in the field as realistically as possible. Via a separate inlet, the defined gas leak (of either natural gas or hydrogen) was introduced into the gas cabinet. During the tests, the dilution of the natural gas (or hydrogen) mixture and the transportation of gas was studied in relation to the ventilation. During all of the tests, the gas concentrations were measured both inside and outside the gas cabinet.

Determining a representative gas leakage (for natural gas) proved to be a challenging task. A representative leakage is dependent on different factors including the configuration of the gas pressure reducing station, the age of the installation, and the maintenance scheme it had during its service life. Odourisation makes it possible to smell natural gas when the gas concentration exceeds 10,000 ppm (1 vol%). In the end, a leakage opening of 1 mm^2 was chosen (mentioned in an annex of the NEN 1059; 2019). Since a gas station is able to operate at different pressures, five leakage rates were defined as reference points for this research. This was done in order to cover a clear and wide range for the behaviour comparison between natural gas and hydrogen. For natural gas, the leakage rates varied between 0.1 m^3_n/h and 7.5 m^3_n/h whereas for hydrogen, these varied between 0.2 m^3_n/h and 22.5 m^3_n/h. It should be noted that the leakage rate for hydrogen at a predefined leakage opening is 1.2 to 3 times larger than for natural gas, depending on the pressure of the upstream system.

The most important data from the tests for the ½ m^3 and the 4 m^3 gas cabinets have been compiled in the two graphs below. It should be noted that the leakage rate on the x-axis is decreasing in size. Furthermore, the definition of "leakage rate 1" on the x-axis represents 7.5 m^3_n/h natural gas as well as 22.5 m^3_n/h hydrogen. This applies to all other leakage rates in the graph as well.

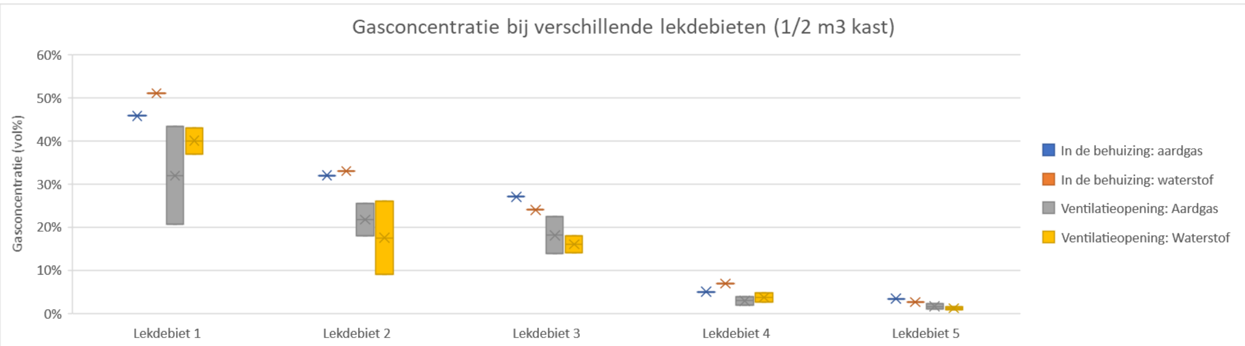


Figure 1. Gas concentration (vol%) at different leakage rates for natural gas and hydrogen in a ½ m^3 gas cabinet

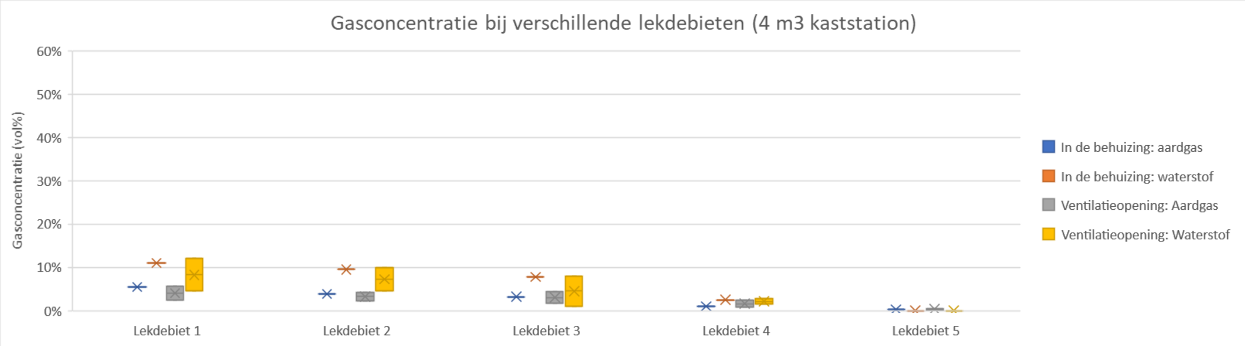


Figure 2. Gas concentration (vol%) at different leakage rates for natural gas and hydrogen in a 4 m³ gas cabinet

When the measurements for the gas cabinets are studied in more detail, the following conclusions can be drawn:

- When all the measurements for the ½ m^3 and the 4 m^3 gas cabinets are studied more closely, it can be concluded that hydrogen more often leads to a flammable mixture at the ventilation openings than natural gas. This is more specifically applicable for larger leakage rates (≥ 6 $m^3{}_n$/h). The logical explanation here is the combination of the larger leakage rates and the wider ranging flammability limits of hydrogen as compared to natural gas. The question that arises from the above is also to what extent the leakage opening and the selected leakage rates are deemed to realistically represent a gas leakage. To facilitate this important dialogue, this report provides some recommendations on the matter at a later point.
- From Figure 1 and Figure 2, the influence of wind speed can be clearly seen by the bandwidth of the gas concentrations at the ventilation openings of the gas cabinets.
- The behaviour of a natural gas or hydrogen leak was different for the two gas cabinets that were tested. It is also worth noting that a different relationship (linear versus logarithmic) was established for both cabinets when comparing the gas concentrations in the cabinet with the gas concentration at the ventilation openings. The gas concentration in the gas cabinets was on average higher than the gas concentration at the ventilation openings for the ½ m^3 gas cabinet. For the 4 m^3 gas cabinet, the phenomena was exactly the other way around. The behaviour relating to ventilation was different when the two geometries were compared.
- One of the conclusions from this research programme is that the selected leakage opening leads to quite significant leakage rates. The 1 mm^2 here should be considered as an incident rather than a regular leakage/malfunction. In close collaboration with the steering committee, an attempt was made to track the original reason for selecting the 1 mm^2 leakage opening, however the source has not yet been identified.
- In view of the ATEX analysis, the results of the tests for the ½ m^3 and 4 m^3 gas cabinets were reviewed with an expert from GasUnie. The advice on the approach/outcome was to re-assess the leakage rates as well as the leakage opening according to the NEN-EN-60079-10-1 (explosive atmospheres) where a leakage opening (dependent on the boundary conditions) between 0.025 and 0.25 mm^2 should be used (Table B.1 – "Suggested hole cross sections for secondary grade of releases"), which leads to substantially smaller leakage rates at 8 bar pressure (according to the calculations).

Recommendations:

- Additional research will be necessary in order to study the effects of smaller leakage rates (more in line with practice). The results will allow industry partners to distinguish an incident from regular leakages/malfunctions and give better insight on the natural gas/hydrogen concentrations that can be expected.
- Since the DSOs use a range of different gas cabinets in the urban environment, it would be beneficial to understand which specific gas cabinets are used most frequently before hydrogen is introduced in the gas infrastructure. During this step, all cabinets can be compared using a functional set of specifications (including the ventilation rate, the mechanical design, the expected gas leakage rate) to allow a comparison to be made to the gas cabinets tested in HyDelta.
- Based on the outcome of the ongoing research focusing on (leakages) in 1000 gas stations that use natural gas, it would be advisable to compare these results with this research “HyDelta Gas stations – Ventilation”. The outcome of this ventilation research may have to be reconsidered if it emerges that the selected leaks from this study are substantially larger than the leakages that occur in practice.

Table of contents

1. Introduction

HyDelta is a national research programme and collaboration that aims to remove barriers that slow down or even stop hydrogen projects. Part of the HyDelta programme is the Gas Stations work package. In the Netherlands, gas pressure reducing stations (for natural gas) are usually located in the public space. This is permitted, as there is no ATEX zone outside the cabinets of the gas pressure reducing stations, provided they meet the ventilation requirements and conditions as stipulated in NEN1059: 2019.

The NEN:1059, 2019 states that with a ventilation rate of more than 5 times per hour, ATEX zone 2 applies inside the cabinet. In that case, there is no zoning outside the cabinet. In case of a small leakage, this should result in sufficient ventilation.

If gas pressure reducing stations are to be used for hydrogen distribution, the currently applicable standards and requirements will have to be reconsidered. In this research, the following questions are examined:

1. *Are any adjustments to the cabinet necessary in order to safely use hydrogen and, if so, which ones?*
2. *Is it possible for a flammable or explosive natural gas or hydrogen mixture to occur outside the cabinet under normal conditions?*

These main questions are addressed in the process of answering the following sub-questions:

1. *What is the maximum leakage rate in a station that needs to be taken into account? (Chapter 2)*
2. *Does the inside of the station actually comply with ATEX zoning 2, given the currently applied ventilation and the maximum leakage rate, both for natural gas as well as for hydrogen?*
3. *Does a flammable mixture occur outside the cabinet with the currently applied ventilation and maximum leakage rate, both for natural gas and hydrogen?*
4. *If the answer to question 3 is 'yes', can it also be confirmed in the field that ignition does indeed take place? If so, what are the implications?*

Sub-question 4 will be further explored (beyond the scope of this research) in three steps. In the process, international research and available information will be catalogued in order to compile a list of scenarios relating to leakages in gas pressure reducing stations. Using this list, real-life scenarios will then be selected, which will be used to determine the probability of ignition and its effects. For this purpose, a variety of research methods will be provided. The aim is to formulate a project plan (HyDelta WP1B - Explosion Work Plan (D1B.3b)) in 2021 in order to be able to carry out these tests in 2022.

2. Approach

Broad outline of test method

The test setup consists of:

- Gas cylinders containing hydrogen, natural gas and nitrogen
- A gas pressure regulator and a mass flow controller (MFC).
- A standard cabinet (½ m^3), supplied by Enexis.
- A standard cabinet station (4 m^3), supplied by Enexis.
- A pipe used to introduce a leak with an outflow opening of 1 mm² into the station. The leak is positioned in the middle of the cabinet. It is also possible to connect a needle valve to the outflow opening.

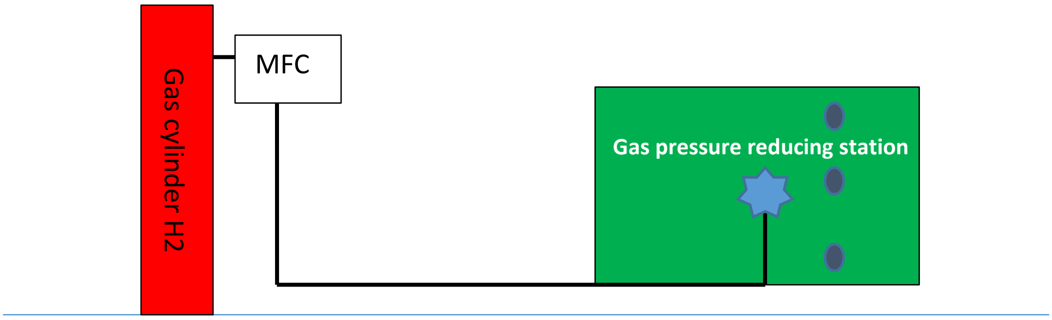


Figure 1. Schematic diagram of test setup

Measuring points and measuring equipment

The natural gas or hydrogen concentration is measured at the following points:

- Inside the cabinet at 4 points (bottom, middle and 2x top). The "middle" measuring point (2) is 10 cm away from the outflow opening. The "bottom" (1) and "top" (3) measuring points are directly below and above the "middle" measuring point, at a distance of 5 cm from the ground level or the top of the cabinet (for the ½ m^3 cabinet). The "top" measuring point (4) in the cabinet station is at the height of the roof line, which is not the highest point. The measuring points are arranged schematically as follows:

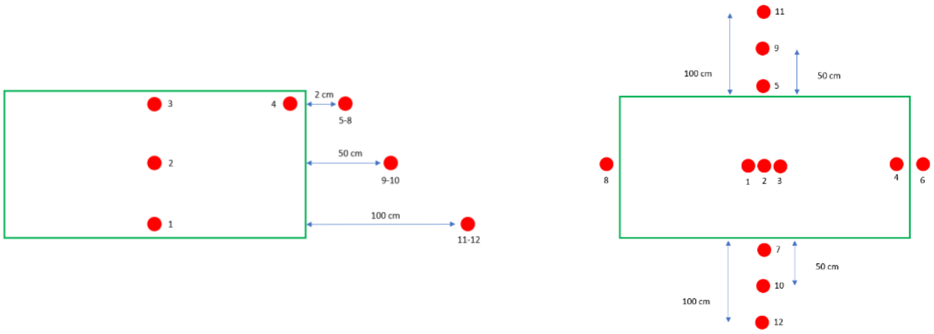


Figure 2. Arrangement of the measuring points in the test setup (½ m³ cabinet), side view (left) and top view (right)

- Directly outside the cabinet at 4 points (points 5, 6, 7 and 8), all of the sides at 2 cm distance from the ventilation openings in the middle. The Riken Keiki sensors were used for this purpose, 0 – 100 vol% hydrogen. For the tests with natural gas, the MultiRae sensors were used. (0-100% LFL and 0-100 vol%).
- The natural gas or hydrogen concentration were measured at 0.5 and 1 metre away from the cabinet (points 9, 10, 11 and 12). The sensors (all MultiRaes) were placed 1 metre above ground level. These meters contain both a ppm sensor and an LFL sensor for hydrogen.

Wind and ventilation

The wind can have a major influence on the tests. For this reason, two situations were created: an indoor situation (windless) and an outdoor situation. To simulate a windless situation, the cabinet station was placed in a large tent. In addition, the same series of measurements were performed on a day that was expected to have a constant wind force (of wind force 2 or 4) in order to limit the influence of natural draughts.

Photos of the setups

The stations were therefore tested both in an outdoor and in an indoor/windless situation. In the field, stations are always outside. However, it is expected that natural ventilation during times that are windless/have little wind will be less effective than when there is natural ventilation through wind. In order to simulate situations that are windless and/or have little wind, both the ½ m^3 cabinet and the 4 m^3 cabinet station were placed in a tent.

Figure 3. The ½ m^3 cabinet in an outdoor situation

Figure 4. The ½ m^3 cabinet in a tent

Figure 5. The 4 m^3 cabinet station in an outdoor situation

Figure 6. The 4 m^3 cabinet station in a tent

Natural gas and hydrogen were introduced into the cabinet in a controlled manner from a gas cylinder using a mass flow meter (MFM) and mass flow controller (MFC) respectively. This gas flowed out in the middle of the cabinet from a leakage opening with a surface area of 1 mm^2. Measuring points were installed in the cabinet – one at 5 cm from the bottom, one in the middle, one at 5 cm from the roof line and one near the ventilation opening. Sensors were also placed on all four sides of the cabinet in order to take measurements outside the cabinet just below the ventilation opening. Finally, sensors were placed for taking measurements at a distance of 0.5 metres and at a distance of 1 metre. These sensors were suspended 1 metre above the ground, as shown in the photos above. This enabled the dilution behaviour of the gas leak to be determined.

3. Selected leakage rates

Leakage rate

This chapter answers the question: *What is the maximum leakage rate in a station that needs to be taken into account? And how does this relate to a real-world leak that is possible in the field?*

When assuming a leak, it must first be established what type of leak is involved. A leak may be the result of an incident, but it can also occur gradually during the operation of a technical installation. In that case, the results in terms of leakage size and rate will probably not be the same.

Field leakage rate and relation to standards committee NEN 1059

A leakage opening of 1 mm^2, as described in the standard, was under discussion. Remarks have been included in the GT-170223 report (zoning of gas stations, phase 2) about this.

In short: if a gas leak is present in a gas station (with an opening of 1 mm^2), ignition sources at the cabinet should not cause an ignition externally.
In 2016, the above assumption was tested by creating a natural gas leak in a gas station (designed as a wooden box with the dimensions of a gas station). The gas station was then surrounded with ignition sources. The test indicated that within the assumed maximum leakage rate according to NEN 1059 (a leak of 1 mm^2), (light) explosions can indeed occur.

These results were discussed in the standards committee. Further research was then carried out into the leakages that actually occur at gas stations. Measurement data was provided to determine the maximum size of the leaks found. This revealed that the leaks used in the 2016 research (3 m^3_n/h and 4.6 m^3_n/h) do not occur in the field. 0.6 m^3_n/h appears to be the maximum leak that occurred in reliable measurements within the measurement set of approx. 8,000 measurements.

In practice, a leakage of 0.6 m^3_n/h natural gas is the maximum leakage using reliable measurements based on statistical analysis. Compared to a leakage rate (through a leakage opening of 1 mm^2 at 8 bar) of 7.5 m^3_n/h natural gas and 22.5 m^3_n/h hydrogen, the measured leakage rate in the field is many times smaller than the leakage rate that arises through a leakage opening of 1 mm^2.

At the time of writing, work had just started on a research proposal for the NEN:1059 standards committee. The natural gas concentration at the ventilation openings will be measured at 1000 stations. The aim is to establish with statistical reliability that less than 1% of the measurements show a natural gas concentration higher than 100% LFL for natural gas (corresponds to 5 vol%).

The research may provide important input into the risk assessments, as it will make it clearer which leaks need to be taken into account in practice.

Leakage rate during the field trials

Firstly, the leakage rates chosen for this research are presented in a table in which both the units m^3_n/h and g/s are indicated. The starting point for the size of the leak through which the gas is introduced into the cabinet has a surface area of 1 mm^2.

Table 1 - Leakage rates for natural gas and hydrogen

	Leakage rate 1	Leakage rate 2	Leakage rate 3	Leakage rate 4	Leakage rate 5
Natural gas (m^3_n/h)	7.5	4.6	3.0	0.45	0.1
Natural gas (g/s)	1.67	1.02	0.67	0.10	0.022
Hydrogen (m^3_n/h)	22.5	12.0	6.0	0.9	0.2
Hydrogen (g/s)	0.56	0.30	0.15	0.023	0.0050

The following explanation provides further guidance on how these values will be reached:

- Size of the leakage/leakage opening of 1 mm^2 as a starting point. At a pressure of 8 bar, this results in a leakage rate of 7.5 m^3_n/h natural gas. This is leakage rate 1 in Table 1.
  Prior to the test, the outflow with both natural gas and hydrogen will be determined for a leak with a size of 1 mm^2 and an initial pressure of 8 bar. In addition, this leakage rate will also be calculated, in accordance with Appendix E.3 of the NEN:1059, 2019.
- Leakage leading to a leakage rate of 4.6 m^3_n/h natural gas. In order to remain in line with new research for the NEN:1059, a leakage will be created in the same way with 4.6 m^3_n/h natural gas (see also GT-170223 report). The same opening and pre-pressure will be used for a leak with hydrogen.

Previous tests have shown that the leakage rate for hydrogen is approximately twice the rate for natural gas, considering leakage rates 3, 4 and 5. In the H21 research, ratios between 1.1 and 2.2 were identified. Research in Hy4heat has demonstrated that the leakage rate is strongly dependent on the geometry of the leak and can even vary between 1.3 and 3. Based on the information available at the start of this research, it was decided to apply a factor of 2 for the remaining tests. The choices are further explained in the paragraphs below.

Based on the test matrix, in most cases there are “small leaks”, which are also referred to as audible leaks. For this purpose, 1 g/s of natural gas is considered a commonly used reference value. The same value cannot be used for hydrogen, as this represents a flow rate that is many times higher.

Behaviour of hydrogen with leakages in the gas distribution grid (DNV-GL, 2020)

The most recent report on this subject was published in 2020 and was commissioned by Netbeheer Nederland. It explains that the ratio between the volumetric flow of natural gas and hydrogen depends on the type of leak:

- Laminar flow: hydrogen leakage is a factor of 1.3 times that of natural gas.
- Turbulent flow: hydrogen leakage is a factor of 2.9 times that of natural gas.
- Diffuse flow: hydrogen leakage is a factor of 3.1 times that of natural gas

Maximum leakage rate with ATEX zoning according to NEN:1059, 2019, Annex E3

The NEN:1059, 2019 (section 7.3.11) defines the maximum leakage rate. It states: *“An installation space may be classified as a non-hazardous area if a gas leak with an opening of no more than 1 mm^2 at the prevailing pressure under normal operating conditions cannot produce a dangerous amount of explosive gas/air mixture.”* For clarity’s sake, that is applicable to natural gas but it could also apply to hydrogen. There is no definition of the “prevailing pressure under normal operating conditions”. There are two pressures in a gas pressure reducing station, the incoming pressure (maximum 8 bar) and the outgoing pressure (usually 100 mbar). The worst case scenario is a leak in the high pressure part of the station, 8 bar. This leakage rate (at 1 mm^2 and 8 bar) will certainly be taken into account during the research.

Natural gas leakage rate versus hydrogen leakage rate

In this chapter, a number of relevant sources are cited in order to establish the leakage rate of hydrogen.

Future-proof gas networks (Kiwa Technology, 2017)

Page 37 of the Future-proof gas networks report (GT-170272) addresses the relationship between the volumetric flow of hydrogen and natural gas with a leak of equal size.

The conclusion is that any leaking connection in a hydrogen network will be approximately 25% higher in terms of volumetric flow than the same leakage connection in a natural gas network.

