HyDelta 2

WP6B – Safety – Suitability of Assets and Working Methods

D6B.2A - Report on ignition scenarios when using inflatable gas stoppers // D6B.2B - Report on ignition test results

Status: final

Document summary

Corresponding author

Corresponding author	S.L.M. Lueb
Associated with	Kiwa Technology
E-mail address	sander.lueb@kiwa.com

Document history

Version	Date	Authors	Associated with	Summary of changes
1	08 February 2023	Sander Lueb, Michel Bos	Kiwa Technology	Draft
2	13 March 2023	Sander Lueb, Michel Bos	Kiwa Technology	Comments incorporated from the EAG.
3	24 March 2023	Sander Lueb, Michel Bos	Kiwa Technology	Additions following EAG discussion on 15/03 and adding of further results on leak tightness measurements (IPCO stoppers DN 60 and DN 200 and Kleiss stopper DN 200)
def	24 April 2023	Sander Lueb, Michel Bos	Kiwa Technology	Processing of a few comments from the Supervisory Group and addition of links to video material.

Distribution level

PU	Public	X
RE	Restricted to • Project partners including Expert Assessment Group • External entity with whom a duty of confidentiality exists	

Document review

Partner	Name
Kiwa Technology	Arie Kooiman
RENDO	Johan Jonkman
Stedin	Gilles de Kok
Enexis	Henk Smit
Westland Infra	Rick den Hartog
Liander	Rob Nispeling
Coteq	Henk Engberts
Kleiss	Alex Punt
IPCO	André van den Heuvel
NBNL, Gasunie, Kiwa, DNV, TNO, NEC, Hanze	HyDelta Supervisory Group

Executive summary

As part of the national research programme, HyDelta, a study was conducted on the suitability of inflatable inflatable gas stoppers as a fast temporary seal in a hydrogen distribution network (of the RNBs: regional network operators).

The study as described in this report is part of work package D6-B2 "Safe use of hydrogen in the low-pressure distribution network and urban areas; suitability of assets and working methods". Inflatable gas stoppers are also used in the transport network (from Gas Transport Services, GTS), but the application is different from in a distribution network. The results in this report do not relate to the application of inflatable stoppers in the gas transport network.

The research question addressed in the report is as follows;
Are inflatable inflatable gas stoppers, as they are currently applied in natural gas distribution networks, suitable for application in a hydrogen distribution network?

To answer this question, eight sub-questions were formulated. These were answered by conducting theoretical research and by carrying out practical experiments. The theoretical research was focused on ignition scenarios when using inflatable gas stoppers and the experiences of grid operators with malfunctioning inflatable gas stoppers.

The practical research consisted of:

- Performing leak-tightness measurements on two types of stoppers in two types of pipe materials (PVC and PE), and four different diameters.
- Determining the maximum leakage rate at which the concentration in a working pit remains below 10% LEL.[1]
- Determining how a gas stopper behaves in case of direct ignition of leakage gas near the pipe end.
- Determining how a gas stopper behaves when a combustible mixture in the working pit is ignited due to an increased leakage rate from the pipe end.
- Determining how a gas stopper behaves when extinguishing a gas fire.

The aforementioned experiments were conducted with both hydrogen and natural gas.

The main conclusions from this study are as follows:

Inflatable inflatable gas stoppers, as they are currently applied in natural gas distribution networks, can also be applied in a hydrogen distribution network if additional measures are considered.

In normal operations, when placing inflatable gas stoppers at a distance of 1 metre from an outlet, there is no difference between a natural gas and hydrogen distribution network. A small natural gas leak (<0.2 m^3/h) and a small hydrogen leak (<0.6m^3/h) near the stopper were found to be ignitable.

1

100% LEL = 5.9% Groningen natural gas
100% LEL = 4.0% hydrogen
LEL refers to the lower flammability limit. Below the lower flammability limit, there is insufficient fuel present to sustain a combustion reaction. LEL and LFL refer to the same lower flammability limit. For hydrogen, the LEL/LFL is 4 vol% hydrogen in air.
UEL refers to the upper flammability limit. Above the upper flammability limit, there is insufficient oxygen present to maintain a combustion reaction. UEL and UFL refer to the same upper flammability limit. For hydrogen, the UEL/UFL is 75 vol% hydrogen in air.
Kiwa uses the abbreviations LEL and UEL for the lower and upper flammability limits of a gas, respectively. Kiwa uses these abbreviations in order to stay in line with Dutch and European standards as well as to avoid any confusion of the concepts.

This could cause the stopper to break, which is also the case with a natural gas leak. So far, this kind of failure has only occurred to a limited extent in practice. However, preventing the presence of ignition sources in working pits is and remains a key issue in preventing this kind of failure with natural gas as well as hydrogen. Taking a few additional measures could further reduce the risks.

During an incident response, inflatable gas stoppers were placed at a safe distance from an outlet (depending on the wind direction and the related LEL limit, among other factors). In this practical test, a distance of 20 metres was chosen. The current stoppers are not suitable for application in hydrogen networks without the incorporation of additional measures. In fact, it appears that if even a limited leakage rate of hydrogen is ignited, a stopper can be ejected due to the intense ignition.

Measures to reduce the risks include applying two stoppers (block & bleed), applying forced ventilation in the working pit, and measuring the gas concentration near the pipe end. The effectiveness and feasibility of these measures will need to be further investigated. This report includes recommendations for gas stopper manufacturers, the Gastec QA Board of Experts, and regional grid operators.

Contents

1. Rationale

1.1 General

This research has been carried out within the framework of the national HyDelta research programme. The programme focuses on the safe integration of hydrogen into the existing gas transport and distribution infrastructure and aims to remove barriers that hamper innovative hydrogen projects. The complete research programme is divided into work packages. For an explanation of the various work packages, please visit www.hydelta.nl

This report covers the application of inflatable gas stoppers in the distribution network. Inflatable gas stoppers are also used in the transport network, but behind a 'stopple'. In this application, there is virtually no pressure differential across the stopper and the stopper is always part of a 'block & bleed' application.

1.2 Problem definition

In the current natural gas network, inflatable gas stoppers are used for cases such as temporary shutdowns (due to incidents or works on the gas network). It is not clear whether the current application of inflatable gas stoppers (procedures and resources) can be extended to hydrogen in the same way. This is mainly because of the differences in the properties of natural gas and hydrogen, such as density, flammability limits, burning rate and explosive force. Besides undesirable consequences such as fires and explosions, faster displacement of oxygen is also an aspect to be considered.

1.3 Objective

To determine whether inflatable inflatable gas stoppers are suitable as a fast temporary seal in a hydrogen distribution network.

1.4 Research questions

The main question as addressed in this report is as follows:

- Are inflatable gas stoppers, as they are currently applied in natural gas distribution networks, suitable for application in a hydrogen distribution network?

To answer the main question, the following sub-questions have been formulated:

- What are the leakage rates of inflatable gas stoppers, as they are currently used in the natural gas network, if they are applied in a hydrogen network?
- How should working procedures be adjusted?
- What is the maximum acceptable leakage rate when using inflatable gas stoppers in a hydrogen network in order to continue working safely in a working pit?
- How does a gas stopper behave in the case of direct ignition (fire) of leakage gas at the pipe end?
- How does a gas stopper behave in the case of an explosion in the working pit (different gas concentrations)?
- How does a gas stopper behave (when stopping the gas supply) if a fire is being extinguished by inflating the gas stopper?
- What ignition scenarios are conceivable when using inflatable gas stoppers? (theoretical research)
- What additional mitigating measures are feasible in order to prevent any undesirable effects of hydrogen ignition? (theoretical research)

2. Method

2.1 Approach to theoretical research

Several sources were examined for the theoretical research. The sections below outline the approach for each source. The results of this research are presented in Chapter 3.

Literature research into the use of inflatable gas stoppers.

Available literature was researched for information on the use of inflatable gas stoppers in combination with hydrogen, including the Kiwa report GT-200231 Safe Sectioning of Hydrogen Networks. An internet search was also conducted and the research available in ScienceDirect was reviewed.

Concise market research

The market was searched for suppliers of inflatable gas stoppers for hydrogen networks.

Leak tightness based on approval requirements

The approval requirements for inflatable gas stoppers are examined on the requirements for the leak tightness of inflatable gas stoppers.

Accidents involving inflatable gas stoppers

Two approaches at looking at possible accidents involving inflatable gas stoppers were considered. The first approach was to look for incidents where inflatable gas stoppers are indicated as a fault source in the accident reports. These reports are submitted to Kiwa by the network operators as part of the registration of incident reports for the “Kenniscentrum Gasnetbeheer”. Here, the period from 2003 onwards was considered.

The research above revealed virtually no incidents or experiences where the ignition of leaking gas had occurred. Therefore enquiries were made with grid operators concerning their other experiences with gas stopper faults in the natural gas network (the second approach). The results of these enquiries are summarised in Chapter 3.

2.2 Approach to leakage testing

In consultation with the Expert Assessment Group, it was decided to test two types of stoppers (Kleiss and Ipco), two pipe materials (PVC and PE), and four different diameters: 63, 110, 160 and 200 mm. Testing was done as much as possible on stoppers that were already in use, and which were provided by the various grid operators. Tests were conducted at pressures of 100 and 200 mbar, using both natural gas and hydrogen. This was not a leak tightness test as per KE 194 (which takes 30 minutes per test) as the following procedure was used. After the pipe section (about 1 metre in length) containing the pressurised stopper was placed under pressure using the relevant gas, the extent of the leakage was determined using a flow meter. While switching to a different gas, the stopper was deflated and re-pressurised in between.

2.3 Approach for determining the maximum flow rate at which concentration in the working pit remains <10% LEL

Two pipe sections (PVC, diameter 160 mm) were installed in a working pit on the Kiwa Technology site. The working pit was 1.7 metres by 1.2 metres (2 m^2) and had a depth of 1 metre. In the working pit, 12 measuring points were installed to determine the percentage of LEL. The size of the leakage was set using rotameters. The outdoor temperature and wind speed were recorded during the measurements. To eliminate any influence from the wind, a tent was placed above the working pit.

By measuring with different leakage rates, the maximum flow rate at which the gas concentration remained below 10% LEL was determined. This maximum flow rate was determined for both natural gas and hydrogen. A schematic representation of the test setup is shown below as well as some pictures of the field test.

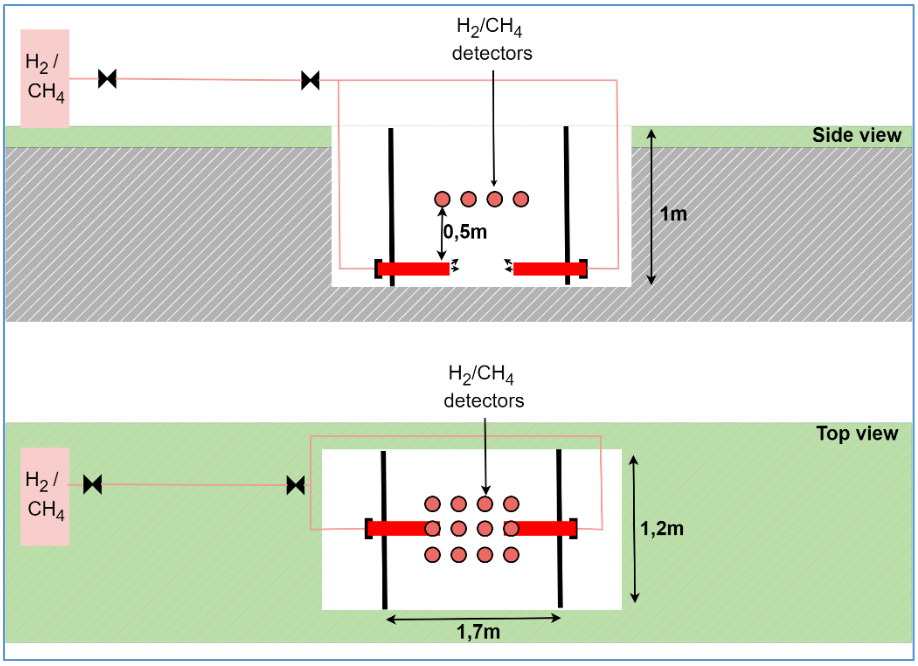


Figure 1 Schematic representation of measurement setup maximum flow rate at concentration <10% LEL

Photo 1 and Photo 2 The working pit and tent used to shield the wind

During the measurements, three of the four tent sides were completely closed. The other side was partially closed using the red screen as visible in the picture. When Chapter 4 mentions one side being half open, this refers to opening the section as indicated by the yellow arrows in the picture.

2.4 Instant ignition in the case of hydrogen or natural gas leakage

These measurements were carried out at the Twente Safety Campus site. The measurements took place above ground, using concrete blocks to create a working pit into which the gas pipeline flowed. The data recorded here and the measurement method are as follows:

- PE pipe with a diameter of 160 mm and SDR class 17.6
- The stopper was placed at two different distances from the working pit (1 metre and 20 metres)
- The stopper was made by Kleiss (the most commonly used in the Netherlands)
- During the measurement, the gas was supplied by a 1 metre pipe length via a stopper lance
- During the measurement, the gas was supplied by a 1 metre pipe length via a saddle.
- The direct ignition was carried out using a continuously active spark igniter at a short distance (2 cm) from the outlet of the PE pipe (160 mm).
- After ignition, the gas supply was manually stopped
- The temperature sensor was fitted between the stopper and the pipe (with the measurement point in the part of the pipe where the gas flowed)

The diagrams below show the direct ignition measurements performed.

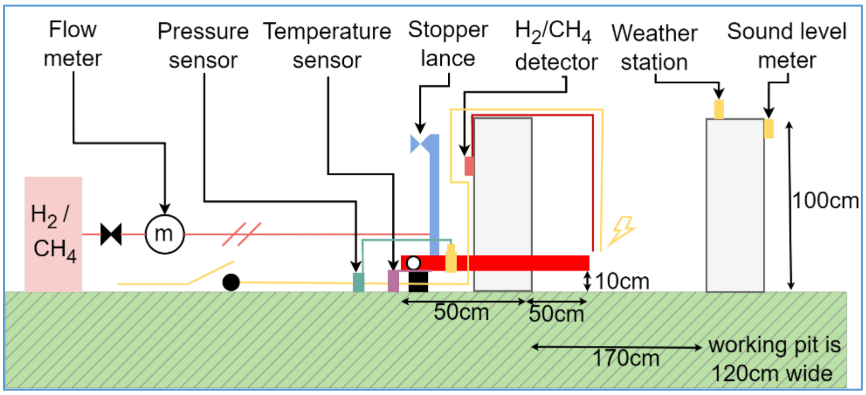


Figure 2 Direct ignition measurement setup with a pipe length of 1 metre

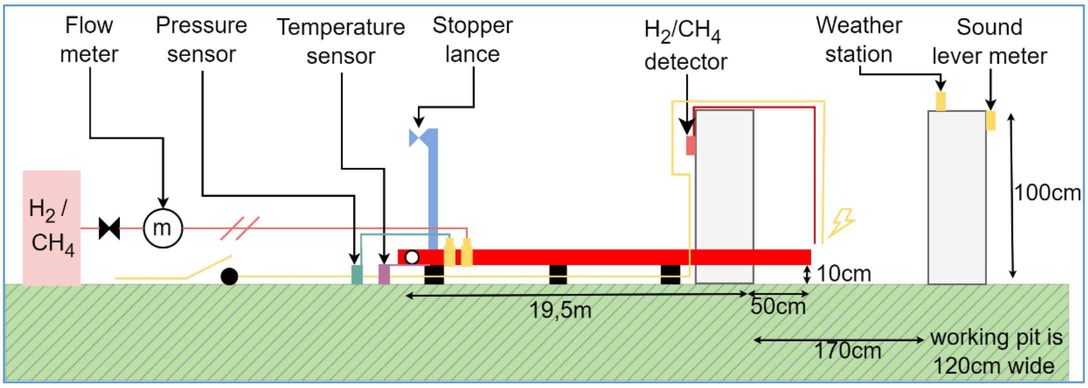


Figure 3 Direct ignition measurement setup with a pipe length of 20 metres

The following photos are of the field test.

Photo 3 The setup with the 1 metre pipe.

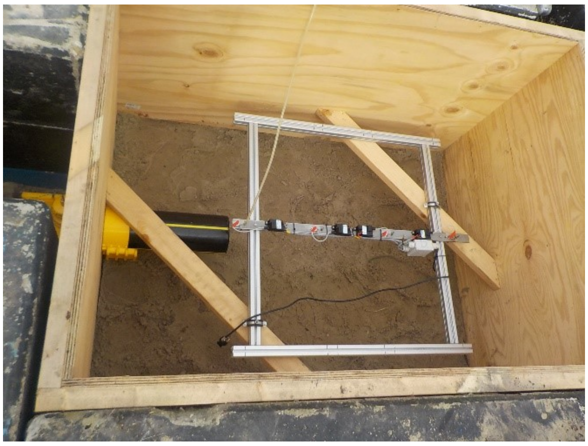


Photo 4 and Photo 5 The position of the spark igniters.

Photo 6 The setup with the 20 metre pipe

Photo 7 Overview of the working pit

An overview of all measurements carried out at the Twente Safety Campus can be found in Annex V.

N.B.

- For measurements 1 to 7 (direct ignition of natural gas and hydrogen, respectively), a rack with four spark igniters was used. This was also used for the delayed ignition measurements.
- In measurements 21 and 22 (direct ignition of hydrogen), a single spark igniter near the outlet was used.
- In the measurements with delayed ignition (measurements 8 to 20 and 23 to 37), the rack was placed at a higher position. See Photo 8 Raised positions of the spark igniters.

The value 0.15 m^3/h was chosen for the leakage rate of natural gas for measurements 1 and 2. This flow rate can lead to concentrations in the working pit of >10% LEL according to the results obtained from the measurements carried out as described in 2.3 (with leakage from two outlets). The chosen value of 0.15 m^3/h are therefore lower than the maximum according to QA 194 (which is 0.463 m^3/h of natural gas, for an explanation see 3.5) and equal to the natural gas flow rate to be expected based on the (stricter) QA criteria KE 214 (which is 0.15 m^3/h).

It was then decided to choose the flow rate for hydrogen at measurements 3 and 4 to be 3 times higher than the value for natural gas of 0.15 m^3/h, or a hydrogen flow rate of 0.45 m^3/h. A factor of 3 was the maximum under a purely turbulent flow of the leakage rate and therefore represents the worse case scenario.

For the measurement of direct ignition of a small leakage rate of natural gas in a 20 metre pipeline (measurements 5 and 6), it was decided to increase the flow rate to 0.20 m^3/h because at a flow rate of 0.15 m^3/h, no discernible concentration of natural gas could be measured at the outlet after 15 minutes of measurement. The value 0.20 m^3/h natural gas is still smaller than the maximum according to QA criteria 194 (which is 0.463 m^3/h, for an explanation see 3.5). Then, for measurements 7, 21 and 22, the flow rate for hydrogen was again chosen to be 3 times higher than the value used for natural gas, or a hydrogen flow rate of 0.60 m^3/h. Again, a factor of 3 was the maximum for a purely turbulent flow of the leakage rate and therefore represents the worse case scenario.

NB: the selected leakage rates for hydrogen (0.45 m^3/h and 0.60 m^3/h) are less than or equal to the maximum hydrogen leakage rate expected based on QA criteria 194 (0.6 m^3/h), but greater than the maximum hydrogen leakage rate expected based on QA criteria 214 (0.2 m^3/h). For further explanation, see also 3.5

In the context of this application, outside in an open working pit, a natural gas leak of <0.2 m^3/h and a hydrogen leak of <0.6 m^3/h can be considered a small gas leak.

2.5 Delayed ignition of hydrogen or natural gas leakage

These measurements were carried out at the Twente Safety Campus site. The measurements took place above ground, using concrete blocks to create a working pit into which the gas pipeline flowed. The data recorded here and the measurement method are as follows:

- PE pipe with a diameter of 160 mm and SDR class 17.6.
- The stopper was placed at two different distances from the working pit.
- The stopper was made by Kleiss (the most commonly used in the Netherlands).
- The gas was supplied through a saddle.
- The ignition was activated once the target gas concentrations were reached.
- After ignition, the gas supply was manually stopped.
- The temperature sensor was fitted between the stopper and the pipe (with the measurement point in the part of the pipe where the gas flowed).
- Ignition was achieved using four spark igniters positioned 60 cm above the bottom of the working pit, in line and above the pipe.

The measurement setup as used in the delayed ignition tests was largely similar to the measurement setup as used in the direct ignition tests. The main difference was the position of the igniters. In the delayed ignition tests, the igniters were placed at a greater distance from the outlet.

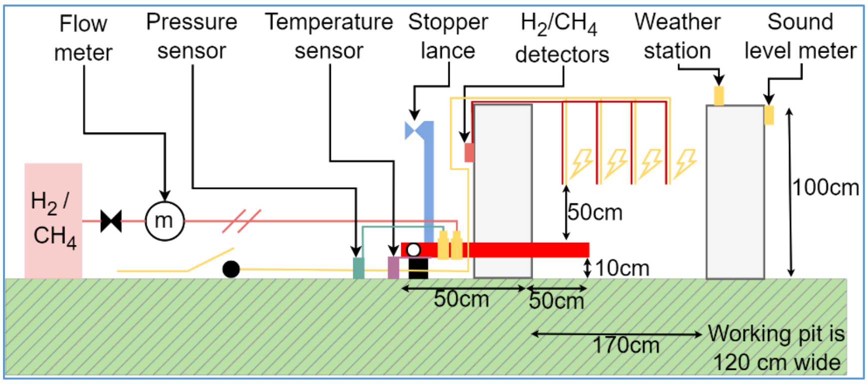


Figure 4 Measurement setup for delayed ignition with a pipe length of 1 metre

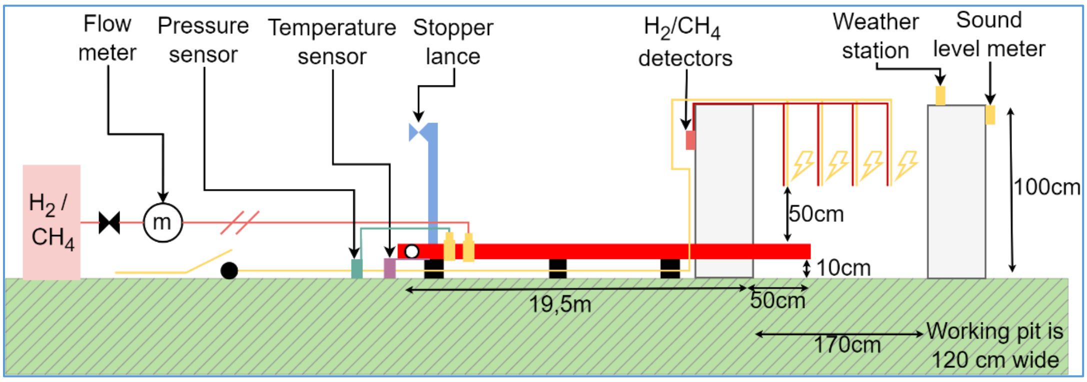


Figure 5 Measurement setup for delayed ignition with a pipe length of 20 metre

Photo 8 Raised positions of the spark igniters for the delayed ignition tests

2.6 Placement of a stopper after ignition of the hydrogen or natural gas

These measurements were carried out at the Twente Safety Campus site. The measurements took place above ground, using concrete blocks to create a working pit into which the gas pipeline flowed. The data recorded here and the measurement method are as follows:

- PE pipe with a diameter of 160 mm and SDR class 17.6.
- The stopper was placed 20 metres from the outlet.
- The stopper was made by Kleiss (the most commonly used in the Netherlands)
- The gas was supplied through a saddle.
- In the measurements with natural gas (40 to 42), the gas was ignited using a gas burner placed in the working pit. This was to prevent the spark igniter from melting. For measurements with hydrogen, the first measurement (43) in this series was performed using a gas burner, which was then switched to a spark igniter. For further explanation, see 4.5.2. When hydrogen is ignited with spark igniters, the spark is applied some time after the hydrogen is released.
- After ignition of the gas, the stopper was inflated.
- In these measurements, the temperature sensor was fitted in a saddle.

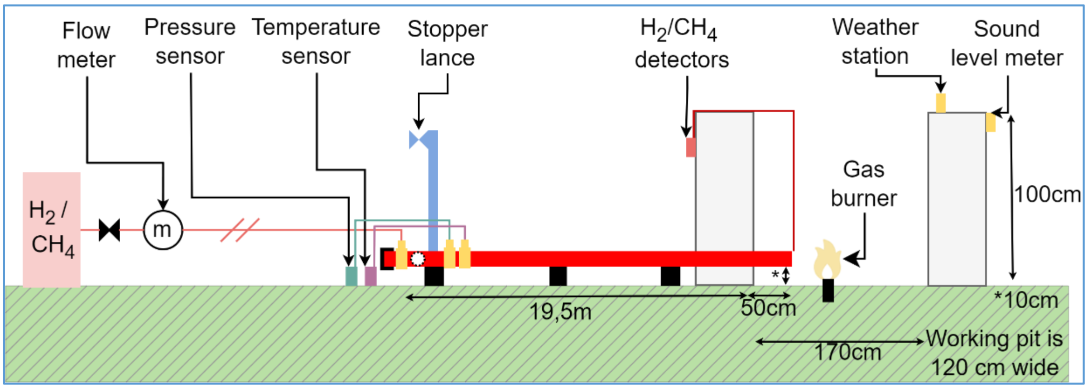


Photo 9 Measuring setup when extinguishing a gas fire

See the following pages for a few photos of the measurement setup.

Photo 10 and Photo 11 The measurement setup as used when setting a stopper in case of a gas fire.

Photo 11 shows the saddles containing the pressure sensor and temperature sensor

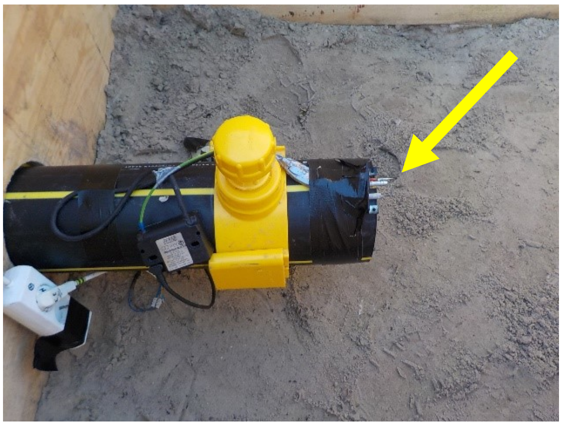


Photo 12 shows the position of the gas burner as the ignition source and Photo 13 shows the spark igniters as the ignition source

3. Literature review

3.1 Insight when using inflatable gas stoppers.

In today's low-pressure natural gas network (≤200 mbar), inflatable gas stoppers are commonly used for sectioning pipe sections and making pipes pressure/gas-free. Inflatable gas stoppers are temporary sealing devices that are balloon-shaped. They can be inserted into a pressurised gas pipe and then inflated to seal the pipe. The inflatable gas stoppers are used for various types of work, such as fitting or removing pipe sections or stopping the free flow of gas following a leak.

The Kiwa report GT-200231 Safe Sectioning of Hydrogen Networks [1] was reviewed. The main conclusions from this report were that with planned work, the risks with hydrogen are estimated to be equivalent to what is currently the case with natural gas. This includes the recommendation of flushing the pipe section to be worked on with nitrogen after setting the stoppers.

Another important recommendation from the report is to investigate the effects of small stopper leaks on gas concentrations in the gas pipeline, and therefore the likelihood of an explosive mixture forming. Since hydrogen has broader flammability limits[2] and a higher combustion rate than natural gas, the probability of ignition increases and the pressure can increase due to an ignition. This could cause a stopper to collapse, resulting in complete gas leakage.

During further research on the internet, one study was found that involved this research. DVGW conducted the study "H2STOP" [2]. In that study, inflatable gas stoppers were tested with natural gas, where hydrogen was blended with admixture levels between 0% and 50%. The applied pressures were 1 to 5 bar. The report concluded that inflatable gas stoppers could be safely used for mixed gases. What stood out was that it was only at 5 bar and with a high concentration of hydrogen that three times more hydrogen leaked than in the same test with 100% natural gas.

