HyDelta 3

WP5C – Inflatable gas stoppers – Technology & Safety in the Hydrogen Network

D5c.1 Behaviour IPCO and Kleiss inflatable gas stoppers during ignition in pipes // D5c.2 – Effectiveness double inflatable gas stoppers

Status: final

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Document summary

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Summary

As part of the Dutch national research programme, HyDelta, a study was conducted on the suitability of inflatable gas stoppers as a fast temporary seal in a hydrogen distribution network (of the Regional Network Operators).

The study as described in this report is part of Hydelta 3.0 work package 5 "Technology & safety in the hydrogen network" and concerns the sub-research WP5C; inflatable gas stoppers. It concerns the use of inflatable gas stoppers in both incident control and planned work. Inflatable gas stoppers are also used in the transport network (of Gas Transport Services, GTS, but the application is different from the application in a distribution network. The results in this report do not relate to the application of inflatable gas stoppers in the gas transport network (> 8 bar).

Based on the research on inflatable gas stoppers as performed in HyDelta 2.0 [1] it was concluded that inflatable gas stoppers can be used as a closing device in hydrogen distribution networks. If the inflatable gas stopper is placed at a distance of more than 1 meter from the outlet opening, then additional measures are required according to the HyDelta 2.0 report [1].

The ignition tests in the above-mentioned report were, however, only performed with Kleiss inflatable gas stopper, while in the Netherlands inflatable gas stoppers of the IPCO brand are also used. The effectiveness of a proposed additional measure must also be demonstrated. In addition, the tests on inflatable gas stoppers in HyDelta 2.0 were only performed in a pipe with a diameter of 160 mm. The effects in pipes with a smaller diameter may be different. These aspects have been investigated and described in the present report.

Based on the research carried out, the following is concluded;

- The use of single inflatable gas stoppers in a hydrogen distribution network is not always safe.
- IPCO inflatable gas stoppers can be used as a temporary sealing device in hydrogen distribution networks. There are specific recommendations depending on the diameter and length of the pipe in which the inflatable gas stoppers are used. These recommendations apply not only to IPCO inflatable gas stopper, but also to Kleiss inflatable gas stopper.
- It is not necessary to insert double inflatable gas stoppers in pipes with a diameter of 110 mm or smaller. An explosive ignition of hydrogen in a pipe with a length of 20 meters and a diameter of 110 mm does not lead to the collapse of a single inflatable gas stopper. This applies to the inflatable gas stoppers of IPCO and Kleiss .
- Inserting double inflatable gas stoppers with a diameter larger than 110 mm increases safety. Even if the nitrogen purging has not yet started. However, failure of both inflatable gas stoppers cannot be ruled out. During the preparatory work for inserting the second, inner, inflatable gas stopper, undesirable events can occur. The inflated outer inflatable gas stopper can burst, a part of the inlet on the pipe can come loose and the not yet inflated inner inflatable gas stopper can break.

Since inflatable gas stoppers can still fail in a block & bleed application, it is recommended to complete the preparations for setting the two inflatable gas stoppers simultaneously. This way, both inflatable gas stoppers can be inflated shortly after each other and the nitrogen purging can be started quickly. This reduces the chance of unsafe situations.

Based on the findings as described in this report and in the inflatable gas stoppers report of " HyDelta 2" [1] the use of inflatable gas stoppers is as follows;

Table 1 Application of single or double inflatable gas stoppers depending on activity and pipe diameter

Description of activity		**Diameter of the pipe**		
		≤ DN 100	DN 150	≥ DN 200
Planned work (distance inflatable gas stopper to opening ≤ 1m)	Extension on an offshoot	single	single	double
	Installing T-piece	single	single	double
	Repairing a leak after above-ground leak detection	single	single	double
Incident response (distance inflatable gas stopper to opening > 1 m)	Extinguish gas fire	single	single	double
	Stop gas outflow	single	double	double
For natural gas, according to the Dutch VWI G-24, two inflatable gas stoppers must be placed in series at; • pipes with diameter ≥ DN 150 in case of application of inflatable gas stoppers without QA • pipes with diameter > DN 300 For hydrogen, the starting point is that inflatable gas stoppers are selected with a QA quality mark. In addition, the limit for the use of inflatable gas stopper when used in a hydrogen network has been lowered from > DN 300 for natural gas to ≥ DN 200 because the outflow of gas in the event of unexpected inflatable gas stopper failure is greater with hydrogen than with natural gas. Placing double inflatable gas stoppers involves purging with nitrogen.				

To keep the application simple, it is possible to choose to use of double inflatable gas stoppers where this is not strictly necessary according to the table above.

Contents

1. Rationale

1.1 General

This research has been carried out within the framework of the Dutch national research program HyDelta. This programme focuses on the safe integration of hydrogen into the existing gas transport and distribution infrastructure and aims to remove barriers for innovative hydrogen projects. The entire research program is divided into work packages. For an explanation of the different work packages, see www.hydelta.nl

This report concerns 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 gas stopper and the stopper is always part of a "block & bleed " application.