Research into hydrogen outflow (Kiwa Technology, 2018)

In 2018, research was carried out on small leaks in indoor installations (GT-180259). Leaks of 1 litre per hour (natural gas) were simulated, and the size of the leak with hydrogen was subsequently measured over the same leak. This showed that an existing leak with hydrogen results in a leak with approximately 60% more flow as compared to natural gas.

4. Discussion of results

In the two paragraphs below, one measurement result for natural gas and hydrogen is presented. Both tests were carried out in the ½ m³ cabinet at the highest leakage rate in an outside situation (with natural draughts). These paragraphs are intended as an example of how all the results have been processed. These results are included in Annexes V to VIII of this report.

Leakage rate 7.5 m^3_n/hr - natural gas

During the first test, a maximum leakage opening in accordance with the NEN 1059 was created at a pre-pressure of 8 bar in the ½ m³ cabinet, where the concentration increases to a maximum of 46 vol%. During this experiment, the wind was weak at wind force 2 to 3, mainly from a westerly direction. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

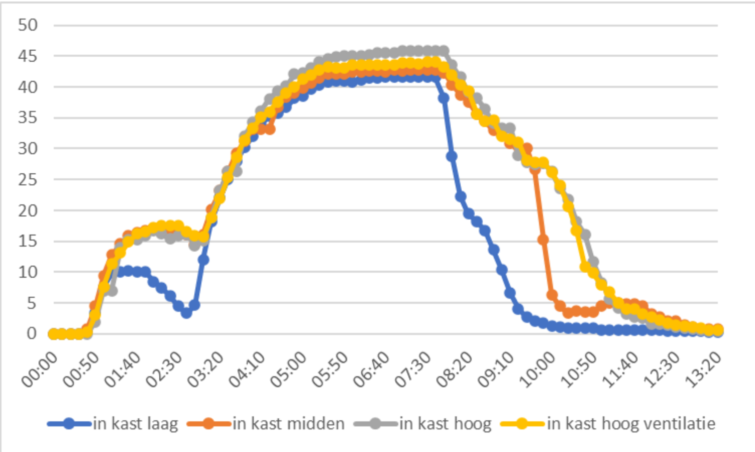


Figure 7. Concentration (vol% CH4) in the ½ m³ cabinet with a leak of 1 mm² at 8 bar

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	21 vol%	40 vol%	43 vol%	30 vol%

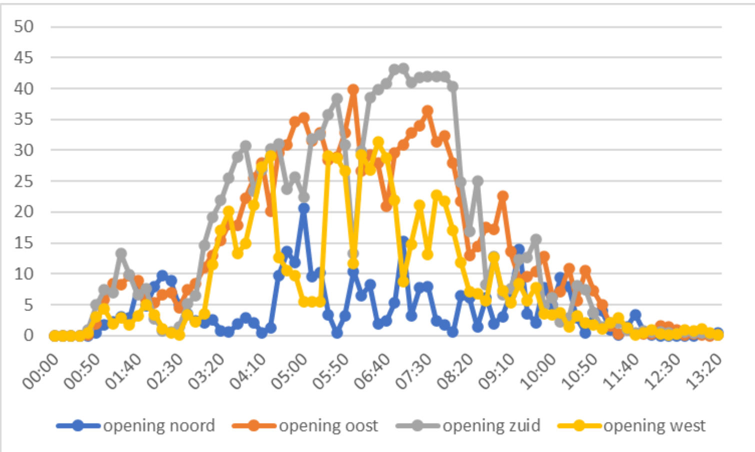


Figure 8. Concentration at the ventilation openings (vol% CH4) in the ½ m³ cabinet with a leak of 1 mm² at 8 bar

During the experiment, the concentration of natural gas outside the gas pressure reducing station increased to a maximum of 23% LFL. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 22.5 m^3_n/hr - hydrogen

When the defined leak for hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 22.5 m^3_n/h. This leakage led to a hydrogen concentration of up to 50 vol% in the cabinet. During this experiment, the wind was weak, mainly wind force 1 to 2, varying between west, northwest and northeast.

The concentration at all measuring points in the cabinet remained almost the same during the entire test. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

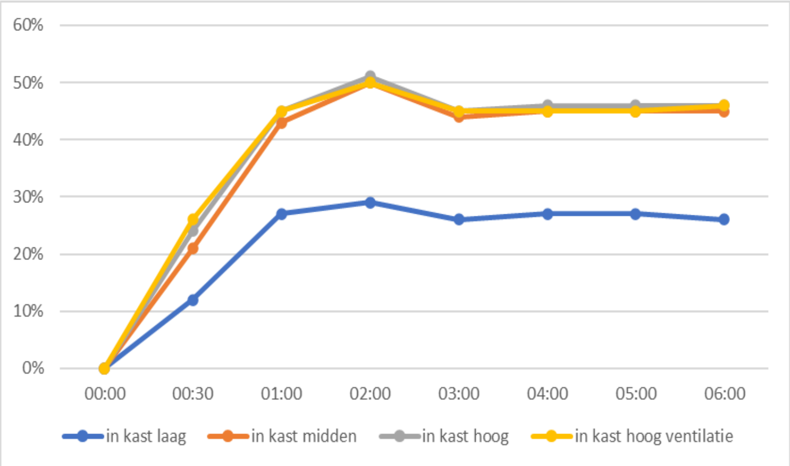


Figure 9. Concentration (vol % H_2) in the ½ m^3 cabinet with a leak of 1 mm^2 at 8 bar

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	40.0 vol%	37.0 vol%	39.0 vol%	43.0 vol%

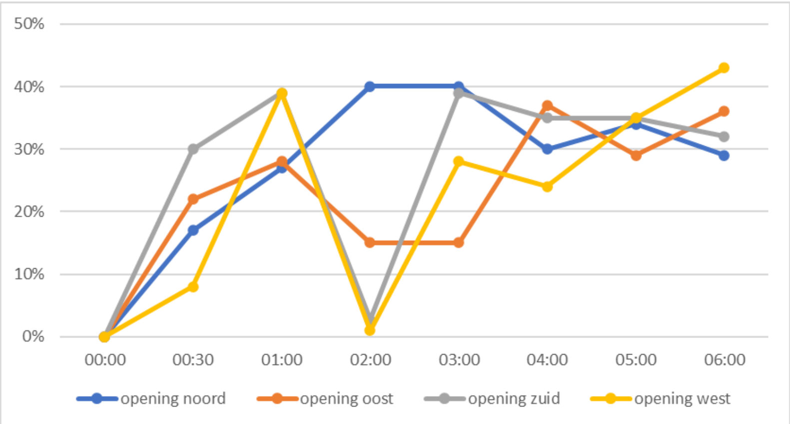


*Figure 10. Concentration at the ventilation openings (vol% H_2) in the ½ m^3 cabinet with a leak of 1 mm^2 at 8 bar**

*) due to wind direction and speed at t = 2 minutes, a zero value was recorded during this test.

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. The meter used has a ppm sensor with a measuring range up to 1000 ppm and this value was also reached. The meter also contains a %LFL sensor. At a distance of 0.5 metres (east), a value of 100% LFL was also detected.

Measured leakage rates and natural gas/ hydrogen concentrations

The results of the entire test programme are compiled in Annexes V to VIII. The key data from all of these tests are briefly summarised in the tables below. The values in red indicate when the maximum concentration measurement falls within the flammability limits of the gas/air mixture. If a field in the tables below is blank, this means that no value was measured.

Table 2 - ½ m³ cabinet results - outside situation for natural gas (top) and hydrogen (bottom). LFL natural gas ≥ 5 vol% and LFL hydrogen ≥ 4 vol%. A measurement was taken outside the cabinet at a distance of 0.5 metres.

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
7,5	45,8%	20,6%	39,8%	43,3%	31,3%	23%LFL	>1000 ppm
4,6	32,0%	22,7%	22,5%	25,4%	18,0%	13% LFL	>1000 ppm
3	27,0%	19,1%	18,4%	22,4%	13,8%	6% LFL	>1000 ppm
0,45	5,0%	3,5%	1,9%	3,0%	3,9%	-	160 ppm
0,1	3,4%	2,2%	1,0%	1,3%	2,1%	-	170 ppm

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
22,5	51,0%	40,0%	37,0%	39,0%	43,0%	100%LFL	>1000 ppm
12	33,0%	26,0%	9,0%	25,0%	20,0%	14% LFL	>1000 ppm
6	24,0%	14,0%	14,0%	17,0%	18,0%	13% LFL	>1000 ppm
0,9	6,9%	2,6%	4,8%	4,0%	3,7%	-	160 ppm
0,2	2,6%	1,1%	0,8%	1,1%	1,5%	-	200 ppm

Table 3 - 4 m³ cabinet station results - outside situation for natural gas (top) and hydrogen (bottom). LFL natural gas ≥ 5 vol% and LFL hydrogen ≥ 4 vol%. A measurement was taken outside the cabinet at a distance of 0.5 metres.

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
7,5	5,5%	5,6%	5,4%	2,4%	3,4%	12% LFL	>1000 ppm
4,6	3,9%	4,3%	4,0%	2,2%	3,4%	4% LFL	>1000 ppm
3	3,2%	4,0%	3,1%	1,7%	4,4%	4% LFL	>1000 ppm
0,45	1,0%	0,8%	1,5%	0,9%	2,4%	-	1000 ppm
0,1	0,3%	0,2%	0,4%	0,3%	0,5%	-	500 ppm

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
22,5	11,0%	11,0%	12,0%	4,5%	5,8%	-	720 ppm
12	9,5%	8,7%	10,0%	4,6%	5,4%	-	710 ppm
6	7,8%	4,1%	8,0%	6,6%	1,0%	-	220 ppm
0,9	2,5%	1,5%	2,8%	1,8%	1,6%	-	130 ppm
0,2	0,0%	0,0%	0,0%	0,0%	0,0%	-	50 ppm

Table 4 - ½ m³ cabinet results – low wind situation for natural gas (top) and hydrogen (bottom). LFL natural gas ≥ 5 vol% and LFL hydrogen ≥ 4 vol%. A measurement was taken outside the cabinet at a distance of 0.5 metres.

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
3	34,8%	14,4%	13,0%	15,5%	6,2%	8% LFL	>1000 ppm
0,45	13,1%	8,2%	6,2%	5,9%	4,4%	4% LFL	>1000 ppm
0,1	3,8%	4,3%	1,3%	0,9%	1,9%	-	0 ppm

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
6	26,0%	20,0%	11,0%	20,0%	7,8%	-	1000 ppm
0,9	9,8%	6,2%	3,3%	2,7%	3,7%	-	500 ppm
0,2	3,9%	2,6%	1,7%	1,6%	1,5%	-	280 ppm

Table 5 - 4 m³ cabinet station results - low wind situation for natural gas (top) and hydrogen (bottom). LFL natural gas ≥ 5 vol% and LFL hydrogen ≥ 4 vol%. A measurement was taken outside the cabinet at a distance of 0.5 metres.

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
4,6	4,3%	4,0%	1,2%	5,2%	5,2%	5% LFL	>1000 ppm
3	2,7%	3,8%	0,6%	4,2%	4,2%	7% LFL	>1000 ppm
0,45	1,7%	4,3%	1,1%	1,9%	3,8%	-	0 ppm
0,1	0,6%	1,5%	0,4%	0,5%	1,8%	-	0 ppm

Lekdebiet	Max concentratie behuizing	Max concentratie ventilatieopening				Buiten de behuizing	
nm3/hr	vol%	vol%					
		N	O	Z	W	%LFL	ppm
-	-	-	-	-	-	-	-
0,9	5,9%	6,0%	3,5%	4,9%	4,0%	-	280 ppm
0,2	1,4%	1,4%	0,8%	0,5%	1,2%	-	80 ppm

For the largest leakage rates (natural gas and hydrogen) no measurements were carried out in the low-wind situation as it was possible for this to lead to dangerous situations given that the flammability limits had been greatly exceeded.

The mechanism of ventilation for the ½ m³ cabinet and the 4 m³ cabinet station is further explained in the section on the mechanical design of the cabinets.

Relationships between gas concentration and leakage rate

In order to make a good comparison between the different experiments as described in Appendix V to VIII, a relationship between the leakage rate and natural gas (or hydrogen) concentration has been mapped on the basis of tests.

Different cross-sections can be created, for example a comparison between the ½ m^3 cabinet and the 4 m^3 cabinet station, as well as the differences between an outside situation (wind) and an inside situation (no wind) and the differences between the dilution behaviour of natural gas and hydrogen. A number of graphs have been created for these cross sections, starting with the comparison between the ½ m^3 cabinet and the 4 m^3 cabinet station.

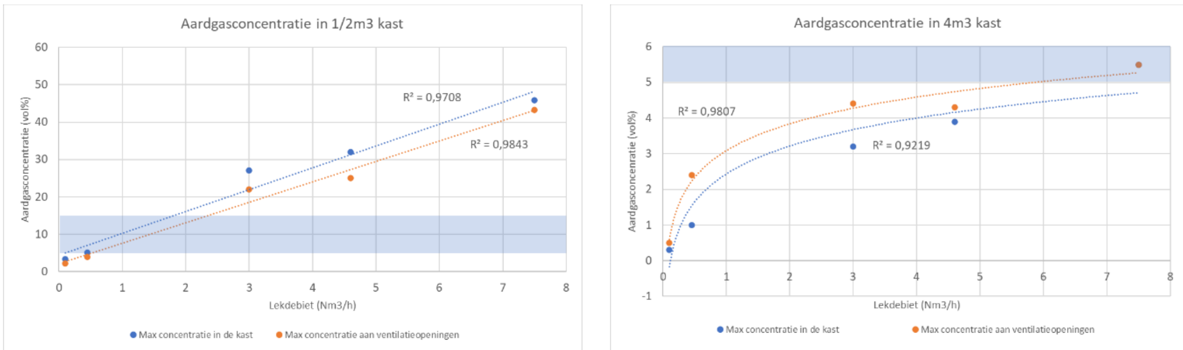


Figure 11. Concentration (vol % CH4) as a function of leakage rate (m_n^3/hr) in the ½ m³ cabinet and the 4 m³ cabinet station in an outside situation

The comparisons have been performed for natural gas in the graphs above and it can be seen that the relationship between leakage rate and gas concentration for the ½ m^3 cabinet is roughly proportional. When the same analysis is made for the 4 m^3 cabinet station, the spread of the measurements is somewhat larger, but a trend line for a logarithmic relationship is a better fit.

It is worth noting that the concentration measurements at the ventilation openings are equal to or even higher than the natural gas concentration in the 4 m^3 cabinet station. In the graphs, a transparent bar indicates the relationship between the flammability limits and the measurements.

In addition, the above analysis for the comparison of the ½ m^3 cabinet and the 4 m^3 cabinet station has been carried out for hydrogen, resulting in the graphs below;

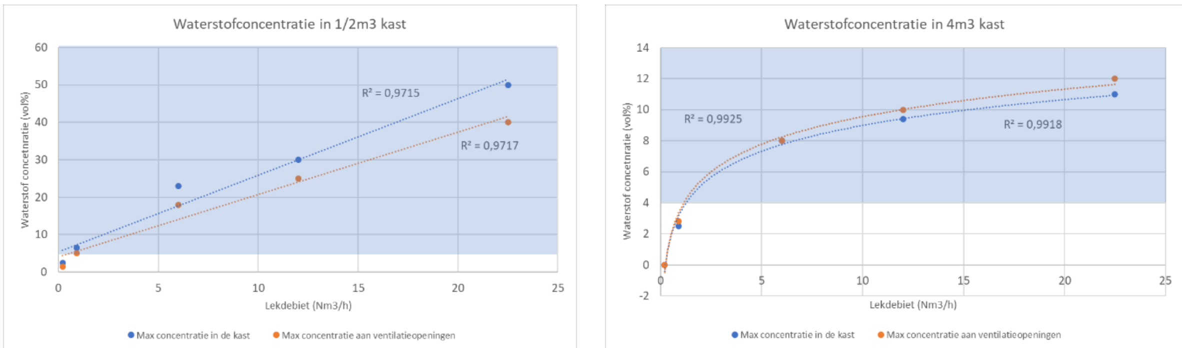


Figure 12. Concentration (vol % H2) as a function of leakage rate (m_n^3/hr) in the ½ m³ cabinet and the 4 m³ cabinet station in an outside situation

The graphs above indicate that the size of the hydrogen leak is roughly proportional to the maximum hydrogen concentration in the ½ m^3 cabinet. This applies to both the maximum hydrogen concentration in the cabinet as well as at the ventilation openings (for all four wind directions). When the same analysis is performed for the 4 m^3 cabinet station, a logarithmic relationship can be derived again. Here for the 4 m^3 cabinet station, the concentration measurements at the ventilation openings are also equal to or even higher than the hydrogen concentration in the cabinet. These observations are not well explained theoretically and can perhaps be attributed to an uneven distribution of gas in the cabinet. This may be due to the type of ventilation (no cross ventilation) and stratification.

When comparing an outside situation (with wind) with an inside situation (without wind), the dataset is smaller. The measurement of large leaks in a low-wind situation in particular can potentially create a dangerous situation, which needs to be avoided at all times. The first comparison involves the measurements of the ½ m^3 cabinet and the 4 m^3 cabinet station in an outside situation and a low-wind situation for natural gas.

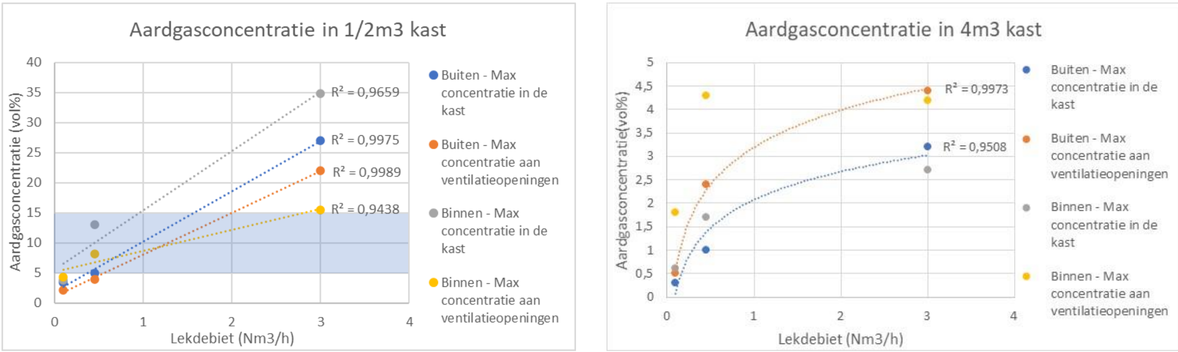


Figure 13. Concentration (vol % CH4) as a function of leakage rate (m_n^3/hr) in the ½ m^3 cabinet and the 4 m^3 cabinet station

As previously established, there is a direct relationship between leakage rate and measured natural gas concentration in the ½ m^3 cabinet when measured in an outside situation. In the low-wind situation (inside), the same relationship can be concluded based on the measurement data. Again it can be seen that the concentration measurements at the ventilation openings are generally equal to or lower than the natural gas concentration in the ½ m^3 cabinet.

When the same analysis is performed for the 4 m^3 cabinet station (outside situation), a logarithmic relationship is also observed. The natural gas concentration in the 4 m^3 cabinet station is lower than the concentration measured at the ventilation openings. The trend line for the indoor/low wind situation can also be established with a larger spread.

The above analysis can also be carried out for the comparison of the ½ m^3 cabinet and the 4 m^3 cabinet station with hydrogen, leading to the graphs below;

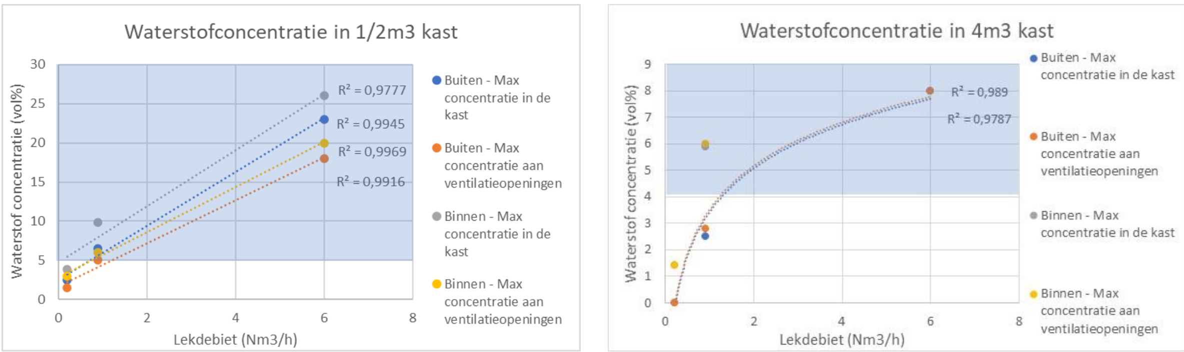


Figure 14. Concentration (vol % H2) as a function of leakage rate (m_n^3/hr) in the ½ m^3 cabinet and the 4 m^3 cabinet station

In the graphs above, it can be seen that the size of the hydrogen leak is approximately linear with the hydrogen concentration in the ½ m^3 cabinet for both the outside situation (as previously established) and the low-wind situation.

When the same analysis is performed for the 4 m^3 cabinet station, a logarithmic relationship can be derived for the outside situation (as previously established). For the indoor situation, the dispersion of the measurements is again larger and it can be seen that for both the ½ m^3 cabinet and the 4 m^3 cabinet station, the larger hydrogen leaks lead to measurements in the explosion range.