3.2 Concise market research

Concise market research was conducted. The results were that no other suppliers were found that provide inflatable gas stoppers tested for use in 100% hydrogen networks. Kleiss and IPCO's inflatable gas stoppers both have the hydrogen certificate based on approval requirement 214. These are also the only inflatable gas stoppers manufactured that have the QA certificate. Other international suppliers of inflatable gas stoppers, such as Hütz+Baumgarten, Städtler+Beck, PLCS and WASK do not have certification for approval requirement 214 or an equivalent certificate, or any other proof that those stoppers are hydrogen-resistant.

---

[2] *Groningen natural gas; LEL = 5.9% and UEL = 15.5%*
Hydrogen; LEL = 4.0% and UEL = 75%
LEL refers to the lower flammability limit. Below the lower flammability limit, there is insufficient fuel present to sustain a combustion reaction. LEL and LFL refer to the same lower flammability limit. For hydrogen, the LEL/LFL is 4 vol% hydrogen in air.
UEL refers to the upper flammability limit. Above the upper flammability limit, there is insufficient oxygen present to maintain a combustion reaction. UEL and UFL refer to the same upper flammability limit. For hydrogen, the UEL/UFL is 75 vol% hydrogen in air.
Kiwa uses the abbreviations LEL and UEL for the lower and upper flammability limits of a gas, respectively. Kiwa uses these abbreviations in order to stay in line with Dutch and European standards as well as to avoid any confusion of the concepts.

3.3 Ignition scenarios

The ignition scenarios are based on NPR 7910-1:2020. The reviewed incident reports and market research responses on gas stopper failure were also considered.

For how a gas/air mixture may be ignited in or near a working pit, the following sources were identified:

- *Hot surfaces*
  The auto-ignition temperature of hydrogen is 585°C (for natural gas it is 670°C). The likelihood of higher-temperature objects entering a working pit is small. However, the Prince Hendrikkade incident in Amsterdam (2020) could possibly have been initiated by an overheated surface in the electrofusion socket.
- *Open fires*
  The use of lighters, burners, etc. can lead to the ignition of hydrogen and natural gas.
- *Cigarettes*
  The temperature of a cigarette itself is a maximum of 400°C, making it essentially insufficient to ignite hydrogen or natural gas. However, when lighting a cigarette with a lighter, for example, there is enough energy to ignite hydrogen and natural gas. It is not known whether the sparking that occurs when discarding a cigarette can ignite hydrogen.
- *Wall heaters*
  This type of heater is becoming less and less common. If a natural gas network is converted to hydrogen, this type of heater will no longer be installed. In a district that is fully converted to hydrogen, the chances of this type of heater being able to lead to ignition would be zero. However, if a hydrogen distribution line is laid through a residential area, this possibility would still exist if a leakage occurs in the distribution line.
- *Static electricity (clothing, plastic pipe materials)*
  The amount of energy required to light hydrogen is much smaller than for natural gas, especially around the stoichiometric blend (for a stoichiometric blend, it is ±0.02 mJ versus ±0.3 mJ). As a result, static electricity generated by normal (especially plastic) clothing is enough to ignite hydrogen. Static electricity due to plastic pipe materials can also create a spark with sufficient energy. Without any mitigating measures, the risk of hydrogen ignition due to static electricity is certainly present.
- *Mechanically generated sparks (digging, stones in the ground, metal working/welding)*
  Mechanical sparks have more energy than static electricity and can therefore ignite hydrogen more easily, and within a wider concentration range, compared to natural gas. In particular, a lot of sparks are often produced when machining metal pipes. But excavation work (mechanical and manual) is also likely to produce a spark.
- *Electrical installations and tools*
  Sparks in electrical appliances and/or tools also have enough energy to easily ignite hydrogen and natural gas. Electrical equipment therefore constitutes a true source of ignition.
- *Lightning strikes*
  Lightning strikes involve high voltages and temperatures that can cause hydrogen and natural gas to easily ignite.
- *Cathodic protection stray currents and protective current*
  Electricity currents due to stray currents from, for example, high-voltage power lines or protective currents from lines under active cathodic protection can, under certain conditions, provide sparks with sufficient energy to ignite hydrogen and natural gas.
- *Mobile phones*

For the most part, mobile phones are considered potential ignition sources. However, the report "Behaviour of hydrogen in the case of leakage in the distribution network" [3] states that the probability of ignition by a mobile phone is highly unlikely.

- *Other ignition sources*
  There are a number of other potential ignition sources, but these would not lead to a hazardous situation in practice when working with hydrogen (or natural gas) in the distribution network. This includes the following ignition sources:
    - High-frequency electromagnetic waves
    - Electromagnetic waves
    - Ionising radiation (X-rays)
    - Ultrasonic waves
    - Adiabatic compression and shock waves
    - Exothermic reaction, including auto-ignition

3.4 Research into gas stopper failure in practice

Accident registration with "Kenniscentrum Gasnetbeheer"

Incidents where a gas stopper failed and led to an incident have been researched. These kinds of incidents are also reported to Kiwa as part of accident registration within the "Kenniscentrum Gasnetbeheer". Appendix II shows the descriptions for each incident. A total of six situations were reported, two of which involved leaking gas at a stopper. The stoppers that do not work well mainly concern those that have larger diameters (DN 150 or larger).

Incident reports via network operators

When looking at the results in the previous section, it should be noted that these only include the reports that require notification according to the requirements of SODM (Dutch regulator). To get an idea of the remaining reports, a questionnaire was circulated to all grid operators with questions pertaining to incidents involving gas stopper failures. Every grid operator responded and a total of 15 notifications were returned. Two (smaller) grid operators were not aware of any incidents involving gas stopper failure. table 1 shows the results of the causes and the type of gas stopper failures.

Table 1: Cause and type of defect of failed inflatable gas stoppers

Cause:	**Type of defect**						**Total**	
	Stopper detached		**Stopper snapped**		**Leakage around stopper**			
External heat load			1	7%	1	7%	2	13%
Excessive pressure			1	7%			1	7%
Pipeline contamination			2	13%	3	20%	5	33%
Excessive flow			2	13%			2	13%
Age/quality of stopper			2	13%			2	13%
Stopper contamination	2	13%					2	13%
Unknown	1	7%					1	7%
Total	**3**	**20%**	**8**	**53%**	**4**	**27%**	**15**	**100%**

Table 2 shows the causes of gas stopper failure in relation to the type of failure of the failed stopper.

The consequences of stopper failure can be divided into two categories. The first category concerns negligible impact. This was mainly because a pipe had not yet been cutted through or an end cap had been placed behind the stopper. In the second category, gas was able to flow out freely, in one case leading to a fire and also on a number of occasions to very large flows of gas that were also difficult to stop with a new stopper.

In this context, it is worth noting that a grid operator sent some 20 malfunctioning stoppers to Kiwa for assessment as part of a project conducted by the "Kenniscentrum Gasnetbeheer". A report of this study is not yet publicly available. Essentially, the bottom line is that the grid operator in question had to deal with leaking inflatable gas stoppers starting in the summer of 2021. The causes of these leaks varied: cracked stoppers, partially cracked stoppers at the press coupling, leaks on the coupling for the stopper lance and a leak on a measuring rod. In practice, these kinds of leaks should or would be identified by a stopper guard that is responsible for monitoring the pressure in the stopper when a placed stopper is present. In any case, these findings show that stopper leakage cannot be ruled out.

Table 2 Effect vs type of failure of failed inflatable gas stoppers

Consequence	**Type of defect**						**Total**	
	Stopper detached		**Snapped**		**Leakage around stopper**			
	Quantity	Perc.	Quantity	Perc.	Quantity	Perc.	Quantity	Perc.
Minimum (Cat. I)	3	20%	4	27%	2	13%	9	60%
Large gas outlet (Cat. II)			4	27%	1	7%	5	33%
Unknown					1	7%	1	7%
Total	**3**	**20%**	**8**	**54%**	**4**	**27%**	**15**	**100%**

3.5 Gastec QA criteria

There are Gastec QA criteria for temporary shut-off elements for gas pipelines, such as stoppers. These are described in KE 194 (February 2019). It stipulates that the leakage between the sealing element and pipe should not exceed 0.3 m^3/h when applied outside of a building. The test on whether this requirement is met was carried out at pressures of 100 and 200 mbar. The test was conducted in both a ductile iron pipe and a PE pipe that was pressed 10% oval at the stopper location. Although not named in the criteria, Kiwa Netherlands has indicated that these tests were carried out with air. For application with hydrogen, additional QA criteria are described in KE 214 (September 2022) where a requirement of 0.1 m^3/h is applied. For more on the implementation of the experiments, see KE 194. Testing therefore took place at pressures of 100 and 200 mbar and using air as the medium.

The leakage rates as determined with air will be higher when natural gas and hydrogen are used due to the difference in viscosity, assuming laminar flow. For conversion from air to natural gas, a factor of 1.54 applies. For conversion from air to hydrogen, this factor is 2.00. For further explanation, see the HyDelta report D1C.2, distribution pipeline density [4]
The quoted value of 0.3 m^3/h, determined with air, corresponds to a natural gas leakage of 0.3 * 1.54 = 0.463 m^3/h. This is based on laminar flow. For hydrogen, this would be a leakage of 0.6 m^3/h.

The value of 0.1 m^3/h mentioned that is determined with air corresponds to a hydrogen leakage of 0.1 * 2.00 = 0.200 m^3/h. For a natural gas leak, this would correspond to a value of 0.1 * 1.54 = 0.154 m^3/h. This is based on laminar flow.

4. Measurement results and findings

4.1 Leak tightness

The tests in 4.1 aim to establish what the leakage rates of inflatable gas stoppers would be, as they are currently used in the natural gas network, if they were applied in a hydrogen network. The results of the leakage measurements, carried out using the method described in section 2.2, have been summarised in table 3.

The leak-tightness limit when using natural gas is 0.463 m^3/h (based on 0.3 m^3/h with air, for an explanation see section 3.5. The leak-tightness limit when using hydrogen is 0.2 m^3/h (based on 0.1 m^3/h with air, for an explanation see section 3.5). If a measured value did not meet the limits listed, the measured value has been highlighted in orange.

Table 3 Measured leakage rates on stoppers already in service from the company Kleiss

External diameter (mm)	Internal diameter (mm)	Material	Stopper manufacturer	Natural gas leakage rate (m^3/h)		Hydrogen leakage rate (m^3/h)		Ratio hydrogen/natural gas	
				100 mbar	200 mbar	100 mbar	200 mbar	100 mbar	200 mbar
63	59	PVC	Kleiss	0.000	0.000	0.000	0.000	n/a	n/a
63	56	PE	Kleiss	0.000	0.000	0.000	0.000	n/a	n/a
110	104	PVC	Kleiss	0.000	0.000	0.001	0.001	n/a	n/a
110	90	PE	Kleiss	0.000	0.000	0.001	0.001	n/a	n/a
160	152	PVC	Kleiss	0.000	0.000	0.000	0.000	n/a	n/a
160	142	PE	Kleiss	0.000	0.000	0.000	0.000	n/a	n/a
200	190	PVC	Kleiss	0.001	0.001	0.001	0.001	n/a	n/a
200	177	PE	Kleiss	0.001	0.001	0.001	0.001	n/a	n/a
The stoppers tested had the following characteristics: Juva / MDS B500 D1(P3) - Ø 60-80 mm - test date 22-02-17 /04 Rendo/ MDS B500 D2(P3) - Ø 80-120 mm - test date 02-03-19 /28 Juva / MDS B500 D3(P3) - Ø 120-170 mm - test date 21-02-17 /13 Liander / MDS B500 D4(P3) - Ø 140-215 mm - test date 09-03-05									

Table 4 Measured leakage rates on stoppers already in service from the company Ipco

External diameter (mm)	**Internal diameter (mm)**	**Material**	**Stopper manufacturer**	**Natural gas leakage rate (m^3/h)**		**Hydrogen leakage rate (m^3/h)**		**Ratio hydrogen/natural gas**	
				100 mbar	200 mbar	100 mbar	200 mbar	100 mbar	200 mbar
63	59	PVC	IPCO	0.036	0.053	0.078	0.140	2.2	2.6
63	56	PE	IPCO	0.053	0.092	0.092	0.176	1.7	1.9
110	104	PVC	IPCO	0.032	0.058	0.050	0.096	1.6	1.7
110	90	PE	IPCO	0.032	0.065	0.055	0.099	1.7	1.5
160	152	PVC	IPCO	0.091	0.153	0.210	0.419	2.3	2.7
160	142	PE	IPCO	0.109	0.173	0.244	0.463	2.2	2.7
200	190	PVC	IPCO	0.051	0.102	0.082	0.174	1.6	1.7
200	177	PE	IPCO	0.095	0.159	0.134	0.295	1.4	1.9
The stoppers tested had the following characteristics: Liander / 210730.03 - 50 mm - int. diam. 50-60 mm - date in use 5-2-21 Enexis / 204532.88 - 100 mm - int. diam. 100-108 mm - date in use 8-2020 Stedin / 150 - 23 Feb 2019 Supplied new / 10-225314.02 - 200mm - int. diam. 190-209 mm (a new stopper was tested since the two stoppers supplied could not be pressurised).									
The DN 150 stopper from Ipco was an (old) stopper without a Gastec QA quality mark. This measurement shows that stoppers without Gastec QA are not suitable for use with hydrogen.									
For the 100 mm stopper, the tested internal diameter at PE (90 mm) deviates from Ipco's statement (100-108 mm). For the 200 mm stopper, the tested internal diameter at PE (177 mm) deviates from Ipco's statement (190-209 mm).									

Sub-conclusions

- All tested Kleiss stoppers were leak tight, both with natural gas and hydrogen.
- All tested Ipco stoppers showed some leakage, both with natural gas and hydrogen.
- With Ipco stoppers, the leakage in PE pipes was slightly higher than in PVC pipes of the same diameter.
- For the Ipco stoppers, the hydrogen leakage at the DN 150 and DN 200 pipeline was greater than the limit set in KE 214.
- Outdated Ipco stoppers, without a Gastec QA quality mark, are not suitable for use with hydrogen.
- For most of the measurements, the hydrogen to natural gas leakage ratio for Ipco stoppers increased at higher pressures (200 mbar compared to 100 mbar).

4.2 Maximum flow rate at which concentration is <10% LEL

The tests in 4.2 aim to determine the maximum acceptable leakage rate when using inflatable gas stoppers in a hydrogen network in order to still work safely in a working pit. In finding the flow rate at which the concentration of gas in the working pit is <10% LEL, the measurements were made as listed in table 5. A natural gas flow rate of 0.25 m^3/h, divided between two stoppers, was started. This is a quarter of the maximum natural gas flow rate resulting from the minimum density requirement in KE 194 (two stoppers each with a leakage of 0.463 m^3/h of natural gas). As the gas concentrations during the measurements per measurement point fluctuated a lot (from 40% LEL to 0% LEL) and the differences between the measurement points were large, it was chosen to measure at four different natural gas flow rates in the range from 25 to 100% of the maximum allowable leakage of 2 stoppers.

For the hydrogen leakage measurements, we decided to choose three hydrogen flow rates that were approximately equal to the natural gas flow rates used in the measurements for natural gas leakage (measurements 5, 6 and 7). A hydrogen flow rate of 1.81 m^3/h was also chosen. That flow rate is twice the natural gas flow rate in measurement 4. Indeed, at the same leakage opening, the leakage rate of hydrogen is about twice that of natural gas.

During the implementation of measurement series 1 to 8, it was found that maximum concentrations were significantly lower when half of one side of the tent was opened. To also take measurements with some ventilation of the working pit, two measurement series were also carried out (9 and 10) without using a tent. In practice, no tent would be placed over the working pit during this type of work. The test conditions without a tent can still be considered the worst case scenario as there was virtually no wind.

Table 5 Representation of measured maximums at different conditions

<table>
<tr><th>Series</th><th>Medium</th><th>Total leakage rate</th><th>Leakage rate per stopper</th><th colspan="3">Tent closed – maximum % LEL *</th><th>1 side half open – maximum % LEL</th></tr>
<tr><td></td><td></td><td>(m^3/h)</td><td>(m^3/h)</td><td>Measurement 1</td><td>Measurement 2</td><td>Measurement 3</td><td>Measurement 4</td></tr>
<tr><td>1</td><td>Natural gas</td><td>0.25</td><td>0.12</td><td>32</td><td>28</td><td>30</td><td>35</td></tr>
<tr><td>2</td><td>Natural gas</td><td>0.60</td><td>0.30</td><td>46</td><td>46</td><td>48</td><td>44</td></tr>
<tr><td>3</td><td>Natural gas</td><td>0.11</td><td>0.06</td><td>22</td><td>16</td><td>18</td><td>8</td></tr>
<tr><td>4</td><td>Natural gas</td><td>0.91</td><td>0.45</td><td>54</td><td>52</td><td>54</td><td>46</td></tr>
<tr><td>5</td><td>Hydrogen</td><td>0.24</td><td>0.12</td><td>20</td><td>26</td><td>24</td><td>8</td></tr>
<tr><td>6</td><td>Hydrogen</td><td>0.59</td><td>0.29</td><td>50</td><td>50</td><td>50</td><td>20</td></tr>
<tr><td>7</td><td>Hydrogen</td><td>0.98</td><td>0.49</td><td>66</td><td>58</td><td>62</td><td>54</td></tr>
<tr><td>8</td><td>Hydrogen</td><td>1.81</td><td>0.90</td><td>100</td><td>100</td><td>100</td><td>50</td></tr>
<tr><td>9</td><td>Hydrogen</td><td>0.29</td><td>0.15</td><td colspan="4">Without tent; at 2 middle measurement points fluctuation % LEL between 2 and 15%. 7% of these readings involved a concentration >10% LEL.</td></tr>
<tr><td>10</td><td>Natural gas</td><td>0.15</td><td>0.07</td><td colspan="4">Without tent; at 2 middle measurement points fluctuation % LEL between 2 and 15%. 3% of these readings involved a concentration >10% LEL.</td></tr>
<tr><td colspan="8"><u>10% LEL is 0.59% natural gas</u>
<u>10% LEL is 0.40% hydrogen</u></td></tr>
<tr><td colspan="8"><u>Notes on series 1 to 8 - shielding with a tent</u>
For each series, three readings of 6 minutes each. A new measurement within a series was started (opening gas supply) after concentrations at all measurement points dropped to zero.
At the end of the series, a measurement with one side of the tent half open (top) and gas supply was also conducted.
<u>Notes on series 9 and 10 - without a tent</u>
One series involved a measurement of a total of 30 minutes (concentration measurements every 10 seconds)</td></tr>
<tr><td colspan="8">During all of the measurement series, the wind force was quiet to very weak</td></tr>
<tr><td colspan="8">*The highest 10 measured values are close to this number. For graphical representation by series, see Appendix IV</td></tr>
</table>

These measurements are shown in graphs by series in Appendix IV.

Reviewing the graphs as presented in Appendix IV, it is noticeable that the outer measurement points in the ring of the working pit (Figure 1) tend to show lower concentrations in the case of hydrogen compared to an equal flow rate of natural gas. To provide insight into this, Tabel 23 has been included, which shows the total number of measured values as well as the number of measured values equal to 0% LEL, >0% LEL and >10% LEL. Here, a distinction was made between measurement points in the ring (all measurement points except B2 and C2 in Photo 14) and middle measurement points (B2 and C2 in Photo 14).

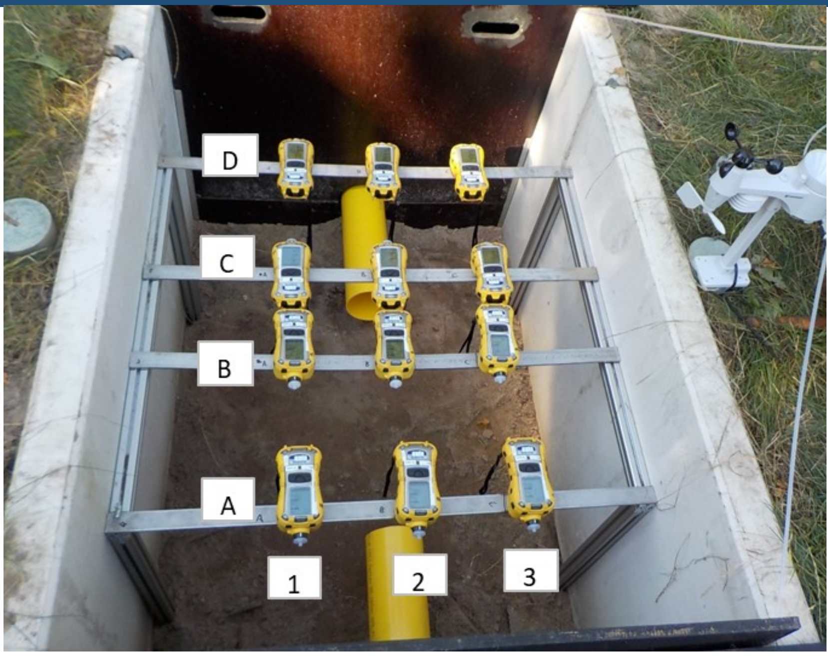


Photo 14 Distribution and coding of the 12 measuring points in the working pit

At a similar flow rate, the percentage of the number of measurement points with a measurement value in the outer ring of the working pit that exceeds the 10% LEL value is higher with natural gas compared to hydrogen. In table 6, this is visualised by showing the distribution of the number of measurement points within a given concentration range in colour. This makes it easy to see that hydrogen is more concentrated in the centre of the working pit than natural gas, and that natural gas is more dispersed over the surface of the working pit.

Appendix IV contains a table with the underlying data. This also shows that the percentage of measurement points >10% LEL in the outer ring of the working pit is higher for natural gas than for hydrogen.

Table 6 Distribution of concentrations in the working point based on number of measured values per concentration range

Natural gas, with tent			Hydrogen, with tent			Natural gas and hydrogen, without tent		
1%	1%	1%	0%	3%	4%	1%	1%	4%
5%	14%	5%	10%	29%	15%	1%	3%	1%
1%	7%	5%	5%	17%	6%	1%	3%	0%
1%	0%	0%	1%	2%	1%	0%	0%	0%
0.11 m^3/h			0.24 m^3/h			Natural gas 0.15 m^3/h		
51%	13%	6%	<>	1%	3%	0%	1%	0%
29%	54%	26%	3%	59%	17%	2%	17%	1%
26%	48%	26%	5%	49%	6%	1%	13%	1%
11%	15%	3%	1%	0%	1%	0%	1%	0%
0.25 m^3/h			0.59 m^3/h			Hydrogen 0.29 m^3/h		
23%	28%	27%	<>	4%	3%			
42%	57%	44%	13%	78%	26%			
33%	53%	37%	6%	71%	13%			
11%	17%	7%	0%	1%	0%			
0.60 m^3/h. With tent.			0.98 m^3/h					
7%	13%	18%	<>	0%	7%			
20%	49%	33%	3%	76%	27%			
25%	34%	33%	5%	53%	25%			
5%	10%	9%	0%	1%	0%			
0.91 m^3/h			1.81 m^3/h					

LEGEND

(green)	<5% of measured values is greater than 10% LEL
(yellow)	5-25% of measured values is greater than 10% LEL
(orange)	25-50% of measured values is greater than 10% LEL
(red)	>50% of measured values is greater than 10% LEL
<>	No data

Sub-conclusions

- The highest concentrations were measured in the centre of the working pit.
- Natural gas spreads more throughout the working pit as compared to hydrogen. In other words, hydrogen is more concentrated in the centre of the working pit.
- At a natural gas leakage rate of 0.15 m^3/h, concentrations >10% LEL[3] can occur.
- At a hydrogen leakage rate of 0.29 m^3/h, concentrations >10% LEL[4] can occur.

4.3 Instant ignition in the case of hydrogen or natural gas leakage

The tests in 4.3 aim to establish how a gas stopper behaves in the event of direct ignition of leak gas near the outlet.

4.3.1 Direct ignition of natural gas - 1 metre

The measurement was carried out twice with a natural gas flow rate of 0.15 m^3_n/h where the supply of natural gas was via the stopper lance. The ignition of the natural gas was not audible. But in both of these measurements, a few minutes after the gas was supplied, a loud bang occurred. The gas stopper appeared to have snapped. Shortly afterwards, the gas supply stopped. The gas supply is not stopped after the ignition of the natural gas but after the stoppers snapped.

In the second measurement, natural gas was ignited twice. (see Appendix **Fout! Verwijzingsbron niet gevonden.**). The stopper snapped with the second ignition.

Table 7 Direct ignition natural gas with stopper 1 m away

	Measurement 1	**Measurement 2**
Medium	Natural gas	Natural gas
Pipe length (m)	1	1
Flow rate (m^3_n/h)	0.15	0.15
Max. concentration of natural gas (vol%) at the outlet	1.0 *	100 *
Temperature at stopper (max.) – (°C)	324	174 (ignited twice)
Sound level - LAF max - (dBa)	114.5	115.0
Pressure near stopper (max.) – (bar)	- **	- **
Ambient temperature (°C)	17.4	14.9
Wind speed (m/s)	0.5	0.4
Video observations outside the working pit	The stopper snapped	The stopper snapped
Video observations inside the working pit	No ignition visible	No ignition visible
Condition of stopper after removal	Stopper ruptured, a hole was visible. Damage due to melting was visible at the lance coupling.	Stopper ruptured, a hole was visible. Damage due to melting was visible at the lance coupling.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	No	No
**The concentration was recorded every 10 seconds. The continuously present ignition source (sparks) explains the difference between the measured values. **A pressure measurement was not possible with these measurements. The quick-response pressure gauge can only log 10 seconds and needs to be reactivated. As a result, the moment of the bang could not be recorded.*		

[3] 100% LEL = 5.9% Groningen natural gas
[4] 100% LEL = 4.0% hydrogen

Sub-conclusion:
During direct ignition of an interrupted natural gas pipeline, where the stopper was about 1 m away from the interruption, the stoppers failed due to ignition of leakage gas flow. In this, the leakage was targeted on the stopper.
It was concluded that in case of ignition of natural gas leaking past a stopper placed at a short distance (about 1 m) from the pipe breakage, this stopper will snap due to the permanently present flame.

4.3.2 Direct ignition of hydrogen - 1 metre

The measurements were carried out twice with a hydrogen flow rate of 0.45 m^3_n/h where the supply of hydrogen was via the stopper lance. The ignition of the hydrogen was quite audible in these two measurements. In the first measurement, ignition took place about 20 seconds after the hydrogen was supplied; in the second measurement, it was about 15 seconds after opening the hydrogen supply. After the audible ignitions, the gas supply is manually stopped. The inflatable gas stoppers were both found to be intact afterwards.

Table 8 Direct ignition hydrogen with stopper 1 m away

	Measurement 3	**Measurement 4**
Medium	Hydrogen	Hydrogen
Pipe length (m)	1	1
Flow rate (m^3_n/h)	0.45	0.45
Max. concentration of hydrogen (%) at the outlet	86*	14*
Temperature at stopper (max.) – (°C)	33	128
Sound level - LAF max - (dBa)	-	-
Pressure near stopper (max.) – (bar)	-**	-**
Ambient temperature (°C)	14.2	14.0
Wind speed [m/s]	0.3	0.4
Video observations outside the working pit	Audible ignition (limited sound)	Audible ignition (limited sound)
Video observations inside the working pit	Audible ignition (limited sound)	Audible ignition (limited sound)
Condition of stopper after removal	Some damage due to melting at lance coupling	No discrepancies
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Yes	Yes

**The concentration was recorded every 10 seconds. The continuously present ignition source (sparks) explains the difference between the measured values.*
***A pressure measurement was not possible with these measurements. The quick-response pressure gauge can only log 10 seconds before it needs to be reactivated. As a result, the moment of the bang could not be recorded.*

Sub-conclusion:
Upon direct ignition of an interrupted hydrogen line, where the stopper was about 1 m away from the interruption, audible ignition of the leakage gas flow occurred. Because of this phenomenon, the hydrogen supply is manually stopped, which also stopped the combustion process. If the supply (the leakage) had remained in place, the stopper could also have snapped as with natural gas. The latter is based on the observed damage due to melting after one of these measurements.