1.2 Problem definition

Based on the research carried out in HyDelta 2 [1] it was concluded that inflatable gas stoppers can be used as a shut-off device in hydrogen distribution networks. If the inflatable gas stopper is placed at a distance of more than 1 meter from the outlet opening, additional measures are required. For a further explanation, see the report as drawn up in the context of HyDelta 2; *D6B.2A & D6B.2B Report on ignition scenarios and experiments during the use of inflatable gas stoppers to mitigate natural gas and hydrogen leaks in the low pressure gas distribution grid (zenodo.org)* . The ignition tests in the above-mentioned report were only performed with Kleiss inflatable gas stoppers, while in the Netherlands inflatable gas stoppers of the IPCO brand are also used. The effectiveness of the additional measures must also be demonstrated. In addition, the tests in HyDelta 2 were only performed in a pipe with a diameter of 160 mm. The effects in pipes with a different diameter may be different.

1.3 Objective

The aim of this study is to answer the following research questions:

- Can IPCO inflatable gas stoppers be used as a temporary shut-off device in hydrogen distribution networks?
- What are the effects of unexpected ignitions in pipes with a diameter smaller than 160 mm for both IPCO and Kleiss inflatable gas stoppers?
- Is the application of block & bleed in combination with nitrogen purging an effective measure to prevent the formation of a flammable mixture and the failure of the inflatable gas stoppers?

2. Method

This chapter describes the test setups and methods used for each series of experiments. 2.1describes the test setup used for the ignition of a gas leak in a situation of regular work (1 meter length of pipe) and in a situation for resolving incidents (20 meter length of pipe). Section 2.2 provides an explanation of the test setup with regard to extinguishing a gas fire. Finally, 2.3 describes the test setup used to assess the effectiveness of setting double inflatable gas stoppers.

2.1 Direct ignition of a hydrogen or natural gas leak

In addition to the measurements in HyDelta 2.0, ignition tests with a limited amount of hydrogen were carried out using IPCO stoppers (diameters 160 and 110 mm) and Kleiss stoppers (diameter 110 mm and some repetition measurements with diameter 160 mm).

These measurements were mainly carried out on the grounds of the Twente Safety Campus [1]. The measurements were carried out above ground, where a work pit was made of chipboard into which the gas pipe ended . The circumstances and the measuring method are as follows:

- PE pipe with an outer diameter of 160 mm and an SDR class 17.6.
- PE pipe with an outer diameter of 110 mm and an SDR class 17.6.
- The stopper was placed at two different distances (1 and 20 meters) from the work pit
- Inflatable gas stoppers of the IPCO and Kleiss brand.
- The supply of gas from a cylinder pack, where the flow rate is controlled by a Mass Flow Controller has been set.
- The gas was supplied during the measurement via a 1 meter length of pipe through the stopper lance.
- The gas was supplied during the measurement via a saddle using a 20-metre pipe length.
- Ignition was applied with a continuously active spark igniter at a short distance (≤ 2cm) from the outlet opening of the PE pipe.
- After an audible ignition in the 1 meter pipe, the gas supply was stopped after ± 30 seconds.
- After ignition in the 20 meter pipe, the gas supply was immediately stopped.
- The temperature sensor is installed between the stopper and the pipe (with the measuring point at the bottom of the part of the pipe where te gas flowed).

Below is a schematic representation of both test setups.

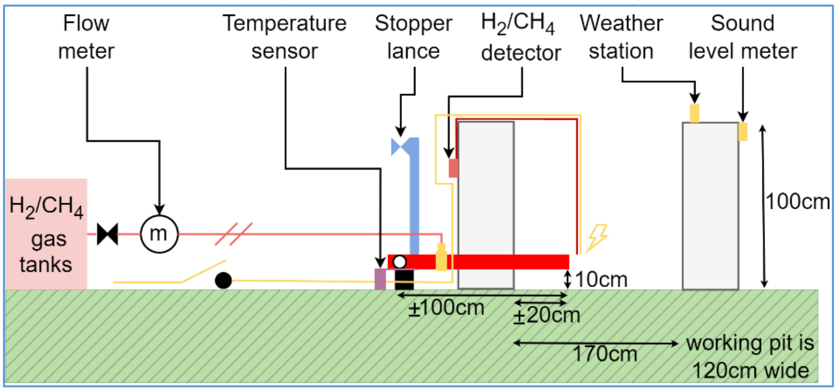


Figure 1 Direct ignition measurement setup with a pipe length of 1 meter

[1] *The measurements on the pipe with a diameter of 110 mm and a length of 1 meter were carried out on the Kiwa site. This was due to a lack of time during the test period on the Twente Safety Campus. A work pit with the same dimensions was created.*