When the above findings are compared with the NEN:1059, 2019 standard, it can be concluded that a very limited number of measurements fall within the flammability limits for natural gas, both in the cabinet and at the ventilation openings. However, when the same analysis is done for hydrogen, this number is higher. This indicates that a larger ventilation surface would be necessary. It should also be noted that measurements above 10% LFL hydrogen outside the cabinet (½ m^3 cabinet) at 0.5 metres distance were only observed for leaks of 6 m_n^3/h and larger. The ventilation openings will then have to be reconsidered for these large(r) leakage rates.

The behaviour of a natural gas or hydrogen leak was different for the two tested cabinets. The relation between leakage rate and measured gas concentration is different (linear versus logarithmic). It is also striking that for both cabinets a different relationship was established when the gas concentration in the cabinet was compared with the gas concentration at the ventilation openings. Looking at Figures 9 (natural gas) and 10 (hydrogen) it can be seen that the gas concentration in the cabinet is higher than at the ventilation openings for the ½ m^3 cabinet. For the 4 m^3 cabinet station, this relationship is exactly the other way round. This can be clearly seen when looking at the "order" of the blue and the orange trend line in the figures. The behaviour concerning the ventilation of these cabinets is different.

With regard to the ½ m^3 cabinet, outside situation and low wind situation:

- The measured natural gas or hydrogen concentrations (gas in air mixture) are the same in magnitude at the highest leakage rates.
- Logically speaking, the concentration of both natural gas and hydrogen is higher in the ½ m^3 cabinet than at the ventilation openings for all leakage rates.

With regard to the 4 m^3 cabinet station, outside situation and low wind situation:

- The measured concentrations of hydrogen are twice as high as the measured concentrations of natural gas at the highest leakage rates.
- In the cabinet station at the highest leakage rate (7.5 m_n^3/h for natural gas and 22.5 m_n^3/h for hydrogen) the measured gas concentration for natural gas is lower than for hydrogen. At the ventilation openings, both the concentration of natural gas in the air and hydrogen in the air are greater than in the cabinet. The concentrations of natural gas (in the air) as compared to hydrogen (in the air) is about half as high.
- With a smaller leakage rate, the ratio between the measured natural gas concentration and the measured hydrogen concentration in the cabinet decreases. For small(er) leaks, this is approximately 1:2.5. For large leaks this ratio is about 1:2. The design of the cabinet appears to influence the measured concentration.

Mechanical design of cabinets

When considering the construction of the ½ m³ cabinet and the 4 m³ cabinet station, requirements relating to ventilation according to NEN:1059, 2019; 7.3.11 and NEN-EN-IEC 60079-10-1 are applicable. By adjusting the ventilation rate, the exchange of air in the cabinet can be improved. This can be done by using bottom, top and cross ventilation.

The positioning and the size of the ventilation openings are particularly important. Based on the above observations, the design of the cabinets was examined in detail.

Figure 15. Small cabinet (½ m³ cabinet) on left and large cabinet (4 m³ cabinet station) on right

The ½ m³ cabinet has ventilation openings both at the top and the bottom. The cabinet is hinged at the short side of the cabinet and when closed, drops over the base of the gas pressure reducing station. This means that ventilation openings are present at the bottom of the cabinet. The flat roof construction has a surface dimension just larger than the base of the cabinet and extends over the floor area of the cabinet. There are also ventilation openings between the body of the cabinet and the roof. This allows for natural draughts and cross ventilation. The ventilation positions are indicated by yellow arrows in Figure 17.

When looking at the 4 m³ cabinet station, it can be seen that ventilation can only take place through the top of the cabinet. The cabinet stands on a base (anthracite grey) that is completely sealed. There are no other ventilation openings. The pointed roof construction has a surface area slightly larger than the base of the cabinet and covers the cabinet. Between the body of the cabinet and the roof, there are ventilation openings all around. The cabinet can only be ventilated through these openings. The absence of ventilation at the highest point of the cabinet allows gas to accumulate in the roof of the cabinet. As no cross ventilation is possible due to the lack of low ventilation points, the 4 m³ cabinet station ventilates less well than the ½ m³ cabinet.

The above is also reflected in the gas concentration measurements. This would explain why the measured natural gas or hydrogen concentrations at the ventilation openings are higher than the measured concentrations close to the leak for the 4 m³ cabinet station. Due to stratification, air (from outside the cabinet) is mixed to a limited extent with the gas/air mixture in the cabinet station. This process may not dilute the gas/air mixture in the cabinet sufficiently to lower the measured gas concentration. Further research will be required to better understand this phenomenon and recommendations will be made in this report.

Leakage rate and ventilation rate in relation to the NEN 1059

When the aforementioned findings are compared with the NEN:1059, 2019 standard, it can be concluded that for natural gas, both in the cabinet and at the ventilation openings, several measurements indicate that the degree of ventilation is insufficient. When the same analysis is performed for hydrogen, this number is greater, which is also a result of the larger flammability limits for hydrogen. This involves significant leakage rates for both natural gas and hydrogen, considering the tables presented earlier in this chapter. It should also be noted that measurements above 10% LFL hydrogen outside the cabinet at 0.5 metres distance are only observed for leaks of $6m_n^3$/h and larger.

The research revealed that the chosen leakage opening led to significant leakage rates, which were not considered statistically probable. The current methodology according to the NEN1059;2019 uses the leakage opening for defining the required ventilation. It is therefore recommended to review the leakage opening as currently defined in NEN1059:2019. One good option would be to bring it in line with NEN-EN 60079-10-1, which would result in significantly lower leakage rates. In NEN-EN 60079-10-1, leaks are divided into various specific categories with different sizes and causes.

The research into 1000 gas stations running on natural gas as referred to in paragraph 3 can be used as a guide here, and the results for the “Hydelta Gas Stations - Ventilation” research can be reconsidered. This applies in particular in cases where the leakage rates from both studies differ considerably.

In the current research, only two cabinets have been tested and the question can be asked as to what extent this represents all gas pressure reducing stations. Most of the cabinets have a capacity of ½ m^3, although other sizes are also used. An inventory of frequently used cabinets for gas pressure reducing stations is another area of attention with regard to the quality of ventilation (and the required ventilation rate of 5h-1 according to the NEN:1059, 2019). The aim here is to compare the achieved ventilation with the required ventilation rate.

If necessary, the ventilation in the cabinet can be optimised by changing the design. This will only be possible once research has been conducted using a realistic leakage rate. A recommendation has been prepared in this regard.

5. Visualisation with an Esders GasCam

During the experiments with natural gas, the decision was also made to make recordings using an Esders GasCam for a number of measurements. All of these measurements were performed in a low-wind situation with a tent placed around the setup. A minimum ventilation rate is always necessary to ensure safe working conditions and to prevent gas from accumulating. The special camera technology is able to visualise the flow of natural gas using colour images, where the range of colour (between blue and red) indicates the concentration of natural gas. The camera visualises the natural gas concentration in a 2D image. This kind of technology is not yet available for hydrogen.

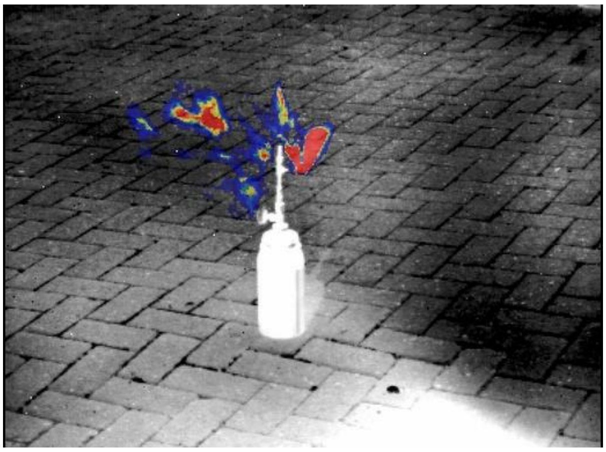


Figure 16. A gas cylinder with free outflow of natural gas, taken with the Esders GasCam.

The recordings were made for leakage rates of 0.1 m_n^3/h; 0.45 m_n^3/h; 4.6 m_n^3/h and 6 m_n^3/h in an indoor/low wind situation.

Firstly, the tent (indoor/low wind situation) has been examined in respect to the behaviour of gas flow around the cabinet station, at the doors and at the ventilation openings. We also considered the outflow of gas from the tent in the interests of safety, to ensure that no accumulation would take place. Some of these recordings have been summarised below.

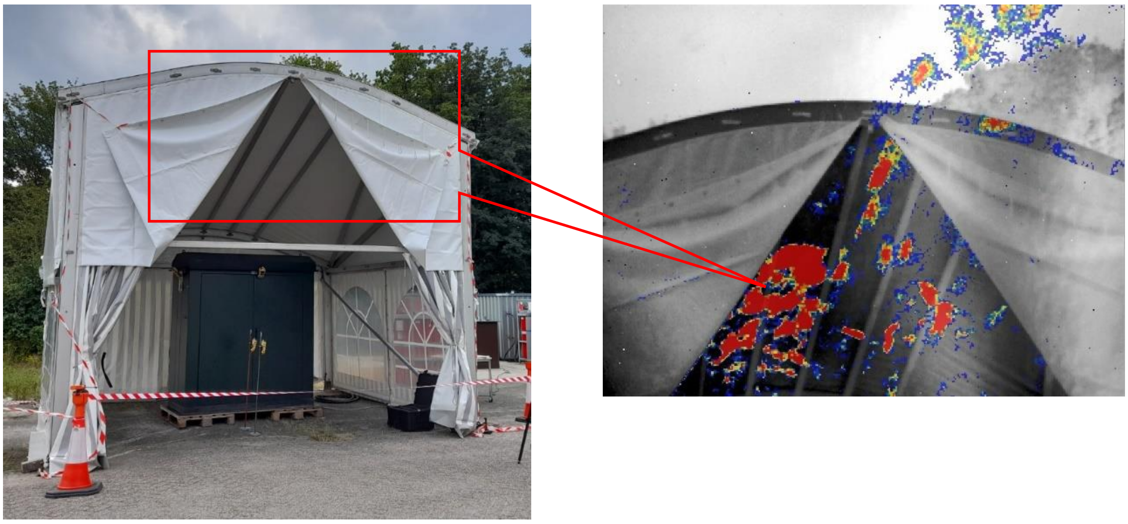


Figure 17. Behaviour of natural gas with outflow from a tent

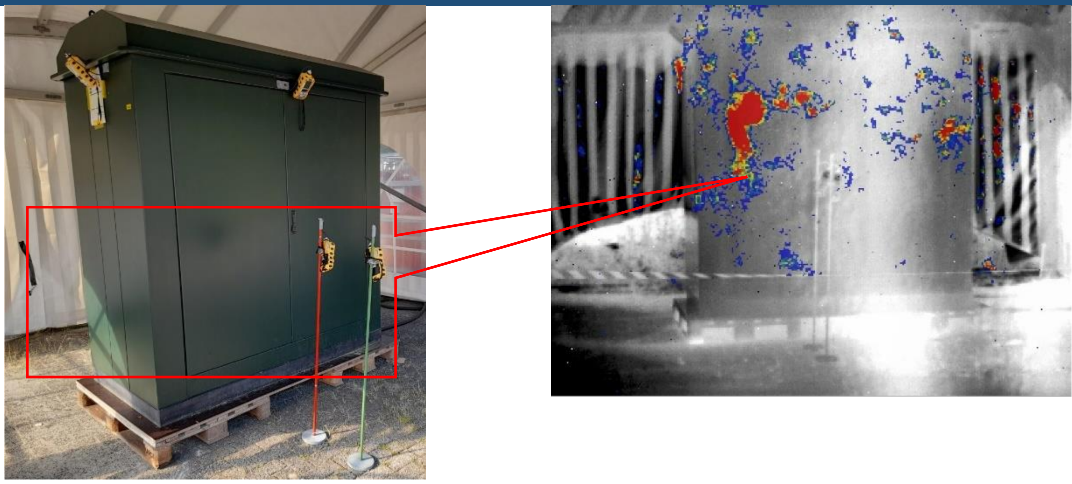


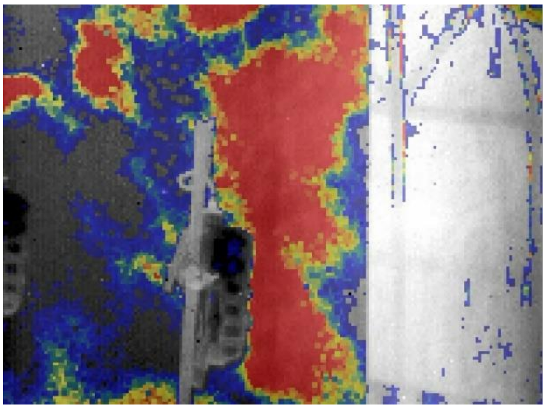
Figure 18. Behaviour of natural gas with outflow from the doors

Figure 19. Behaviour of natural gas with outflow from the ventilation openings

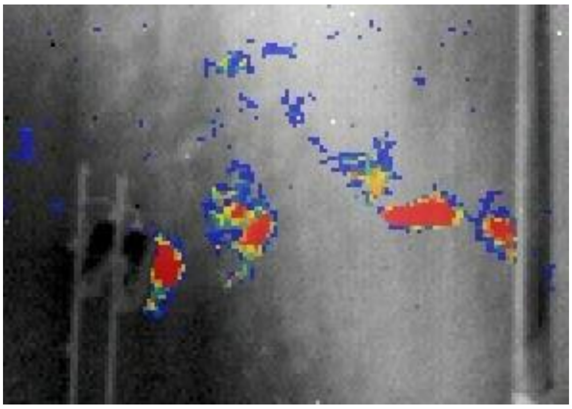
When looking at all the recordings, it is particularly useful to make a comparison between large leaks and small leaks. It is important to visualise the behaviour. When this is done, it is noticeable that the gas clouds escaping through both the doors and the ventilation openings have a periodic character. Moments of relative calm alternate with strongly increased concentrations of gas in cloud form. This periodic behaviour was more pronounced for small leaks than for large leaks. In the latter, the behaviour is more constant and the average gas clouds are larger.

A note should also be made regarding the behaviour of the leaked natural gas and the position of the sensors. The buoyancy of natural gas causes escaping gas from the cabinet station to rise rapidly. The MultiRae sensors around the cabinet station (at 0.5 metres and 1 metre) are at 1 metre above ground level. As a result, only some of the escaping natural gas is registered by the sensors and most of the escaping gas (through the ventilation openings) does not pass the sensors directly.

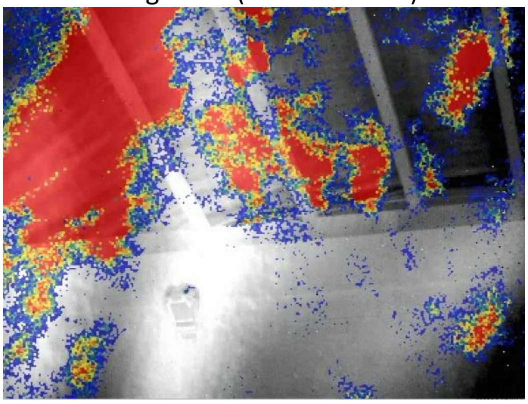
Based on the camera images, there seems to be no difference between the amounts of gas escaping through the ventilation openings or the doors of the cabinet at the same leakage rate.



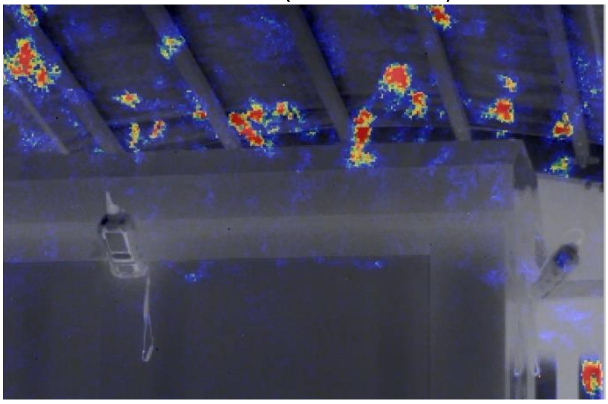
Large leak (doors at front)



Small leak (doors at side)



Large leak (ventilation)

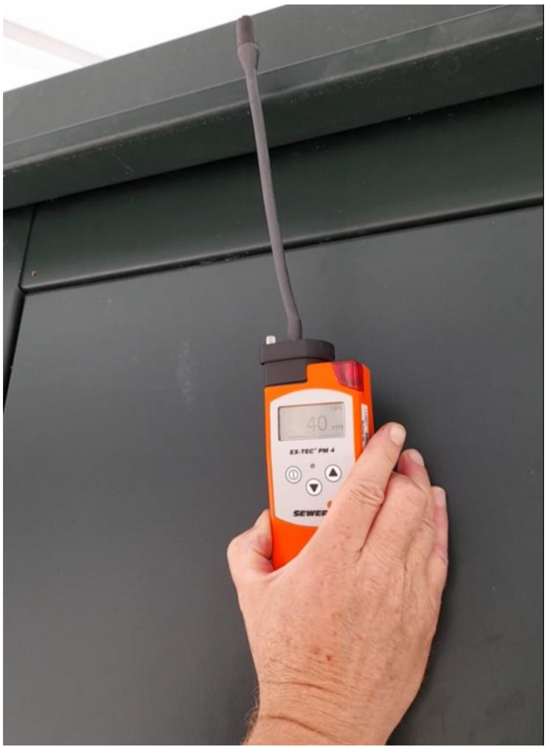


Small leak (ventilation)

Figure 20. Behaviour of natural gas with outflow from the doors (for large and small leaks)

Based on the camera images, a Sewerin leak detector was used to measure the outflow of gas and the measured concentrations of natural gas or hydrogen. The measurements were primarily taken above the ventilation openings. Both for large and small gas leaks, the increased concentrations of natural gas or hydrogen had a periodic character.

The stills below from a short recording show how the measured concentrations could rise in a very short time, and how the value measured by the MultiRAE gas meters could lag behind the value measured by the Sewerin leak detector. This confirms the periodic behaviour of the gas escaping through the ventilation openings.



Measured concentration (t = 22 sec), 40 ppm

Measured concentration (t = 34 sec), 0.15 vol%

Figure 21. Behaviour of natural gas or hydrogen concentration with the Sewerin leak detector

When considering these results, the main aspect to be taken into account is that there is some delay in the recordings on the MultiRAE gas meters of the cloudy behaviour of the gas escaping from the cabinet. In an earlier DNV-GL report (test setup of hydrogen dilution in the meter cabinet - OGNL.10130282-071) periodic fluctuations in the natural gas or hydrogen concentration around a meter cabinet setup were discussed. During these measurements, fluctuations in the measured natural gas or hydrogen concentrations were reported for some experiments, which may be related to the accumulation of gas in a cabinet, as mentioned in a quote from this report;

> *One explanation could be that a gas build-up first occurs in the cabinet which then causes extra ventilation (chimney effect), in turn causing the natural gas or hydrogen concentration to drop. If the natural gas or hydrogen concentration decreases, then the extra ventilation decreases as well and, after a certain period of time, a stable equilibrium is formed again... This could explain the sinusoidal movement of the natural gas or hydrogen concentration in the meter cabinet. There is less draught in a chimney when the air is cold (flue gases) than when it is hot (flue gases). Warm gas is lighter and rises faster. This is comparable to the difference in density between hydrogen and natural gas.*

The results visualised with the Esders GasCam® together with the mapping of the flow behaviour with the Sewerin leak detector and the natural gas or hydrogen concentration measurements provide an additional explanation for this behaviour and can possibly indicate gas accumulation due to low ventilation rates.

6. Conclusions

As part of the HyDelta Gas Stations work package, research has been carried out on the ventilation of cabinets for gas pressure reducing stations. The main goal of the research was to determine whether standard cabinets would also be suitable in terms of ventilation when switching to hydrogen. For two specific cabinets, a ½ m^3 cabinet and a 4 m^3 cabinet station, research was conducted to determine how the leakage rate is related to the concentration of natural gas or hydrogen in and around the cabinets.

Determining a representative gas leakage (for natural gas) proved to be a challenging task. A representative leakage is dependent on different factors including the configuration of the gas pressure reducing station and the age of the installation. Odourisation makes it possible to smell natural gas from 10,000 ppm (1 vol%). In the end, a leakage opening of 1 mm^2 was chosen (mentioned in an annex of the NEN 1059; 2019). Based on different pre-pressures, five leakage rates were then defined that served as reference points in this research for drawing a clear comparison between the behaviour of natural gas and hydrogen.

This was used to check whether a flammable mixture could occur outside the cabinet with the currently applied ventilation and different leakage rates, both for natural gas and for hydrogen. To this end, ventilation tests were carried out for the ½ m^3 cabinet and the 4 m^3 cabinet station in an outside situation and a low-wind situation (where the cabinet was placed in a tent) using a test programme.

- ✓ It was found that both the cabinet and the cabinet station can lead to a flammable mixture at the ventilation openings more often than natural gas. This is more specifically applicable for larger leakage rates (≥ 6 m^3_n/h). This can be traced back to the combination of higher leakage rates and the broader flammability limits of hydrogen as compared to natural gas.

- ✓ Based on the results, the influence of wind can be clearly seen through the bandwidth of the observed gas concentrations at the ventilation openings.

- ✓ The behaviour of a natural gas or hydrogen leakage was different for the two gas cabinets that were tested. It is also worth noting that a different relationship (linear versus logarithmic) was established for both cabinets when comparing the gas concentrations in the cabinet with the gas concentration at the ventilation openings. The hypothesis was that the concentration at the ventilation opening would be lower than or equal to the concentration measured in the cabinet. The hypothesis proved to be correct for the ½ m^3 cabinet, but not for the cabinet station. For the 4 m^3 cabinet station, this relationship is exactly the other way round. The gas concentration in the cabinet is higher on average than at the ventilation openings for the ½ m^3 cabinet. The ventilation behaviour of these cabinets was different.