4.3.3 Direct ignition of natural gas – 20 metres

The measurement was carried out twice at a flow rate of 0.20 m^3_n/h with the supply of natural gas at a distance of 30 cm from the stopper. In the first measurement, after 15 minutes, no concentration increase was detectable near the outlet. For this reason, an additional measurement point was installed to measure the gas concentration inside the pipe (inside the pipe at a distance of 0.6 metres from the outlet). In this measurement, a total of eight increases and eight subsequent sudden decreases in concentrations were observed at the site of the measurement point in the pipe after 18 minutes after opening the gas supply (see graph in Appendix VII, data measurement series 6).

No ignitions were observed in the two measurements (no sound or flame). To visually observe any ignition, a paper strip was attached near the outlet (at measurement no. 5 and measurement no. 6). This was found to be partially burnt during measurement 6. The temperature measurement (see Appendix **Fout! Verwijzingsbron niet gevonden.**, measurement 6) shows that the gas in the pipe had ignited several times.

At the end of measurement 6 (duration 60 minutes), the pipe was perceptibly warm over a length of 5 metres from the outlet opening.

Table 9 Direct ignition natural gas with stopper 20 m away

	Measurement 5	Measurement 6
Medium	Natural gas	Natural gas
Pipe length (m)	20	20
Flow rate (m^3_n/h)	0.20	0.20
Max. natural gas concentration (%) – outlet opening	0	5
Max. concentration of natural gas (%) – at the top of the pipe at 0.6m from outlet opening	-	24
Temperature at stopper (max.) – (°C)	< 20	81
Sound level - LAF max - (dBa)	90.1	84.3
Pressure near stopper (max.) – (bar)	- **	- **
Ambient temperature (°C)	12.0	15.2
Wind speed [m/s]	0.3	0.3
Video observations outside the working pit	No details	No details
Video observations inside the working pit	No details	Paper moved occasionally and burned away slowly
Condition of stopper after removal	Assessment after measurement 6	No discrepancy.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 6	Yes
***A pressure measurement was not possible with these measurements. The quick-response pressure gauge can only log 10 seconds before it needs to be reactivated. As a result, the moment of the bang could not be recorded.*		

<u>Sub-conclusions:</u>
Based on the concentration increases and sudden decreases in gas concentrations and burning of the paper strip at the outlet, it was concluded that quiet ignitions occurred inside the pipe. Because a constant ignition source was present, the natural gas in the pipe ignited up to eight times. A single ignition proved unable to keep the leaking natural gas permanently burning. The stoppers were not affected.

It was concluded that when ignition of natural gas leakage flow of about 0.2 m^3_n/h leaks past a stopper placed at a greater distance (about 20 m) from the pipe breakage, this stopper will remain intact because the combustion process in the pipe is not sustained.

4.3.4 Direct ignition of hydrogen - 20 metres

The measurement was performed three times at a flow rate of 0.60 m^3_n/h with the supply of gas at a distance of 30 cm from the stopper. In the first measurement, a considerable rumbling could be heard after 15 minutes. In the next two measurements, a very audible ignition took place after about 10 minutes. The pipe did not become noticeably warmer on the outside. In the first measurement, the stopper was unaffected; in the second and third measurements, it broke.

Table 10 Direct ignition hydrogen with stopper 20 m away

	Measurement 7	**Measurement 21***	**Measurement 22***
Medium	Hydrogen	Hydrogen	Hydrogen
Pipe length (m)	20	20	20
Flow rate (m^3_n/h)	0.60	0.60	0.60
Max. concentration of hydrogen (%) – outlet	7	1	3 with peak at end of 11
Max. concentration of hydrogen (%) – at the top of the pipe at 0.6 m from outlet opening	>100% LEL	>100% LEL	>100% LEL
Temperature at stopper (max.) – (°C)	270	85	-
Sound level - LAF max - (dBa)	131.3	129.2	133.2
Pressure near stopper (max.) – (bar)	- **	-**	3.4
Ambient temperature (°C)	14.5	13.2	14.7
Wind speed (m/s)	0.0	0.3	0.3
Video observations outside the working pit	Intense ignition observed	Intense ignition observed	Intense ignition observed, stopper shot out of pipe
Video observations inside the working pit	Intense ignition observed	Intense ignition observed	Intense ignition observed, stopper shot out of pipe
Condition of stopper after removal	No discrepancy	The connection piece on the ball had come loose from the connection pipe	The balloon detached from the connection
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Yes	No	No

**Measurements 21 and 22 took place on a different day from measurement 7.*
***A pressure measurement was not possible with these measurements. The quick-response pressure gauge can only log 10 seconds before it needs to be reactivated. As a result, the moment of the bang could not be recorded.*

<u>Sub-conclusions:</u>

With a relatively small hydrogen leak (0.6 m^3_n/h) near a gas stopper at a distance of 20 metres from the pipe breakage and the presence of an ignition source, a violent ignition occurred, causing the stopper to fail. The conclusion is that for a hydrogen pipeline, the current stoppers are not suitable as a seal for situations where the stopper is placed at a large distance from the outlet.

NB: the stoppers as used in the test appear to be virtually leak tight. Thus, the applied leakage rate of 0.6 m^3/h does not correspond to the observed leakages from the respective stoppers. In practice, leaks cannot be ruled out due to contamination or damage in the pipe. In addition, after stopping the uncontrolled gas flow, some gas will remain in the pipe for a while. This means that there will be a gas/air mixture in the pipe at some point as created in this test.

4.4 Delayed ignition of hydrogen or natural gas leakage

The tests in 4.4 aim to establish how a gas stopper behaves in the event of an ignition in the working pit.

4.4.1 Delayed ignition of natural gas - 1 metre

These measurements were carried out six times, where the ignition was activated as soon as a concentration of 5%, 10% and 15% natural gas in the air was reached at one of the four measurement points in the working pit, respectively (note; at a distance of 0.5 metres higher than the top of the pipe). Two measurements were taken for each concentration. The measured concentrations are listed in Appendix VII and the measured temperatures at the stopper in Appendix **Fout! Verwijzingsbron niet gevonden.**.

The ignition of the released gas was quiet. After the gas was ignited, the supply was manually stopped. The gas from the pipe then burned away quietly at all six readings.

Table 11 Delayed ignition of natural gas with a stopper 1 metre away, concentration of natural gas >5%.

Guideline 5%	**Measurement 9**	**Measurement 10**
Medium	Natural gas	Natural gas
Pipe length (m)	1	1
Flow rate (m^3_n/h)	3	4
Max. conc. of natural gas in the working pit (%)	9 (quite a sudden increase)	7
Temperature at stopper (max.) – (°C)	59	149
Sound level - LAF max - (dBa)	88.6	73.7
Pressure near stopper (max.) – (bar)	< 0.02	< 0.02
Ambient temperature (°C)	15.0	17.0
Wind speed [m/s]	0.2	0.3
Video observations outside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas
Video observations inside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas
Condition of stopper after removal	Assessment after measurement 10.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 14.	Assessment after measurement 14.

In the next two measurements, ignition occurred after a concentration >10% natural gas was observed for the first time. Compared to the previous measurements, the flame in the working pit was, logically, significantly larger. The temperature as observed at the stopper also increased substantially with the temperature rising more slowly (see Appendix **Fout! Verwijzingsbron niet gevonden.**, measurement 11 and 12). The temperature rise was slower compared to measurements 9 and 10. The stopper remained intact.

Table 12 Delayed ignition of natural gas with a stopper 1 metre away, concentration of natural gas >10%.

Guideline 10%	Measurement 11	Measurement 12
Medium	Natural gas	Natural gas
Pipe length (m)	1	1
Flow rate (m^3_n/h)	7	7
Max conc. of natural gas in the working pit (%)	13.9	12.3
Temperature at stopper (max.) – (°C)	230	349
Sound level - LAF max - (dBa)	98.8	83.8
Pressure near stopper (max.) – (bar)	< 0.02	< 0.02
Ambient temperature (°C)	16.4	16.0
Wind speed (m/s)	0.3	0.3
Video observations outside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas
Video observations inside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas
Condition of stopper after removal	Assessment after measurement 12.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 14.	Assessment after measurement 14.

In the next two measurements, ignition occurred after a concentration >15% natural gas was observed for the first time. The temperature as observed at the stopper also increased significantly in one of these measurements (see Appendix **Fout! Verwijzingsbron niet gevonden.**, measurement 14). The stopper remained intact.

Table 13 Delayed ignition of natural gas with a stopper 1 metre away, concentration of natural gas >15%.

Guideline 15%	Measurement 13	Measurement 14
Medium	Natural gas	Natural gas
Pipe length (m)	1	1
Flow rate (m^3_n/h)	7	7.5
Max conc. of natural gas in the working pit (%)	13.5	18.2
Temperature at stopper (max.) – (°C)	85	480
Sound level - LAF max - (dBa)	-	87.7
Pressure near stopper (max.) – (bar)	< 0.02	< 0.02
Ambient temperature (°C)	18.7	16.8
Wind speed [m/s]	0.3	0.1
Video observations outside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas
Video observations inside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas
Condition of stopper after removal	Assessment after measurement 14.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 14.	Yes

Sub-conclusion:
The stopper placed about 1 m from the pipeline interruption will not collapse due to delayed ignition of a large flow rate of natural gas flowing from the interrupted pipeline.

4.4.2 Delayed ignition of hydrogen – 1 metre

Originally, the idea was to create hydrogen concentrations in the working pit of 5, 10, 20, 30, 50 and 80%, respectively. With the MFC used, with the maximum flow rate of 15.5 m^3/h hydrogen, the maximum achievable concentration in the working pit was found to be 12%. Achievable concentration depends heavily on the wind. During the measurements, there was virtually no wind; when the wind picked up slightly, the concentration of hydrogen dropped very quickly.[5]

The measured temperatures near the stopper are listed in Appendix **Fout! Verwijzingsbron niet gevonden.** and the measured concentrations are listed in Appendix VII.

The ignition of the released hydrogen was powerful. After the hydrogen was ignited, the supply was manually stopped. The hydrogen from the pipe burned quickly.

Table 14 Delayed ignition of hydrogen with a stopper 1 metre away, concentration of hydrogen approx. 5%.

Guideline 5%	**Measurement 15**	**Measurement 16**
Medium	Hydrogen	Hydrogen
Pipe length (m)	1	1
Flow rate (m^3_n/h)	4	4
Max conc. of hydrogen in the working pit (%)	4	6
Temperature at stopper (max.) – (°C)	168	147
Sound level - LAF max - (dBa)	-	91.6
Pressure near stopper (max.) – (bar)	< 0.02	< 0.02
Ambient temperature (°C)	14.4	14.5
Wind speed [m/s]	0.0	0.0
Video observations outside the working pit	Audible and visible	No images
Video observations inside the working pit	Short, powerful ignition.	No images
Condition of stopper after removal	Assessment after measurement 16.	No discrepancy
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 20.	Assessment after measurement 20.

[5] N.B. At a later point when, after the tests described in this section had already been carried out, a gas meter with a larger capacity was installed in the test setup. A concentration of 20% was achieved at 36 m^3/h. In the tests described in 4.5 (extinguishing a gas fire), a flow rate of 80 m^3/h was supplied. This led to concentrations of up to 55%.

Table 15 Delayed ignition of hydrogen with a stopper 1 metre away, concentration of hydrogen approx. 10%.

Guideline 10%	**Measurement 17**	**Measurement 18**	**Measurement 20**
Medium	Hydrogen	Hydrogen	Hydrogen
Pipe length (m)	1	1	1
Flow rate (m^3_n/h)	8	8	15.5
Max conc. of hydrogen in the working pit (%)	9	8	12
Temperature at stopper (max.) – (°C)	156	172	126
Sound level - LAF max - (dBa)	97.8	97.9	95.8
Pressure near stopper (max.) – (bar)	< 0.02	< 0.02	< 0.02
Ambient temperature (°C)	14.5	14.3	13.9
Wind speed [m/s]	0.1	0.1	0.1
Video observations outside the working pit	Audible, not visible.	Audible and visible.	Audible and visible.
Video observations inside the working pit	Short, powerful ignition.	Short, powerful ignition.	Short, powerful ignition.
Condition of stopper after removal	Assessment after measurement 20.	Assessment after measurement 20.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 20.	Assessment after measurement 20.	yes

Increasing the flow in order to obtain a higher concentration in the working pit had no added value in the context of this assignment. At a hydrogen flow rate greater than 15 m^3/h, the velocity in this pipe was >0.2 m/s. The concentration of hydrogen in the pipe was then 100% [5] At these speeds, there is no flame impact and the stopper would not be affected. Obviously, the explosive force in the working pit would be greater.

Sub-conclusion:
The stopper placed about 1 m from the pipe breakage in a hydrogen pipeline will not collapse as a result of delayed ignition of a large flow rate of hydrogen flowing from an interrupted line.

4.4.3 Delayed ignition of natural gas – 20 metres

In this section, 10 measurements were performed where the intention was to trigger the ignition as soon as a concentration of 5%, 10% and 15% natural gas in the air was reached at one of the four measurement points in the working pit, respectively (note: at a distance of 0.5 metres higher than the top of the pipe).

In the measurements with guide values for gas concentration in the working pit of 5% and 15%, respectively, the gas was found to continue burning after the first measurement (no. 28 and 34, respectively) after stopping the gas supply (at some distance). Sufficient oxygen was apparently still allowed to enter the pipe to maintain the flame. As soon as the new measurement (no. 29 and 35, respectively) was started by opening the gas supply, the flame exited the pipe.

The measured temperatures near the stopper are listed in Appendix **Fout! Verwijzingsbron niet gevonden.** and the measured gas concentrations are listed in Appendix VII.

Table 16 Delayed ignition of natural gas with a stopper 20 metre away, concentration of natural gas >5%.

Guideline 5%	**Measurement 28**	**Measurement 29**	**Measurement 30**	**Measurement 31**
Medium	Natural gas	Natural gas	Natural gas	Natural gas
Pipe length (m)	20	20	20	20
Flow rate (m^3_n/h)	4	4	4	4
Max conc. of natural gas in the working pit (%)	4.5	5	5	5
Temperature at stopper (max.) – (°C)	< 20	< 20	< 20	< 20 (two small increases)
Sound level - LAF max - (dBa)	Maximum values during all four measurements was 82.3			
Pressure near stopper (max.) – (bar)	< 0.07	No data	No data	No data
Ambient temperature (°C)	17.0	16.8	17.2	17.3
Wind speed [m/s]	0.1	0.1	0.1	0.1
Video observations outside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas.*	Visible, quiet ignition of natural gas.*	Visible, quiet ignition of natural gas
Video observations inside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas.*	Visible, quiet ignition of natural gas.*	Visible, quiet ignition of natural gas
Condition of stopper after removal	Assessment after measurement 31.	Assessment after measurement 31.	Assessment after measurement 31.	No discrepancies
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 31.	Assessment after measurement 31.	Assessment after measurement 31.	Yes
*In measurement 29 and 30, without adding a spark, a flame was suddenly visible. Apparently, the natural gas kept burning slowly in the pipe (from the previous reading). See also the thermal images in Appendix VIII. After measurement 30, the flame in the pipe had extinguished, however.				

Table 17 Delayed ignition of natural gas with a stopper 20 metre away, concentration of natural gas >10%.

Guideline 10%	**Measurement 32**	**Measurement 33**
Medium	Natural gas	Natural gas
Pipe length (m)	20	20
Flow rate (m^3_n/h)	7	7
Max conc. of natural gas in the working pit (%)	14.4	9.1
Temperature at stopper (max.) – (°C)	< 20	27 (clear peak)
Sound level - LAF max - (dBa)	75.2	79.9
Pressure near stopper (max.) – (bar)	< 0.02	<0.02
Ambient temperature (°C)	16.4	16.4
Wind speed [m/s]	0.1	0.1
Video observations outside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas.
Video observations inside the working pit	Visible, quiet ignition of natural gas	Visible, quiet ignition of natural gas.
Condition of stopper after removal	Assessment after measurement 33.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 33.	Yes.

Table 18 Delayed ignition of natural gas with a stopper 20 metre away, concentration of natural gas >15%.

Guideline 15%	**Measurement 34**	**Measurement 35**	**Measurement 36**	**Measurement 37**
Medium	Natural gas	Natural gas	Natural gas	Natural gas
Pipe length (m)	20	20	20	20
Flow rate ($m^3{}_n$/h)	8	8	8	8
Max conc. of natural gas in the working pit (%)	15.6	0	0	0
Temperature at stopper (max.) – (°C)	< 20	< 20	< 20	< 20
Sound level - LAF max - (dBa)	-	Maximum values during all four measurements is 89.2		
Pressure near stopper (max.) – (bar)	< 0.02	-	-	-
Ambient temperature (°C)	15.9	16.1	16.1	17.0
Wind speed (m/s)	0.0	0.0	0.0	0.1
Video observations outside the working pit	Visible, quiet ignition of natural gas	Fire in the pit within 30 seconds of opening supply*	Fire in the pit within 10 seconds of opening supply*	Fire in the pit within 10 seconds of opening supply*
Video observations inside the working pit	Visible, quiet ignition of natural gas	Fire in the pit within 30 seconds of opening supply	Fire in the pit within 10 seconds of opening supply	Fire in the pit within 10 seconds of opening supply
Condition of stopper after removal	Assessment after measurement 37.	Assessment after measurement 37.	Assessment after measurement 37.	No discrepancies
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 37.	Assessment after measurement 37.	Assessment after measurement 37.	Yes
*With measurement 35, 36 and 37, without adding a spark, a flame was suddenly visible. Apparently, the natural gas kept burning slowly in the pipe (from the previous measurement). In fact, these were not delayed ignitions.				

Sub-conclusion:
The stopper placed at a larger distance (about 20 m) from the pipeline interruption will not collapse due to delayed ignition of a large flow rate of natural gas flowing from the interrupted pipeline.

4.4.4 Delayed ignition of hydrogen – 20 metres

These measurements were carried out four times where the ignition was activated as soon as a concentration of 5% and 10% hydrogen in air was reached at one of the four measuring points in the working pit, respectively (note: at a distance of 0.5 metres higher than the top of the pipe). Two measurements were taken for each concentration.

The ignition of the released hydrogen was quiet. After the hydrogen was ignited, the supply was manually stopped.

The measured gas concentrations are listed in Appendix VII.

Table 19 Delayed ignition of hydrogen with a stopper 20 metres away, concentration of hydrogen >5%.

Guideline 5%	**Measurement 24**	**Measurement 25**
Medium	Hydrogen	Hydrogen
Pipe length (m)	20	20
Flow rate (m^3_n/h)	6	6
Max conc. of hydrogen in the working pit (%)	5	5
Temperature at stopper (max.) – (°C)	< 30	< 30
Sound level - LAF max - (dBa)	97.3	91.0
Pressure near stopper (max.) – (bar)	< 0.04	< 0.04
Ambient temperature (°C)	16.3	16.1
Wind speed (m/s)	0.2	0.2
Video observations outside the working pit	Initial visible, quiet ignition. After the tap was closed, powerful combustion continued.	An almost instant powerful ignition. After the tap was closed, no additional effect.
Video observations inside the working pit	Initial visible, quiet ignition. After the tap was closed, powerful combustion continued.	An almost instant powerful ignition. After the tap was closed, no additional effect.
Condition of stopper after removal	No discrepancies	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 27.	Assessment after measurement 27.

Table 20 Delayed ignition of hydrogen with a stopper 20 metres away, concentration of hydrogen >10%.

Guideline 10%	**Measurement 26**	**Measurement 27**
Medium	Hydrogen	Hydrogen
Pipe length (m)	20	20
Flow rate (m^3_n/h)	15	15
Max conc. of hydrogen in the working pit (%)	10	10
Temperature at stopper (max.) – (°C)	< 30	< 30
Sound level - LAF max - (dBa)	-	93.2
Pressure near stopper (max.) – (bar)	< 0.04	< 0.04
Ambient temperature (°C)	16.3	16.1
Wind speed [m/s]	0.2	0.3
Video observations outside the working pit	Visible, quiet ignition.	Visible, quiet ignition.
Video observations inside the working pit	Powerful ignition.	Powerful ignition.
Condition of stopper after removal	No discrepancies	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 27.	Yes

Sub-conclusion:
The stopper placed at a greater distance (about 20 m) from the pipe breakage in a hydrogen line would not collapse due to a delayed ignition of a relatively large flow rate of hydrogen flowing out of the interrupted line.

4.5 Placement of a stopper after ignition of the hydrogen or natural gas

The tests in 4.5 aim to establish how a gas stopper behaves when extinguishing a gas fire due to ignited free-flowing gas.

4.5.1 Stopper placement in case of fire due to free-flowing natural gas

The measurement was carried out three times during which the gas flowing from the pipe was ignited with a gas burner placed at the bottom of the working pit. A spark igniter was not chosen because it would potentially burn out with the first measurement.

Table 21 Placement of stopper in a burning natural gas pipeline

	Measurement 40	**Measurement 41**	**Measurement 42**
Medium	Natural gas	Natural gas	Natural gas
Pipe length (m)	20	20	20
Flow rate ($m^3{}_n$/h)	24	23	23
Max conc. of natural gas in the working pit (%)	-	-	-
Temperature at stopper (max.) – (°C)	<20	<20	<20
Sound level - LAF max - (dBa)	89.0	90.6	90.6
Pressure near stopper (max.) – (bar)	<0.02	<0.02	<0.02
Ambient temperature (°C)	16.7	18.5	21.8
Wind speed (m/s)	0.7	0.7	0.7
Video observations inside the working pit	Visible, quiet ignition of natural gas. Flame quietly extinguishes when setting stopper.	Visible, quiet ignition of natural gas. Flame quietly extinguishes when setting stopper.	Visible, quiet ignition of natural gas. Flame quietly extinguishes when setting stopper.
Condition of stopper after removal	Assessment after measurement 42.	Assessment after measurement 42.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after measurement 42.	Assessment after measurement 42.	Yes.

<u>Sub-conclusion</u>

A burning natural gas pipeline can be sealed with a stopper without any issues. N.B. This applies if the stopper does not leak.

4.5.2 Placement of the stopper in case of fire from free-flowing hydrogen

The measurement was carried out four times with the outflowing hydrogen being ignited during the first measurement with a gas burner placed at the bottom of the working pit. In the first measurement, the gas burner was blown out after ignition and flame impact occurred in the hydrogen line. This was followed by an outflow of unburned hydrogen. The hydrogen supply was then shut down manually.

Afterwards, a spark igniter was fitted at the top of the pipe. It was used in the following 3 measurements.

Table 22 Placement of stopper in burning hydrogen line

	Measurement 43	Measurement 44	Measurement 45	Measurement 46
Medium	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Pipe length (m)	20	20	20	20
Flow rate (m^3_n/h)	80	80	84	80
Max conc. of hydrogen 0.5 **from the edge** in working pit (%)	55	53	45	40
Temperature at stopper (max.) – (°C)	<20	<20	<20	<20
Sound level - LAF max - (dBa)	Maximum during both measurements is 123.1		122.4	120.8
Pressure near stopper (max.) – (bar)	0.29	0.05	0.04	0.04
Ambient temperature (°C)	20.3	21.0	19.3	19.0
Wind speed (m/s)	0.9	0.8	0.9	0.3
Video observations inside the working pitlans	First there was a powerful ignition of hydrogen in the working pit, then flame impact followed by outflow of unburned hydrogen.	Powerful ignition (spark applied, after some time an outflow of hydrogen). The flame extinguished quietly after setting the stopper. After a few minutes, some hydrogen still ignited.	Powerful ignition (spark applied, after some time an outflow of hydrogen). The flame extinguished quietly after setting the stopper. After a few minutes, a little hydrogen ignited two more times.	Powerful ignition (spark applied, after some time an outflow of hydrogen). The flame extinguished quietly after setting the stopper. After a few minutes, some hydrogen still ignited
Condition of stopper after removal	Assessment after measurement 46.	Assessment after measurement 46.	Assessment after measurement 46.	No discrepancies.
Possible to keep stopper pressurised for 3 minutes? (yes/no)	Assessment after	Assessment after	Assessment after	Yes.

	measurement 46.	measurement 46.	measurement 46.	
In measurements 43, 44 and 45, the PPE (personal protection equipment) as used by the researchers at a distance of 20 metres from the working pit set off an alarm that the concentration of hydrogen was >10% LEL.				

Sub-conclusion

A burning hydrogen line can be sealed with a stopper without any issue. N.B. This applies if the stopper does not leak.

N.B. A flow rate of 80 m3/h was tested, corresponding to about 1 m/s. The flow rate would be many times higher with an actual leakage. This study investigated the effect of stopping burning hydrogen. In practice, if the gas outflow is stopped with a stopper, the velocity would decrease and eventually reach the outflow velocity of 1 m/s, with additional pumping of the stopper lowering the outflow velocity further. This study assessed whether possible flame impact would adversely affect the stopper function. Flame impact will occur at lower gas exit velocities.

In a hydrogen network, the flow rate would potentially be three times higher as compared to the flow rate in a natural gas network. Finding out whether a stopper could be placed at these speeds would require further investigation. This is expected to be possible because with the same resistance (the larger stopper), about three times as much hydrogen is able to pass compared to natural gas.

5. Mitigating measures

Based on the measurements carried out, especially in the case of a 'small' hydrogen leak (<0.6 m^3_n/h) at the location of a gas stopper, degradation of the stopper is possible if an ignition source is present in the working pit. The stopper could burn (in the case of a stopper about 1 metre away from the outlet) or the stopper could snap (in the case of a stopper 20 metres away from the outlet).

Measures to reduce the risk of stopper deterioration would focus on preventing:

- A gas leak
- The formation of a combustible mixture
- An ignition

Based on the literature research carried out and the information gathered from the grid operators, the current measures when applying stoppers in the natural gas distribution network do not seem to lead to stopper combustion. The **current** measures include:

1. Checking for stopper tightness before placement.
2. Checking for stopper tightness after placement.
3. Preventing ignition in the working pit by cordoning off the pit, not using tools that generate sparks and using anti-static clothing.
4. Measuring gas concentrations in the working pit. If a person is present in the working pit, this is done using that person's gas detector.

When applying stoppers to hydrogen, the following **additional** measures are proposed:

For stoppers placed at a distance of **about 1 metre** from the pipe end:

1. Forced ventilation of the working pit.
2. Measuring gas concentration at the pipe end (top of pipe)
3. After the stoppers are set and the pipe section where the work is planned is depressurised, degas the affected section by flushing with nitrogen.

When placing a stopper at a distance of 1 metre from the pipe end in a hydrogen network, the current measures are expected to be sufficient to ensure safe application. Especially in pilot projects, it makes sense to consider and/or validate the proposed additional measures.

For stoppers placed at a distance **greater than 1 metre** from the pipe end:

1. Applying a stopper type with a sturdier design than those tested[6]. This would either require the application of a different type of stopper or a modification of the current type, which would have to be performed by the manufacturer.
2. Application of a double stopper with degassing between the stoppers (block & bleed)
3. Application of a single stopper with a ventilation outlet behind the stopper (air moving)
4. Forced ventilation of the working pit.
5. Measuring gas concentration at the pipe end (top of pipe)
6. After a single stopper or double stopper is set, degas the section between the stopper and the outlet by flushing with nitrogen.

[6] Although the stopper tested was found to be almost completely leak tight, some leakage in practice cannot be ruled out due to contamination or damage to the pipe. In addition, when free gas flow is stopped by setting a stopper, gas will always be present in the sealed pipe. This gas slowly flows out of the pipe as air enters it. A flammable gas/air mixture will be present in the pipe for an extended period of time. With hydrogen, the period is simply longer than natural gas due to hydrogen's broader flammability limits. In the event of an unexpected ignition, the impact with hydrogen has been found to be greater than that of natural gas.