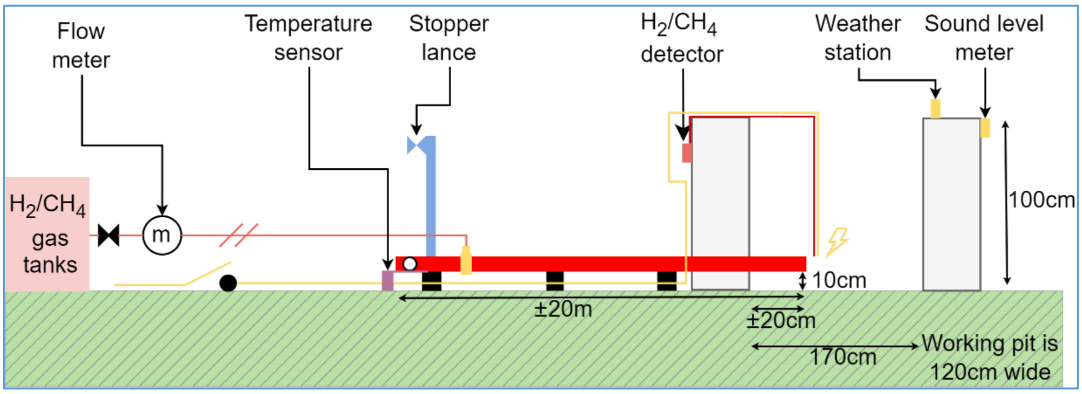


Figure 2 Direct ignition measurement setup with a pipe length of 20 meters

Below are some pictures of the test setup.

Photo 1 The setup with the pipe with a diameter of 110 mm of 20 meters

Photo 2 Position of the spark igniter and the measuring point near the outlet opening

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

In addition to the measurements in HyDelta 2.0, tests related to the extinguishing of a natural gas fire and a hydrogen fire were carried out with IPCO stoppers (diameters 160 and 110 mm) and Kleiss stoppers (diameter 110 mm and some repeat measurements with diameter 160 mm).

These measurements were carried out at the Twente Safety Campus site. The measurements were carried out above ground, where a work pit was made of chipboard into which the gas pipe ended. The circumstances and the measuring method are as follows:

- PE pipe with an outer diameter of 160 mm and an SDR class 17.6.
- PE pipe with an outer diameter of 110 mm and an SDR class 17.6.
- The stopper was placed 20 meters from the outlet opening.
- Inflatable gas stoppers of the IPCO and Kleiss brand.
- The supply of gas from a cylinder package, where the flow rate was measured with a rotameter.
- The gas was supplied through a saddle.
- The ignition was applied with a continuously active spark igniter at a short distance (≤ 2cm) from the outlet opening of the PE pipe. The ignition was activated a few minutes after the gas flow was started.
- After igniting the gas, the stopper was inflated.
- The temperature sensor is mounted in a saddle for these measurements.

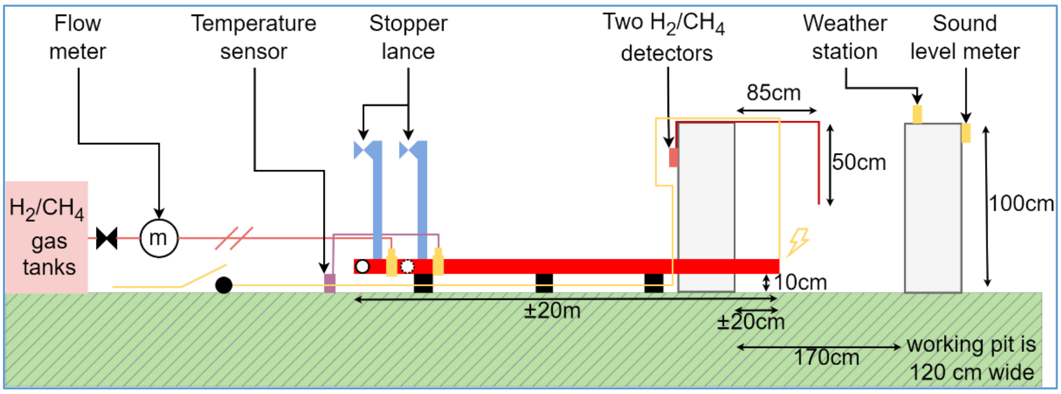


Photo 3 Measurement setup for extinguishing a gas fire

On the next page some pictures of the test setup.