- ✓ One of the conclusions from the research questions was that the selected leakage opening leads to quite significant leakage rates. The question here is to what extent the selected leakage opening and the selected leakage rates are considered realistic for a gas leak. The 1 mm^2 here should be considered an incident rather than a regular leakage/malfunction. In close consultation with the steering committee, a great deal of effort has been made to identify the original reason for selecting this leakage opening, but the source has not been determined.

With the above results, the question is: To what extent, with the currently applied ventilation and the maximum leakage rate, does the inside of a cabinet comply with ATEX zoning 2 for both natural gas and hydrogen?

The above mentioned standard is based on the technical leak tightness of the installation according to the NEN-EN 1127 Annex B (B.3 - “Enhanced tightness”) of the NPR-7910-1. However, because very small leaks are not noticed immediately, it is recommended to classify the inside of the cabinet as ATEX zoning 2 where the zone does not extend outside the cabinet. This means that there is no need for zoning outside the cabinet.

In view of the ATEX analysis, the results of the tests for the ½ m^3 cabinet and 4 m^3 cabinet station were reviewed with an expert from GasUnie. The advice here was to re-assess the leakage rates as well as the leakage opening according to the NEN-EN-60079-10-1 (explosive atmospheres) where a leakage opening (dependent on the boundary conditions) between 0.025 and 0.25 mm^2 should be used (Table B.1 – “Suggested hole cross sections for secondary grade of releases”), which leads to substantially smaller leakage rates at 8 bar pressure (according to the calculations).

In contrast to the tests carried out, this then leads to much lower concentrations of natural gas or hydrogen in and around the cabinets. It is worth noting that the ventilation should depend on the leakage rate for defining the percentage of ventilation area and not always just on the floor area.

7. Recommendation

As a follow-up to the first main question in the introduction to the ventilation report, KIWA recommends that the cabinets for gas pressure reducing stations be examined in more detail. Based on the two cabinets and the selected leakages that were tested in this test programme, it appeared that, depending on the mechanical design of the cabinet and the selected leakage opening (1 mm^2), it is possible for accumulation of gas to occur. This applies to both natural gas and hydrogen, where for the latter, ventilation is more important due to the significantly larger leakage rates and the broader range of ignition.

The following recommendations are proposed:

- ✓ The determination of the ventilation rate and the availability of ventilation are dependent on location and mechanical design. This includes wind speed and the surface area of the ventilation grilles. It is recommended that the measurements in the report be repeated for a smaller, leakage opening that is more realistic (with natural gas and hydrogen) and that an ATEX calculation be carried out accordingly. A low ATEX zoning is expected based on the above. This will ensure with certainty that the cabinet meets the set requirements in the event of a leak.

- ✓ As there are a variety of cabinets for gas pressure reducing stations used in the Netherlands, it would be wise to examine which cabinets are currently in frequent use before introducing hydrogen. These cabinets should first be compared with a set of functional requirements (e.g. ventilation rate, mechanical design, expected leakage rate) in order to make a comparison with the cabinets already tested. It is recommended to develop a set of functional requirements and to fully understand all the variables. With the help of CFD and/or tests, it is possible to gain insight into how a gas mixture originates in a cabinet, to what extent stratification plays an important role and how the ventilation of a cabinet ensures a good degree of air exchange. If necessary, the geometry of the cabinet can then be optimised.

- ✓ It is also recommended to review the leakage opening as currently defined in NEN1059:2019 for determining an ATEX zone. One good option would be to bring it in line with the NEN-EN 60079-10-1, in which a smaller leakage opening is considered for a fault situation.

- ✓ Based on the results of the current research on (leaks in) 1000 gas stations running on natural gas, it is also recommended to compare this “Hydelta Gas Stations - Ventilation” research with the findings. The outcome of this ventilation research may have to be reconsidered if it emerges that the selected leaks from this study are substantially larger than the leakages that occur in practice.

References

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[2] Dutch practice guideline for explosion hazards NPR 7910-1 – 2021

[3] Dutch standard NEN-EN-IEC 60079-10-1 - 2021

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[8] B. Bierling, H. Vlap, R. Bahlmann, Test setup dilution of hydrogen in the meter cabinet – OGNL.10130282-071, Alliander, DNV-GL, OGNL.10130282-071, February 2020

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I Overview of questions HyDelta WP1B

This work package addresses the following questions

Material resistance:

- Can the soft components of the regulators and safety devices used in natural gas distribution be adversely affected when switching to hydrogen distribution? (no. 207, see KIWA report GT-200237)

Operation of the station:

- Are the current stations suitable for safely reducing hydrogen gas (the station as a whole)? (no. 206, see HyDelta report - D1B.1 - Gas pressure regulators on natural gas and hydrogen)
- What effects does increasing the speed have on the overall operation of the station? (no. 213, see HyDelta report - D1B.1 - Gas pressure regulators on natural gas and hydrogen)
- Are adjustments to the cabinet necessary in order to safely use H2 and, if so, which ones? (ventilation & earthing) (no. 212, see HyDelta report - D1B.3 - Ventilation)

Working safely on and with stations using hydrogen:

- What mitigating measures (VWI) are necessary to commission and decommission a station? (no. 208, see HyDelta Report - D1B.2 - Safety when working on gas stations)
- Is it possible to safely equalise the pressure if a safety device has failed? (no. 209, part of 208, see HyDelta Report - D1B.2 - Safety when working on gas stations)
- Is there a need for a more thorough inspection of filters in gas pressure regulators? This section is specifically about filters; the increased gas velocity can lead to more dirt being transported, which can lead to increased stress on the filters (no. 173, see HyDelta report - D1B.4 - Gas filters)

II Overview of the composition of the guidance and sparring groups

Table 6 – Composition of the guidance group and sparring group

Name	Employer	Guidance group	Sparring group
R. van Hooijdonk	Enexis	V	V
J. Jonkman	Rendo	V	V
R. Scholten	Rendo	V	V
P. Verstegen	Alliander	V	V
R. Verhoeve	Stedin		V
J. Voogt	Enexis		V
S.J. Elgersma	Gasunie		V
M. van der Laan	Kiwa Technology	V	V
R. van Aerde	Kiwa Technology		
S. van Woudenberg	Kiwa Technology	V	V
The guidance group has been assigned a more active role in implementing the sub-research as compared to the sparring group. The sparring group was involved in setting up the test programme and in assessing the draft reports.			

III Photos of the test setup

Figure 22. The ½ m³ cabinet in an outdoor

Figure 23. The ½ m³ cabinet containing the gas pressure

Figure 24. The 4 m³ cabinet station in an outdoor situation

Figure 25. The 4 m³ cabinet station containing the gas pressure reducing station

Figure 26. MultiRAE Lite IR natural gas detector

Figure 27. Riken Keiki NP 1000 hydrogen detector

Figure 28. Esders GasCam®

IV Measuring equipment used

Table 7 – Details on measuring equipment used

Description	Manufacturer and type	Kiwa no.
Natural gas detector	MultiRAE - Lite IR	114033
Natural gas detector	MultiRAE Lite IR	114034
Natural gas detector	MultiRAE Lite IR	114036
Natural gas detector	MultiRAE Lite IR	114037
Natural gas detector	MultiRAE Lite IR	114038
Natural gas detector	MultiRAE Lite IR	114039
Natural gas detector	MultiRAE Lite IR	114040
Natural gas detector	MultiRAE Lite IR	114041
Natural gas detector	MultiRAE Lite IR	114043
Hydrogen detector	Riken Keiki NP 1000	114633
MFM	Bronkhorst type F-106AZ	-
MFC	Bronkhorst, type F-202AC-FAC-55-V	-
Gas camera (methane)	Esders GasCam® SG	-
Gas detector	Sewerin Ex-Tec PM4	-

Natural gas

- The Multirae have a measuring range of 0 - 100% LFL and 0-100 vol% natural gas.
- The four Multirae sensors used as measuring points at a larger distance (at 0.5 m and 1 m downwind) from the gas pressure reducing station have a measuring range of 0 - 100% LFL and 0-100 vol% natural gas.

Hydrogen

- The Riken Keiki sensors have a measuring range of 0 – 100 vol% hydrogen.
- The four Multirae sensors used as measuring points at a larger distance (at 0.5 m and 1 m downwind) from the gas pressure reducing station have a measuring range of 0-1000 ppm hydrogen. These specific Multirae sensors are also equipped with a 0 - 100% LFL sensor for hydrogen.

V Measurement results – ½ m^3 cabinet outside situation

Leakage rate 7.5 m^3/hr - natural gas

During the first test, a maximum leakage opening in accordance with the NEN 1059 was created at a pre-pressure of 8 bar in the ½ m^3 cabinet, where the concentration increases to a maximum of 46 vol%. During this experiment, the wind was weak at wind force 2 to 3, mainly from a westerly direction. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

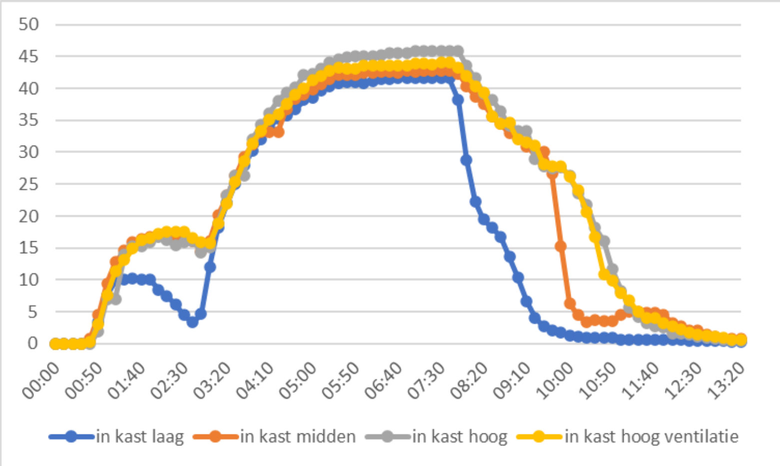

Figure 29. Concentration (vol% CH4) in the ½ m³ cabinet with a leak of 1 mm² at 8 bar

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	21 vol%	40 vol%	43 vol%	30 vol%

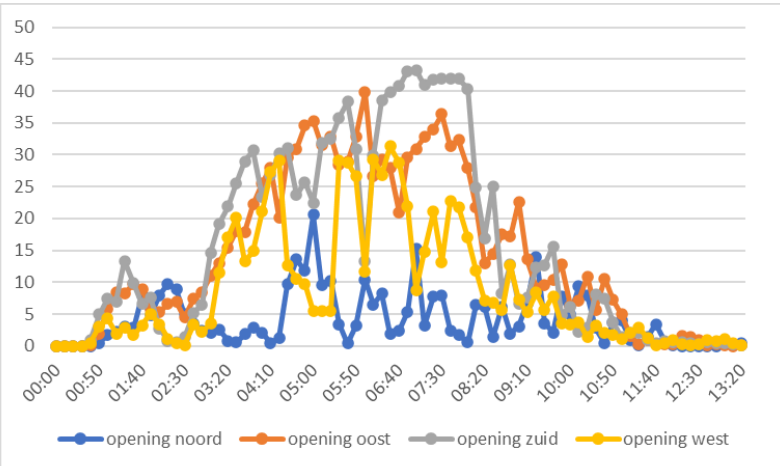

Figure 30. Concentration at the ventilation openings (vol% CH4) in the ½ m³ cabinet with a leak of 1 mm² at 8 bar

During the experiment, the concentration of natural gas outside the gas pressure reducing station increased to a maximum of 23% LFL. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 22.5 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 22.5 m^3_n/h. This leakage led to a hydrogen concentration of up to 50 vol% in the cabinet. During this experiment, the wind was weak, force 1 to 2, varying between west, northwest and northeast.

The concentration at all measuring points in the cabinet remained almost the same during the entire test. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

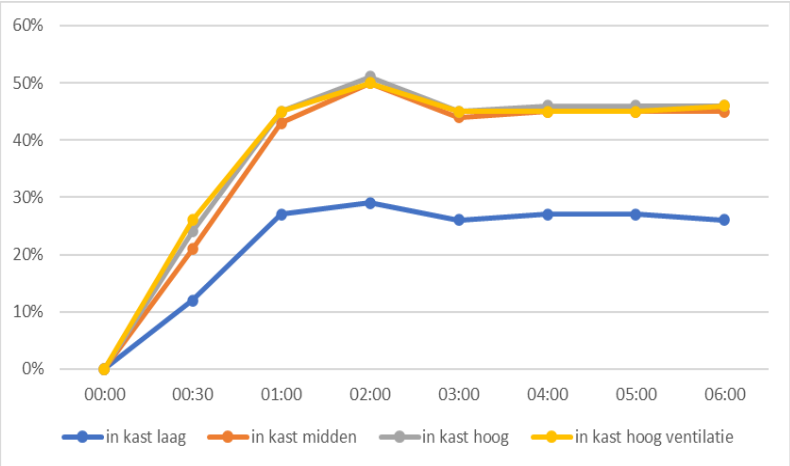

Figure 31. Concentration (vol % H_2) in the ½ m^3 cabinet with a leak of 1 mm^2 at 8 bar

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	40.0 vol%	37.0 vol%	39.0 vol%	43.0 vol%

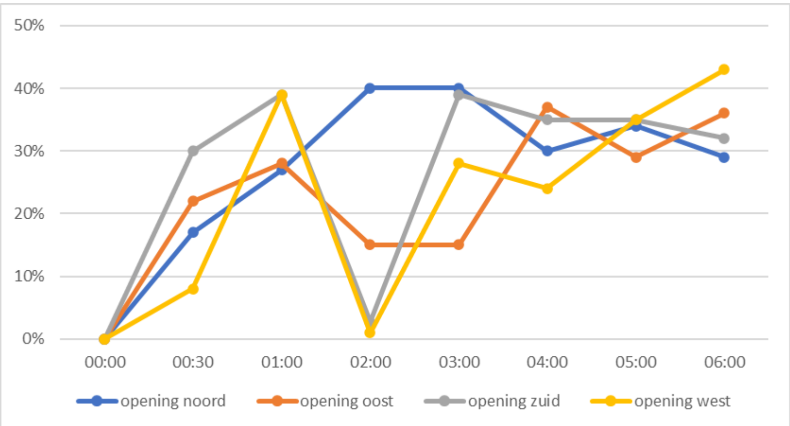

Figure 32. Concentration at the ventilation openings (vol% H_2) in the ½ m^3 cabinet with a leak of 1 mm^2 at 8 bar

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and this value was also reached. At a distance of 0.5 metres (east), a value of 100% LFL was also detected.

Leakage rate 4.6 m³/h - natural gas

At a leakage rate of 4.6 m^3_n/h the natural gas concentration in the ½ m³ cabinet increased to a maximum concentration of 36 vol%. During this experiment the wind was moderate, wind force 3 to 4, stable between north and northeast. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

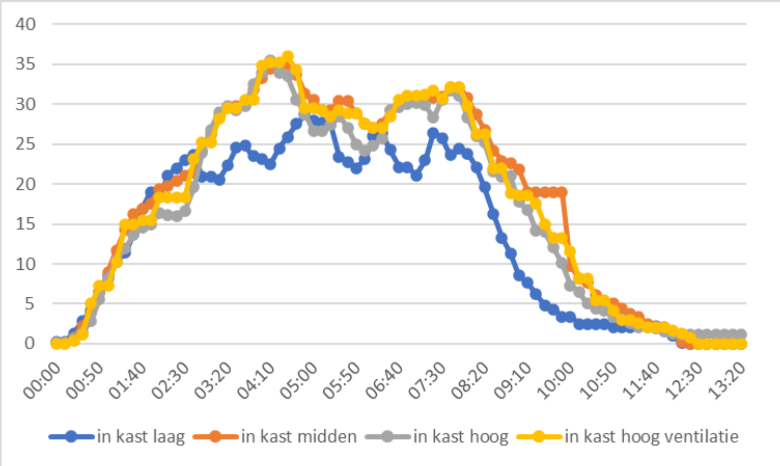

Figure 33. Concentration (vol % CH4) in the ½ m³ cabinet with a leakage rate of 4.6 m³/h

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	22.7 vol%	22.5 vol%	25.4 vol%	18.0 vol%

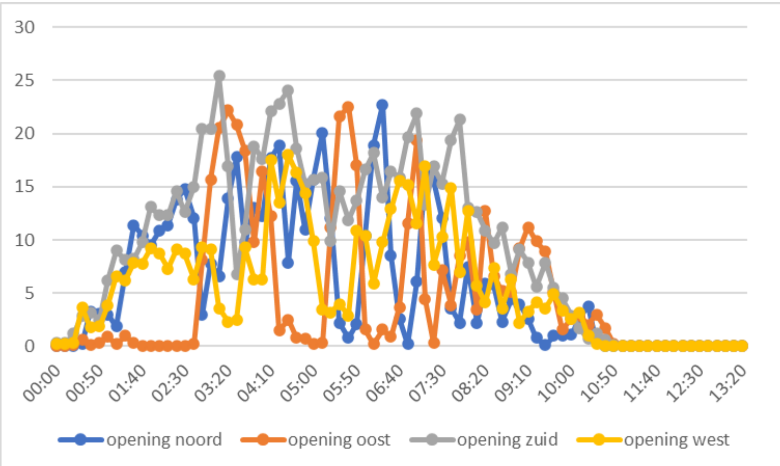

Figure 34. Concentration (vol% CH_4) at the ventilation openings of a ½ m³ cabinet with a leakage rate of 4.6 m³/h.

During the experiment, the concentration of natural gas outside the gas pressure reducing station increased to a maximum of 13% LFL. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 12 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 12 m^3_n/h. This leakage led to a hydrogen concentration of up to 33 vol% in the cabinet. During this experiment, the wind was moderate, force 4 to 5, varying between north and south-east.

The concentration at all measurement points in the cabinet stabilised during the experiment. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

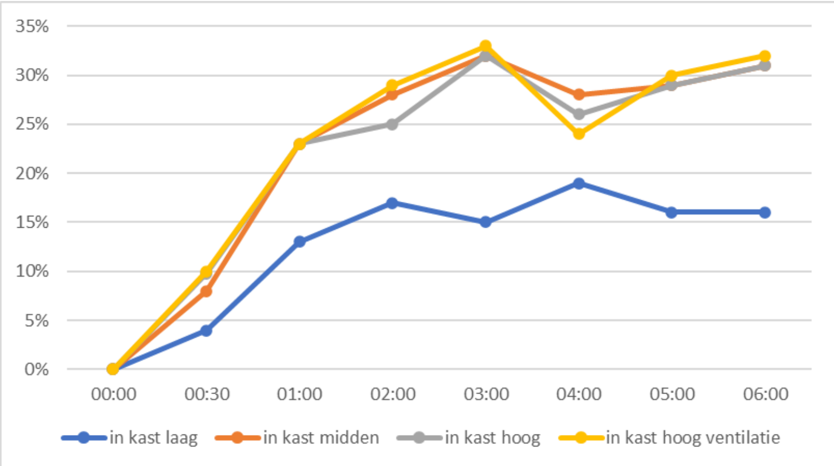

Figure 35. Concentration (vol % H_2) in the ½ m^3 cabinet with a leakage rate of 12 m^3/h hydrogen

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	26.0 vol%	9.0 vol%	25.0 vol%	20.0 vol%

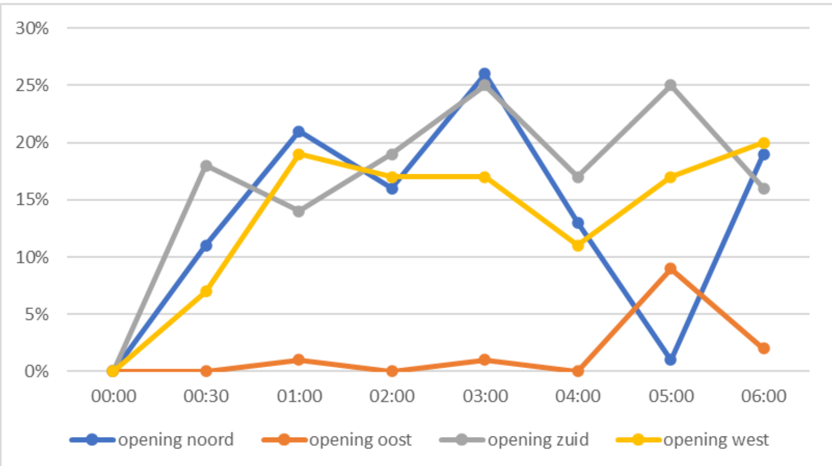

Figure 36. Concentration with the ventilation openings (vol% H_2) in the ½ m^3 cabinet with a leakage rate of 12 m^3/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and this value was also reached. At a distance of 0.5 metres (east), a value of 14% LFL was also detected.