The aforementioned measures can be applied independently, with the understanding that by applying air moving (measure 3), the working pit will also be additionally ventilated (measure 4) by the entry of air into the interrupted pipe. The disadvantage of measures 3 and 4 is that although the gas concentration of hydrogen will decrease, a combustible mixture will form over a period of time. Given the broader flammability limits for hydrogen, that period is longer for hydrogen than for a similar situation with natural gas.

6. Conclusions

6.1 Answers to the research questions

Based on the theoretical and practical research conducted, the research questions can be answered as follows.

- **Are inflatable gas stoppers, as they are currently applied in natural gas distribution networks, suitable for application in a hydrogen distribution network?**

Inflatable gas stoppers are suitable when placed at a distance of 1 metre from an outlet (in regular operations). A small natural gas leak and a small hydrogen leak near the stopper were found to be ignitable. This could cause the stopper to break, which was also the case with the natural gas leak in both measurements. So far, this kind of failure has only occurred to a limited extent in practice. However, preventing the presence of ignition sources in working pits is and remains a key issue in preventing this kind of failure with natural gas as well as hydrogen. Additional measures can also be taken to further reduce risks in hydrogen applications.

For incident control, inflatable gas stoppers are placed at a distance of about 20 metres from an outlet. For this application in hydrogen networks, the current stoppers are not suitable without additional measures. The more powerful ignition of hydrogen as well as hydrogen's broader flammability limits mean that the probability of gas blowout failure is higher than with natural gas.

Further explanation follows via the answers to the **sub-questions** below

- **What are the leakage rates of inflatable gas stoppers, as they are currently used in the natural gas network, if they are applied in a hydrogen network?**

The inflatable gas stoppers, as they are currently used by the regional grid operators, are either made by the manufacture Kleiss or Ipco. The stoppers from Kleiss are more widely used than those from Ipco.
As far as the application on natural gas is concerned, both manufactures of stoppers bear the Gastec QA quality mark, based on KE 194. The leakage rate of a stopper according to these approval requirements should be less than 0.3 m^3/h (tested with air, at pressures of 100 and 200 mbar). Using 0.3 m^3/h tested with air as an acceptable limit would correspond to a leakage rate of 0.6 m^3/h hydrogen.
The tested, already used, stoppers from Kleiss were found to fully seal hydrogen in plastic pipes; the leakage rate was 0.001 m^3/h.
In the tested stoppers from Ipco, at a pressure of 200 mbar, the following leakage rates of hydrogen in a PE pipe were measured:
DN 60 0.176 m^3/h (used stopper)
DN 100 0.099 m^3/h (used stopper)
DN 150 0.463 m^3/h (obsolete stopper type, without Gastec QA quality mark)
DN 200 0.295 m^3/h (new, unused stopper)

- **How should working procedures be adjusted?**

The working procedures related to stoppers in case of normal operations (expansions, replacements, repairs of limited leaks such as those detected in leak checks) do not need to be specifically adjusted for hydrogen application situations. Here, the assumption is that a gas stopper would be placed at a short distance (about 1 metre) from the work site.

For incident control and the application of stoppers, adjustments to the working procedures are desirable, however. See the mitigation measures in Chapter 5. Adjustment of working procedures would therefore have to focus on expanding the measures as follows:

- Applying a double stopper ('block and bleed')
- Ventilating the pipe by air moving, if necessary.
- Possibly forced ventilation of the working pit.
- Measuring the gas concentration at the top of the pipe near the outlet.
- The flushing procedure for the blocked pipe section.

- **What is the maximum acceptable leakage rate when using inflatable gas stoppers in a hydrogen network in order to continue working safely in a working pit?**

In a working pit of 1.7 metres by 1.2 metres with a depth of 1 metre, the leakage rate for hydrogen should not exceed 0.29 m^3_n/h when there are two outlets present. The maximum leakage rate per stopper is therefore 0.146 m^3_n/h of hydrogen. That is lower than the leakage criterion set in KE 214 (2022). That criterion set mentions 0.1 m^3_n/h based on air; this indicates 0.2 m^3_n/h when related to hydrogen. The permissible flow rate in KE 214 should therefore be reduced to 0.07 m^3_n/h.

- **How does a gas stopper behave in the case of a borderline acceptable gas leakage across the gas stopper, in the case of a direct ignition (fire) of this leakage gas at the pipe end?**

Undesirable situations arose.
In the case of direct ignition (near the outlet) of a 'small' leak, the stopper can burn out for both natural gas (0.15 m^3_n/h) and hydrogen (0.45 m^3_n/h) in the case of a stopper placed about 1 metre from the outlet.
Direct ignition (near the outlet) of a 'small' hydrogen leak (0.6 m^3/h) may cause the stopper to break with hydrogen due to a powerful ignition phenomena in the case of a stopper placed 20 metres from the outlet.
It should be noted here that the maximum hydrogen leakage according to KE 214 must be <0.2 m^3/h and that the Kleiss stoppers tested proved to be almost completely leak-tight during the leak tightness tests. However, it cannot be ruled out that in practical situations, the leakage limit may be unexpectedly exceeded due to contamination or damage in the pipe.
If a free outflow of gas is stopped by setting a stopper, gas (natural gas or hydrogen) will flow out of the pipe. After some time, an explosive mixture will then be present in the pipe. With hydrogen, due to its broader flammability limits, that moment is greater than that of natural gas[7].

- **How does a gas stopper behave in the case of an explosion in the working pit (different gas concentrations)?**

No undesirable effects were observed with delayed ignitions at different gas concentrations in the working pit. Compared to natural gas, the ignition with hydrogen was more powerful. With natural gas, the gas burned slowly out of the pipe with the flame retreating into the pipe. The temperature at the stopper increased slightly. But the stopper was ultimately unaffected. These measurements involved an increased gas outflow to obtain a higher gas concentration in the working pit. Due to this larger gas outflow, the flame was at a greater distance from the stopper compared to the measurements with a small leakage and a pipe length of 1 metre.

[7] In the report HyDelta WP1C; among other observations, it was found that when air entered into a hydrogen pipeline in the event of a pipeline rupture, a flammable mixture was present in the DN100 and DN200 pipeline for a prolonged period of time (>1.5 hours) at 1 metre from the outlet. It should be noted that this was a 200-metre pipeline that was completely filled with hydrogen prior to the measurement. When a stopper is placed at a distance of 20 metres, the amount of hydrogen that flows out is a lot smaller.

- **How does a gas stopper behave (when stopping the gas supply) if a fire is being extinguished at the pipe end?**

Inflatable gas stoppers experience no adverse effects if the gas supply is stopped by inflating the stopper. The stopper is capable of extinguishing a gas fire (natural gas and hydrogen), with the stopper continuing to perform its function after extinguishing.

NB

At the applied hydrogen leakage rate (80 m^3/h) and at a distance of 20 metres from the working pit, the PPE (personal protection equipment) was found to set off an alarm indicating that 10% LEL had been exceeded. This was the case in three out of the four measurements.

- **What ignition scenarios are conceivable when using inflatable gas stoppers? (theoretical research)**

Besides the known ignition scenarios with natural gas, such as open flames and electrical equipment, hydrogen is more likely to ignite because much less ignition energy is required at higher percentages of gas/air mixtures. This creates the risk of ignition due to static electricity. Especially when combined with plastic pipe work, where sparking can take place near the end of the pipe. If a gas/air mixture is present in the pipe (e.g. due to a leak), this can have a major effect. Ignition due to mechanically generated sparks, as a result of digging or metal work, for example, is also a very real scenario.

- **What additional mitigating measures are feasible in order to prevent any undesirable effects of hydrogen ignition? (theoretical research)**

See Chapter 5.

6.2 Relationship between leak-tightness measurements, concentration measurements and ignition tests.

Testing the leak-tightness of the existing stoppers showed that the stoppers from Kleiss were sufficiently leak-tight for hydrogen. The leakage here was virtually zero. With the stoppers from Ipco, three of the four stoppers assessed had already been used, and leakage hydrogen was 0.10 to 0.46 m^3/h. This leakage rate at a stopper would lead to concentrations of hydrogen higher than 10% LEL in a working pit of 1.7 by 1.2 by 1 metre. This is evidenced by the concentration measurements carried out as described in this report. Those measurements also show that for a leakage rate of hydrogen that is less than 0.98 m^3/h (distributed over two outlets), the concentration remains below 100% LEL.

A stopper with a small leakage rate of hydrogen (such as 0.45 m^3/h) placed in a short pipe length (1 metre) would lead to a permanent flame in the pipe if ignited in the working pit (1.7 by 1.2 by 1 metre). This could cause the stopper to break. This ignition would only be possible if the ignition source was directly at the pipe end. At a greater distance (>50 cm) from the outlet, the leakage gas would be diluted to the point where it could not be ignited.

A stopper with a small leakage rate of hydrogen (such as 0.60 m^3/h) placed at a large distance from the break in the pipe (20 metres, diameter DN 150), leads to an explosive ignition when ignited. In this explosive ignition, a substantial flame jet is created in the working pit and there is a high probability that the gas stopper would break loose due to the pressure of the explosion. This happened in two of the three measurements during this study. With a smaller diameter pipe, this same leakage (0.60 m^3/h) would lead to a gas/air mixture with a higher concentration of hydrogen and it would therefore react differently. For a pipe with a diameter smaller than DN 150, smaller leakage amounts of hydrogen (i.e. smaller than 0.60 m^3/h) could lead to similar, powerful, ignitions as observed for the DN 150 pipe. In addition, for a smaller diameter pipe (such as DN 60 and DN 100), the released hydrogen and entering air would experience more resistance than with a larger diameter pipe (such as DN 150).

If a stopper leaks a larger amount of hydrogen (4 to 15 m^3/h), and it is then ignited in the working pit, the hydrogen would burn at the pipe end. The ignition in the working pit was powerful, but barely audible at a distance of 20 metres. The pressure of the explosion in the working pit did not affect the stopper.

If a large flow rate of burning hydrogen (such as 80 m^3/h or larger) is throttled with a gas stopper, the flame size at the pipe end decreases and the gas burns away quietly in the pipe. The hydrogen flame slowly retracted into the pipe. Sometime after the stopper was installed, most of the hydrogen was burned away and the flue gas outflow was significantly reduced. This allowed air to enter more easily and ensured powerful combustion of the remaining hydrogen. A brief flame jet was visible in the working pit.

7. Recommendations

The following recommendations are presented based on the study conducted;

1. It is advisable to bring this report to the attention of manufacturers and suppliers of temporary sealing devices. These manufacturers could then develop stopper designs that are more resistant to the ignition of a limited hydrogen leak.
2. It is advisable to bring this report to the attention of the Gastec QA Board of Experts. The aim here would be to consider the leak-tightness criteria in more detail. Both for natural gas and for hydrogen.
3. Furthermore, it is recommended to consider the effects on inflatable gas stoppers in the case of direct ignition of a hydrogen leak, delayed ignition of a hydrogen leak and extinguishing a gas fire for diameters other than 160 mm. With larger diameters, the consequences may be different due to the larger amount of explosive mixture that is possible to form. With smaller diameters, additional measures may not be necessary because the stopper would hold.
4. This study investigated extinguishing natural gas fires and hydrogen fires. In the process, the stoppers used were completely leak-tight. Extinguishing a fire with a slightly leaky stopper has not been studied. It may make sense to do so, in order to establish that no undesirable effects occur.
5. It is advisable to carry out ignition tests with the inflatable gas stoppers from Ipco as well. According to the manufacturer, the design of these stoppers is more resistant to the more powerful ignition of hydrogen.
6. Conduct further research into the effectiveness of the mitigation measures proposed in Chapter 5. For example, it would be necessary to investigate whether a double stopper can withstand an unexpected ignition of the hydrogen present in the pipe after the free flow of hydrogen is stopped.
7. Investigate what the maximum flow rate is in a hydrogen application where a gas stopper can be placed in a pipe. This would preferably be with multiple diameters and different types of stoppers.
8. When converting to a hydrogen network, consider the use of valves and inflatable gas stoppers where the valves are used for sectioning a network and the inflatable gas stoppers for reducing the working area.
9. Determine the size of a hydrogen gas cloud in the event of a sizeable gas leak in a working pit[8]

[8] In the Kiwa GT-200096 report, CFD calculations were carried out for natural gas and hydrogen in the context of flaring and venting. Here, a maximum flow rate of 300 m^3/h was investigated. In case of a gas leak, these flow rates would be significantly higher.

References

[1] Kiwa Technology, "Veilig Sectioneren van Waterstofnetten," 2021.

[2] DVGW, "Hydrogen Research Projects," DVGW, Bonn, 2020.

[3] DNV-GL, "Gedrag van waterstof bij lekkages in het gasdistributienet," 2020.

[4] Kiwa Technology, "HyDelta D1C.2, dichtheid van distributieleidingen," 2021.

[5] Kiwa Technology, "HyDelta D1C.1 Spoelen van aardgasleidingen met waterstof," 2021.

[6] Bang et al, "Deflagration-to-detonation transition in pipes," in *Applied Mathematical Modelling*, 2019.

[7] Federal Institute for Materials Research and Testing, "Explosion Processes and DDT of various flammable gas/air mixtures in long closed pipes containing obstacles," Berlin, 2008.

[8] G.L. Oakley et al, "Investigations into concerns about BS EN 12874: 2001 flame arresters," 2004.

I. Accident database overview Kiwa Technology

The incidents known to Kiwa Technology regarding the failure of a gas stopper that resulted in an incident being reported in accordance with the requirements of SODM are listed below. For this study, reports were included between 2003 and 2020.

28 September 2022: Bergen op Zoom, IJssellaan 43.
Leaking stopper ø315 PVC, spontaneously ruptured open, resulting in large gas outflow. Gas flow stopped by setting 3 stoppers simultaneously at a good distance. No fire occurred in the process. Incident is under investigation.

13 January 2020: Amsterdam, Prins Hendrikkade.[9]
Leaking gas stopper due to heating of misplaced electrofusion socket in a PE ø315 mm. In the process, the **gas ignited** and a fire started. Ignition source could not be determined with certainty, however, it seems plausible that it came from a misplaced electrofusion socket being welded at the time. The PE melting away then released the filaments of the socket and may have resulted in excessive temperatures in the pipe.

04-09-2014 Amsterdam, Admiralengracht / Hoek F. v. Almondestraat,
During own work on the main gas pipeline, a gas stopper snapped resulting in free gas outflow. The free gas outflow was stopped by setting a new gas stopper. Pipe type grey cast iron, ND 250-400. No ignition occurred.

2014, Lelystad, Kogge 8
During work on a DN200 steel pipe, a stopper ruptured. Not far from the stopper, a blowtorch was used to remove the lining of the pipe, which caused the stopper to collapse due to the heat. A fire also started in the process.

09 July 2012, Beverwijk, Belgiëlaan.
The outcome of the investigation did not indicate a poor quality stopper, or any ageing or wear. The most likely cause was a sharp object/pipe part. The first stopper broke, the second stopper leaked, but additional pumping could stop the gas flow. DN 300 GGY, large outflow >40 m/s 10,000 m3/h natural gas. No ignition occurred.

28 August 2012, Utrecht, Amsterdamsestraatweg
Very large outflow of gas due to excavation work. Inflatable gas stoppers fail when inflating, a container of sand at the outlet lowered the outflow so that a stopper could be placed. DN400 GGY. Outflow >30 m/s and about 14,000 m^3/h of natural gas. No ignition occurred.

[9] This notification was also indicated through the questionnaire sent to grid operators, see Annex II

II. Responses received from grid operators – summary of questions ans given answers by the DSO's

What was the probable reason that the stopper was not functioning properly?	Contamination and frequently used stoppers	Knocked over due to the large flow with a large gas leak	Knocked over due to the large flow with a large gas leak, also cut into the stopper when it knocked over	Dirt at the bottom of the pipe	Age of stopper	Dirt in the gas line	Most likely, there was a small amount of leakage gas along the stopper that ignited while burning off the lining of the steel pipe	Stopper detached from the clamping point	Stopper did not seal properly due to dirt and rough interior	A misplaced electrofusion socket created a heat load on the stopper, which snapped as a result	This involved a T1 stopper placed in a 315 PVC for a strength test of 1 bar, the probable reason was that this stopper was not suitable for the amount of pressure	Quality of the stopper	Steel splinter caused damage	Stopper was too greasy, meaning there was no grip on the pipe wall, in combination with a damp pipe wall.	Stopper was too greasy, meaning there was no grip on the pipe wall, in combination with a damp pipe wall.
Did the stopper snap or was there gas leakage around the stopper?	Stopper snapped	Stopper snapped	Stopper snapped	Stopper emptied quickly	Stopper snapped	Leakage around stopper	Stopper snapped due to fire/melting	Stopper detached from the clamping point	Leakage around the pipe	snapped	Snapped	Snapped	snapped	Ejected	Ejected
What was the (approximate) date?	2010	2005	2003	2023	2009	2015	2014	2022	2022	2020	2022	2007	2017	2022	2022
Which type/brand of stopper was involved?	Kleiss	Kleiss	Kleiss	Kleiss	Kleiss	Kleiss	Kleiss	Kleiss	Kleiss	Kleiss	T1 stopper Kleiss	White stopper	Kleiss	Kleiss	Kleiss
What pipe material was the stopper placed into and what was the diameter of this pipe?	PVC 110 or 160	PVC 110	PVC-a 200	160 mm PVC	200 sPVC	sPVC 110	219.3 steel	sPVC 200	326 AC		PVC315	PVC	159ST	160/200	160/200
What were the consequences of the stopper not functioning properly? (e.g. free outflow of gas, yes/no ignition, damage, personal injury, etc.)	The effect was minimal; the pipe had not yet been opened; the stopper snapped while setting the second stopper.	This involved a fault where, during the installation of filter pipes for well drilling, the gas pipeline was damaged resulting in a large gas outflow. The snapping of the stopper allowed the gas outflow to resume. An additional risk here was the location, a petrol station.	It involved excavation damage where a ø200 pipe near a district station was ripped completely in half, resulting in large gas outflow. The DS side could be closed with a valve and the other side with a gas stopper. After snapping, the gas outflow resumed.	Because the stopper emptied quickly, there was no outflow	not much, pipe not yet removed	No consequences	Full gas outflow, no personal injuries	Stopper shot out +/- 3 metres into the 200mm sPVC pipe. A temporary end cap had been installed	unknown	Free gas outlet and fire	The snapping of the T1 stopper then caused the MDS500 stopper to snap; both stoppers entered the air-filled pipe.	Free gas outlet	No consequences	minimum	minimum
How was it resolved?	inserted a new stopper.	inserted a new stopper.	inserted a new stopper, including 2nd stopper	By the third time, the mess in the pipe had shifted to the point where we were no longer bothered by it.	reserve stopper placed and old stopper examined	Stopper moved 2x, so had to install multiple saddles	Placed end cap on pipe	New saddle and stopper fitted, then broken stopper was removed.	Put new stoppers on site further away to solve the problem		Depressurised, and used a camera in the pipe to see where the stoppers were	Cap installed and new stopper set	End cap installed	Under investigation	Under investigation
Are there any other comments?			In 2003, the development of stopper lances was still in full swing, the device that prevents a stopper from being knocked backwards was not there yet. Shortly after 2003, there was an interim solution with a kind of shoehorn, and again a little later a return to an older design of a lance with a side outlet.	-											

III. Expected effects with delayed ignition

This HyDelta study looked at the possible effects of a leaking stopper placed in a hydrogen pipeline. To determine these effects, various scenarios and configurations were tested. Here, the worst case, yet conceivable, scenario was also considered. To apply appropriate safety measures and sensors for this scenario, brief literature research was carried out prior to the measurements.
In the scenario studied here, the best conditions for combustion in air (a stoichiometric mixture of 29.5% hydrogen and 70.5% air) was combined with a conceivable scenario. One end of this pipeline was open (at the site of a working pit, this is where, for example, the work takes place) and one end was closed (due to the installed (leaking) stopper), see Figure 6. Behind the stopper was the distribution network with a pressure of 100mbar.

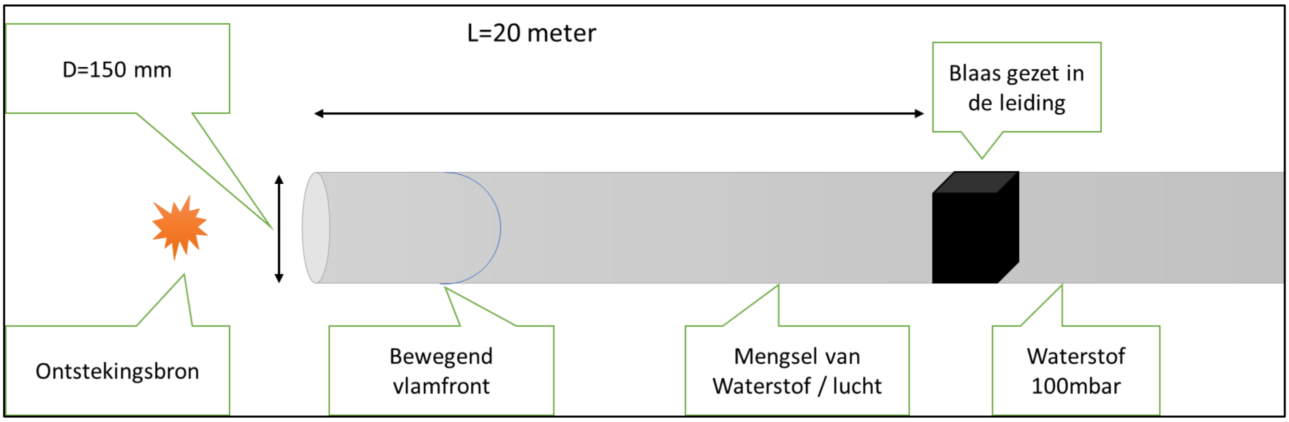


Figure 6: Schematic representation of the situation.

It was assumed that there is 20 metres of pipe between the work site and the stopper. This is a realistic value that can be used when working in emergencies. When the stopper leaks a certain amount of hydrogen, a mixture of hydrogen and air could occur between the stopper and the works. How this hydrogen would then distribute in this space is uncertain at this point. As this is not yet known, it should be assumed (at least prior to testing) that this is a well-mixed homogeneous mixture. If these assumptions are made, it is reasonable to expect detonation to occur for a 20-metre length of pipe with a diameter of 150 mm filled with a stoichiometric mixture. Detonation implies that the flame front of hydrogen accelerates to such an extent that it starts moving at the speed of sound. Laminar flow of a stoichiometric hydrogen mixture around 2.5 m/s. If detonation occurs, the speed of the flame front could reach well over 1000 m/s. This acceleration is caused by the geometry (in this case, a pipeline) combined with increasing turbulence of the flame front and the expansion of the gases during combustion. In the literature, the transition from combustion (with a subsonic flame speed) to detonation (with a (near) supersonic flame speed) is called 'DDT' (Deflagration to Detonation). In some conditions, DDT can occur in pipelines from about L/D>4. [6]

When DDT occurs, maximum pressure is expected at a length-to-diameter ratio of about 50. The L/D in Figure 1 is 133, here, the pressure peak would be at maximum somewhere halfway through; it is uncertainty how the pressure would develop in the pipe after this point. Given the speed of the flame front, it is to be expected that, after the flame front has travelled a certain distance, the flame front would shoot into the rest of the pipe. The pressure peak would then be around 17 bar. Given the speed, a fast (>100kHz) pressure gauge is recommended to measure this pressure peak. The pressure peak of around 17 to 18 times the starting pressure was also found in other literature [7] [8]. However, transient phenomena (overdriven detonation) can cause pressure peaks above 100 bar to occur [7] [8]. In [7] there is a good example of an experimental study of a 23 metre long pipe of 0.159 m in diameter with a variety of fuels. The pipe was sealed and DDT was obtained using partitions. Extreme pressures were found (>100 bar) and some experiments were not repeated because the steel pipe was damaged by the detonations.

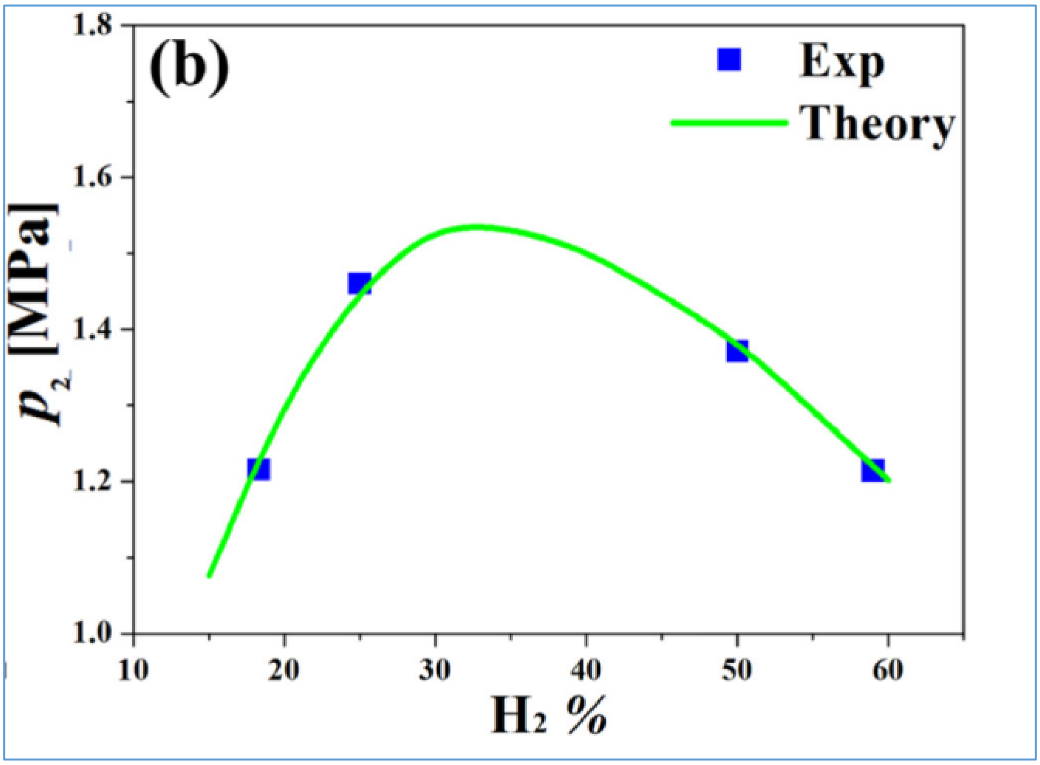


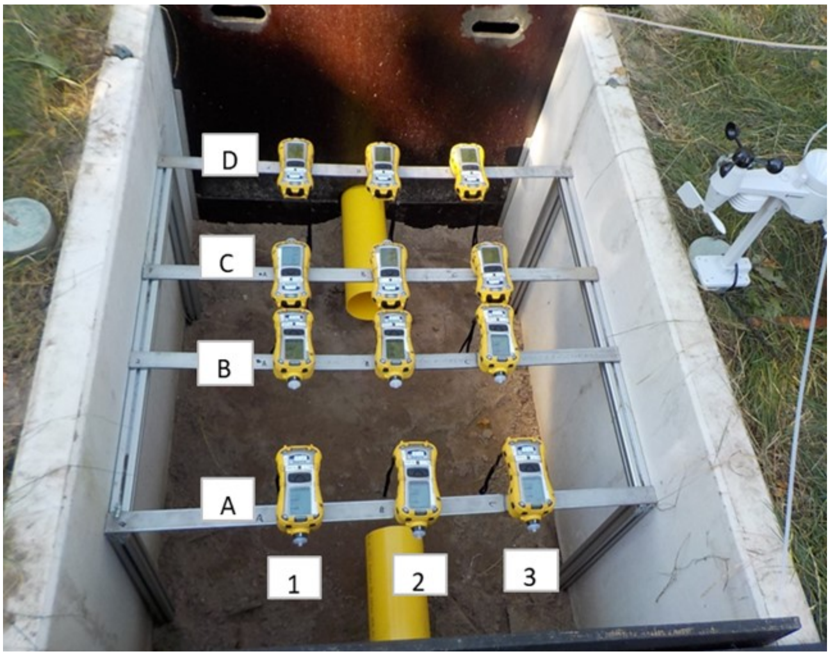
Figure 7: The expected maximum pressure peak as a function of the mixture [1].