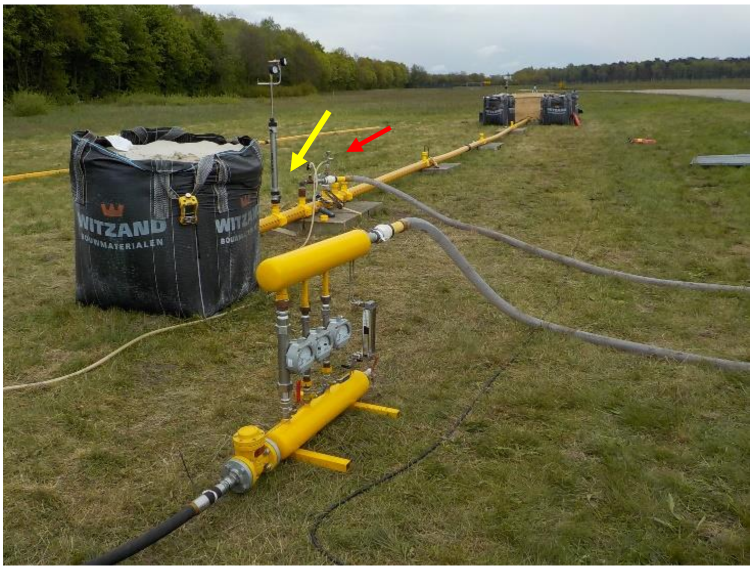


Photo 4 and Photo 5 The measuring setups as used when setting an inflatable gas stopper in the event of a gas fire.

Photo 4 concerns the setup with the pipe with a diameter of 160 mm and photo 5 contains the pipe with a diameter of 110 mm. In the foreground of photo 5 the rotameter for the flow measurement.

The stoppers at the lance constructions indicated by the yellow arrows serve as a seal to the environment. The stoppers at the lance constructions at the positions indicated by the red arrows are inflated remotely after the gas flow has been applied.

Photo 6 The position of the measuring points for the concentrations in the work pit when extinguishing a natural gas or hydrogen fire

2.3 The effectiveness of double stoppers

The effectiveness of placing two stoppers in series to maintain a stopped gas outflow was investigated as described below.

When placing double stoppers, the idea is that the outer stopper is placed first, then the inner stopper, and then nitrogen is feed-in. See appendix I and II for a further explanation of this method and the designation of the inflatable gas stoppers. The effect of an unexpected ignition after placing two stoppers and the effect of an ignition when the inner stopper has not yet been placed (or just not yet) were assessed.

These measurements were carried at the Twente Safety Campus site. The measurements were carried out above ground, where a work pit was made of chipboard into which the gas pipe ended. The circumstances and the measuring method are as follows:

- PE pipe with an outer diameter of 160 mm and an SDR class 17.6.
- PE pipe with an outer diameter of 110 mm and an SDR class 17.6.
- Inflatable gas stoppers of the IPCO and Kleiss brand.
- The supply of gas from a cylinder pack, where the flow rate is controlled by a Mass Flow Controller has been set.
- The gas was supplied through a saddle.
- Ignition was applied with a continuously active spark igniter at a short distance (≤ 2cm) from the outlet opening of the PE pipe.
- After ignition in the 20 meter pipe, the gas supply was immediately stopped.

See 2.3.1 and 2.3.2. for further details of the different experiments.

2.3.1 Ignition after two stoppers have been placed

In these measurements a leakage rate of $0.6 m^3{}_n/h$ hydrogen was applied, starting with an air-filled pipe. This rate ensures a mixture that ignites explosively (see appendix I). The spark igniter was energized immediately after starting the gas flow.

Below are schematic representations of the test setups.

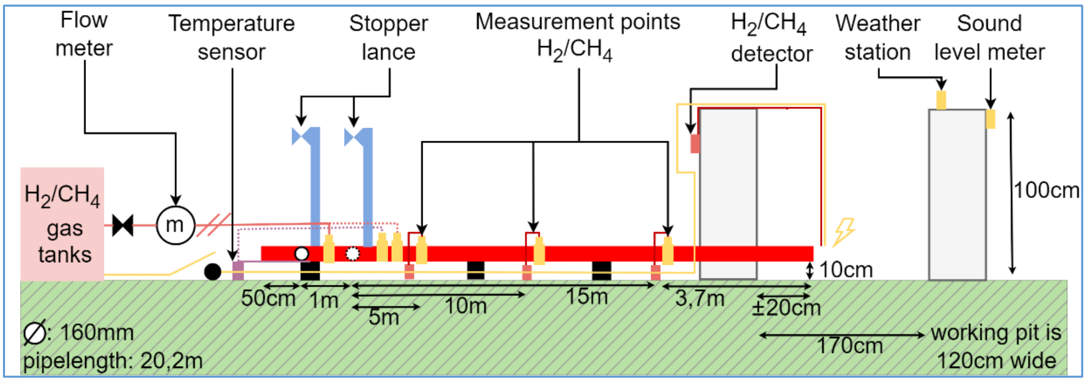


Figure 3 Test setup double inflatable gas stoppers at the 160 mm pipe

In these two-stopper tests, the dotted lines apply with respect to the feeding of gas and the measurement of the temperature at the gas stopper. This applies to Figure 3and Figure 4.