Leakage rate 3 m^3/h - natural gas

At a leakage rate of 3 m^3_n/h the natural gas concentration in the ½ m^3 cabinet increased to a maximum concentration of 27 vol%. During this experiment, the wind was weak to moderate, force 2 to 3, varying between north and south-east. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

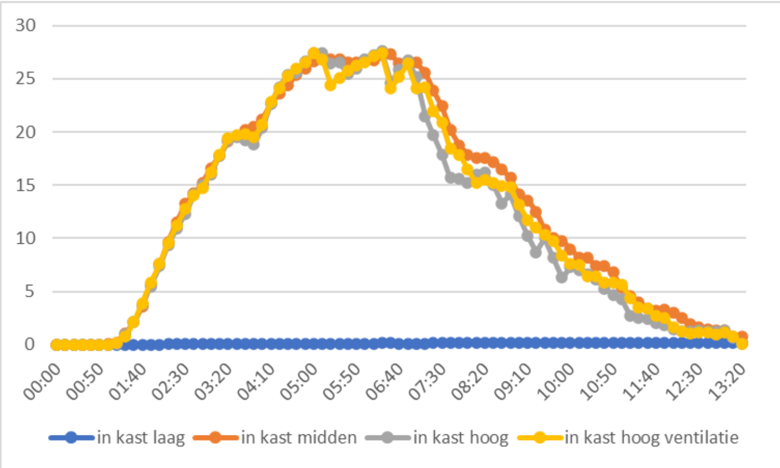

*Figure 37. Concentration (vol % CH4) in the ½ m^3 cabinet with a leakage rate of 3 m^3/h**

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	19.1 vol%	18.4 vol%	22.4 vol%	13.8 vol%

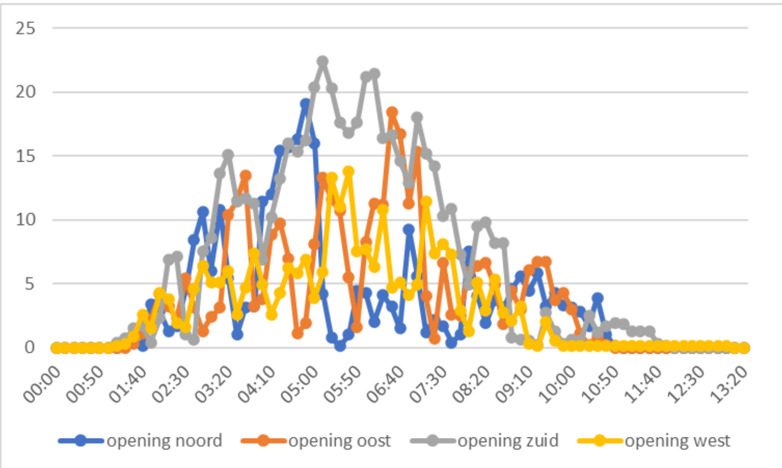

Figure 38. Concentration (vol % CH_4) at the ventilation openings of a ½ m^3 cabinet with a leakage rate of 3 m^3/h

During the experiment, the concentration of natural gas outside the gas pressure reducing station increased to a maximum of 6% LFL. This concentration was measured at 0.5 metres (west) from the cabinet at a height of 1 metre from the ground.

*)the sensor low in the cabinet only recorded zero values during this test.

Leakage rate 6 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 6 m^3_n/h. This leakage led to a hydrogen concentration of up to 23 vol% in the cabinet. During this experiment, the wind was moderate, wind force 3 to 4, varying between north and east. The concentration at all measuring points in the cabinet built up at the top of the cabinet for medium, high and ventilation. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

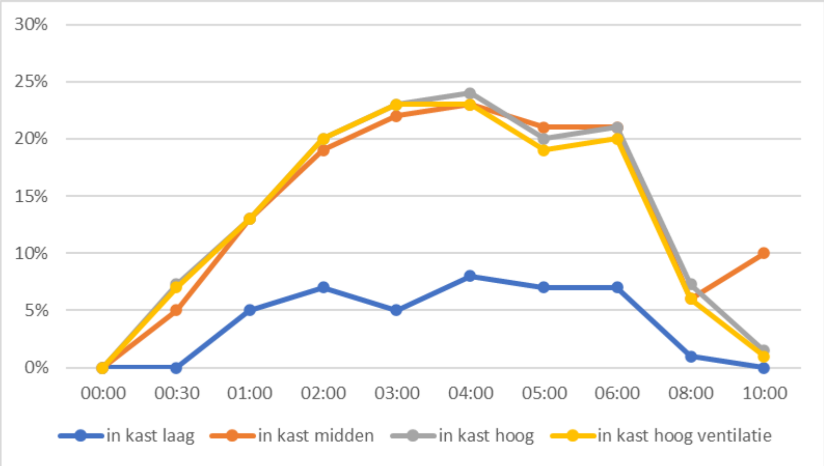

Figure 39. Concentration (vol % H_2) in the ½ m³ cabinet with a leakage rate of 6.7 m³/h hydrogen

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	14.0 vol%	14.0 vol%	17.0 vol%	18.0 vol%

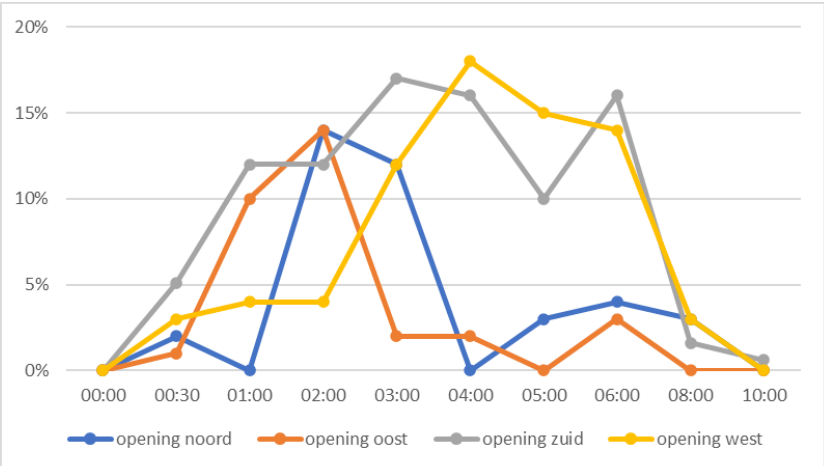

Figure 40. Concentration (vol % H_2) with the ventilation openings in the ½ m³ cabinet with a leakage rate of 6.7 m³/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and this value was also reached. At a distance of 0.5 metres (west), a value of 13% LFL was also detected.

Leakage rate 0.45 m³/h - natural gas

At a leakage rate of 0.45 m^3_n/h the natural gas concentration in the ½ m^3 cabinet increased to a maximum concentration of 5 vol%. During this experiment, the wind was medium to strong, wind force 3 to 6, varying between northwest and east. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

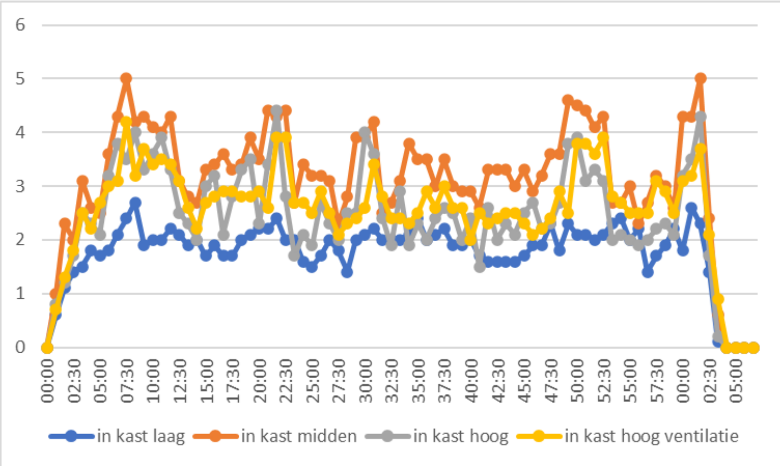

Figure 41. Concentration (vol % CH4) in the ½ m³ cabinet with a leakage rate of 0.45 m³/h

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	3.5 vol%	1.9 vol%	3.0 vol%	3.9 vol%

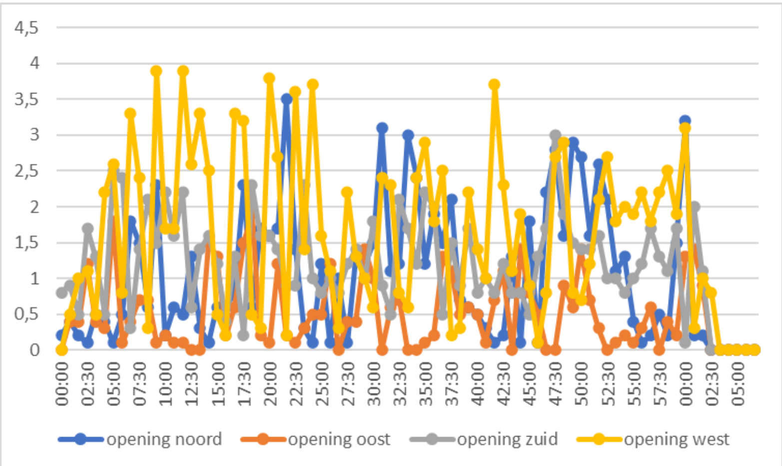

Figure 42. Concentration (vol% CH4) at the ventilation openings of a ½ m³ cabinet with a leakage rate of 0.45 m³/h.

During the experiment the concentration natural gas occasionally reached a maximum of 13% LFL outside the gas pressure reducing station. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 0.9 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.9 m^3_n/h. This leakage led to a hydrogen concentration of up to 7 vol% in the cabinet. During this experiment, the wind was moderate, wind force 3 to 6, varying between northeast and northwest. The concentration at all measuring points in the cabinet built up at the top of the cabinet for medium, high and ventilation. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

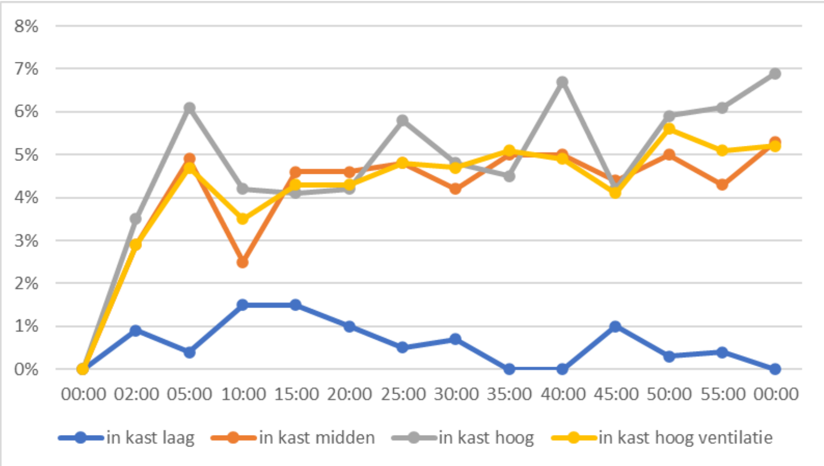

Figure 43. Concentration (vol % H_2) in the ½ m^3 cabinet with a leakage rate of 0.9 m^3/h hydrogen

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	2.6 vol%	4.8 vol%	4.0 vol%	3.7 vol%

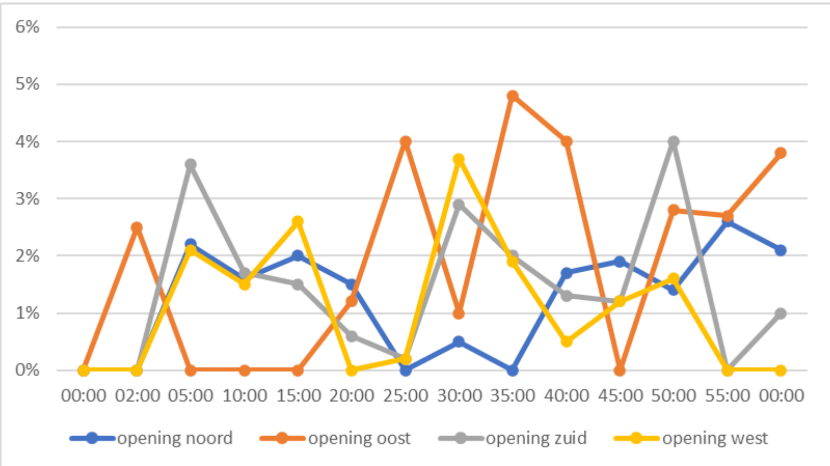

Figure 44. Concentration at the ventilation openings (vol% H_2) in the ½ m^3 cabinet with a leakage rate of 0.9 m^3/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 160 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

Leakage rate 0.1 m^3/h - natural gas

At a leakage rate of 0.1 m^3_n/h the natural gas concentration in the ½ m^3 cabinet increased to a maximum concentration of 3.5 vol%. During this experiment, the wind was weak to medium, wind force 2 to 4, varying between north and northeast. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

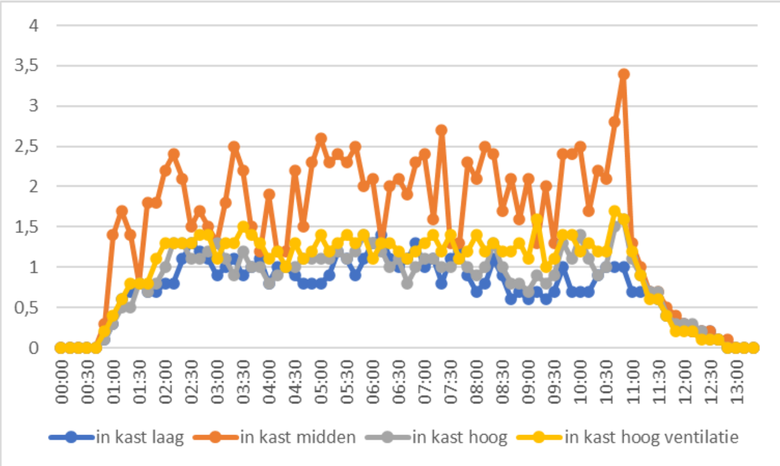

Figure 45. Concentration (vol % CH4) in the ½ m^3 cabinet with a leakage rate of 0.1 m^3/h

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	2.2 vol%	1.0 vol%	1.3 vol%	2.1 vol%

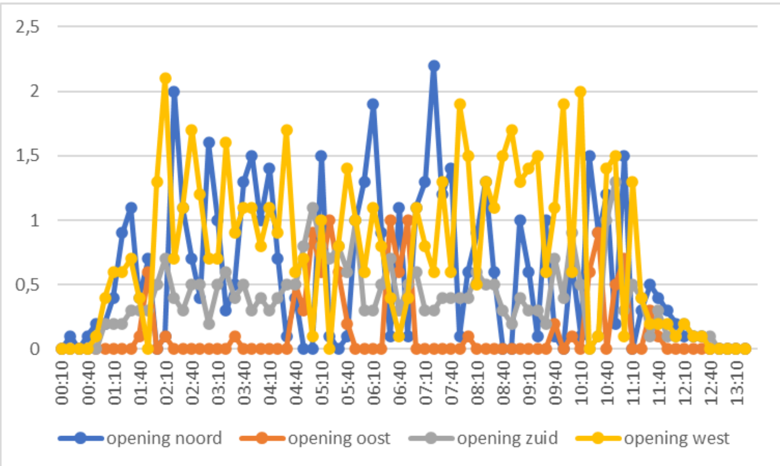

Figure 46. Concentration (vol% CH_4) at the ventilation openings of a ½ m^3 cabinet with a leakage rate of 0.1 m^3/h

At a distance of 0.5 metres from the cabinet, no natural gas or hydrogen concentration was measured at any time, which therefore remained below 0.1% LFL.

Leakage rate 0.2 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.2 m^3_n/h. This leakage led to a hydrogen concentration of up to 2.6 vol% in the cabinet. During this experiment, the wind was weak to medium, wind force 2 to 3, varying between north and east. The concentration of all measuring points in the cabinet only remained the same at the beginning of the test. With the influence of wind, the image became more diffuse. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

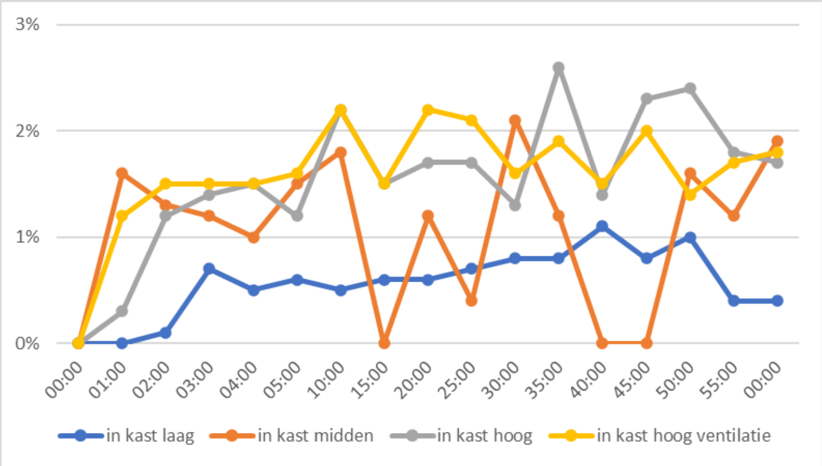

Figure 47. Concentration (vol % H_2) in the ½ m^3 cabinet with a leak of 0.2 m^3/h hydrogen

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	1.1 vol%	0.8 vol%	1.1 vol%	1.5 vol%

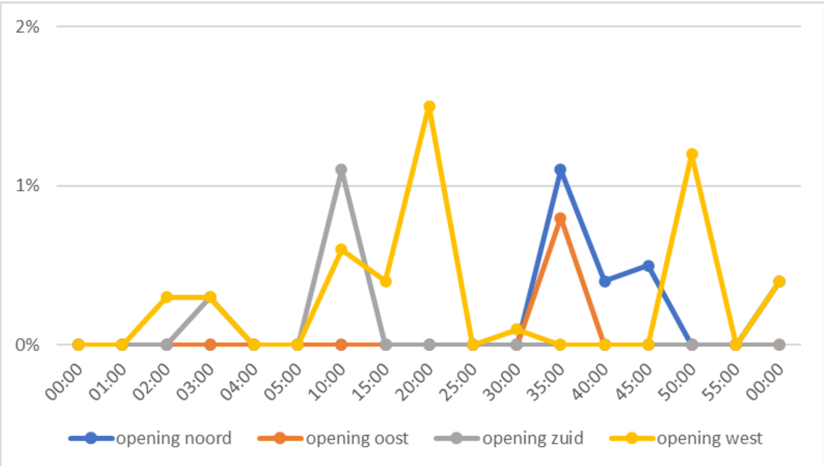

Figure 48. Concentration H2 (vol%) at the ventilation openings of the ½ m^3 cabinet with a leakage rate of 0.2 m^3/h.

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 200ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

VI Measurement results ½ m^3 cabinet, low wind

Leakage rate 3 m^3/h - natural gas

At a leakage rate of 3 m^3_n/h the natural gas concentration in the ½ m^3 cabinet increased to a maximum concentration of 35 vol%. The influence of the wind was only considered if it affected the experiments in the low-wind situation. During this measurement, no influence was observed. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds. The experiment was briefly performed twice given the concentrations in the tent and the low ventilation of this low-wind situation.