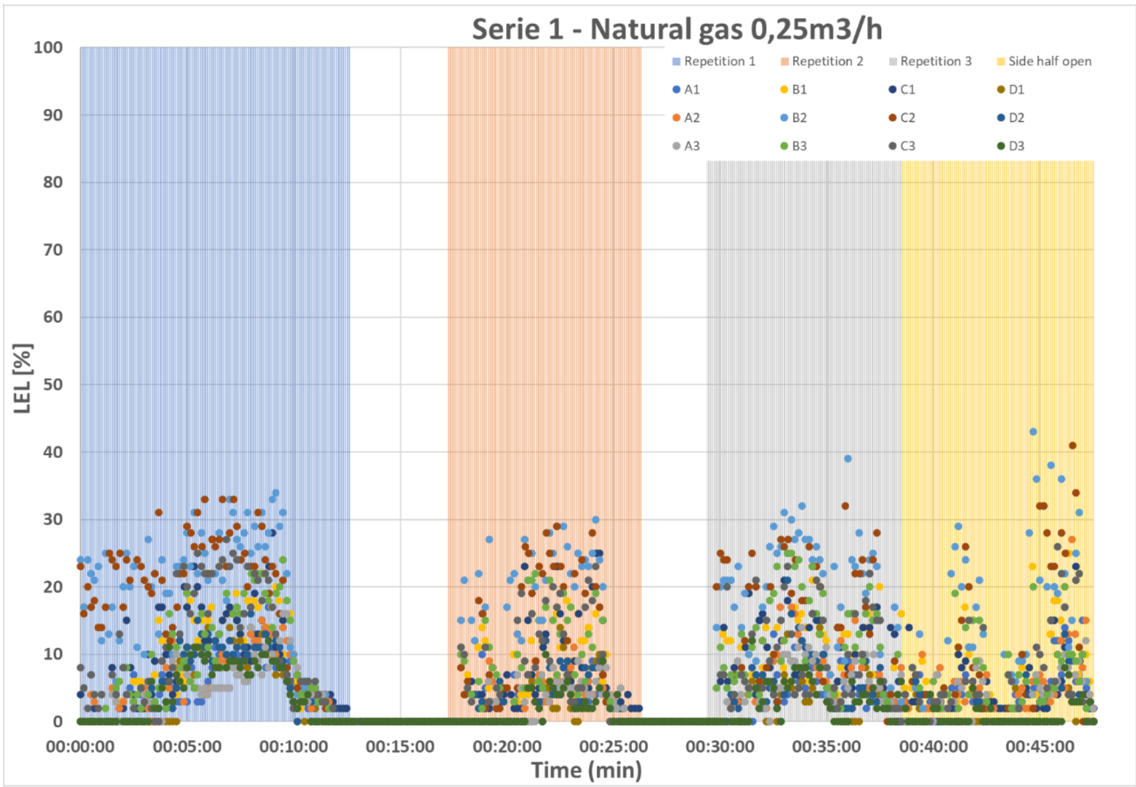
Incidentally, it is worth noting that the occurrence of DDT is mainly determined by the oxidiser, and is less dependent on the fuel. Therefore, H_2 and CH_4 behave in roughly similar ways, with pressure peaks of the same magnitude. DDT is much less likely to occur with natural gas because the laminar flame velocity of a stoichiometric mixture is lower than it is for hydrogen by nearly a factor of 10.

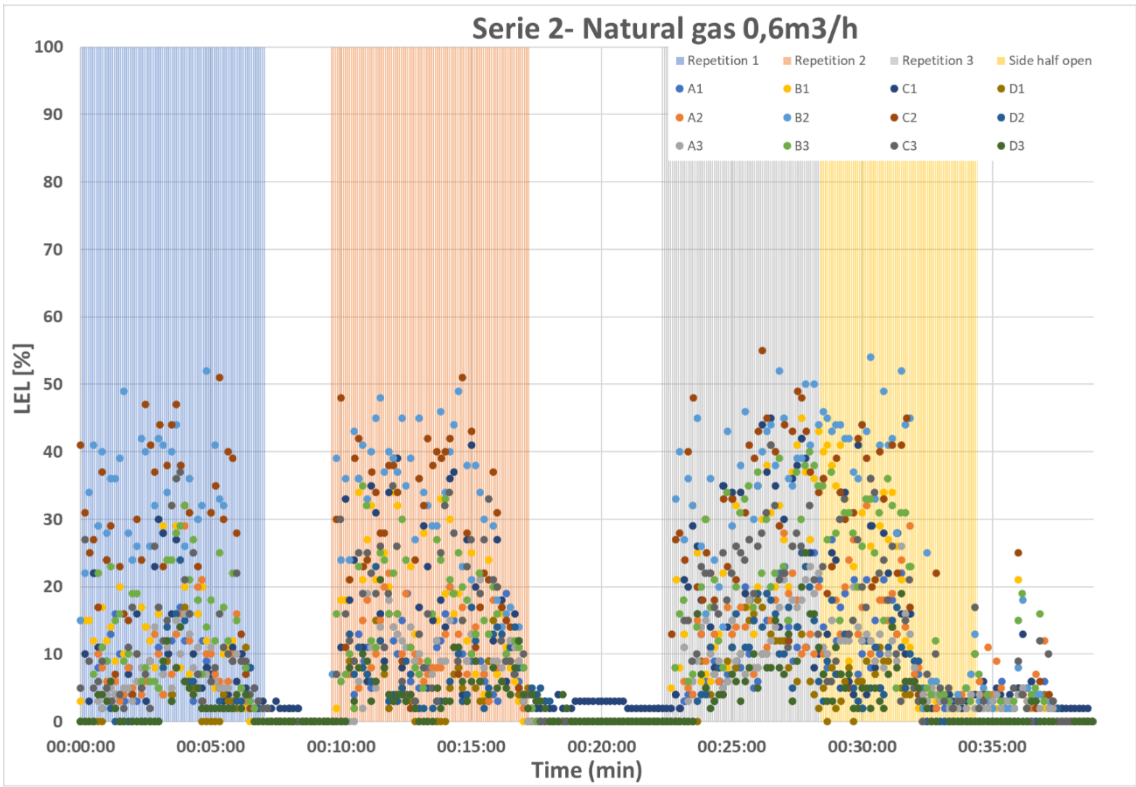
In terms of energy released during ignition, the following can be said. The volume of the pipe is about 1.41 m^3. The total energy released for hydrogen is then (30%) 4.58MJ. For natural gas (9.5%) it is about 4.24MJ. (under normal conditions). If released at supersonic flame speeds, that would mean the same as about 1 kg of TNT (about 4 hand grenades); TNT equivalent - Wikipedia

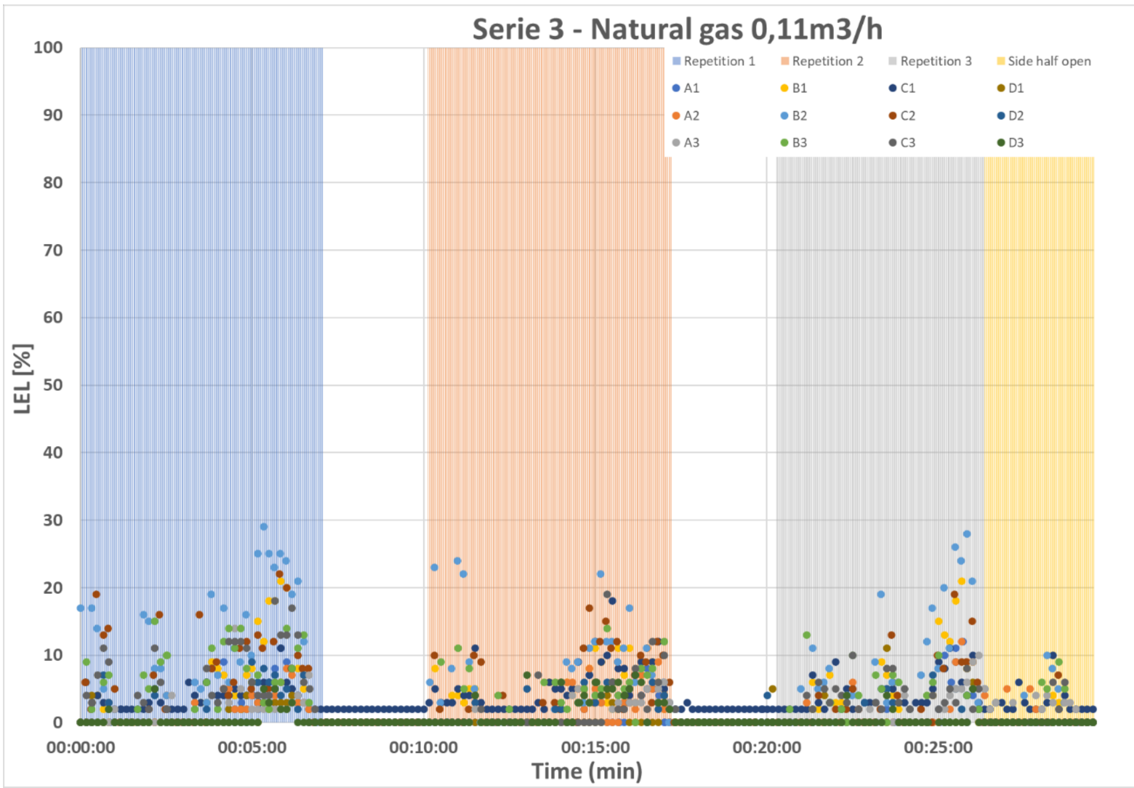
IV. Meaurements of concentrations in a working pit

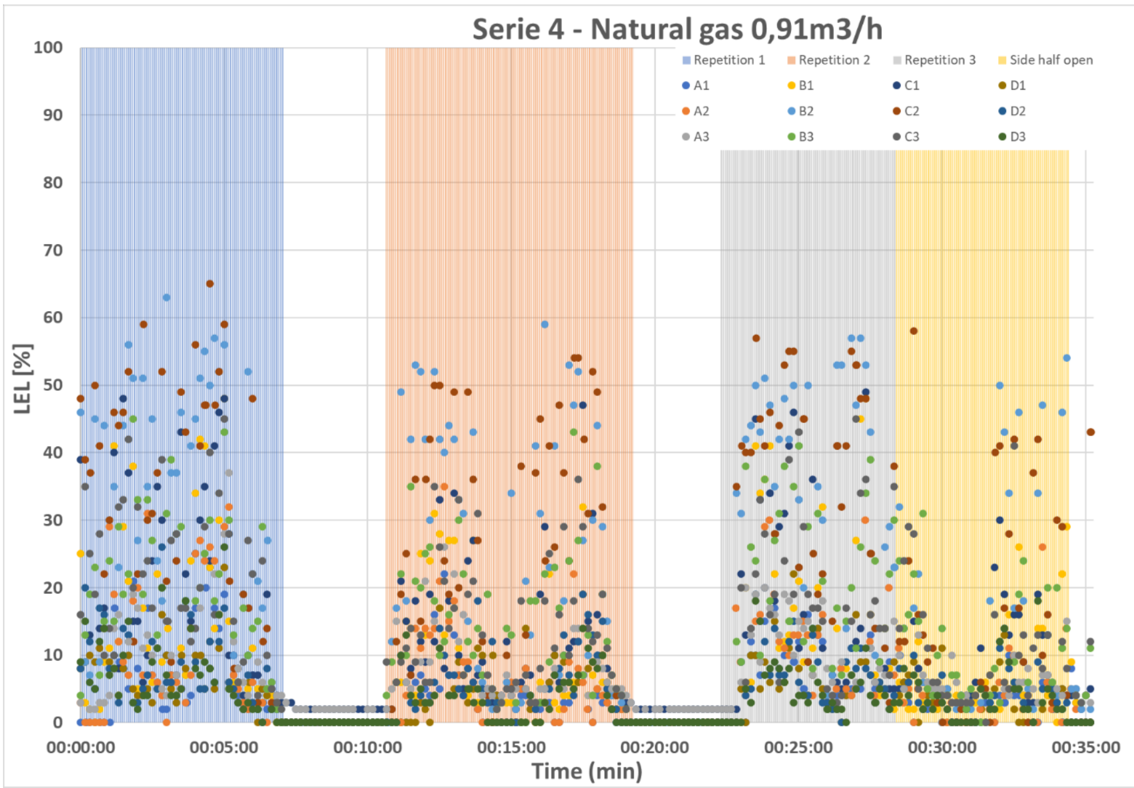
This annex contains the graphs of the measurements (measurement series 1 to 10) to determine the maximum flow rate at which the gas concentration in the working pit is less than 10% LEL. In the graphs, the measuring points are shown as A1 to D3. These measuring points are located in the working pit as follows.

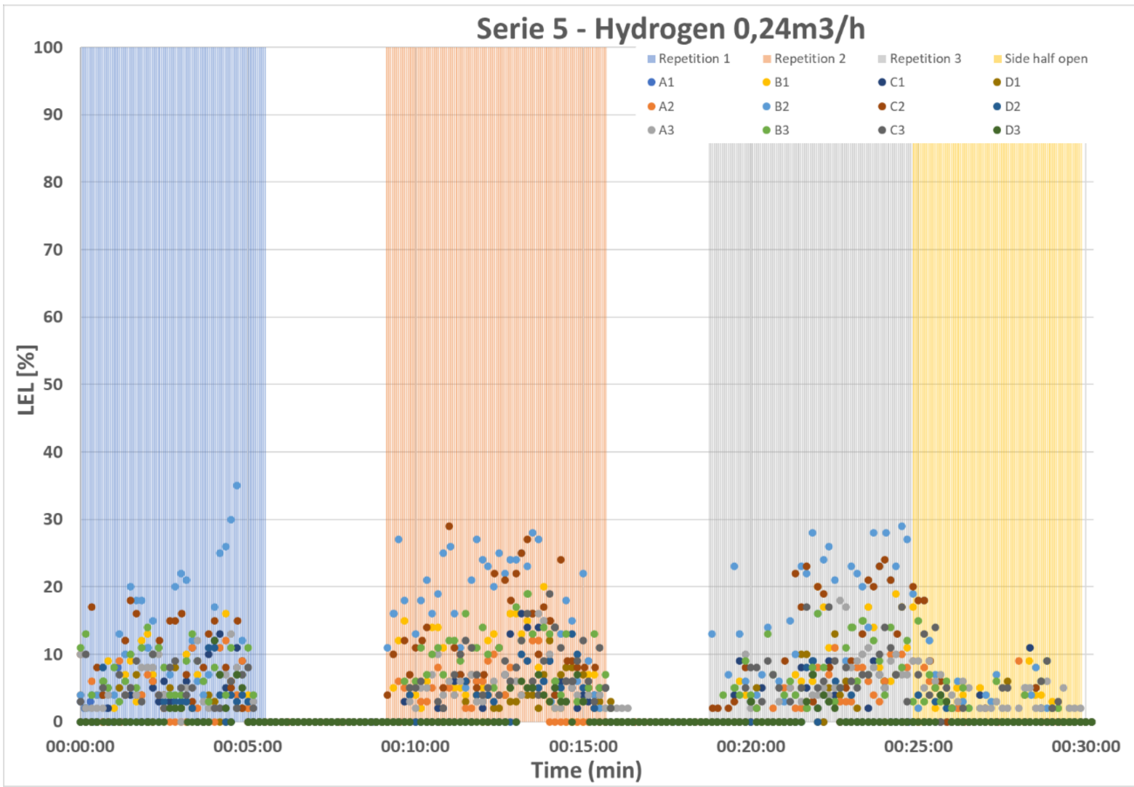


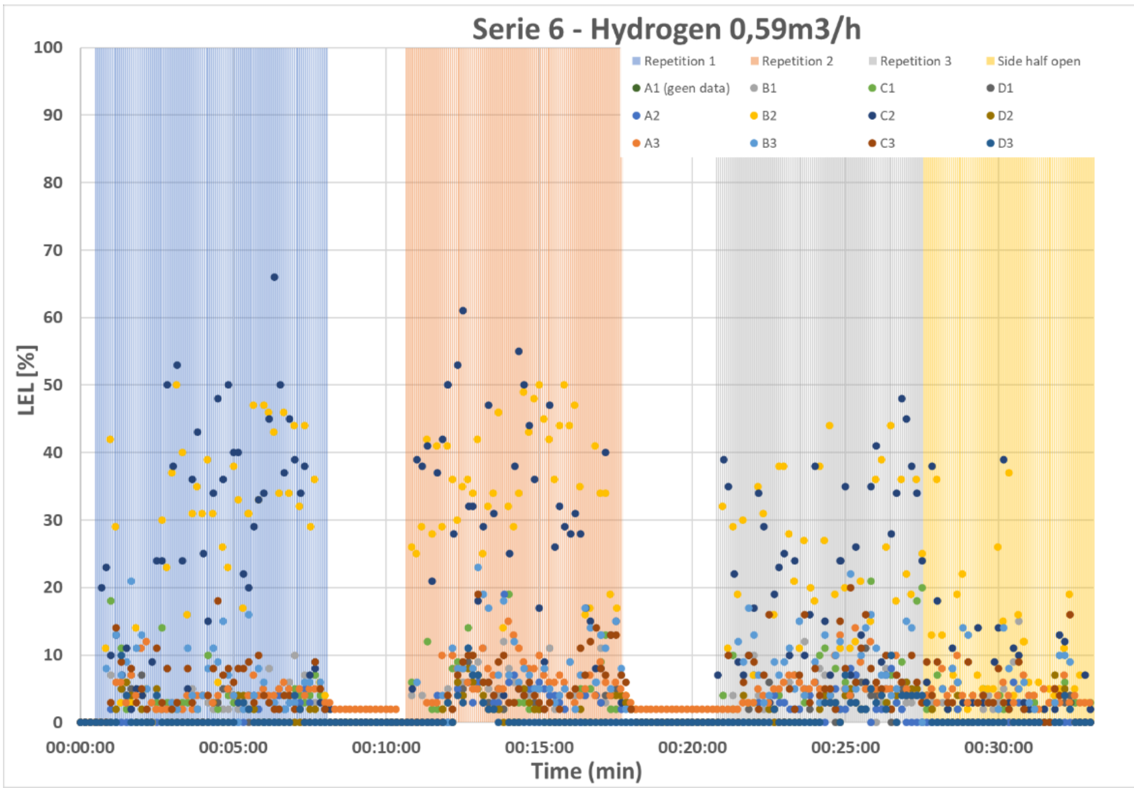

Serie 1 - Natural gas 0,25m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
100
90
80
70
60
50
40
30
20
10
0
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
00:40:00
00:45:00
Time (min)

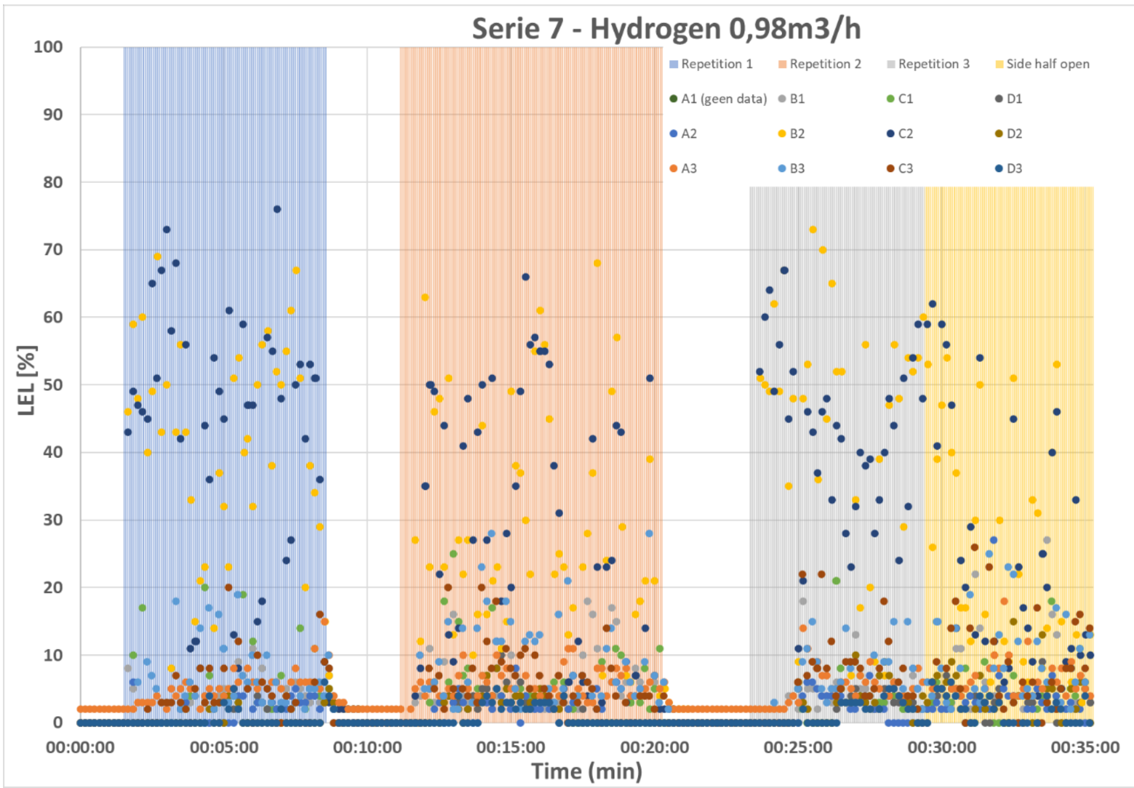

Serie 2- Natural gas 0,6m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
100
90
80
70
60
50
40
30
20
10
0
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
Time (min)


Serie 3 - Natural gas 0,11m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
100
90
80
70
60
50
40
30
20
10
0
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
Time (min)

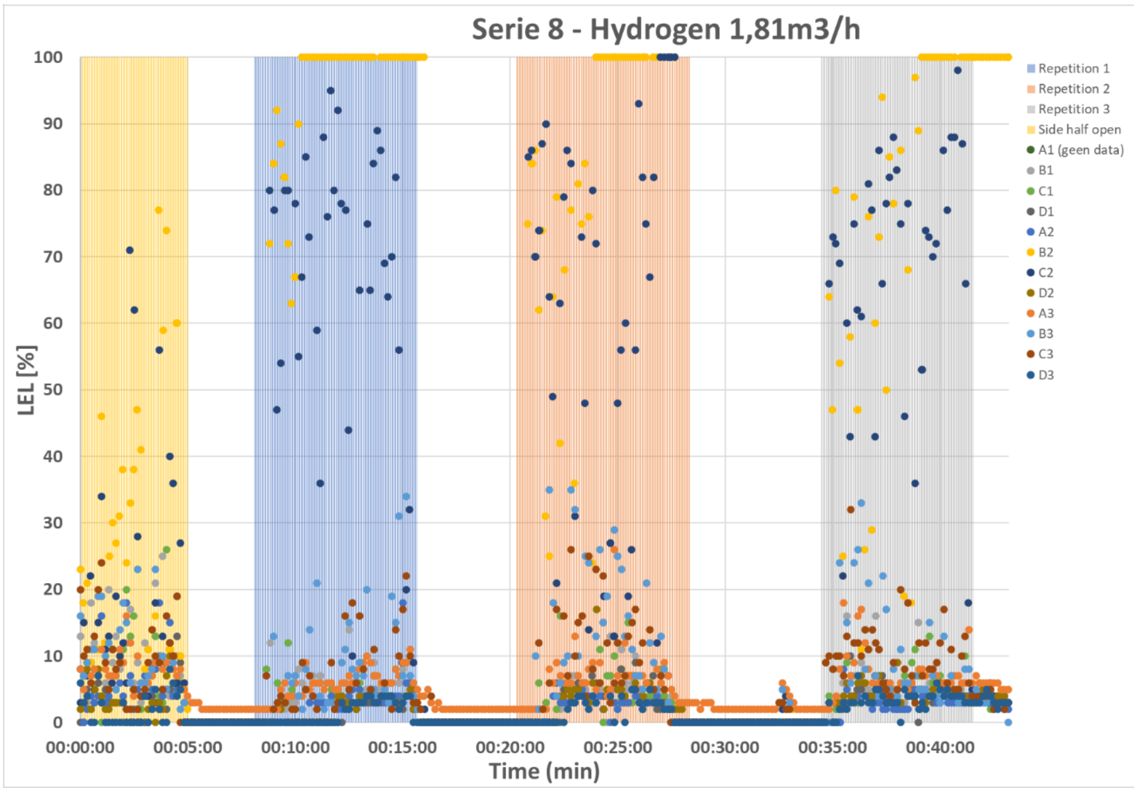

Serie 4 - Natural gas 0,91m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
100
90
80
70
60
50
40
30
20
10
0
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
Time (min)


Serie 5 - Hydrogen 0,24m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
0
10
20
30
40
50
60
70
80
90
100
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
Time (min)

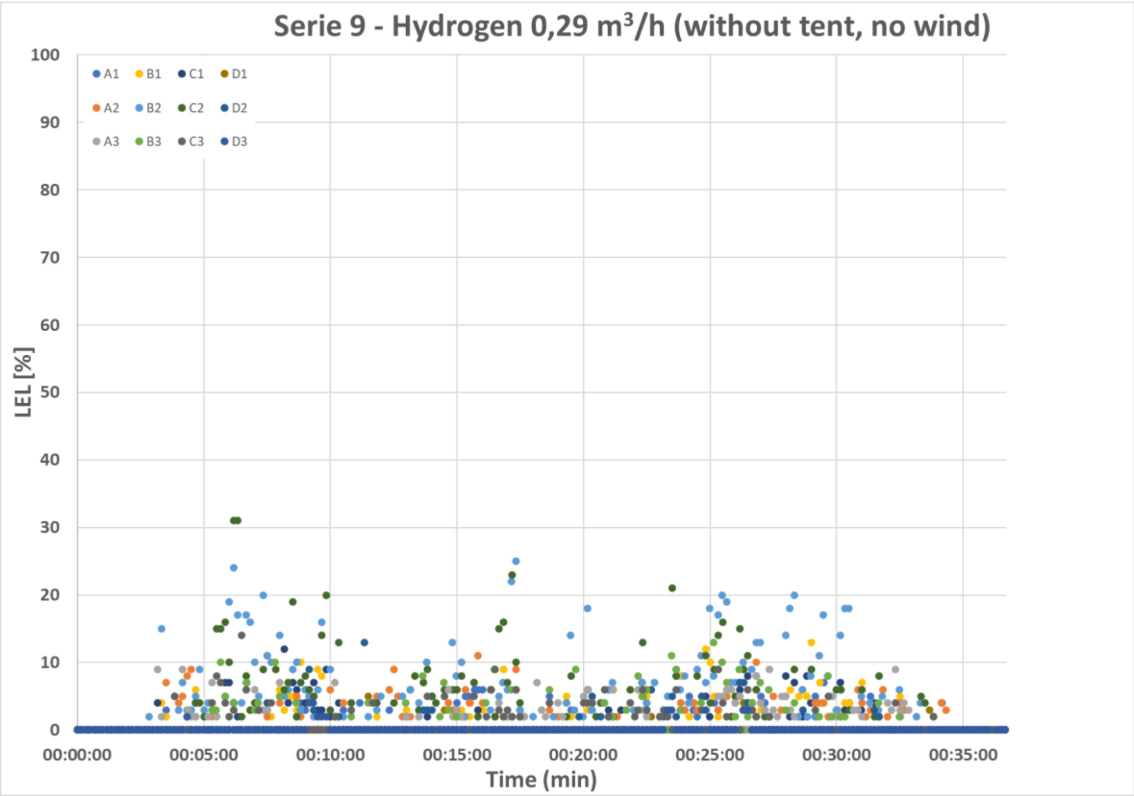

Serie 6 - Hydrogen 0,59m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1 (geen data)
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
0
10
20
30
40
50
60
70
80
90
100
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
Time (min)