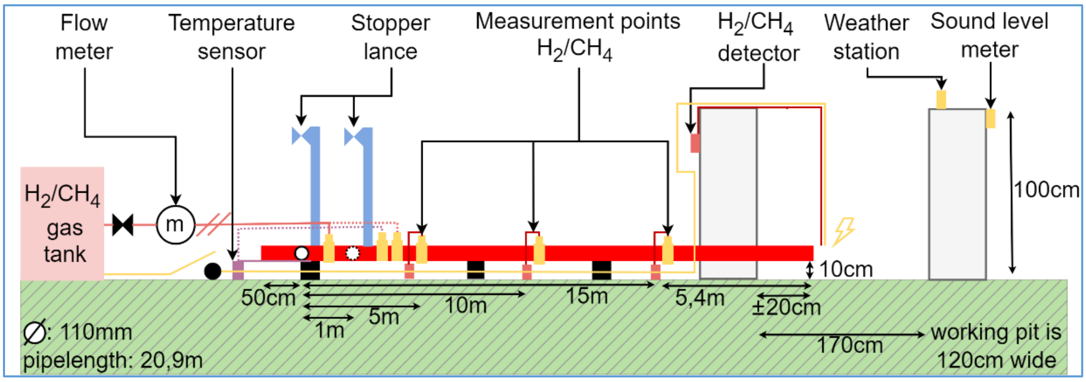


Figure 4 Test setup double inflatable gas stoppers at the 110 mm pipe

Nb.
For the 160 mm pipe, the concentration measurement points in the pipe are located at a distance of 5, 10 and 15 meters <u>from the inner</u> gas stopper.
For the 110 mm pipe, the measuring points of concentrations in the pipe are located at a distance of 5, 10 and 15 meters <u>from the outer</u> gas stopper. Because of this and because the total length of the pipes differs slightly, the distance from the measuring points to the outlet opening in the work pit is also different. For the 160 mm pipe, this is 3.7 meters and for the 110 mm pipe, this is 5.4 meters. The impact of the ignitions on the gas stoppers is not affected by this.

Below is a photo of the test setup.

Photo 7 The test setup with the pipe with a diameter of 110 mm containing 2 stoppers.

2.3.2 Ignition after placement of 1 stopper and the effect on the stopper-inlet-saddle and lance construction

In these tests the outer stopper was placed and preparations were made for placing the second (inner) stopper. The experiments investigated the effect on the stopper inlet (on the pipe) when the lance was not yet inserted and the effect on the lance when it was inserted but only turned one full turn.

The original idea was to use concentration measurements to determine the times at which the hydrogen concentration was 30% at 5, 10 and 15 metres from the stopper respectively. This was done using a pipe filled with 100% hydrogen as a starting point (see Appendix I). The decrease in concentration appeared to be slow and was also strongly dependent on the wind. It was therefore decided to monitor the concentrations during the ignition tests and to apply the spark at the moment when a hydrogen concentration of approximately 30% was reached at 15, 10 or 5 metres from the stopper. For a decrease in concentrations (without ignition), see measurements 60, 61 and 76 in Appendix VI.

The setups in this test are the same as the setups as described 2.3.1. The only differences:

- not placing the inner lance
- not fully tightening the inner lance.
- positioning of temperature sensor and gas inlet directly downstream of the outer inflatable gas stopper.

3. Measurement results and findings

This chapter presents the results and findings of the experiments. In 3.1 and 3.2 the results of the experiments in which a hydrogen or natural gas leak was ignited in a 1 meter pipe and a 20 meter pipe. In 3.3 the results of extinguishing a natural gas and hydrogen fire. In 3.4 the results of the experiments with the setup with double stoppers. Each paragraph starts with a schematic representation of the findings. The condition of the stopper after the test is shown by means of colors. A green color indicates that the stopper is not affected. An orange or red color indicates that a stopper is damaged or is ruptured.

3.1 Direct ignition in the event of a hydrogen or natural gas leak in a 1-meter pipe

The tests described in this section are intended to determine how a single gas stopper behaves in the event of direct ignition of leak gas. The leak gas, which is released near the gas stopper , is ignited at the outlet opening of the pipe in the work pit. The stopper is located 1 meter from the outlet opening. See Chapter 2for a further description of the measuring method and the test setup used. An overview of all measurements performed in this configuration is shown in Figure 5. This concerns measurements 1 to 29. These are shown in tabular form in Appendix III.

Where the stopper is not affected, the relevant frame is shown in green. If the stopper is damaged or ruptured, this frame is colored red or orange. The green, orange and red colored frames contain the measurement number, the gas flow rate and a short description of the condition of the stopper.