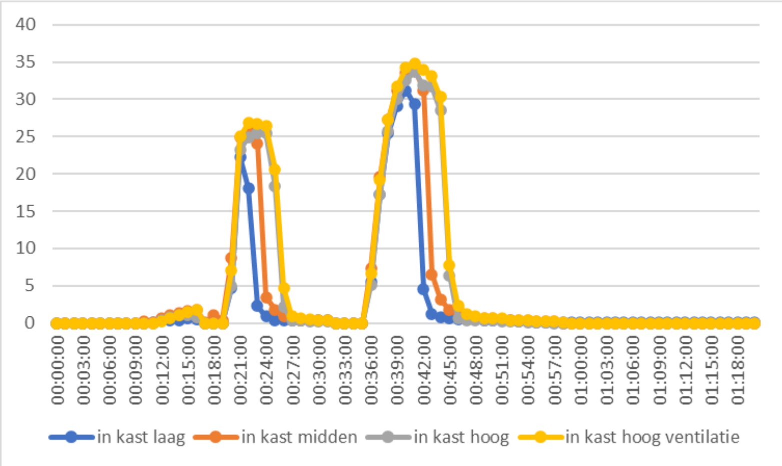

Figure 49. Concentration (vol % CH4) in the ½ m^3 cabinet with a leakage rate of 3 m^3/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	14.4 vol%	13.0 vol%	15.5 vol%	6.2 vol%

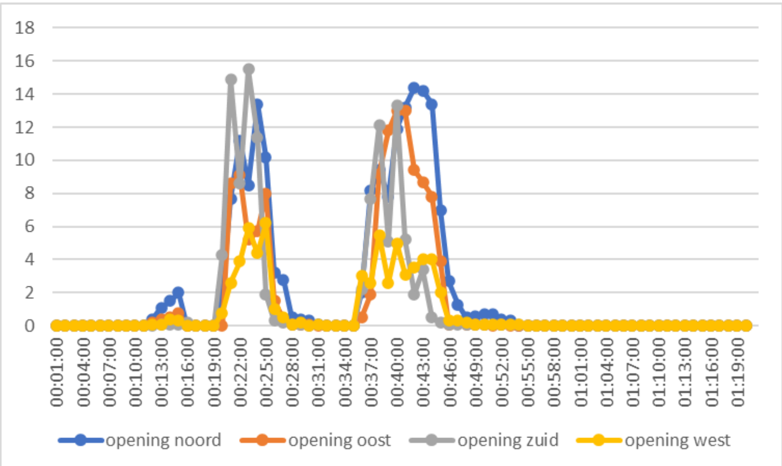

Figure 50. Concentration (vol% CH_4) at the ventilation openings of a ½ m^3 cabinet with a leakage rate of 3 m^3/h (low wind)

During the experiment the concentration natural gas occasionally reached a maximum of 8% LFL outside the gas pressure reducing station. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 6 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 6 m^3_n/h. This leakage led to a hydrogen concentration of up to 25 vol% in the cabinet. The concentration at all measuring points in the cabinet remained almost the same during the entire test. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, no influence was observed. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

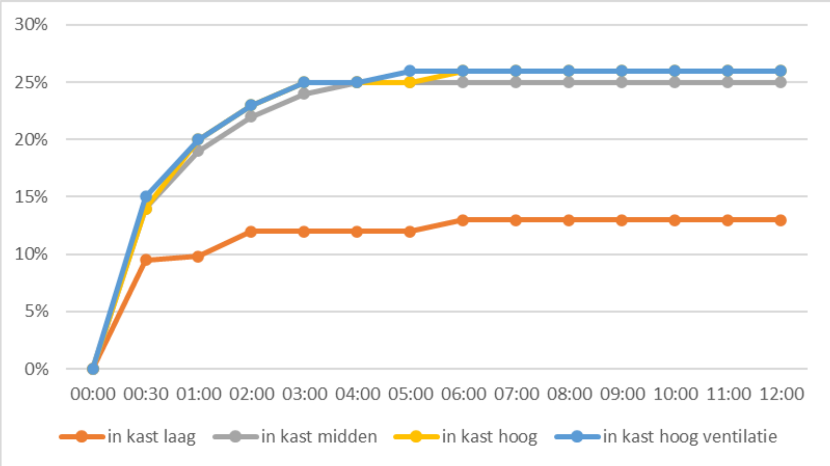

Figure 51. Concentration (vol % H_2) in the ½ m^3 cabinet with a leakage rate of 6.7 m^3/h hydrogen (low wind)

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	20.0 vol%	11.0 vol%	20.0 vol%	7.8 vol%

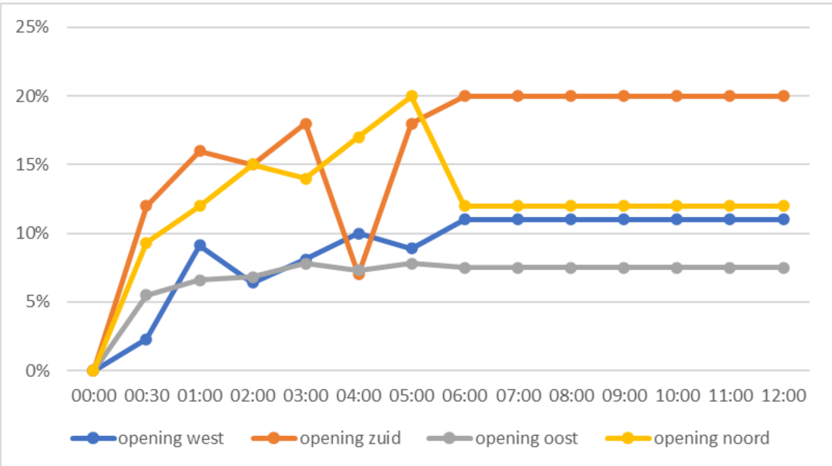

Figure 52. Concentration (vol % H_2) at the ventilation openings in the ½ m^3 cabinet with a leakage rate of 6.7 m^3/h hydrogen (low wind)

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and these values were also reached at both 0.5 metres and 1 metre (west). At a distance of 0.5 metres and 1 metre, no LFL values were detected.

Leakage rate 0.45 m^3/h - natural gas

At a leakage rate of 0.45 m^3_n/h the natural gas concentration in the ½ m^3 cabinet increased to a maximum concentration of 13 vol%. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, a slight influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

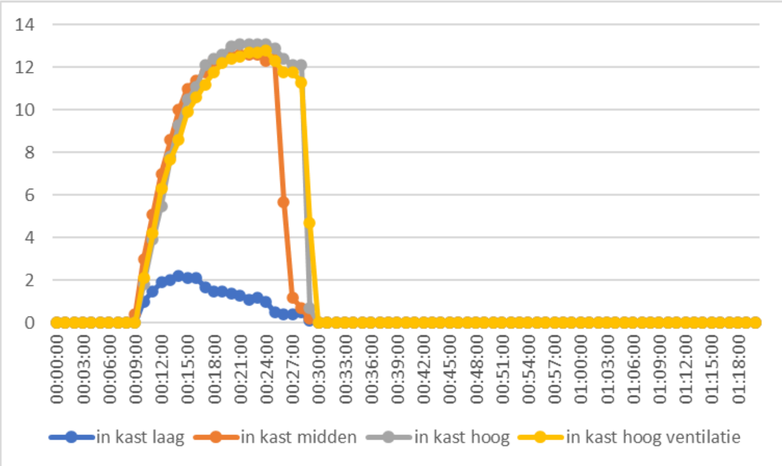

Figure 53. Concentration (vol % CH4) in the ½ m³ cabinet with a leakage rate of 0.45 m³/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	8.2 vol%	6.2 vol%	5.9 vol%	4.4 vol%

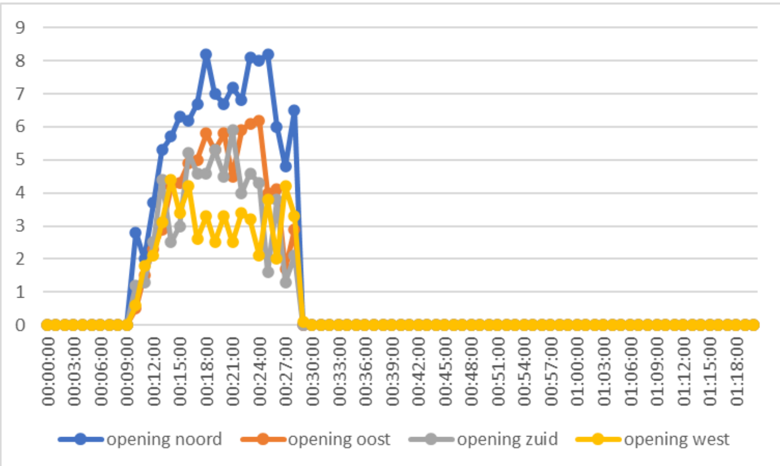

Figure 54. Concentration (vol% CH_4) at the ventilation openings of a ½ m³ cabinet with a leakage rate of 0.45 m³/h (low wind)

During the experiment the concentration natural gas occasionally reached a maximum of 4% LFL outside the gas pressure reducing station. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 0.9 m³/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.9 m^3_n/h. This leakage led to a hydrogen concentration of up to 10 vol% in the cabinet. The concentration at all measuring points in the cabinet remained almost the same during the entire test. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, no influence was observed. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

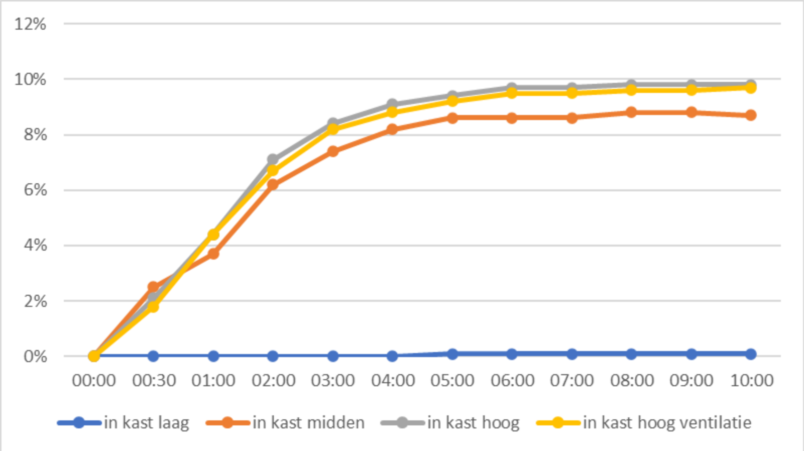

*Figure 55. Concentration (vol % H_2) in the ½ m³ cabinet with a leakage rate of 0.9 m³/h hydrogen (low wind)**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	6.2 vol%	3.3 vol%	2.7 vol%	3.7 vol%

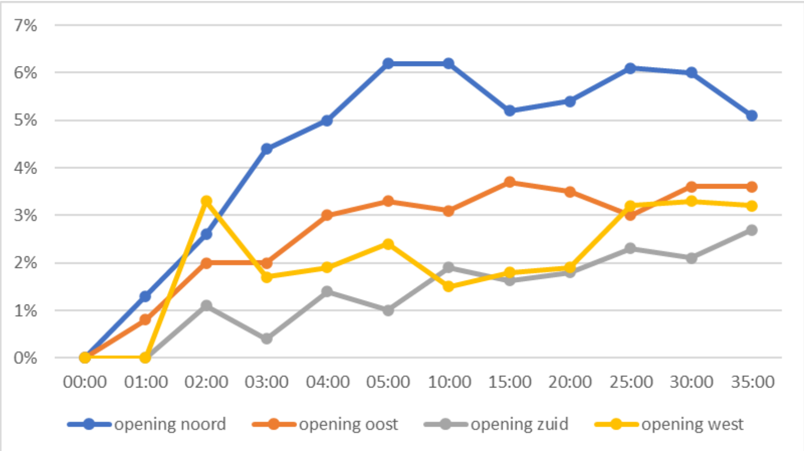

Figure 56. Concentration (vol % H_2) at the ventilation openings in the ½ m³ cabinet with a leakage rate of 0.9 m³/h hydrogen (low wind)

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 500 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

*)the sensor low in the cabinet only recorded zero values during this test.

Leakage rate 0.1 m^3/h - natural gas

At a leak of 0.1 m^3_n/h the natural gas concentration in the ½ m^3 cabinet was up to a maximum concentration of 4 vol% in the middle of the cabinet around the leak. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, an influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

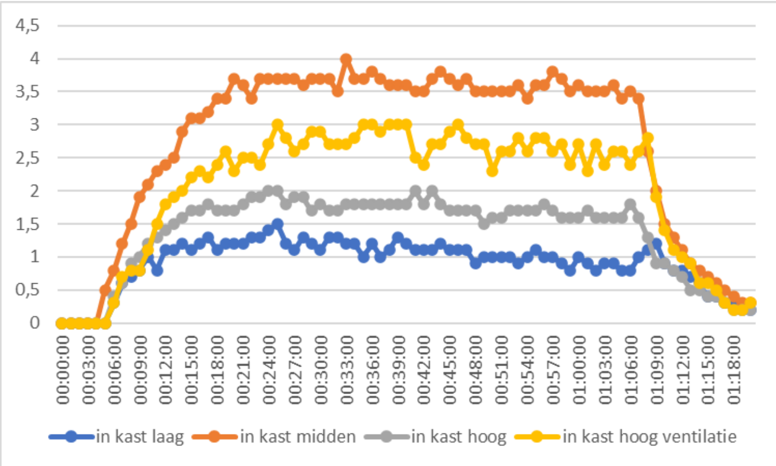

Figure 57. Concentration (vol % CH4) in the ½ m³ cabinet with a leakage rate of 0.1 m³/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	4.3 vol%	1.3 vol%	0.9 vol%	1.9 vol%

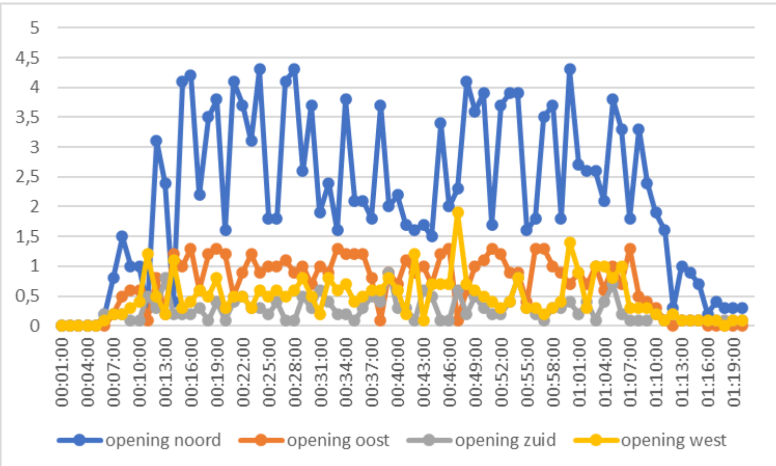

Figure 58. Concentration (vol% CH_4) at the ventilation openings of a ½ m³ cabinet with a leakage rate of 0.1 m³/h (low wind)

At a distance of 0.5 metres from the cabinet, no natural gas or hydrogen concentration was measured at any time, which therefore remained below 0.1% LFL.

Leakage rate 0.2 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.2 m^3_n/h. This leakage led to a hydrogen concentration of up to 4 vol% in the cabinet. The concentration at all measuring points in the cabinet remained almost the same during the entire test. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, no influence was observed. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

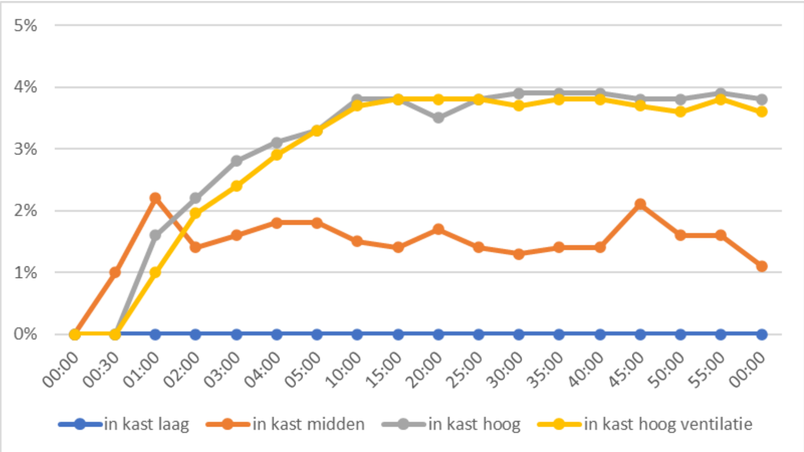

*Figure 59. Concentration (vol % H_2) in the ½ m^3 cabinet with a leakage rate of 0.2 m^3/h hydrogen (low wind)**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	2.6 vol%	1.7 vol%	1.6 vol%	1.5 vol%

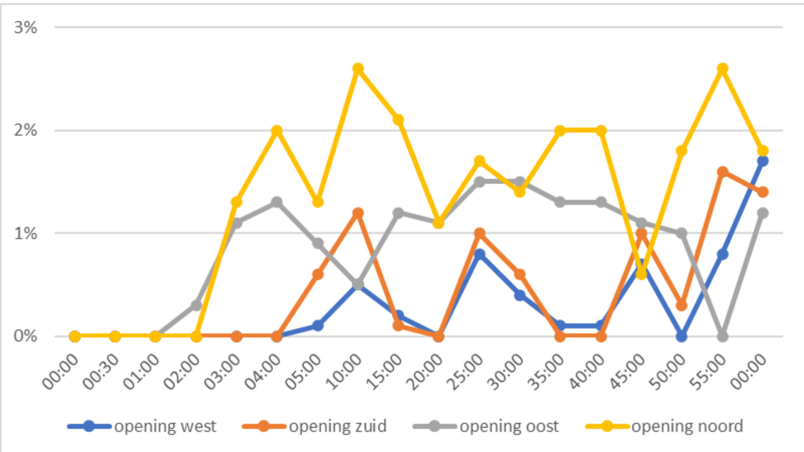

Figure 60. Concentration (vol % H_2) at the ventilation openings in the ½ m^3 cabinet with a leakage rate of 0.2 m^3/h hydrogen (low wind)

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 220 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

*)the sensor low in the cabinet only recorded zero values during this test.

VII Measurement results 4 m3 cabinet, outside situation

Leakage rate 7.5 m^3/hr - natural gas

During the first test, a maximum leakage opening in accordance with NEN 1059 was created at an initial pressure of 8 bar in the 4 m^3 cabinet station, where the concentration increased to a maximum of 5.5 vol%. During this experiment, the wind was weak, wind force 2 to 3, varying between south and west. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

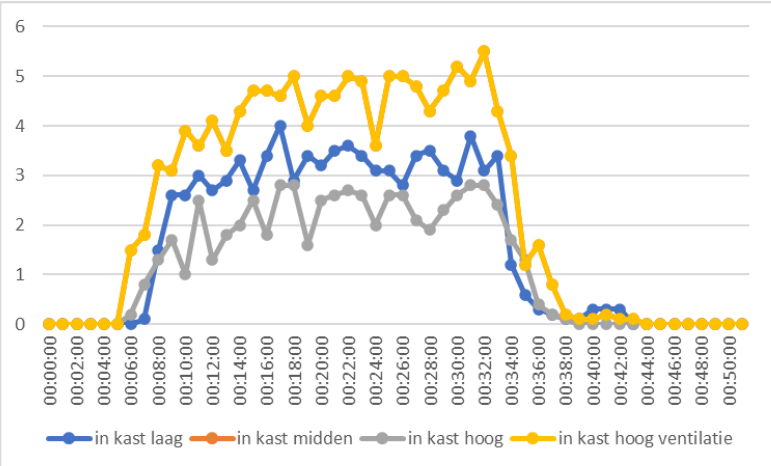

Figure 61. Concentration (vol% CH4) in the 4 m³ cabinet station with a leak of 1 mm² at 8 bar

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	5.6 vol%	5.4 vol%	2.4 vol%	3.4 vol%

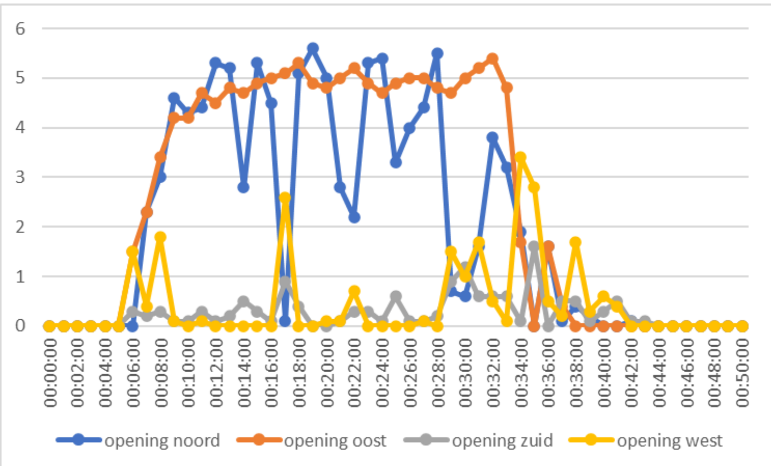

Figure 62. Concentration at the ventilation openings (vol% CH4) in the 4 m³ cabinet station with a leak of 1 mm² at 8 bar

During the experiment, the concentration of natural gas outside the gas pressure reducing station increased to a maximum of 12% LFL. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 22.5 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure and leakage rate, the measured leakage rate was approximately 22.5 m^3_n/h. This leakage led to a hydrogen concentration of up to 11 vol% in the cabinet. During this experiment, the wind was weak, wind force 1 to 2, varying between west, north and northeast. The concentration at all measuring points in the cabinet remained almost the same during the entire test. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

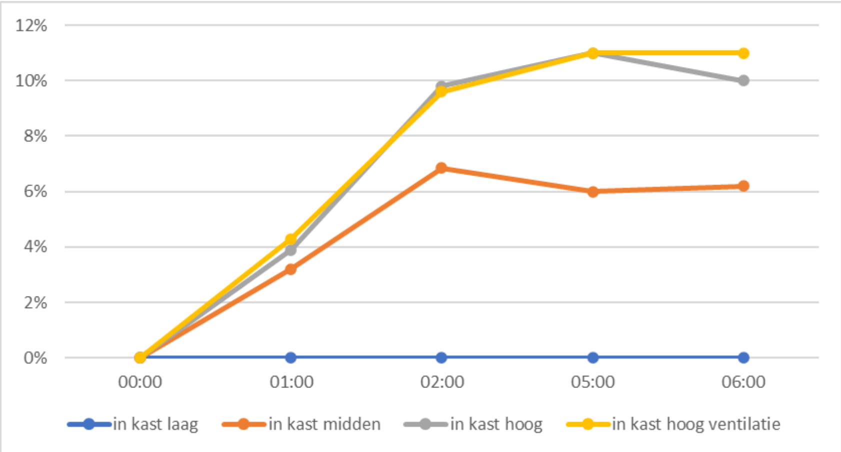

*Figure 63. Concentration (vol % H_2) in the 4 m^3 cabinet station with a leak of 1 mm^2 at 8 bar **

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	11.0 vol%	12.0 vol%	4.5 vol%	5.8 vol%

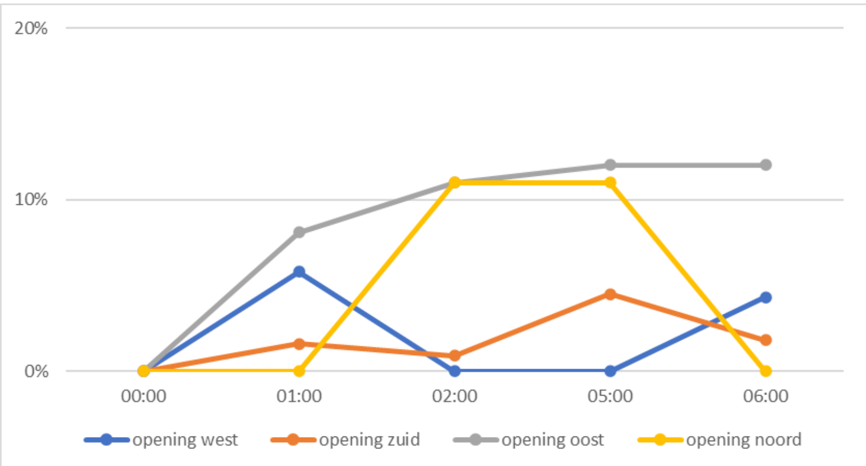

Figure 64. Concentration at the ventilation openings (vol% H_2) in the 4 m^3 cabinet station with a leak of 1 mm^2 at 8 bar

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 720 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected, which was likely due to the short duration of the experiment.