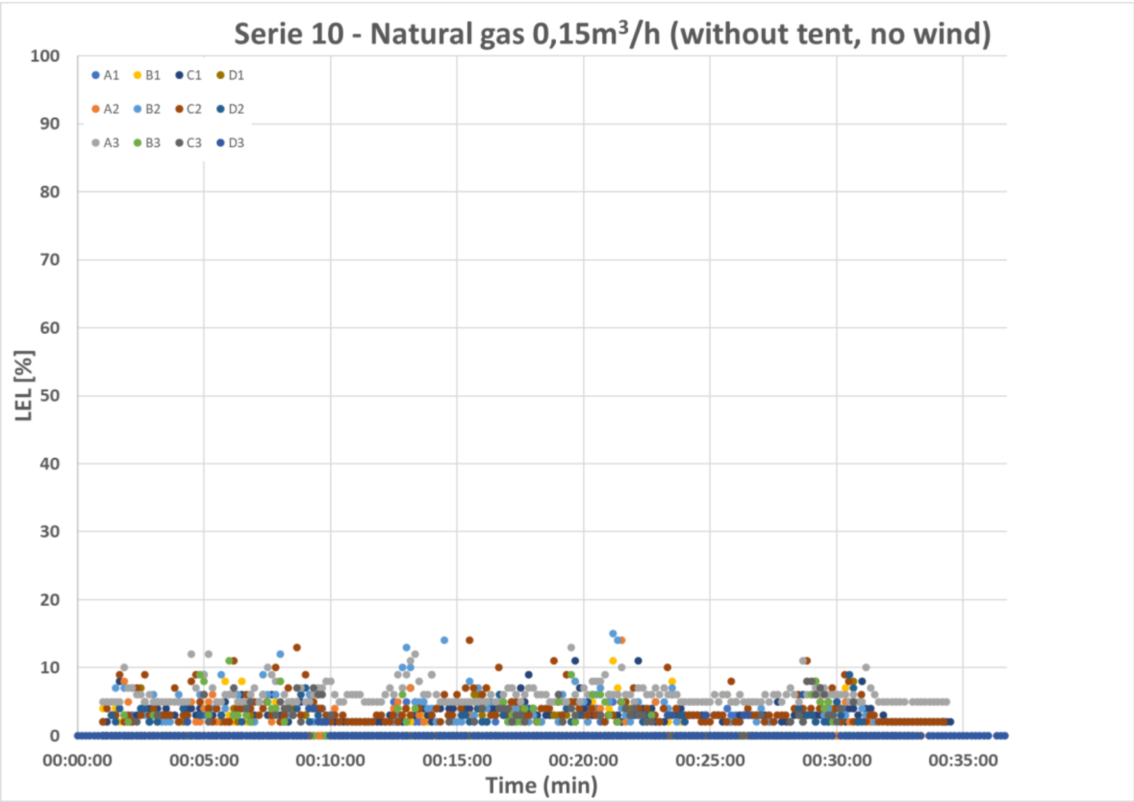


Serie 7 - Hydrogen 0,98m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1 (geen data)
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
Time (min)



Serie 8 - Hydrogen 1,81m3/h
Repetition 1
Repetition 2
Repetition 3
Side half open
A1 (geen data)
B1
C1
D1
A2
B2
C2
D2
A3
B3
C3
D3
LEL [%]
Time (min)


Serie 9 - Hydrogen 0,29 m³/h (without tent, no wind)
A1 B1 C1 D1
A2 B2 C2 D2
A3 B3 C3 D3
LEL [%]
0
10
20
30
40
50
60
70
80
90
100
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
Time (min)


Serie 10 - Natural gas 0,15m³/h (without tent, no wind)
A1 B1 C1 D1
A2 B2 C2 D2
A3 B3 C3 D3
LEL [%]
0
10
20
30
40
50
60
70
80
90
100
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
Time (min)

Tabel 23 Measured values concentrations in working pit. The orange colored values indicate the percentage of the measuring points > 10% LEL in the outer ring of the working pit. Light orange: for hydrogen. Dark orange for natural gas

Serie	**3**	**5**	**1**	**6**	**2**	**7**	**4**	**8**	**10**	**9**
Medium	nat. gas	hydrogen	nat. gas	hydrogen	nat. gas	hydrogen	nat. gas	hydrogen	nat. gas	hydrogen
Tent yes/no	yes	yes	yes	yes	yes	yes	yes	yes	no	no
Flow (m3/h)	0,11	0,24	0,25	0,59	0,60	0,98	0,91	1,81	0,15	0,29
Total number of measurements (mp	2731	1912	2317	1925	2910	2274	2761	714	2298	4340
% mp which are **0 % LEL**	72	67	45	47	39	30	48	48	51	72
% mp which are **> 0% LEL**	28	33	55	53	61	70	52	52	49	28
% mp which are **> 10% LEL**	4	9	22	13	32	20	21	17	1	2
% mp of the ring which are **0 % LEL**	72	69	47	53	40	35	48	51	58	77
% mp of the ring which are **> 0 % LEL**	28	31	53	47	60	65	52	49	42	23
% mp of the ring which are **> 10 % LEL**	2	5	16	4	27	7	17	8	1	1
% mp of B2 and C2 which are **0 % LEL**	68	59	36	21	34	6	46	33	17	48
% mp of B2 and C2 which are **> 0 % LEL**	32	41	64	79	66	94	54	67	83	52
% mp of B2 and C2 which are **> 10 % LEL**	11	23	51	54	55	74	40	63	3	7

The orange shaded numbers indicate the percentage of measured values greater than 10% LEL and as measured in the ring. These show that natural gas spreads more over the entire working well at approximately the same flow rate compared to hydrogen.

V. Overview of measurements carried out at Twente Safety Campus

Table 1

Measurement no.	Date of measurement	Series	Gas	Pipe length (m)	Gas flow rate (m^3_n/hour)	Used in this report? (yes/no)
1	10 Oct '22	C	Natural gas	1	0.15	Yes
2	10 Oct '22	C	Natural gas	1	0.15	Yes
3	10 Oct '22	C	Hydrogen	1	0.45	Yes
4	10 Oct '22	C	Hydrogen	1	0.45	Yes
5	11 Oct '22	C	Natural gas	20	0.20	Yes
6	11 Oct '22	C	Natural gas	20	0.20	Yes
7	11 Oct '22	C	Hydrogen	20	0.60	Yes
8	13 Oct '22	D	Natural gas	1	4	No
9	13 Oct '22	D	Natural gas	1	3	Yes
10	13 Oct '22	D	Natural gas	1	4	Yes
11	13 Oct '22	D	Natural gas	1	7	Yes
12	13 Oct '22	D	Natural gas	1	7	Yes
13	13 Oct '22	D	Natural gas	1	7	Yes
14	13 Oct '22	D	Natural gas	1	7.5	Yes
15	13 Oct '22	D	Hydrogen	1	4	Yes
16	13 Oct '22	D	Hydrogen	1	4	Yes
17	13 Oct '22	D	Hydrogen	1	8	Yes
18	13 Oct '22	D	Hydrogen	1	8	Yes
19	13 Oct '22	D	Hydrogen	1	14	No
20	13 Oct '22	D	Hydrogen	1	15.5	Yes
C	Instant ignition after gas release					
D	Delayed ignition after gas release					
S	Placement of a stopper after ignition of gas					

Measurement 8 was not used because the desired concentration was reached too quickly. No ignition was applied and the next measurement was started after the concentrations had subsided again.

Measurement 19 was not used because no ignition was applied.

Measurement no.	Date of measurement	Series	Gas	Pipe length (m)	Gas flow rate (m^3_n/hour)	Use in this report? (yes/no)
21	14 Oct ‘22	C	Hydrogen	20	0.6	Yes
22	14 Oct ‘22	C	Hydrogen	20	0.6	Yes
23	14 Oct ‘22	D	Hydrogen	20	4	No
24	14 Oct ‘22	D	Hydrogen	20	6	Yes
25	14 Oct ‘22	D	Hydrogen	20	6	Yes
26	14 Oct ‘22	D	Hydrogen	20	15	Yes
27	14 Oct ‘22	D	Hydrogen	20	15	Yes
28	14 Oct ‘22	D	Natural gas	20	4	Yes
29	14 Oct ‘22	D	Natural gas	20	4	Yes
30	14 Oct ‘22	D	Natural gas	20	4	Yes
31	14 Oct ‘22	D	Natural gas	20	4	Yes
32	14 Oct ‘22	D	Natural gas	20	7	Yes
33	14 Oct ‘22	D	Natural gas	20	7	Yes
34	14 Oct ‘22	D	Natural gas	20	8	Yes
35	14 Oct ‘22	D	Natural gas	20	8	Yes
36	14 Oct ‘22	D	Natural gas	20	8	Yes
37	14 Oct ‘22	D	Natural gas	20	8	yes
38	19 Oct ‘22	S	Natural gas	20	40	No
39	19 Oct ‘22	S	Natural gas	20	40	No
40	19 Oct ‘22	S	Natural gas	20	24	yes
41	19 Oct ‘22	S	Natural gas	20	23	Yes
42	19 Oct ‘22	S	Natural gas	20	23	Yes
43	19 Oct ‘22	S	Hydrogen	20	80	Yes
44	19 Oct ‘22	S	Hydrogen	20	80	Yes
45	19 Oct ‘22	S	Hydrogen	20	84	Yes
46	19 Oct ‘22	S	Hydrogen	20	80	Yes
C	Instant ignition after gas release					
D	Delayed ignition after gas release					
S	Placement of a stopper after ignition of gas					

Measurement 23 was not used because the spark igniters did not work (they were damp).

Measurement 38 was not used because the stopper was positioned in the wrong direction.

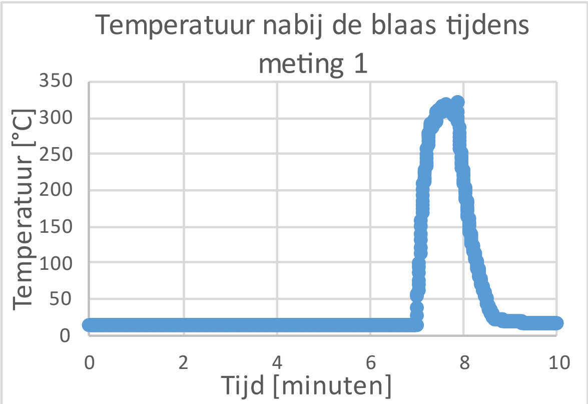
Measurement 39 was not used because the stopper turned over after setting (pressure rose to about 5 bar). A control set was installed at the next measurement.

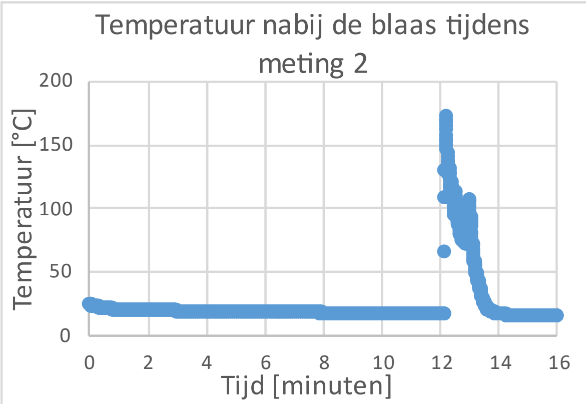
VI. Temperature measurements during ignition test

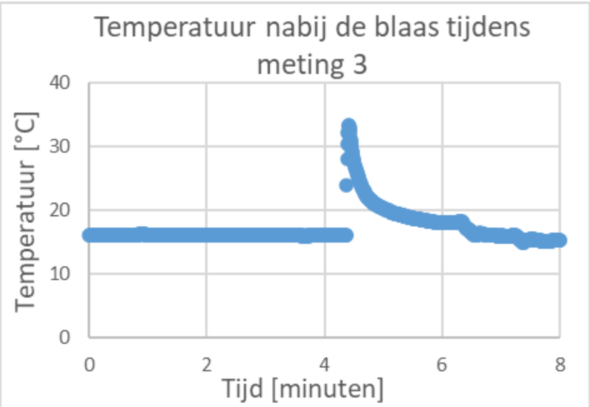
Temperature graphs are included in this Annex in situations where increased temperatures were noticed.

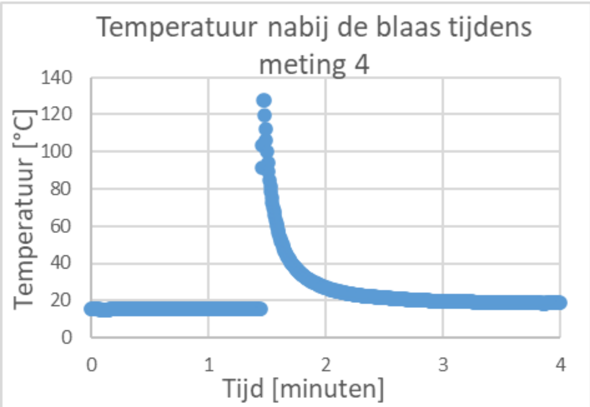
Legend:

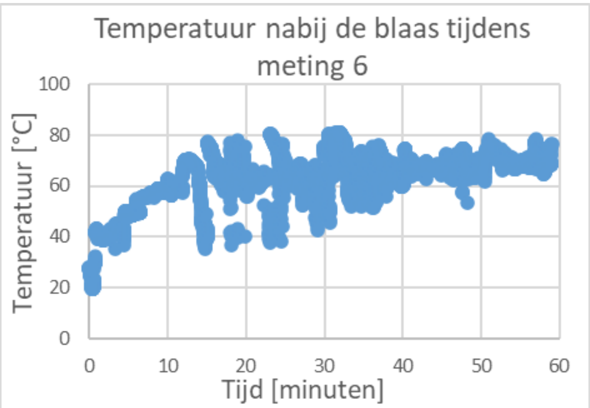
Dutch	English
Temperatuur nabij de blaas tijdens meting x	Temperature at the inflatable gas stopper during measurement x
Temperatuur (°C)	Temperature (°C)
Tijd (min)	Time (min)

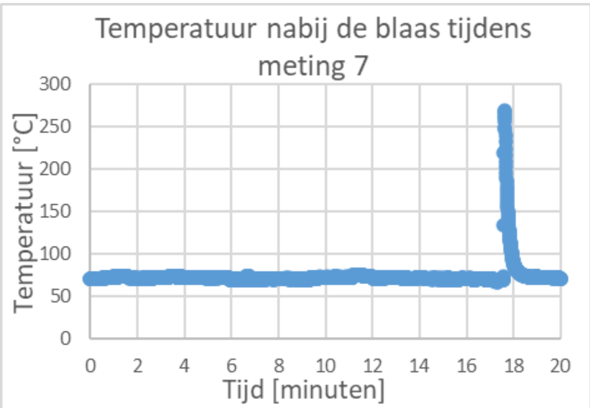


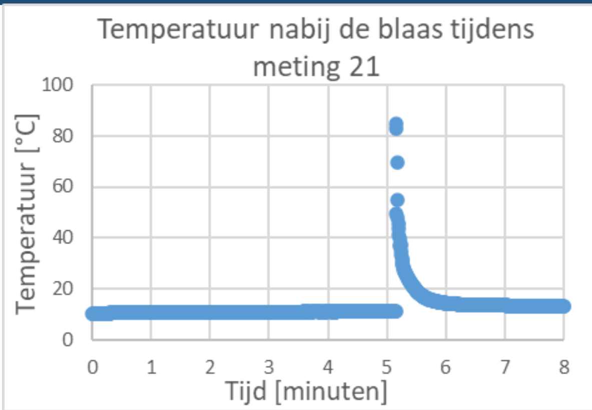


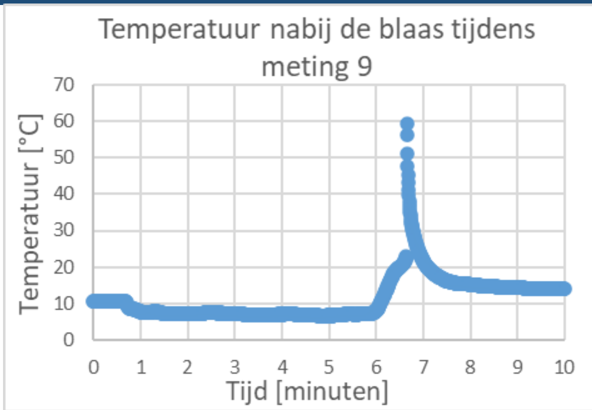


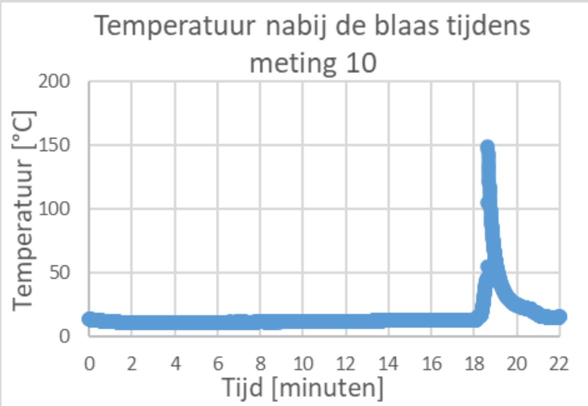


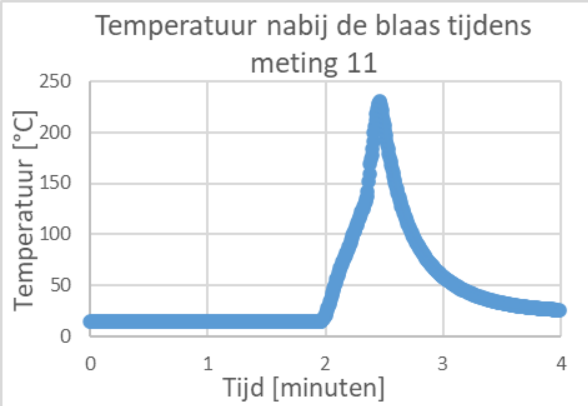


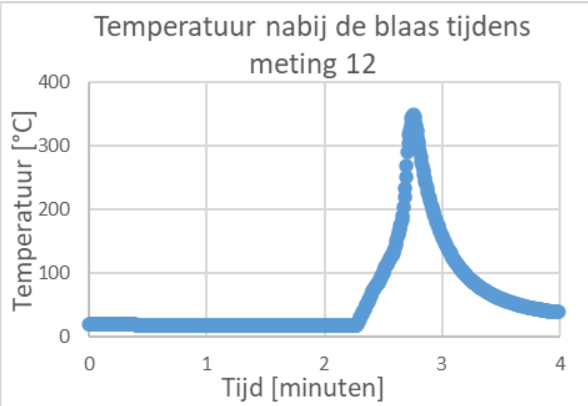


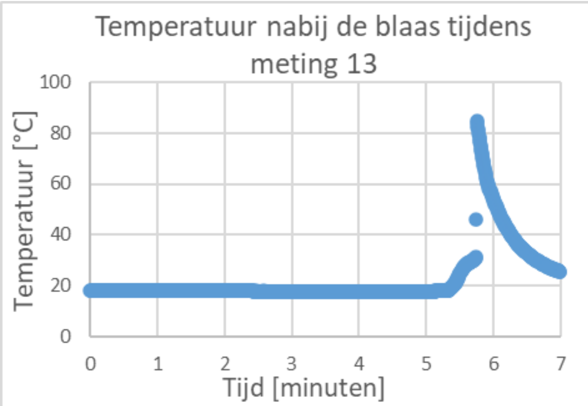

Temperatuur nabij de blaas tijdens meting 21
Temperatuur [°C]
0 20 40 60 80 100
Tijd [minuten]
0 1 2 3 4 5 6 7 8

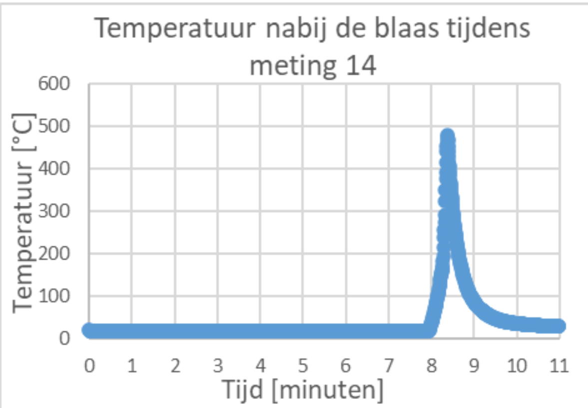

Temperatuur nabij de blaas tijdens meting 9
Temperatuur [°C]
0 10 20 30 40 50 60 70
Tijd [minuten]
0 1 2 3 4 5 6 7 8 9 10

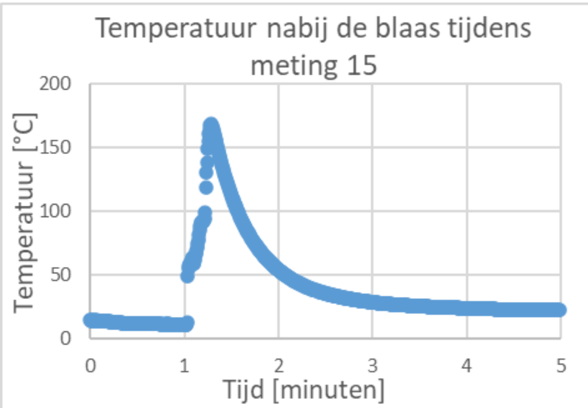

Temperatuur nabij de blaas tijdens meting 10
Temperatuur [°C]
0 50 100 150 200
Tijd [minuten]
0 2 4 6 8 10 12 14 16 18 20 22

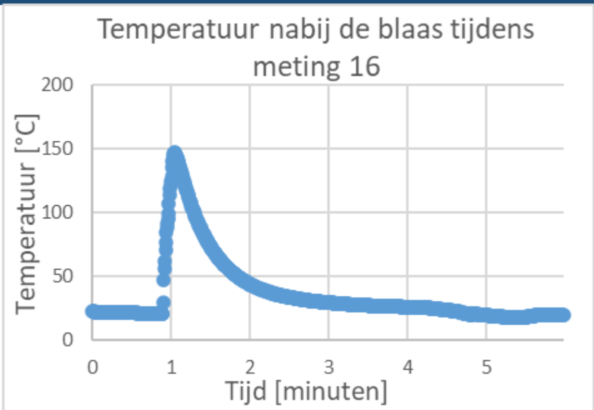

Temperatuur nabij de blaas tijdens meting 11
Temperatuur [°C]
0 50 100 150 200 250
Tijd [minuten]
0 1 2 3 4

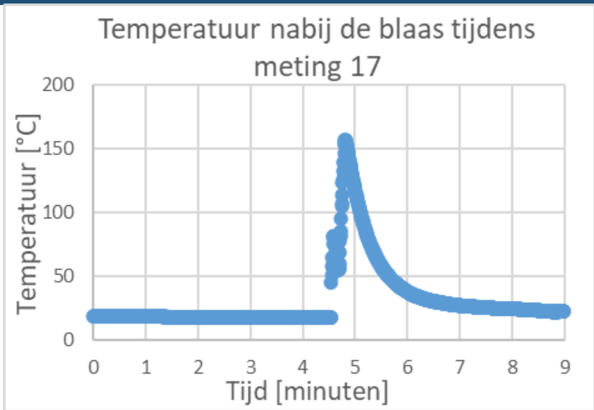

Temperatuur nabij de blaas tijdens meting 12
Temperatuur [°C]
0 100 200 300 400
Tijd [minuten]
0 1 2 3 4

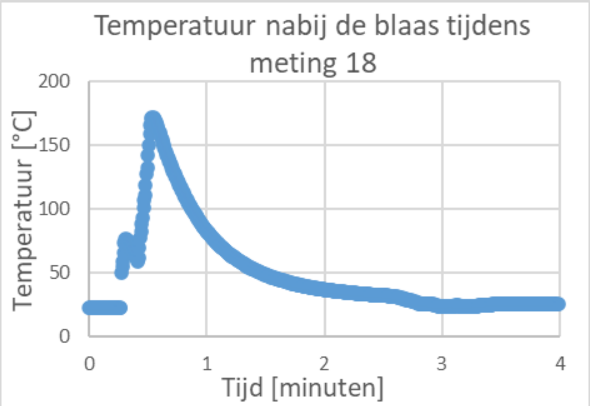

Temperatuur nabij de blaas tijdens meting 13
Temperatuur [°C]
0 20 40 60 80 100
Tijd [minuten]
0 1 2 3 4 5 6 7

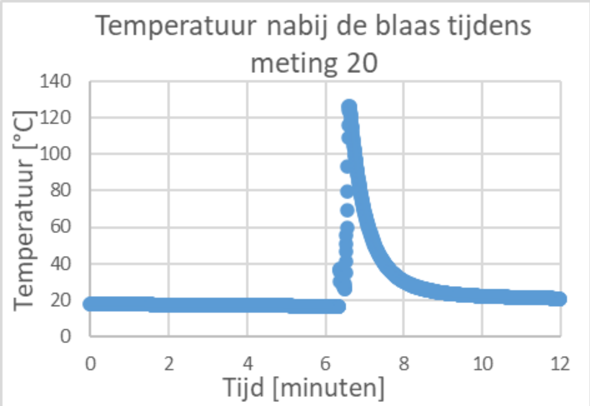

Temperatuur nabij de blaas tijdens meting 14
Temperatuur [°C]
0 100 200 300 400 500 600
Tijd [minuten]
0 1 2 3 4 5 6 7 8 9 10 11

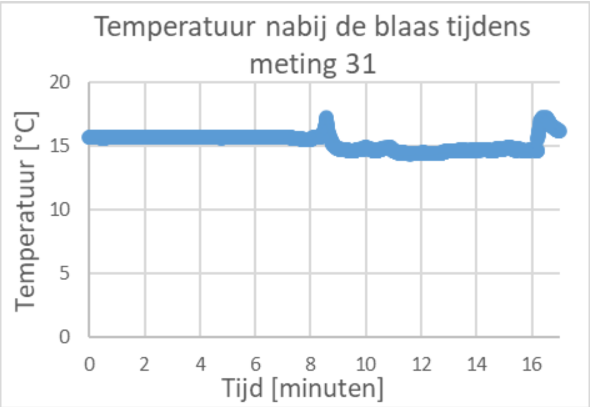

Temperatuur nabij de blaas tijdens meting 15
Temperatuur [°C]
0 50 100 150 200
Tijd [minuten]
0 1 2 3 4 5

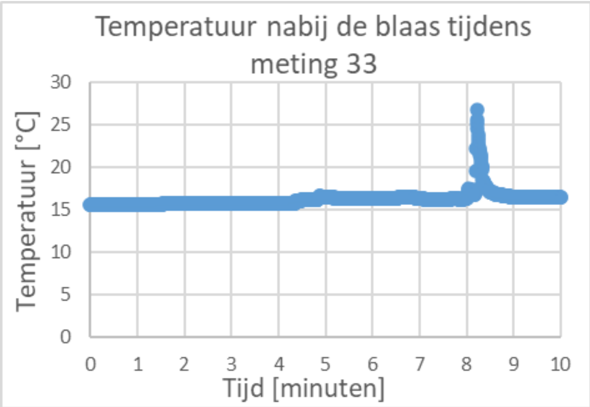

Temperatuur nabij de blaas tijdens meting 16
Temperatuur [°C]
0
50
100
150
200
0
1
2
3
4
5
Tijd [minuten]


Temperatuur nabij de blaas tijdens meting 17
Temperatuur [°C]
0
50
100
150
200
0
1
2
3
4
5
6
7
8
9
Tijd [minuten]


Temperatuur nabij de blaas tijdens meting 18
Temperatuur [°C]
0
50
100
150
200
0
1
2
3
4
Tijd [minuten]


Temperatuur nabij de blaas tijdens meting 20
Temperatuur [°C]
0
20
40
60
80
100
120
140
0
2
4
6
8
10
12
Tijd [minuten]


Temperatuur nabij de blaas tijdens meting 31
Temperatuur [°C]
0
5
10
15
20
0
2
4
6
8
10
12
14
16
Tijd [minuten]

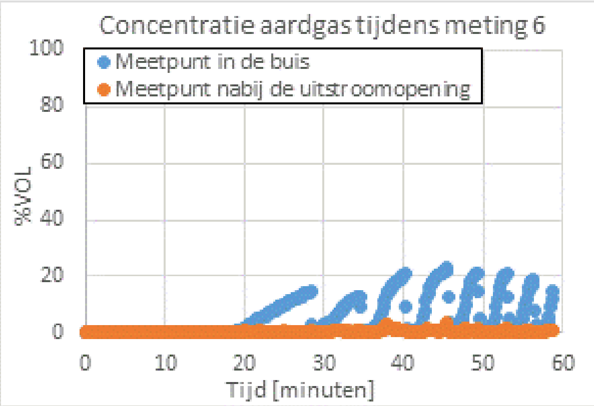

Temperatuur nabij de blaas tijdens meting 33
Temperatuur [°C]
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8
9
10
Tijd [minuten]

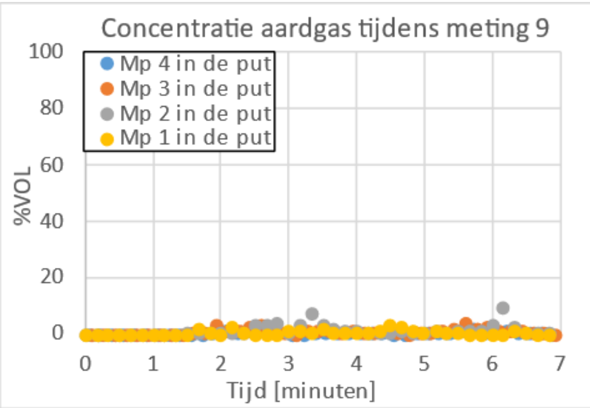
VII. Measurements of concentrations during ignition test

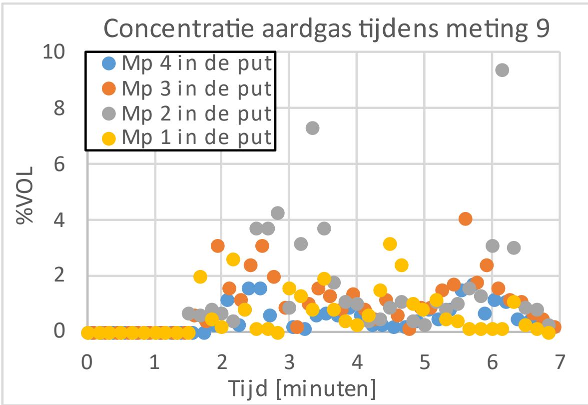
In this annex the results of the concentration measurements in the working pit. These are particularly important for the measurements with the delayed ignition. Where a measurement number is mentioned twice, it is a representation of the gas concentration at a different scale. The measurements are listed in the same order as they are in chapter 4.