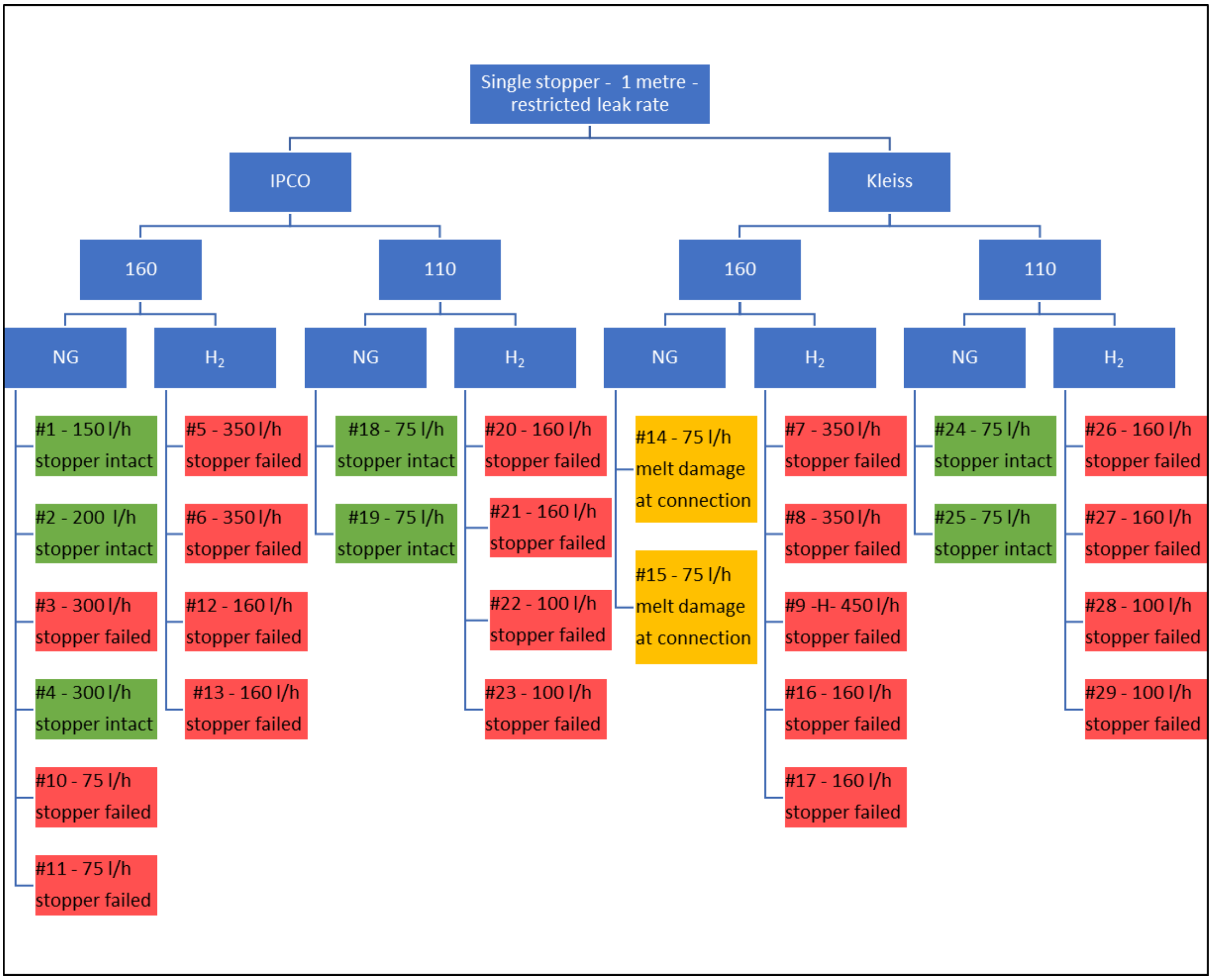


Figure 5 Overview of measurements with a single stopper in a 1 meter pipe length.

<u>*Choice of leakage rates*</u>

For the leakage rate of natural gas at measurement 1, the value 0.15 $m^3{}_n$/h was chosen. This was equal to the flow rate used in the investigation of inflatable gas stoppers as performed in HyDelta 2. Because the stopper remained intact, the flow rate was increased (measurements 2, 3 and 4). For the leakage rate of hydrogen at measurements 5 and 6, the lowest adjustable leakage rate of the relevant Mass Flow Controller (0.35 $m^3{}_n$/h) was chosen. Since the IPCO stopper failed twice at this flow rate, this flow rate was also chosen for the Kleiss stopper. A repetition measurement was also performed with the Kleiss stopper with a flow rate equal to the flow rate in HyDelta 2.

For measurements 10, 11, 14, 15, 18, 19, 24 and 25, a lower natural gas leak rate was chosen. At the time of these measurements (July 2024), it was clear that the QA criteria for natural gas would be adjusted to a natural gas leak rate of 0.075 $m^3{}_n$/h per stopper. Derived from this, this would lead to a maximum hydrogen leak rate of 0.160 $m^3{}_n$/h and is expected to lead to a minimum hydrogen leak rate of 0.100 $m^3{}_n$/h. These flow rates were used for measurements 12, 13, 16, 17, 20 to 23 and 26 to 29. For these measurements in July 2024, a Mass Flow Controller with a lower minimum range was used.