*)the sensor low in the cabinet only recorded zero values during this test.

Leakage rate 4.6 m^3/h - natural gas

At a leak of 4.6 m^3_n/h the natural gas concentration in the 4 m^3 cabinet station was up to a maximum concentration of 3.9 vol%. During this experiment, the wind was moderate, wind force 3 to 4 from various directions. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

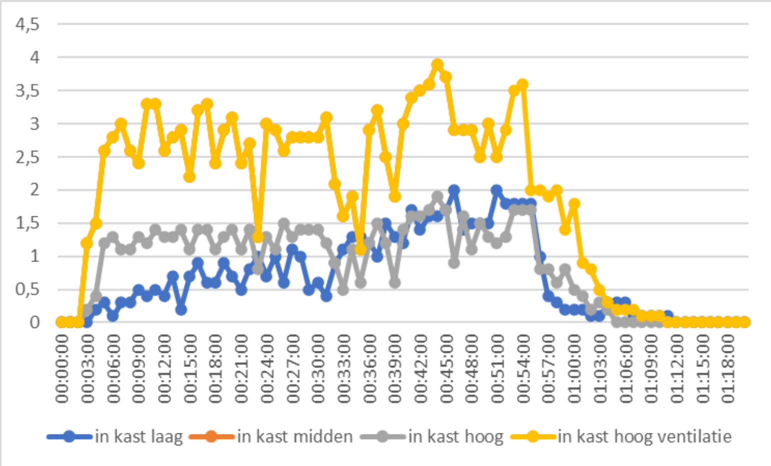

*Figure 65. Concentration (vol % CH4) in the 4 m³ cabinet station with a leakage rate of 4.6 m³/h**

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	4.3 vol%	4.0 vol%	2.2 vol%	3.4 vol%

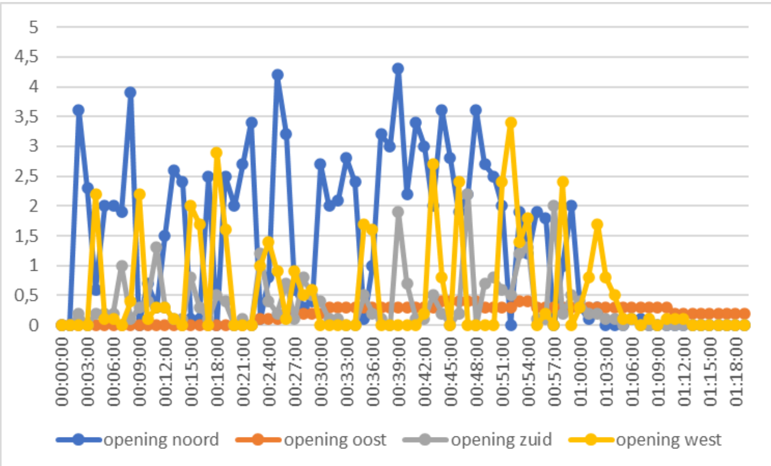

Figure 66. Concentration (vol% CH_4) at the ventilation openings of a 4 m³ cabinet with a leakage rate of 4.6 m³/h.

At a distance of 0.5 metres from the cabinet, no natural gas or hydrogen concentration was measured at any time, which therefore remained below 0.1% LFL.

*)the measurement values for the low and middle sensors were the same. No explanation for this measurement error.

Leakage rate 12 m^3/hr - hydrogen

When hydrogen leakage was created with the same pre-pressure, the measured leakage rate was approximately 12 m^3_n/h. This leakage led to a hydrogen concentration of up to 9.4 vol% in the cabinet. During this experiment, the wind was weak to medium, wind force 2 to 3, varying between northeast and east. The concentration high in the cabinet stabilised during the experiment. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

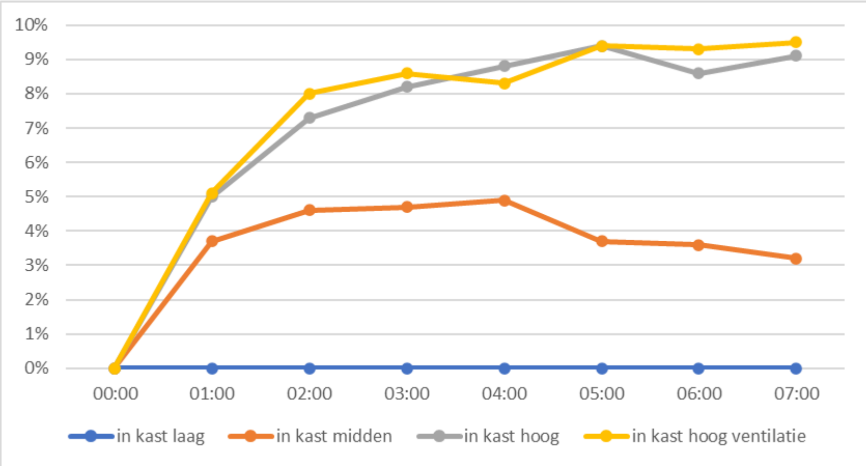

*Figure 67. Concentration (vol % H_2) in the 4 m^3 cabinet station with a leakage rate of 12 m^3/h hydrogen**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	8.7 vol%	10.0 vol%	4.6 vol%	5.4 vol%

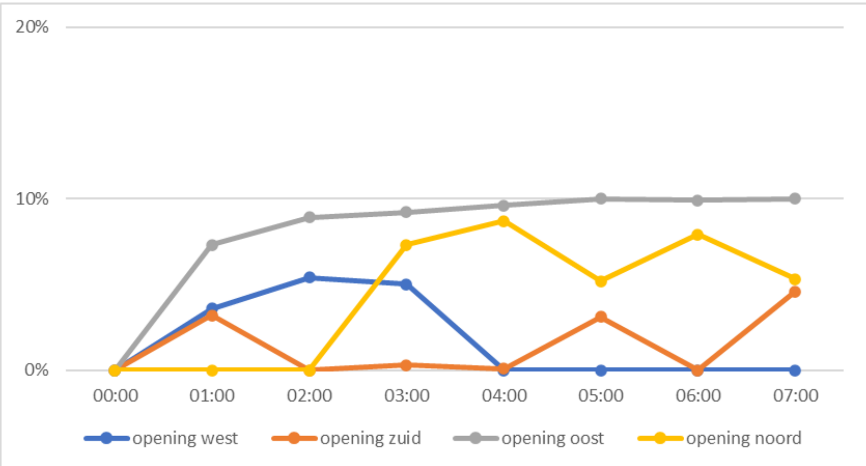

Figure 68. Concentration at the ventilation openings (vol% H_2) in the 4 m^3 cabinet station with a leakage rate of 12 m^3/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 710 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

*)the low sensor in the cabinet did not register any values during this test.

Leakage rate 3 m^3/h - natural gas

At a leak of 3 m^3_n/h the natural gas concentration in the 4 m^3 cabinet station was up to a maximum concentration of 3.2 vol%. During this experiment, the wind was weak to moderate, force 2 to 4, varying between north and south-east. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

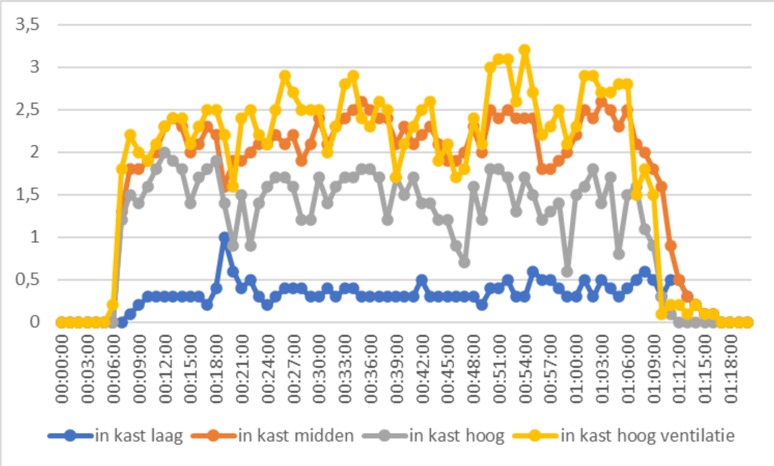

Figure 69. Concentration (vol % CH4) in the 4 m^3 cabinet station with a leakage rate of 3 m^3/h

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	4.0 vol%	3.1 vol%	1.7 vol%	4.4 vol%

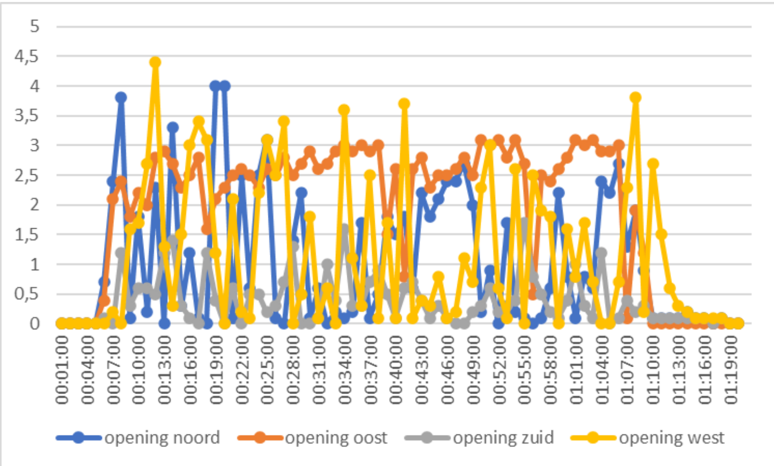

Figure 70. Concentration (vol % CH_4) at the ventilation openings of a 4 m^3 cabinet with a leakage rate of 3 m^3/h

During the experiment, the concentration of natural gas outside the gas pressure reducing station increased to a maximum of 4% LFL. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 6 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 6 m^3_n/h. This leak led to a hydrogen concentration of up to 8 vol% in the cabinet. During this experiment, the wind was weak, wind force 2, varying between north and west. The concentration high in the cabinet stabilised during the experiment. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

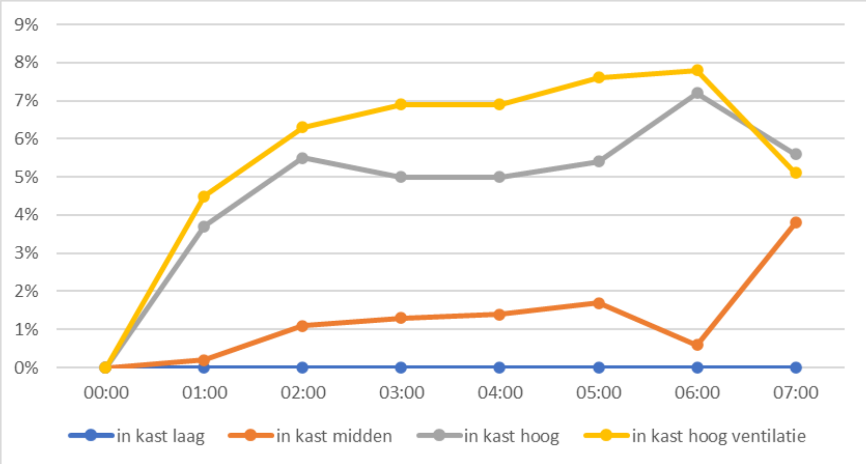

*Figure 71. Concentration (vol % H_2) in the 4 m³ cabinet station with a leakage rate of 6.7 m³/h hydrogen**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	4.1 vol%	8.0 vol%	6.6 vol%	1.0 vol%

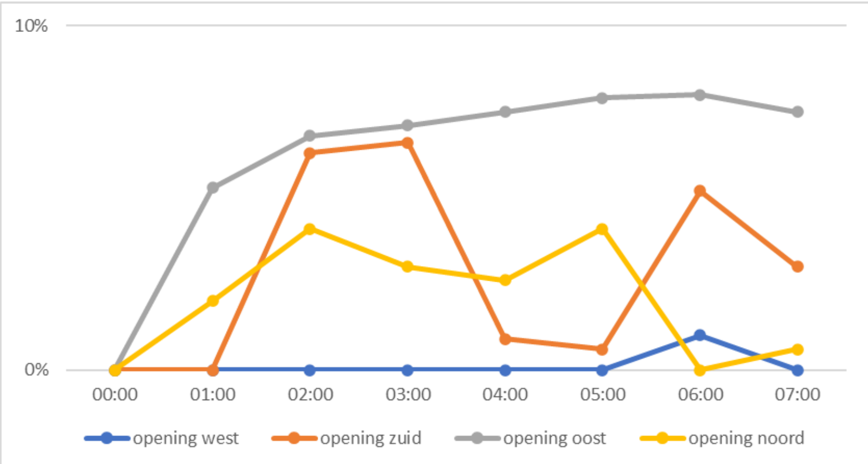

Figure 72. Concentration (vol % H_2) at the ventilation openings in the 4 m³ cabinet station with a leakage rate of 6.7 m³/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 220 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

*)the sensor low in the cabinet only recorded zero values during this test.

Leakage rate 0.45 m³/h - natural gas

At a leak of 0.45 m^3_n/h the natural gas concentration in the 4 m³ cabinet station was up to a maximum concentration of approximately 1 vol%. During this experiment, the wind was medium to strong, wind force 2 to 3, varying between north and southeast. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

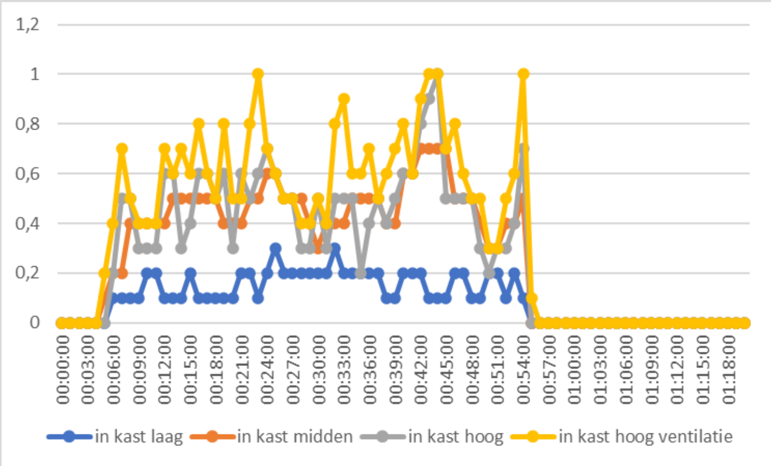

Figure 73. Concentration (vol % CH4) in the 4 m³ cabinet station with a leakage rate of 0.45 m³/h

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	0.8 vol%	1.5 vol%	0.9 vol%	2.4 vol%

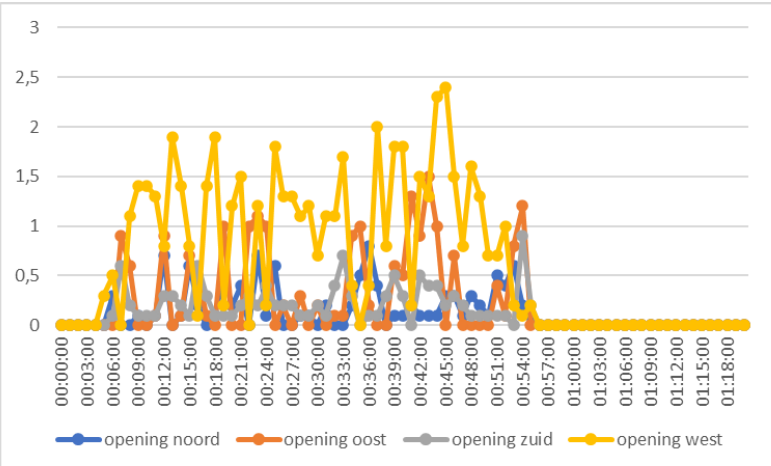

Figure 74. Concentration (vol% CH4) at the ventilation openings of a 4 m³ cabinet with a leakage rate of 0.45 m³/h.

At a distance of 0.5 metres and 1 metre from the cabinet, no natural gas or hydrogen concentration was measured at any time, and it therefore remained below the 0.1% LFL.

Leakage rate 0.9 m³/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.9 m^3_n/h. This leakage led to a hydrogen concentration of up to 2.5 vol% in the cabinet. During this experiment, the wind was weak to medium, wind force 2 to 3, varying between northeast and northwest. The concentration at all the measuring points in the cabinet had significant variations in character and the height concentrations were measured at the top of the cabinet and at the ventilation. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

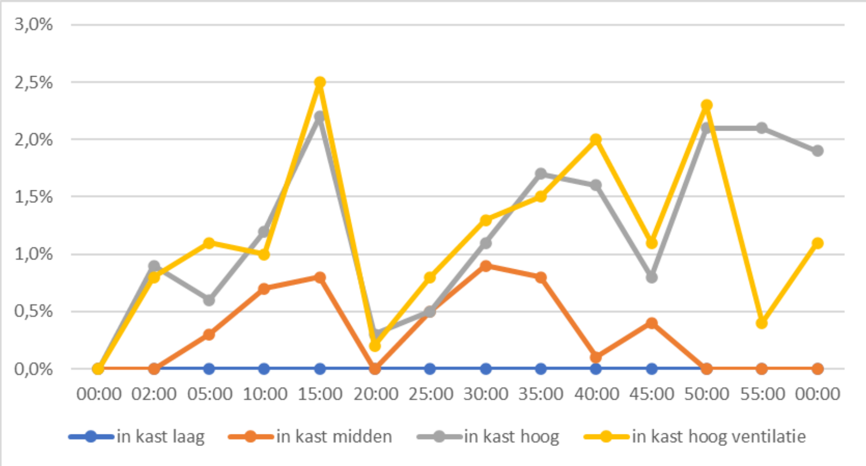

*Figure 75. Concentration (vol % H_2) in the 4 m³ cabinet station with a leakage rate of 0.9 m³/h hydrogen**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	1.5 vol%	2.8 vol%	1.8 vol%	1.6 vol%

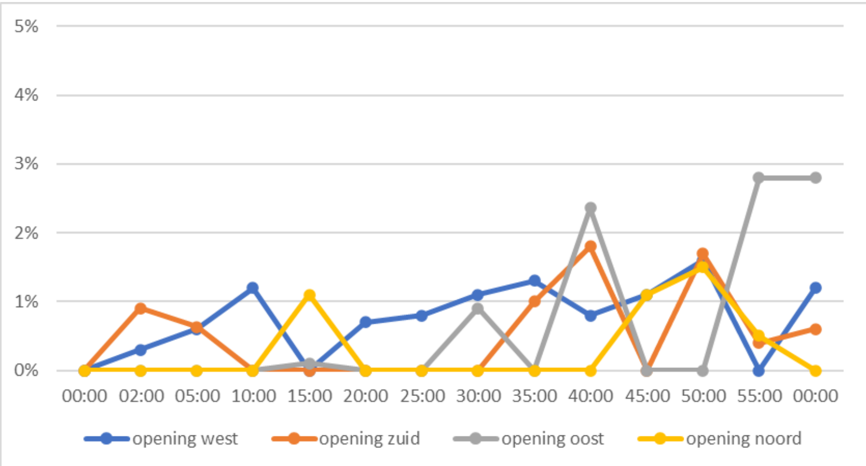

Figure 76. Concentration at the ventilation openings (vol% H_2) in the 4 m³ cabinet station with a leakage rate of 0.9 m³/h hydrogen

At a distance of 0.5 metres and 1 metre from the cabinet, no natural gas or hydrogen concentration was measured at any time, and it therefore remained below the 0.1% LFL.

*)the sensor low in the cabinet only recorded zero values during this test.

Leakage rate 0.1 m³/h - natural gas

At a leakage rate of 0.1 m^3_n/h the natural gas concentration in the ½ m^3 cabinet increased to a maximum concentration of 0.3 vol%. During this experiment, the wind was weak, wind force 1 to 2, varying between north and east. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

The concentration at all the measuring points in the cabinet was variable during the experiment. The graph below shows the concentration of natural gas as a function of time in minutes and seconds.

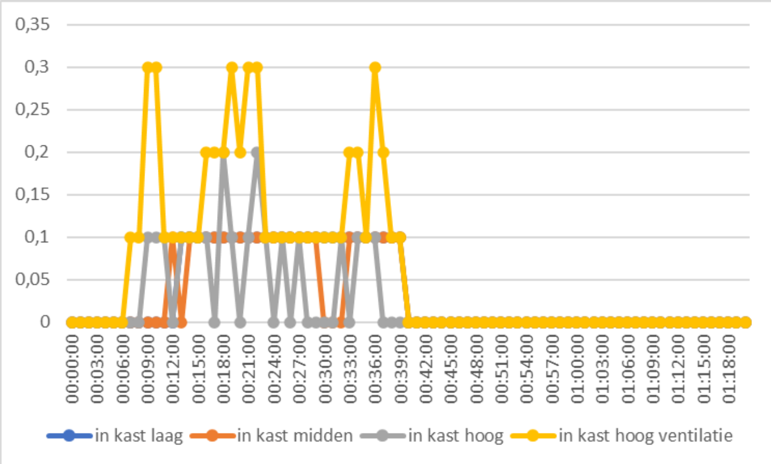

Figure 77. Concentration (vol % CH4) in the 4 m³ cabinet station with a leakage rate of 0.1 m³/h

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	0.2 vol%	0.4 vol%	0.3 vol%	0.5 vol%

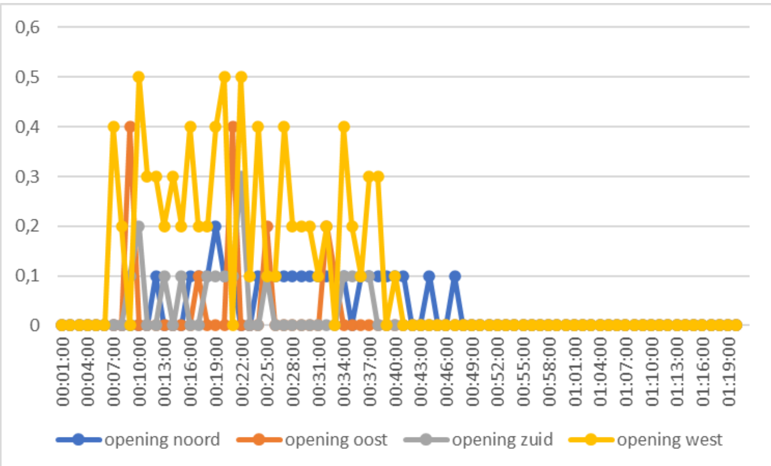

Figure 78. Concentration (vol% CH_4) at the ventilation openings of a 4 m³ cabinet with a leakage rate of 0.1 m³/h

At a distance of 0.5 metres and 1 metre from the cabinet, no natural gas or hydrogen concentration was measured at any time, and it therefore remained below the 0.1% LFL.