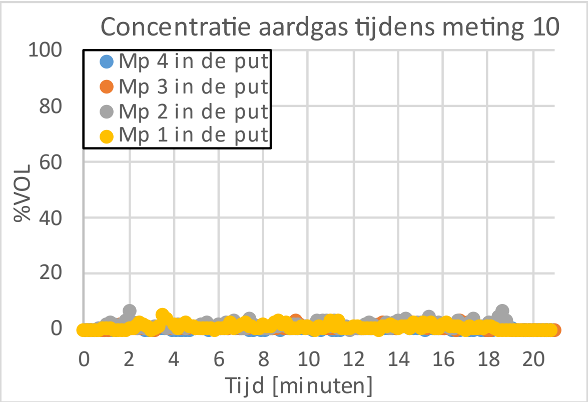
Legend:

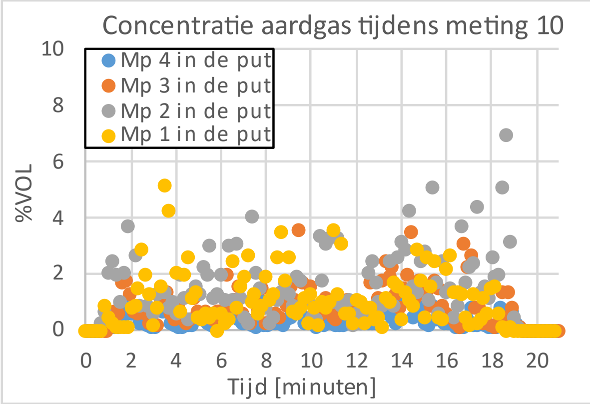
Dutch	English
Concentratie aardgas tijdens meting x	Concentration natural gas during measurement x
Concentratie waterstof tijdens meting x	Concentration hydrogen during measurement x
Tijd (min)	Time (min)
Meetpunt (MP) in de buis	Measuring point (MP) in the pipe
Meetpunt nabij de uitstroomopening	Measuring point at the outlet of the pipe
MP x in de put	MP x in the working pit
MP in de buis	MP in the pipe
Meetpunt zijkant put 0,5m vanaf rand	Measuring point at the side of the working pit 0,5m of the edge

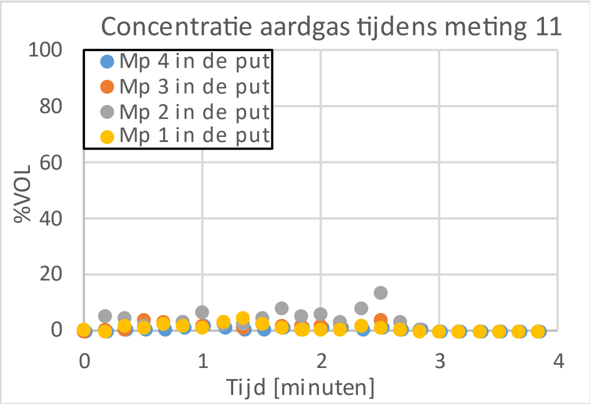


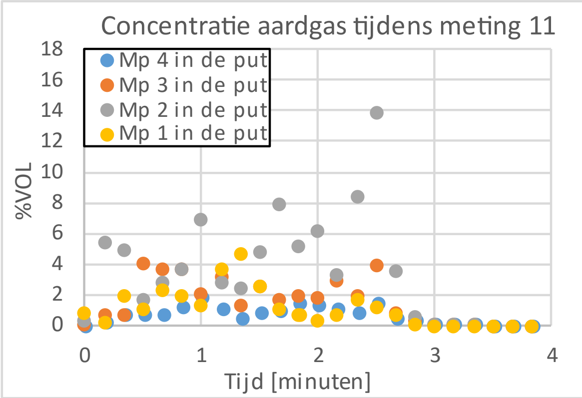


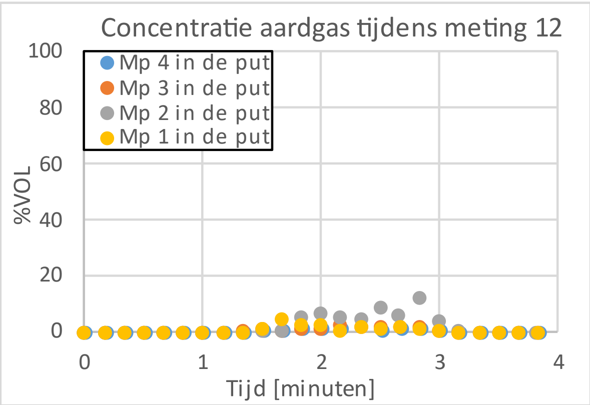


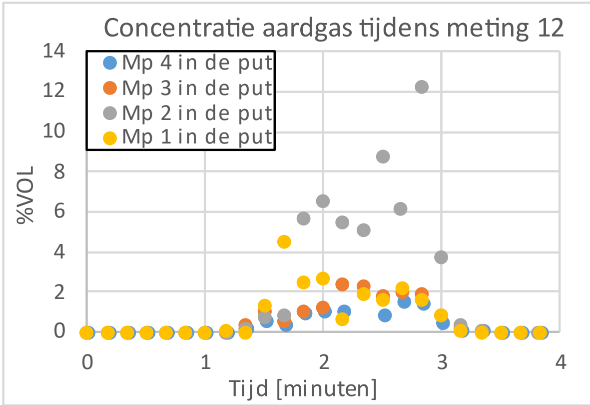

Concentratie aardgas tijdens meting 10
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

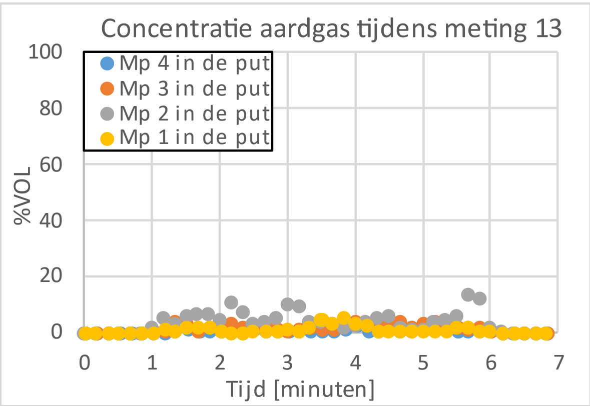

Concentratie aardgas tijdens meting 10
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

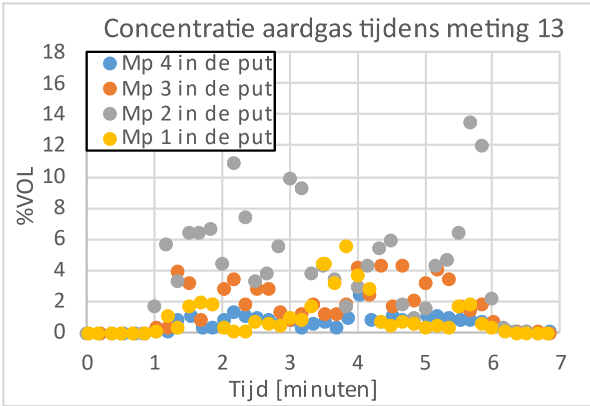

Concentratie aardgas tijdens meting 11
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

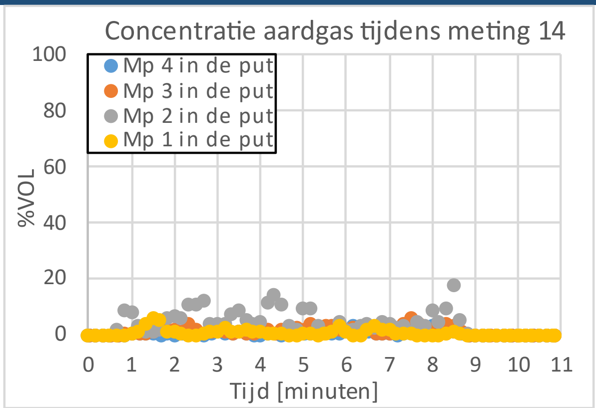

Concentratie aardgas tijdens meting 11
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

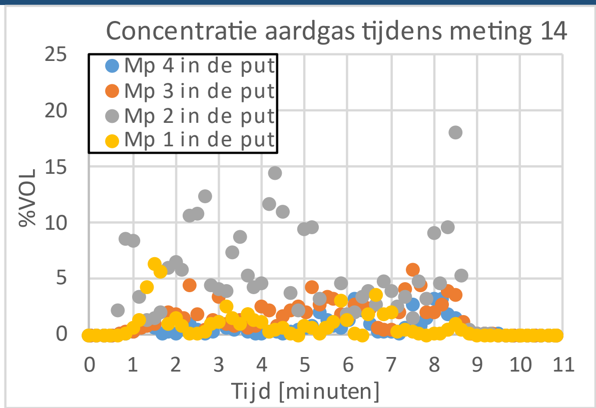

Concentratie aardgas tijdens meting 12
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

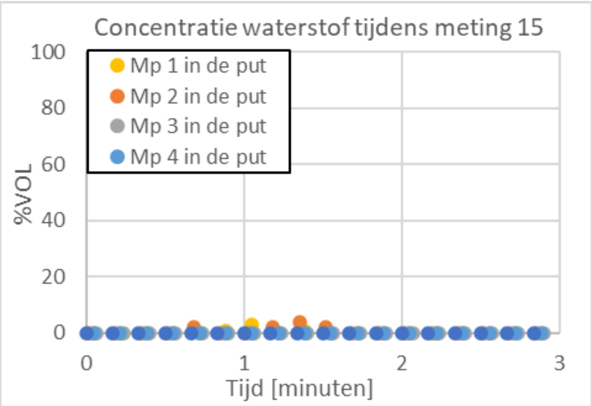

Concentratie aardgas tijdens meting 12
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

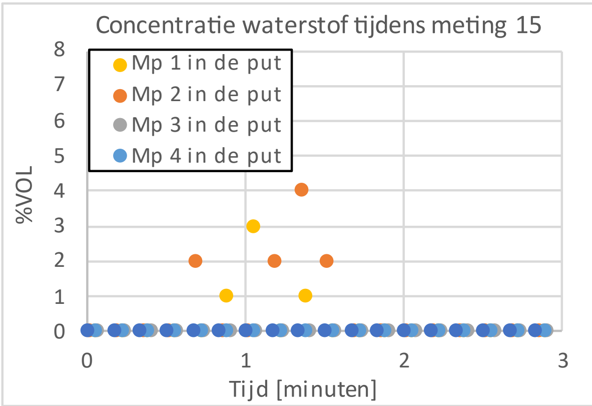

Concentratie aardgas tijdens meting 13
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

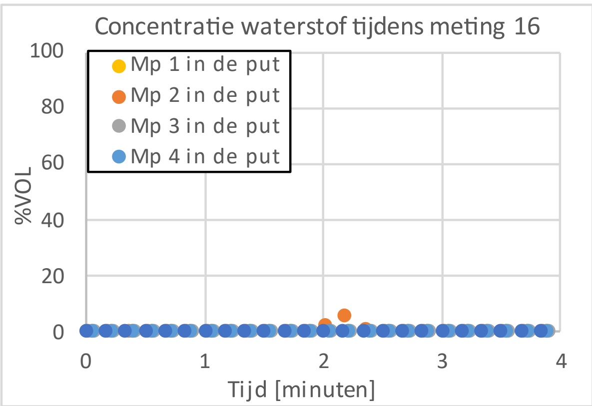

Concentratie aardgas tijdens meting 13
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

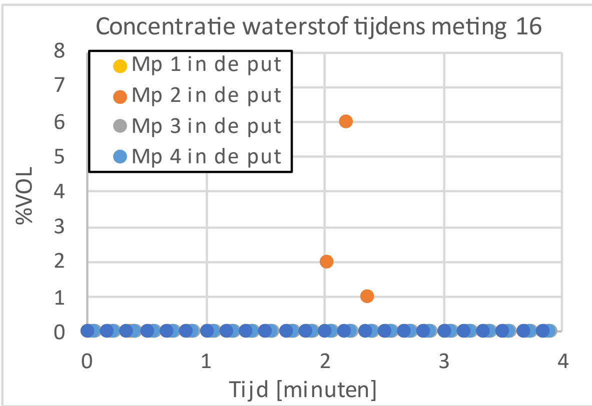

Concentratie aardgas tijdens meting 14
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
Tijd [minuten]

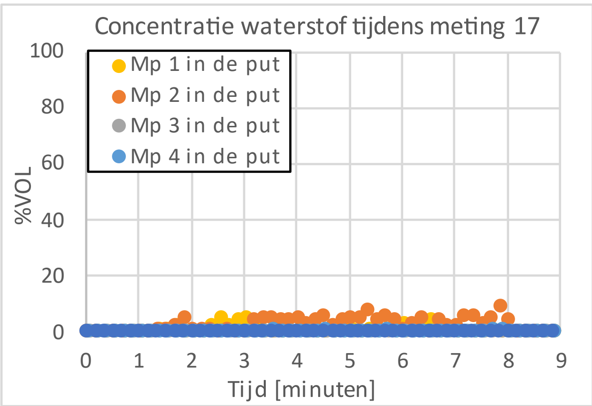

Concentratie aardgas tijdens meting 14
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
Tijd [minuten]

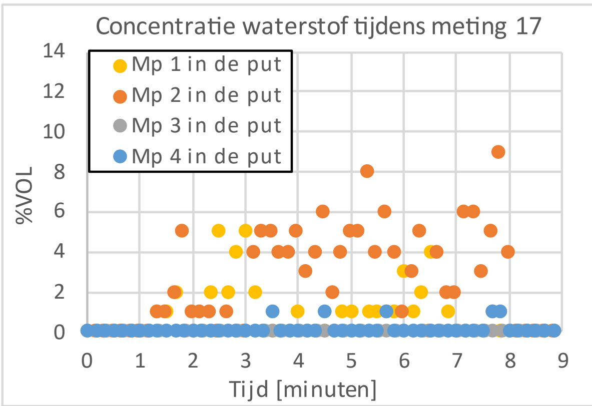

Concentratie waterstof tijdens meting 15
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
100
80
60
40
20
0
0 1 2 3
Tijd [minuten]

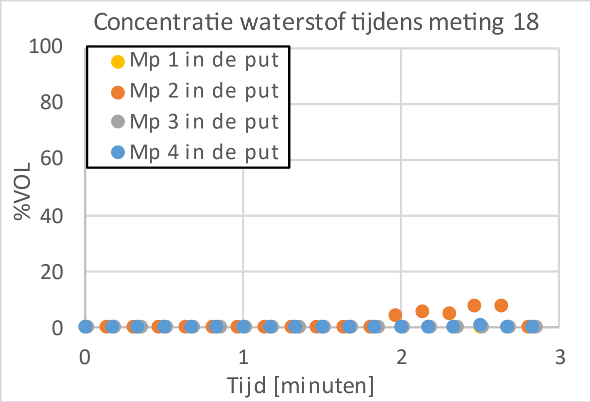

Concentratie waterstof tijdens meting 15
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
8
7
6
5
4
3
2
1
0
0 1 2 3
Tijd [minuten]

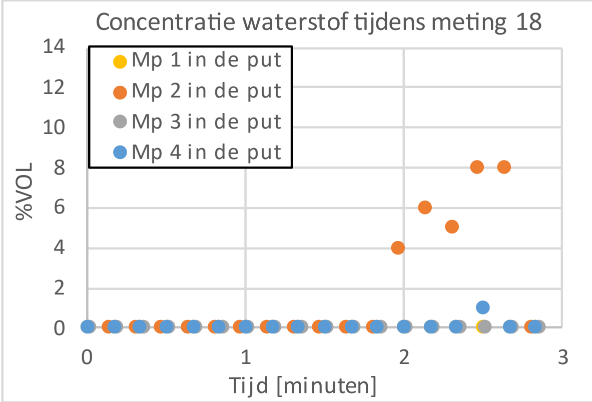

Concentratie waterstof tijdens meting 16
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
100
80
60
40
20
0
0 1 2 3 4
Tijd [minuten]

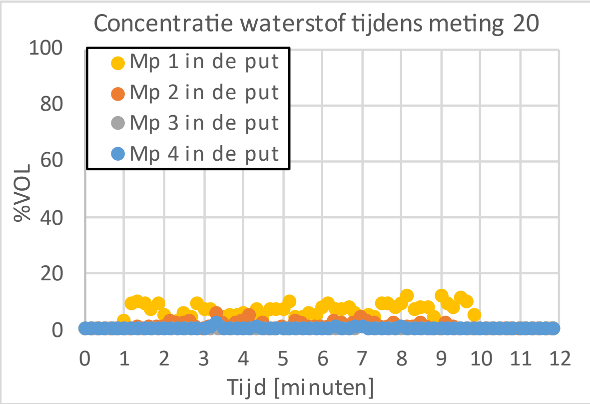

Concentratie waterstof tijdens meting 16
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
8
7
6
5
4
3
2
1
0
0 1 2 3 4
Tijd [minuten]

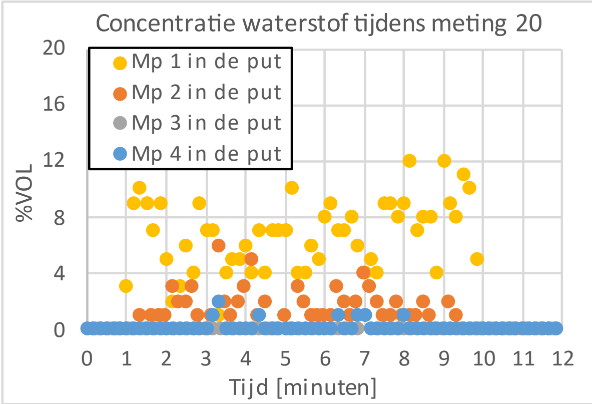

Concentratie waterstof tijdens meting 17
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9
Tijd [minuten]

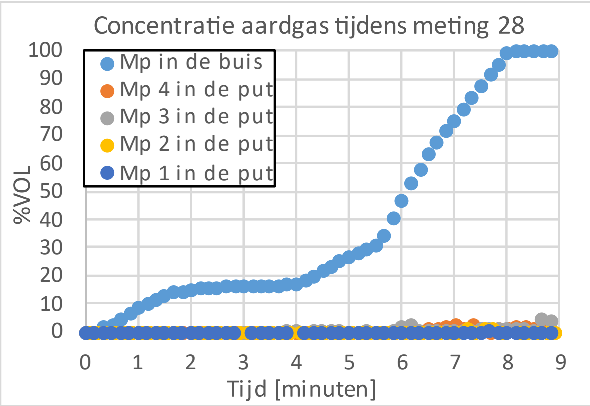

Concentratie waterstof tijdens meting 17
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9
Tijd [minuten]

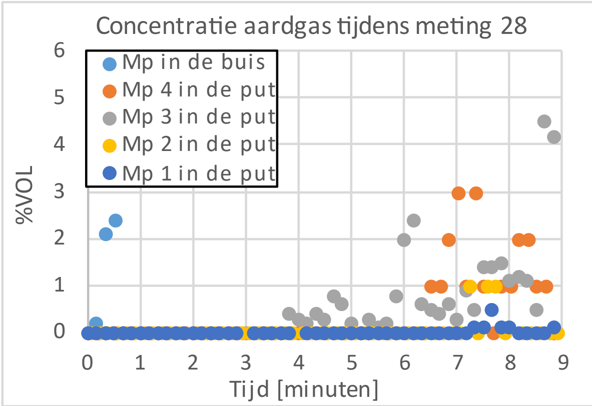

Concentratie waterstof tijdens meting 18
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

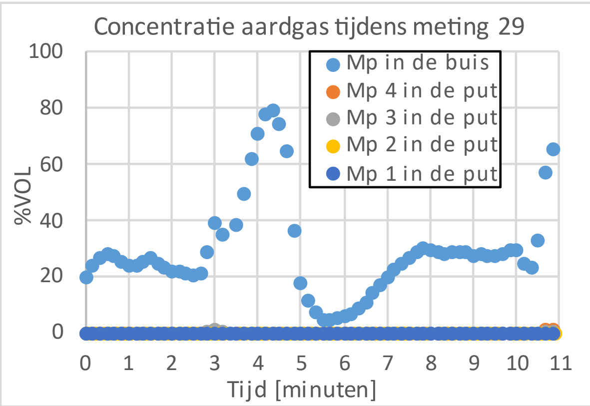

Concentratie waterstof tijdens meting 18
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

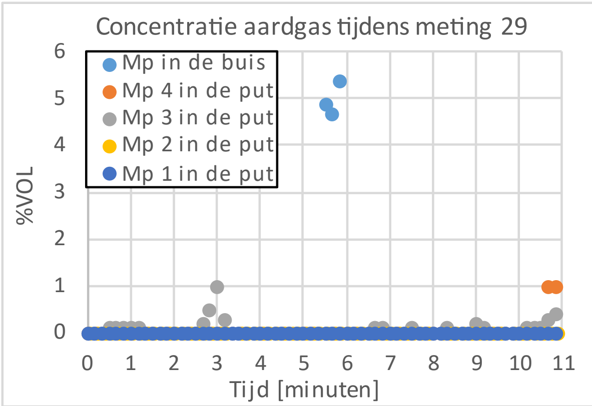

Concentratie waterstof tijdens meting 20
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

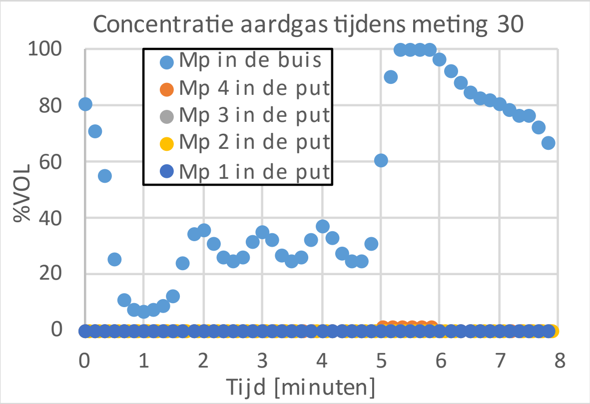

Concentratie waterstof tijdens meting 20
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

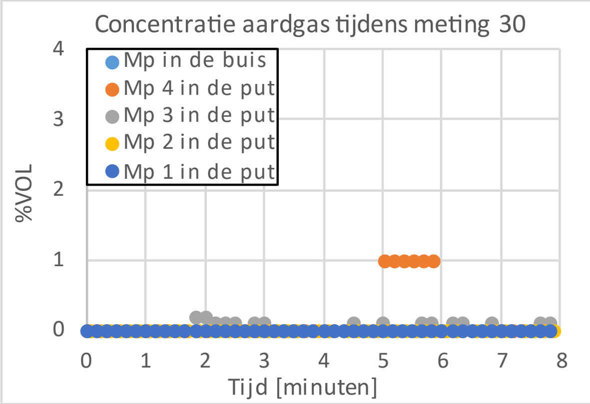

Concentratie aardgas tijdens meting 28
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

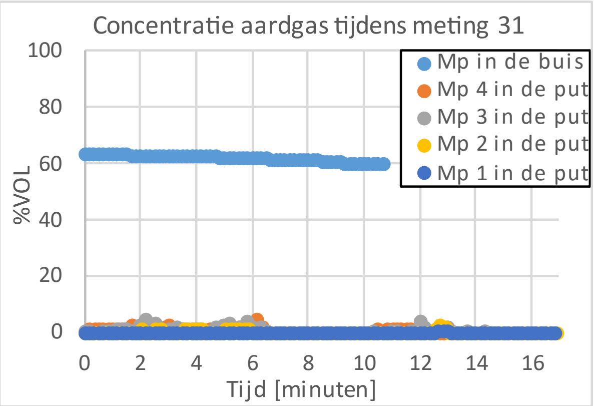

Concentratie aardgas tijdens meting 28
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

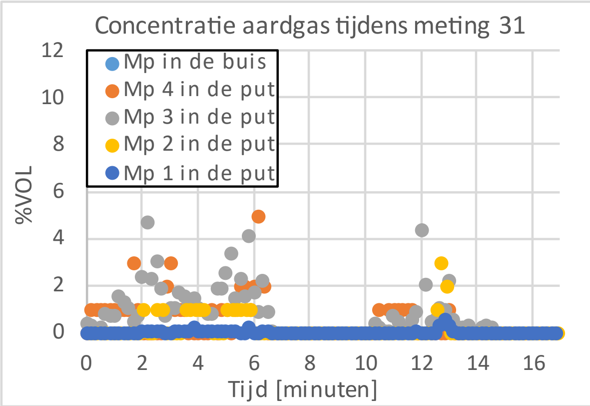

Concentratie aardgas tijdens meting 29
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

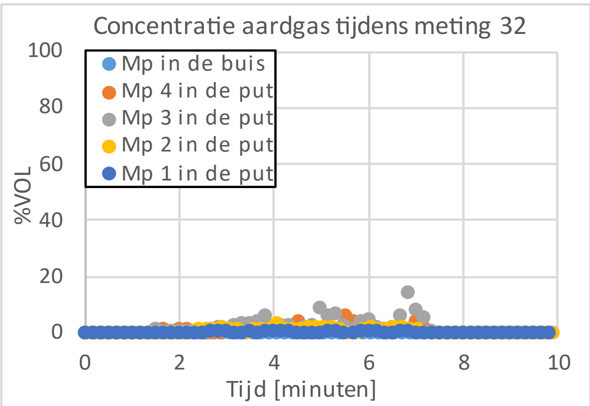

Concentratie aardgas tijdens meting 29
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