3.1.1 Direct ignition natural gas - 1 meter

The measurement was carried out eight times with a natural gas flow rate of 75 l/h, with the natural gas supplied via the stopper lance. Per diameter (160 mm and 110 mm) and per stopper (IPCO and Kleiss) twice. In case of the pipe with a diameter of 110 mm, no damage to the stoppers occurred, despite observed ignitions of the natural gas. This was the case for the pipe with a diameter of 160 mm. If the stopper did not burst, the gas supply is stopped after approximately 5 minutes.

For the pipe with a diameter of 160 mm, four measurements were also carried out with a larger leak rate. These measurements were carried out at a different time (April 2024) and at a different location (Twente Safety Campus). The leak rate was started with 150 l/h (in line with HyDelta 2). The stopper remained intact. For this reason, it was decided to also carry out measurements at larger leak rates, namely 200 and 300 l/h. At a leak rate of 200 l/h, the stopper remained intact. At 300 l/h the stopper remained intact once and at the other time the stopper ruptured. The stronger wind above and in the work pit during the measurements with the larger leak rate probably caused the natural gas to ignite (see temperature increase measurements 1 to 4, Appendix V) but not continued burning.

For further details of the measurements, see Appendices IV, V, VI and VII.

<u>Sub-conclusions:</u>
In a pipe with a diameter of 160 mm and a length of 1 meter, the tested natural gas leakage rate of 75 l/h could be ignited. The burning natural gas leads to damage of the stoppers, whereby the stopper failed in two of the four situations.

Due to the presence of wind, a leakage rate of 150 to 300 l/h does not always lead to damage to the inflatable gas stoppers in the event of an ignition source directly at the outlet opening.

In a pipe with a diameter of 110 mm and a length of 1 meter, the natural gas leak rate of 75 l/h could be ignited, but this did not lead to damage to the stoppers.

3.1.2 Direct ignition hydrogen – 1 meter

The measurement was performed eight times with a hydrogen flow rate of 160 l/h, with the hydrogen supply via the stopper lance. Per diameter (160 mm and 110 mm) and per stopper (IPCO and Kleiss) twice. In all eight situations the stopper burst.

For the pipe with a diameter of 110 mm, four measurements were also carried out with a smaller leak rate, namely 100 l/h. The IPCO stoppers burst and the Kleiss stoppers melt on the connection pipe due to the flame present near the outlet of the lance. This eventually causes them to leak.

Five measurements were performed on the 160 mm diameter pipe with a larger flow rate than the previously mentioned 160 l/h. A flow rate of 350 and 450 l/h was chosen. The gas stoppers burst during these measurements. During these measurements (at a different time and location) there was a stronger wind.

For further details of the measurements, see Appendices IV, V, VI and VII.

Sub-conclusions:

In a pipe with a diameter of 160 mm and a length of 1 meter, the tested hydrogen leak flow rate, varying from 160 l/h to 350 l/h, could be ignited, whereby the burning hydrogen leads to failure of the stoppers. This applies to both IPCO and Kleiss stoppers.

In a pipe with a diameter of 110 mm and a length of 1 meter, the tested hydrogen leak flow rate, varying from 100 l/h to 160 l/h, could be ignited, whereby the burning hydrogen leads to failure of the stoppers. This applies to both IPCO and Kleiss stoppers.

3.2 Direct ignition in a hydrogen or natural gas leak in a 20 meter pipe

The tests described in this section are intended to determine how a single gas stopper behaves in the event of direct ignition of leaking gas or residual gas near the outlet opening in a long length pipe. An overview of all measurements performed in this configuration is shown in Figure 6. This concerns measurements 30, 31, 34 to 37 and 42 to 47. These are shown in tabular form in Appendix III.

Where the stopper is not affected, the relevant frame is shown in green. If the stopper is damaged or ruptured, this frame is colored red. The green and red colored frames contain the measurement number, the gas flow rate and a short description of the condition of the stopper.