Leakage rate 0.2 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.2 m^3_n/h. This leak did not lead to a build-up of hydrogen concentration in the cabinet, nor were increased concentrations of hydrogen measured at the ventilation openings.

During this experiment, the wind was weak to medium, wind force 2 to 4, varying between north and east.

At a distance of 0.5 metres and 1 metre from the cabinet, no natural gas or hydrogen concentration was measured at any time, and it therefore remained below the 0.1% LFL.

VIII Measurement results 4 m^3 cabinet, no wind

Leakage rate 4.6 m^3/h - natural gas

At a leak of 4.6 m^3_n/h the natural gas concentration in the 4 m^3 cabinet station was up to a maximum concentration of 4.3 vol%. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, a slight influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

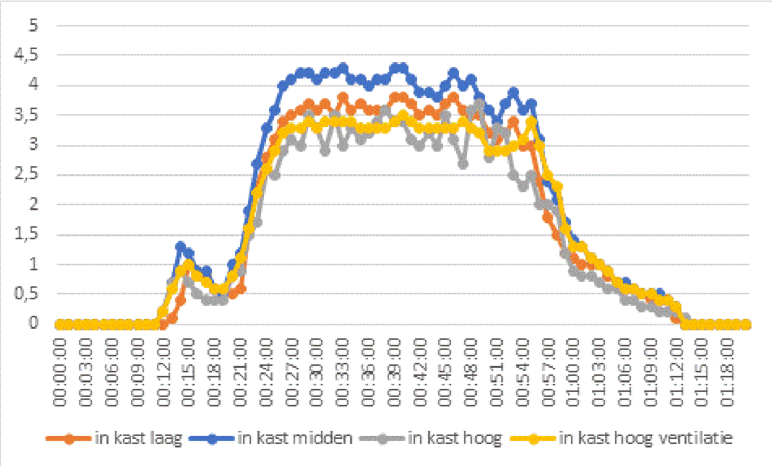

Figure 79. Concentration (vol % CH4) in the 4 m^3 cabinet station with a leakage rate of 4.6 m^3/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	4.0 vol%	1.2 vol%	5.2 vol%	5.2 vol%

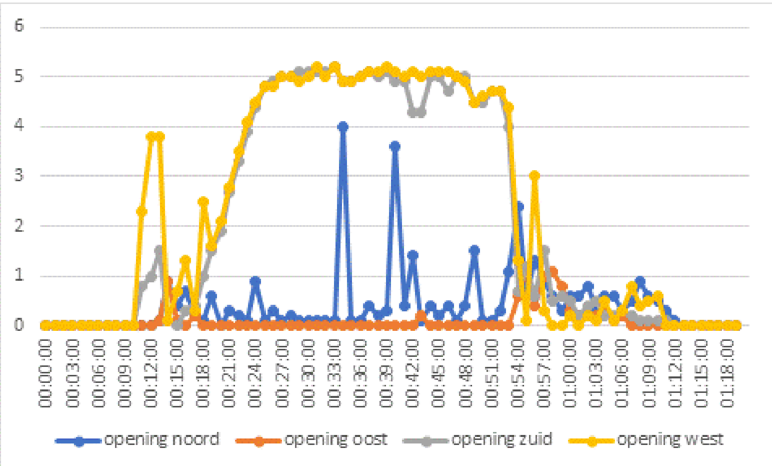

Figure 80. Concentration (vol% CH_4) at the ventilation openings of a 4 m^3 cabinet with a leakage rate of 4.6 m^3/h (low wind)

During the experiment the concentration natural gas occasionally reached a maximum of 5% LFL outside the gas pressure reducing station. This concentration was measured at a distance of 0.5 metres (east) from the cabinet at a height of 1 metre from the ground.

Leakage rate 3 m^3/h - natural gas

At a leak of 3 m$^3{}_n$/h the natural gas concentration in the 4 m^3 cabinet station was up to a maximum concentration of 2.7 vol%. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, a slight influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

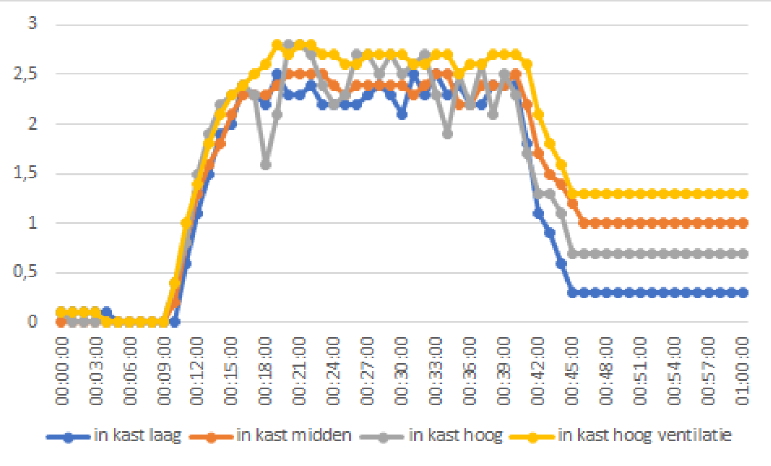

Figure 81. Concentration (vol % CH4) in the 4 m³ cabinet station with a leakage rate of 3 m³/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	3.8 vol%	0.6 vol%	4.2 vol%	4.2 vol%

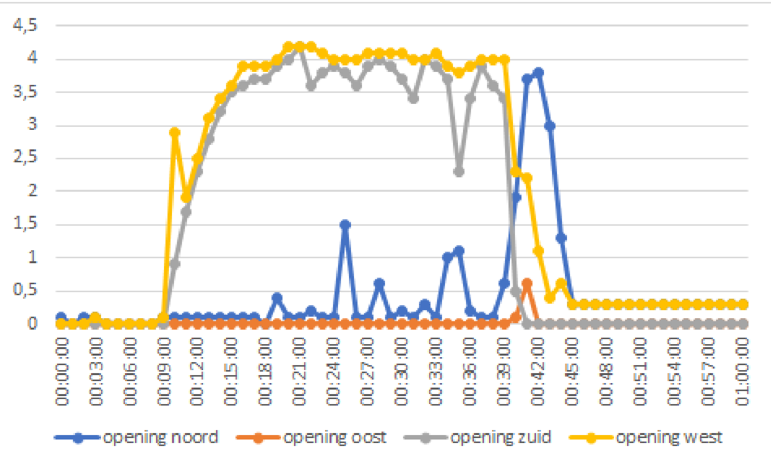

Figure 82. Concentration (vol% CH_4) at the ventilation openings of a 4 m³ cabinet with a leakage rate of 3 m³/h (low wind)

During the experiment the concentration natural gas occasionally reached a maximum of 7% LFL outside the gas pressure reducing station. This concentration was measured at 0.5 metres (west) from the cabinet at a height of 1 metre from the ground.

Leakage rate 0.45 m^3/h - natural gas

At a leak of 0.45 m^3_n/h the natural gas concentration in the 4 m^3 cabinet station was up to a maximum concentration of 1.7 vol%. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, a slight influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

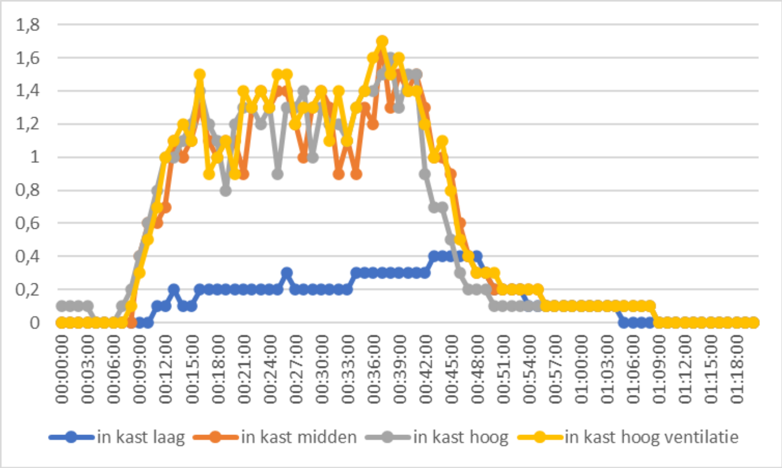

Figure 83. Concentration (vol % CH4) in the 4 m³ cabinet station with a leakage rate of 0.45 m³/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	4.3 vol%	1.1 vol%	1.9 vol%	3.8 vol%

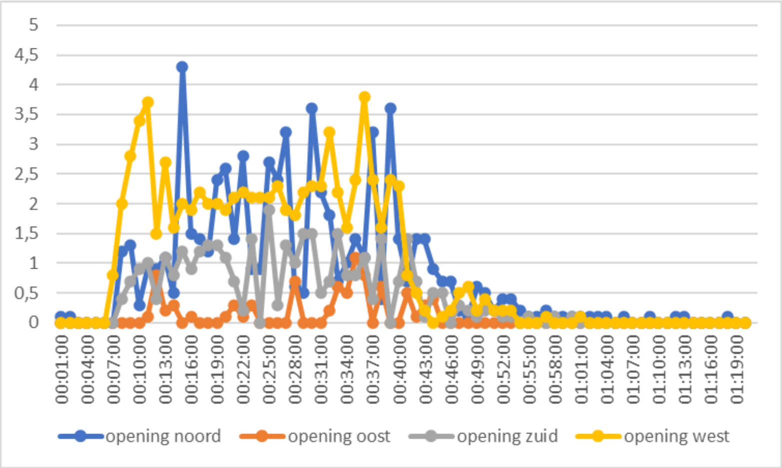

Figure 84. Concentration (vol% CH_4) at the ventilation openings of a 4 m³ cabinet with a leakage rate of 0.45 m³/h (low wind)

At a distance of 0.5 metres from the cabinet, no natural gas or hydrogen concentration was measured at any time, which therefore remained below 0.1% LFL.

Leakage rate 0.9 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.9 m^3_n/h. This leakage led to a hydrogen concentration of up to 6 vol% in the cabinet. The concentration at all measuring points in the cabinet remained almost the same during the entire test. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, no influence was observed. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

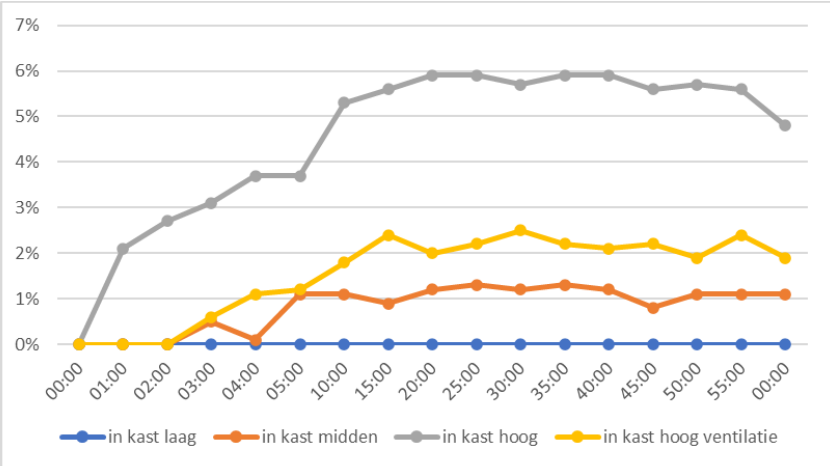

*Figure 85. Concentration (vol % H_2) in the 4 m^3 cabinet station with a leakage rate of 0.9 mm^3/h hydrogen**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	6.0 vol%	3.5 vol%	4.9 vol%	4.0 vol%

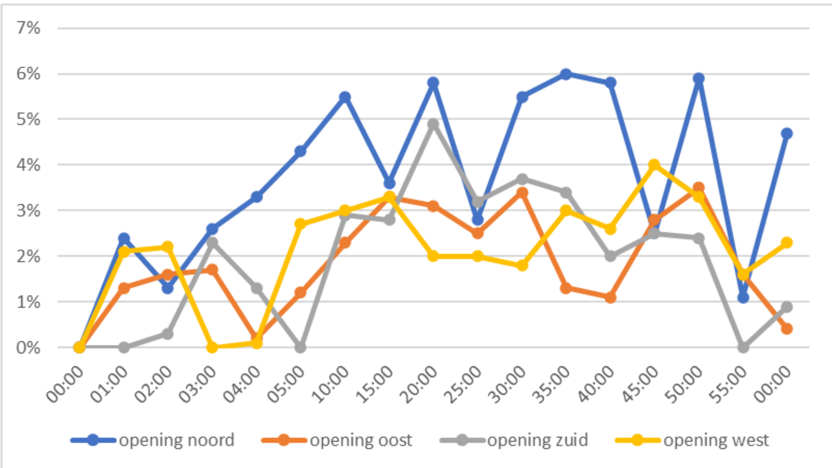

Figure 86. Concentration at the ventilation openings (vol% H_2) in the 4 m^3 cabinet with a leakage rate of 0.9 m^3/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 280 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

*)the sensor low in the cabinet only recorded zero values during this test.

Leakage rate 0.1 m³/h - natural gas

At a leak of 0.1 m^3_n/h, the natural gas concentration in the 4 m³ cabinet station was up to a maximum concentration of 0.6 vol% in the middle of the cabinet around the leak. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, a slight influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of natural gas (in vol%) is shown as a function of time in minutes and seconds.

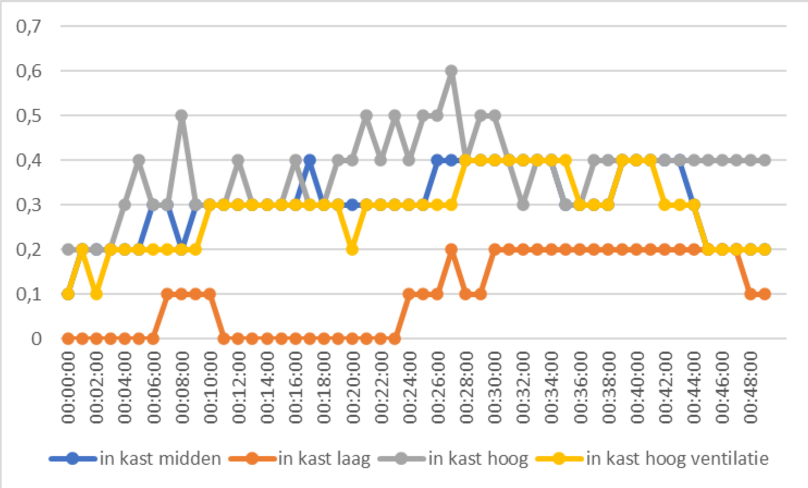

Figure 87. Concentration (vol % CH4) in the 4 m³ cabinet station with a leakage rate of 0.1 m³/h (low wind)

The graph and table below show the time-dependent image of the measured concentration of natural gas (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of natural gas is shown as a function of time in minutes and seconds.

	North	East	South	West
Natural gas concentration	1.5 vol%	0.4 vol%	0.5 vol%	1.8 vol%

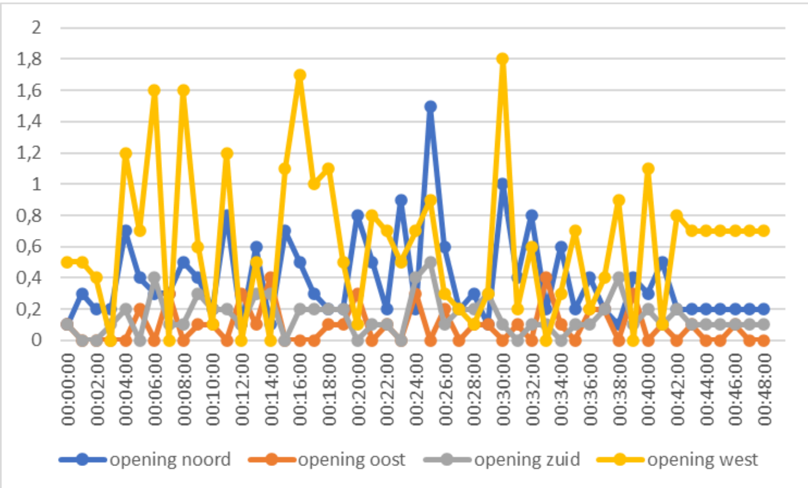

Figure 88. Concentration (vol% CH_4) at the ventilation openings of a 4 m³ cabinet with a leakage rate of 0.1 m³/h (low wind)

At a distance of 0.5 metres from the cabinet, no natural gas or hydrogen concentration was measured at any time, which therefore remained below 0.1% LFL.

Leakage rate 0.2 m^3/hr - hydrogen

When a leakage with hydrogen was created with the same pre-pressure, the measured leakage rate was approximately 0.2 m^3_n/h. This leakage led to a hydrogen concentration of up to 1.4 vol% in the cabinet. The concentration at all measuring points in the cabinet remained almost the same during the entire test. The influence of wind was only considered if it affected the experiments in the low wind situation. During this measurement, a slight influence of the wind was observed, leading to a preference for the ventilation openings. In the graph below, the concentration of hydrogen is shown as a function of time in minutes and seconds.

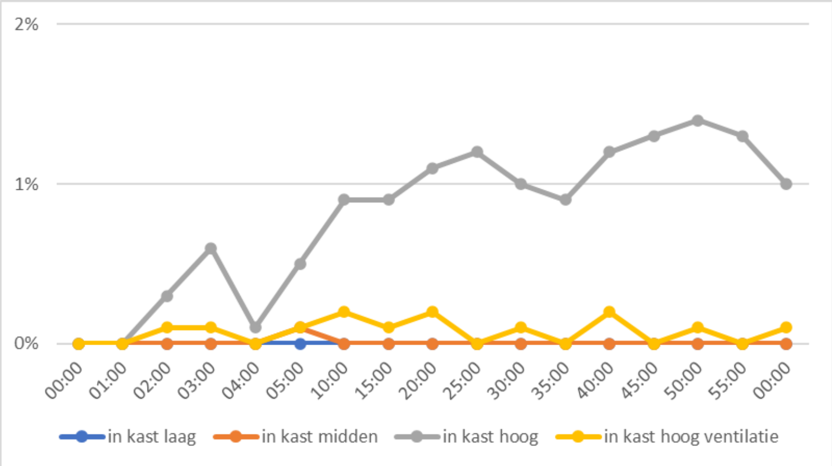

*Figure 89. Concentration (vol % H_2) in the 4 m^3 cabinet station with a leakage rate of 0.2 m^3/h hydrogen**

The graph and table below show the time-dependent image of the measured concentration of hydrogen (in vol%) at the ventilation openings with the maximum concentration in red. Again, the concentration of hydrogen is shown as a function of time in minutes and seconds.

	North	East	South	West
Hydrogen concentration	1.4 vol%	0.8 vol%	0.5 vol%	1.2 vol%

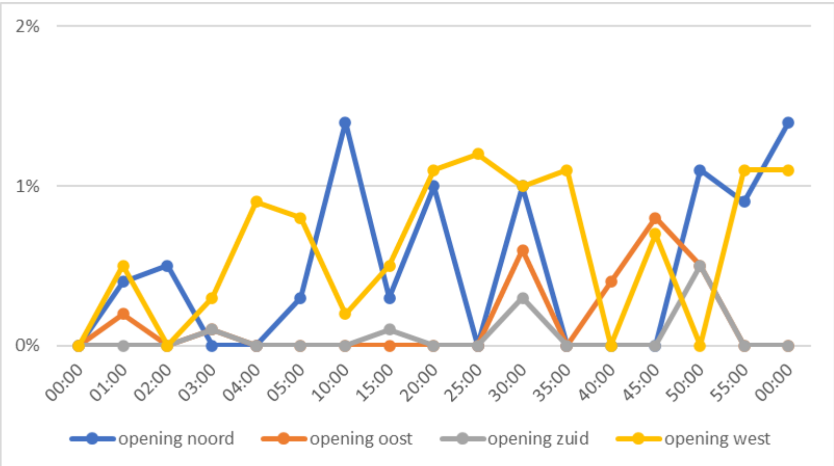

Figure 90. Concentration at the ventilation openings (vol% H_2) in the 4 m^3 cabinet with a leakage rate of 0.2 m^3/h hydrogen

Hydrogen sensors were also measured at a distance of 0.5 metres and 1 metre from the cabinet. These have a measuring range of up to 1000 ppm and 80 ppm was reached. At a distance of 0.5 metres and 1 metre, no LFL values were detected.

*)the sensor low in the cabinet only recorded zero values during this test.