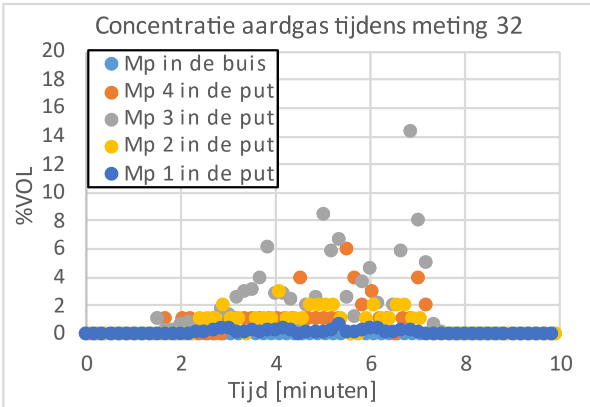

Concentratie aardgas tijdens meting 30
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

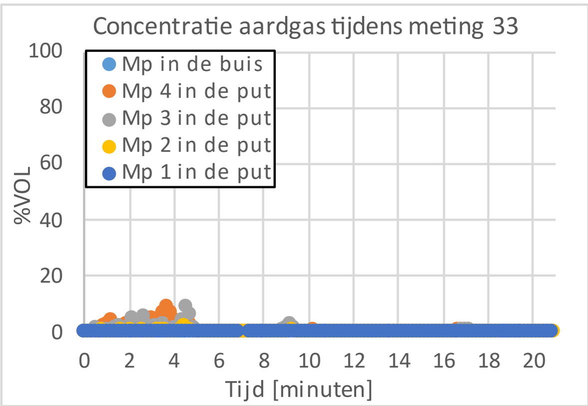

Concentratie aardgas tijdens meting 30
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

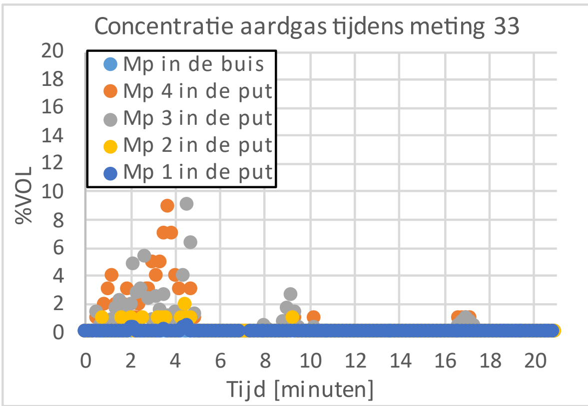

Concentratie aardgas tijdens meting 31
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

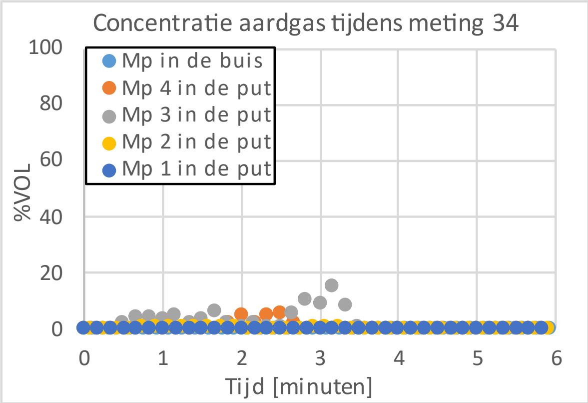

Concentratie aardgas tijdens meting 31
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

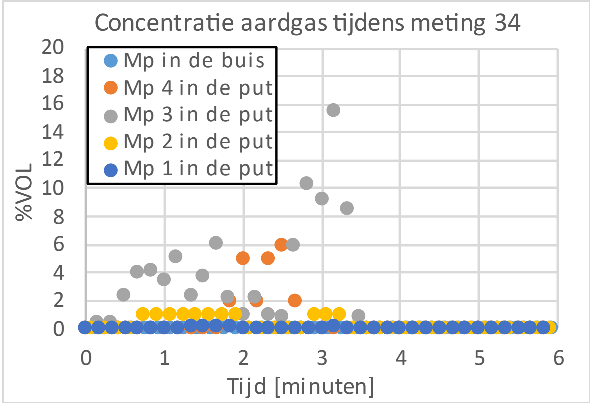

Concentratie aardgas tijdens meting 32
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

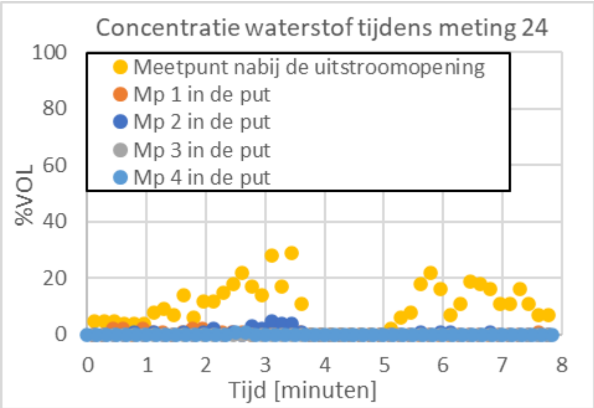

Concentratie aardgas tijdens meting 32
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

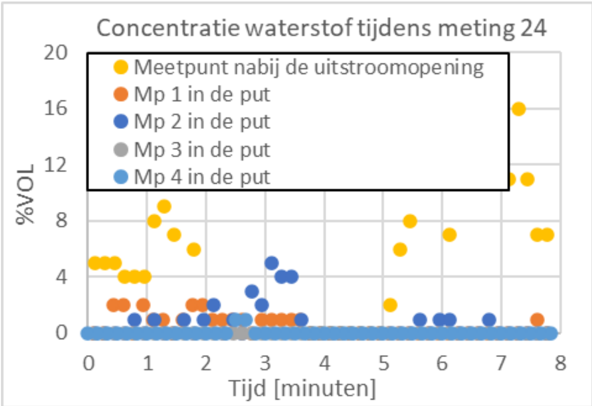

Concentratie aardgas tijdens meting 33
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

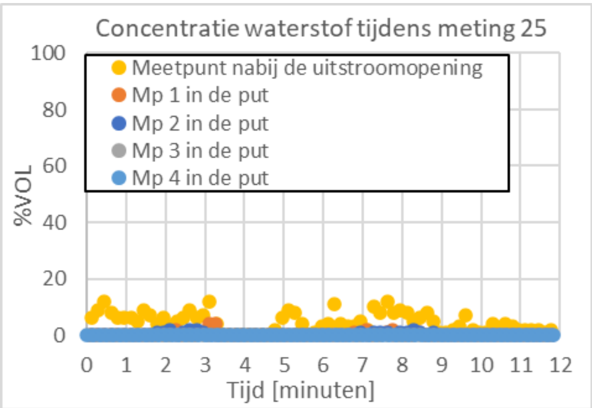

Concentratie aardgas tijdens meting 33
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

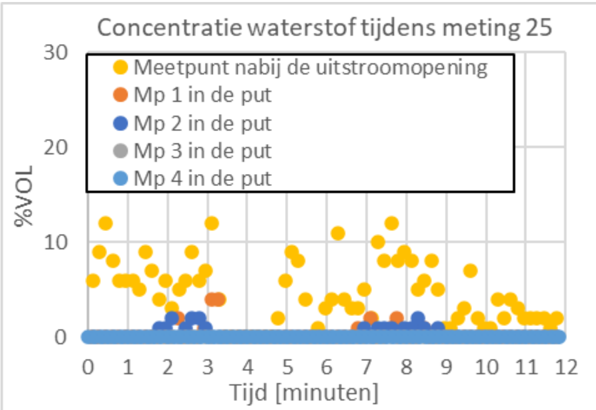

Concentratie aardgas tijdens meting 34
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

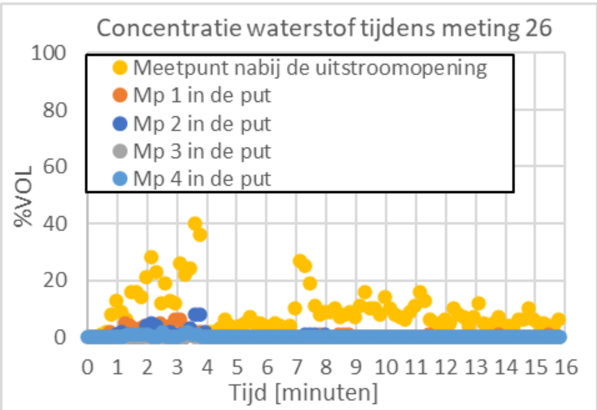

Concentratie aardgas tijdens meting 34
Mp in de buis
Mp 4 in de put
Mp 3 in de put
Mp 2 in de put
Mp 1 in de put
%VOL
Tijd [minuten]

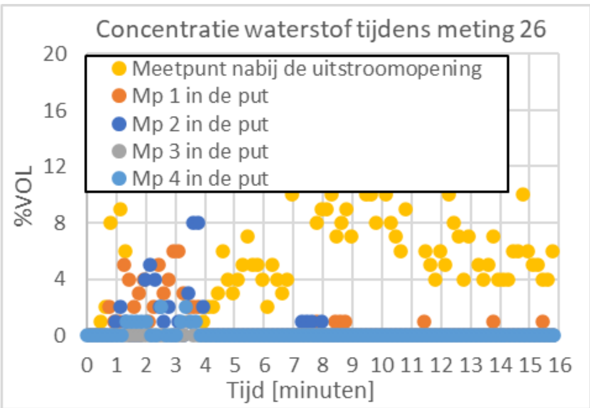

Concentratie waterstof tijdens meting 24
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

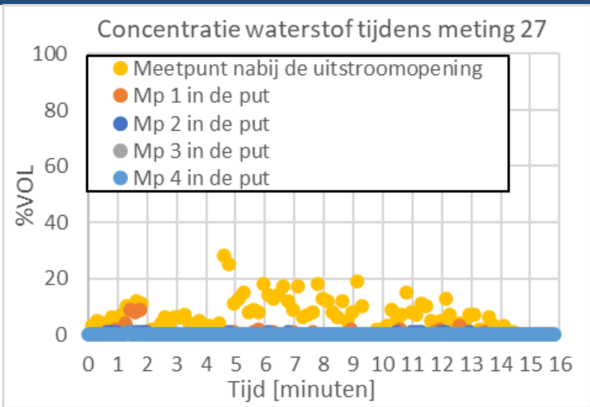

Concentratie waterstof tijdens meting 24
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

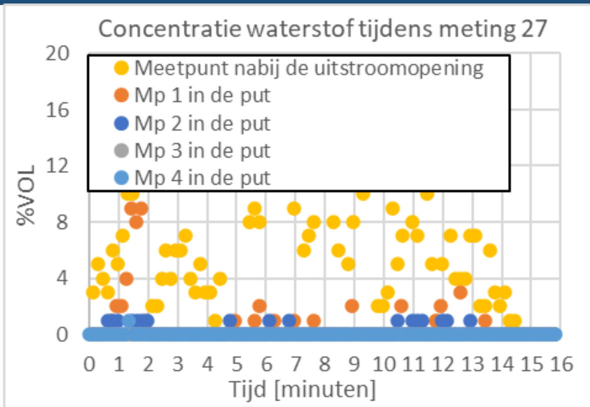

Concentratie waterstof tijdens meting 25
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

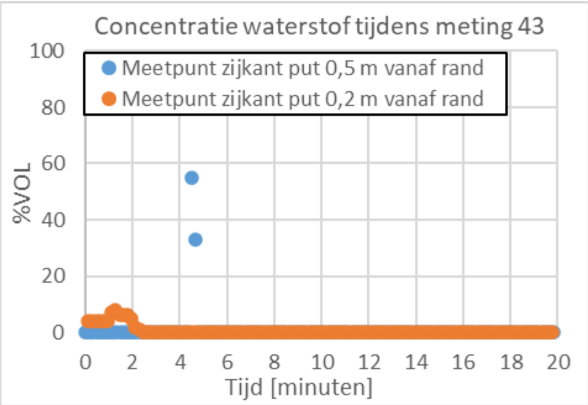

Concentratie waterstof tijdens meting 25
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

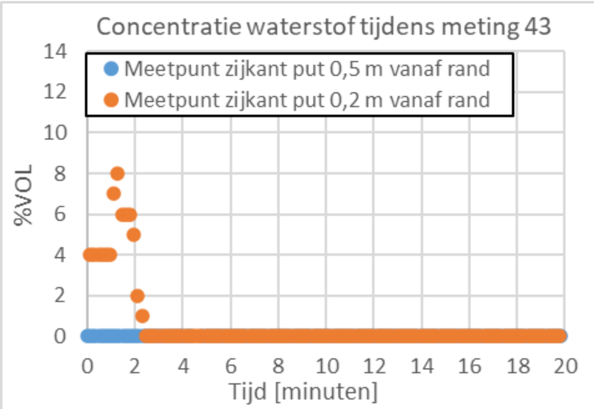

Concentratie waterstof tijdens meting 26
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

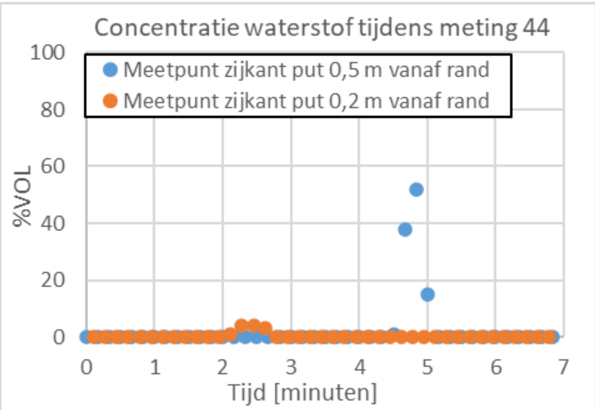

Concentratie waterstof tijdens meting 26
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

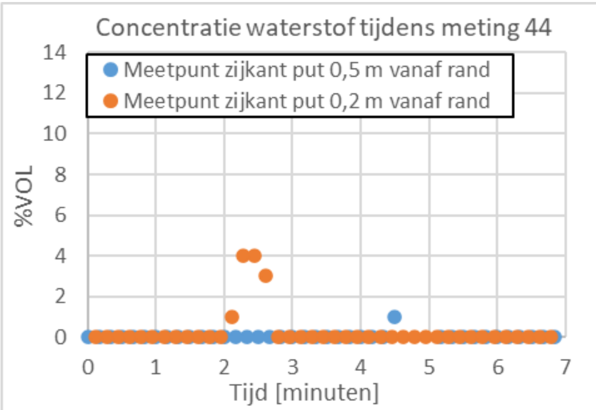

Concentratie waterstof tijdens meting 27
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

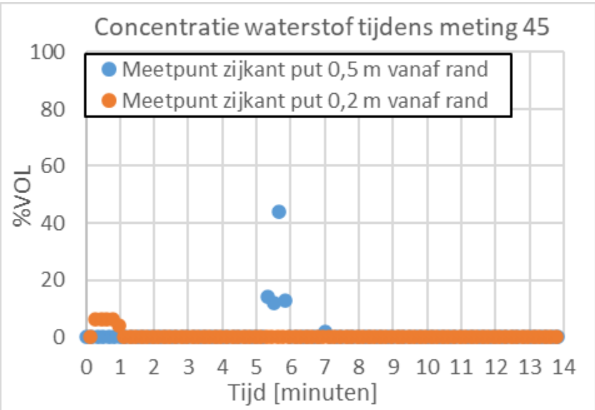

Concentratie waterstof tijdens meting 27
Meetpunt nabij de uitstroomopening
Mp 1 in de put
Mp 2 in de put
Mp 3 in de put
Mp 4 in de put
%VOL
Tijd [minuten]

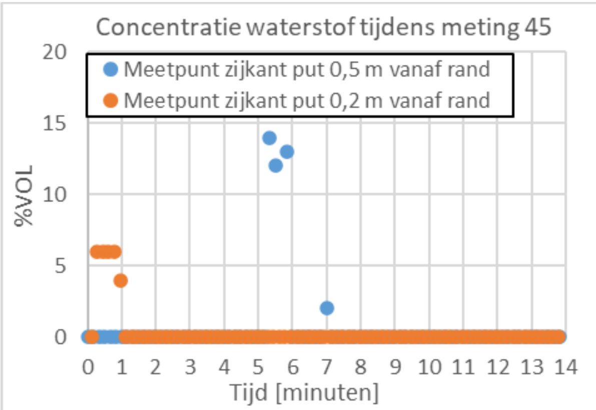

Concentratie waterstof tijdens meting 43
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
Tijd [minuten]

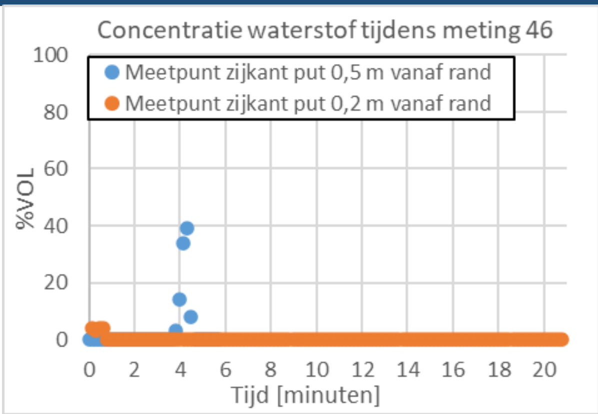

Concentratie waterstof tijdens meting 43
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
Tijd [minuten]

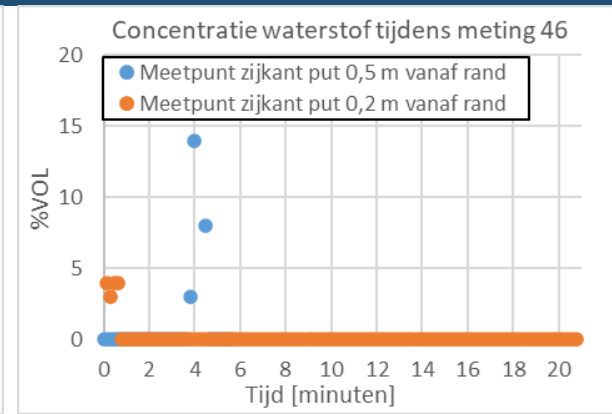

Concentratie waterstof tijdens meting 44
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
Tijd [minuten]


Concentratie waterstof tijdens meting 44
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
Tijd [minuten]


Concentratie waterstof tijdens meting 45
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
Tijd [minuten]


Concentratie waterstof tijdens meting 45
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
Tijd [minuten]


Concentratie waterstof tijdens meting 46
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
0
20
40
60
80
100
0 2 4 6 8 10 12 14 16 18 20
Tijd [minuten]


Concentratie waterstof tijdens meting 46
Meetpunt zijkant put 0,5 m vanaf rand
Meetpunt zijkant put 0,2 m vanaf rand
%VOL
0
5
10
15
20
0 2 4 6 8 10 12 14 16 18 20
Tijd [minuten]

VIII. Thermal images

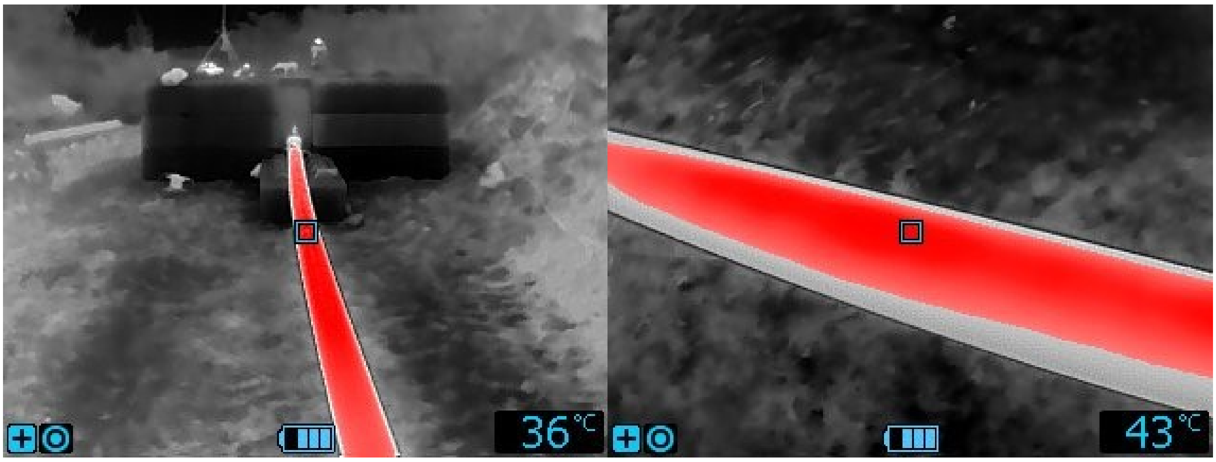


Photo 15: Thermal images after measurement 26

Photo 16: Thermal image after measurement 30, left: measured immediately outside the working pit, right: inside the working pit

On Photo 15: Thermal images after measurement 26. photo 15 shows the overview on the left after measurement 26 (delayed ignition, 20 m^3/h hydrogen). On the right, the highest measured peak temperature value is shown. These temperatures were measured about 10 minutes after the hydrogen was ignited. Because no reference measurement was taken beforehand in terms of temperature, it is not easy to determine when the temperature rise occurred.

In photo 16, temperatures are shown after measurement 30 (delayed ignition, 4 m^3/h natural gas). In the process, a fire spontaneously started without an active ignition; a small fire was found to still be present inside the pipe, which would explain the high temperature.

Photo 17: Thermal image measurement 27 (15m3/h H2)

Photo 18: Thermal image measurement 34 (8m3/h natural gas)

photo 17 and photo 18 show the thermal images at the delayed ignitions for hydrogen and natural gas, respectively. The natural gas flame is slightly larger and has a higher temperature. Orange/red spots can be seen in the thermal image of the natural gas flame, indicating temperatures of around 450°C.

IX. Assessment of stoppers used

After completion of the experiments, the stoppers were assessed for damage and for density. The table below displays these findings. Photos of the stoppers with abnormalities are shown on the following pages.

Meas. No.	No	Date	Code stopper *	Serie	Sticker	Length pipe (m)	Gas	Visual assessment stopper	Tightness (3 minutes pressurized at 0,1 bar)	Assessment connection of stopper
1	I	10/10/2022	30-08-22 / 14	C	C1	1	NG	Big hole	Not possible to put on presssure	Melt damage in lance coupling
2	II	10/10/2022	05-09-22 / 66	C	C2	1	NG	Big hole	Not possible to put on presssure	Melt damage in lance coupling
3	III	10/10/2022	30-08-22 / 10	C	C3	1	H2	No deviation	Can be kept on pressure	Melt damage in lance coupling
4	IV	10/10/2022	05-09-22 / 63	C	C4	1	H2	No deviation	Can be kept on pressure	No deviation
5-6	V	11/10/2022	30-08-22 / 34	C	C5	20	NG	No deviation	Can be kept on pressure	No deviation
7	VI	11/10/2022	05-09-22 / 58	C	C6	20	H2	No deviation	Can be kept on pressure	No deviation
8-14	VII	13/10/2022	05-09-22 / 81	D	D1	1	NG	No deviation	Can be kept on pressure	No deviation
15-20	VIII	13/10/2022	30-08-22 / 23	D	D2	1	H2	No deviation	Can be kept on pressure	No deviation
21	I	14/10/2022	30-08-22 / 13	C	C7	20	H2	Inflatable part is acceptable	Not possible to put on presssure	Coupling released. Connection coupling is broken (about 60% of this part).
22	II	14/10/2022	30-08-22 / 18	C	C8	20	H2	Inflatable part is released from connection	Not possible to put on presssure	Coupling is acceptable. Three tubes are connected to the coupling, the outer tube was released. The spring in the tubes is not present anymore.
23-27	III	14/10/2022	05-09-22 / 75	D	D3	20	H2	No deviation	Can be kept on pressure	No deviation
28-37	IV	14/10/2022	05-09-22 / 71	D	D4	20	NG	No deviation	Can be kept on pressure	No deviation
38-39	I	19/10/2022	05-09-22 / 59	E	E1	20	NG	No deviation	Can be kept on pressure	No deviation
40-42	II	19/10/2022	05-09-22 / 73	E	E2	20	NG	No deviation	Can be kept on pressure	No deviation
43-46	III	19/10/2022	05-09-22 / 69	E	E3	20	H2	No deviation	Can be kept on pressure	No deviation
	Stopper not acceptable					Stopper acceptable				
Inflatable stoppers of Kleiss are used, type MDS B500 D3(P3) - Ø 120-170 mm - the unique code (including testdate of Kleiss) is mentioned above										

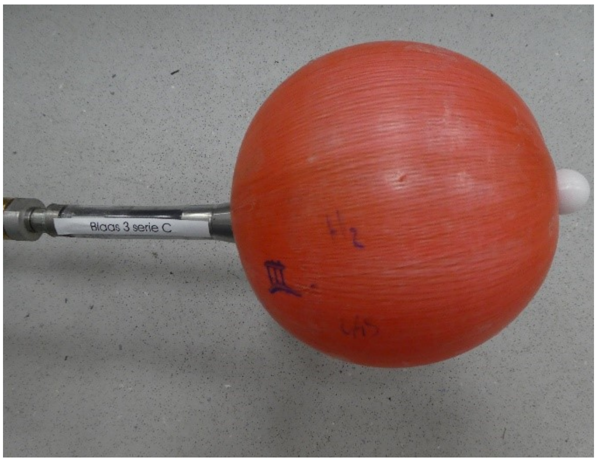
Stopper C1; damaged with measurement 1 – direct ignition of natural gas

Stopper C1; a hole created due to excessive temperature

Stopper C2; damaged with measurement 2 – direct ignition of natural gas

Stopper C2; a hole created due to excessive temperature

Stopper C2; damaged at lance connection (damage due to melting)



Stopper C3; damaged with measurement 3 – direct ignition of hydrogen, damaged at lance connection (damage due to melting)

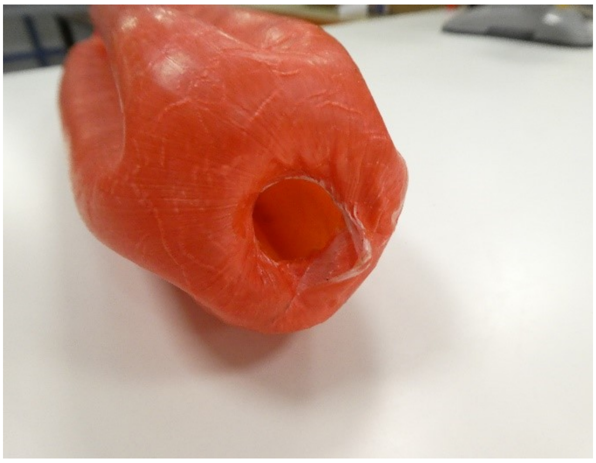
Stopper C3; the stopper could be pressurised and maintained (approval)

Stopper C7; in measurement 21 (direct ignition of hydrogen in a 20 metre pipe), the connecting pipe broke off

Stopper C7; a detail of the broken part of the connection

Stopper C7; a detail of the broken part of the lance connection

Stopper C8; in measurement 22 (direct ignition of hydrogen in a 20 metre pipe), the stopper detached.



Stopper C8; the connection of the detached stopper

X. Links to video material

During the ignition tests at the Twente Safety Campus, the different measurements were captured on video. The video material can be seen using the links below;

Direct ignition: HyDelta, WP6B-2: Gas stopper experiments, Part 1
https://youtu.be/Kr890wk9H5I

Delayed ignition: HyDelta, WP6B-2: Gas stopper experiments, Part 2
https://youtu.be/qKJJoAw25to

Extinguishing a fire: HyDelta, WP6B-2: Gas stopper experiments, Part 3
https://youtu.be/Ph8tWDWkJR0

Complete video: HyDelta, WP6B-2: Gas stopper experiments, Complete
https://youtu.be/pDTR5Btnz9Y