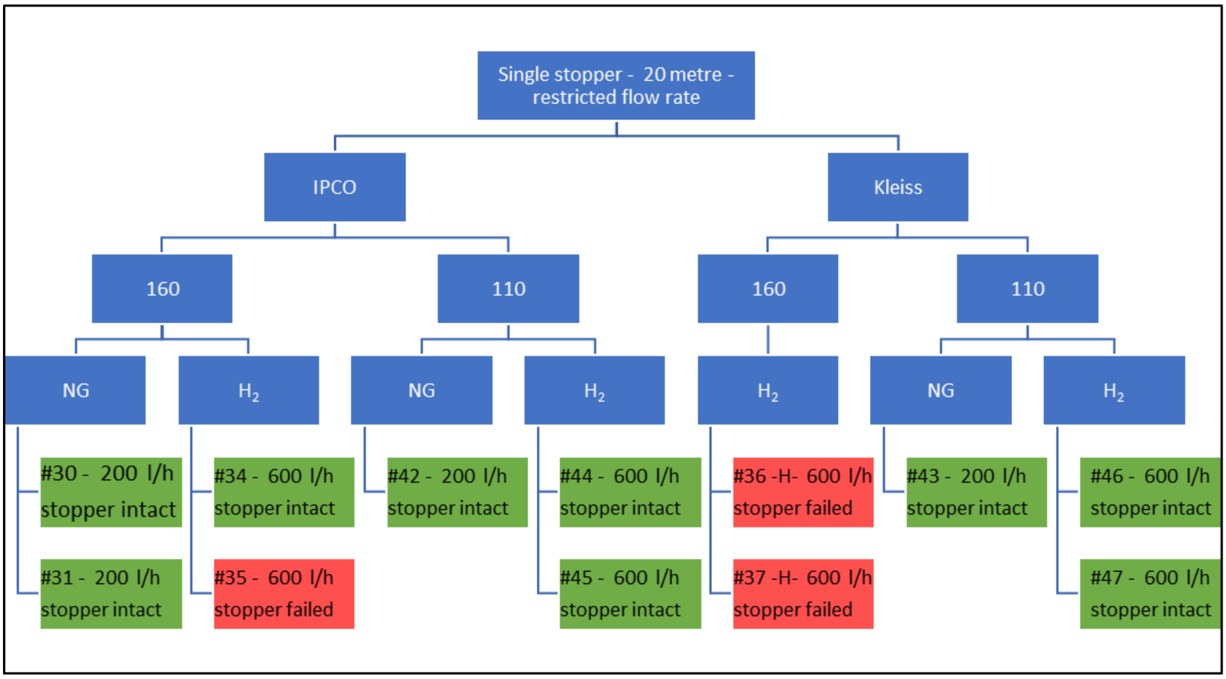


Figure 6 Overview of measurements with a single stopper in a 20 meter pipe length.

Choice of leakage rates

For the leakage rate at measurements 30, 31, 42 and 43, the value 0.20 $m^3{}_n$/h was chosen for natural gas and for measurements 34 to 37 and 44 to 47, a leakage rate of 0.60 $m^3{}_n$/h for hydrogen was chosen. This is in accordance with the set flow rates in the research as carried out in HyDelta 2. These flow rates cannot be interpreted as an expected leakage rate. With these flow rates, a mixture could be obtained in the pipe within a reasonable time (approximately 10 minutes) which causes a considerable explosive force. For the maximum leakage rates based on QA criteria, see paragraph 3.1, the passage under figure 5.

3.2.1 Direct ignition natural gas – 20 meters

Four measurement series were performed using 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. During these measurement series with the 110 mm pipe, multiple ignitions were observed in one measurement. With the pipe with a diameter of 160 mm, ignition occurred only once in each measurement. This can be seen in particular on the basis of the video images. The IPCO and Kleiss stoppers remain intact during all tests. During these four measurements, a measuring point was installed halfway along the pipe to measure the concentrations of natural gas in the pipe. These concentrations show that there is no flashback of a flame.

The Kleiss stoppers were not tested in a 160 mm diameter pipe because those measurements had already been performed in HyDelta 2.

For further details, see Appendices IV and VI (measurements 30, 31, 42 and 43).

<u>Sub-conclusions:</u>
Based on the measured gas concentrations and the video images of the outlet opening, it is concluded that no explosive ignitions occurred in the pipe. Because a constant ignition source was present, the natural gas ignited several times per measurement series. These ignitions were not able to keep the leaking natural gas burning. The stoppers are not affected.

In the event of ignition of a natural gas leakage flow of approximately 0.2 $m^3{}_n$/h along a stopper, which is placed at a greater distance (approximately 20 m) from the pipe rupture, the stopper will remain intact because the combustion process in the pipe does not sustain itself.

3.2.2 Direct ignition hydrogen – 20 meters

Eight measurement series were carried out using a flow rate of 0.60 $m^3{}_n$/h with hydrogen supplied at a distance of 30 cm from the stopper.

The Kleiss stoppers in a pipe with a diameter of 160 mm were already tested in the HyDelta 2 study. These were also carried out as repetition measurements in this study.

Both the IPCO stoppers and the Kleiss stoppers remain intact when igniting in the 110 mm diameter pipe.

In the case of the 160 mm diameter pipe, the ignitions are noticeably more severe. This leads to the bursting of an IPCO stopper once and to the bursting of a Kleiss stopper twice.

In the event of a relatively small hydrogen leak (0.6 $m^3{}_n$/h) near a gas stopper at a distance of 20 meters from the pipe break and the presence of an ignition source, a violent ignition occurred in a pipe with a diameter of 160 mm, causing the stoppers to fail.

For further details see Appendices IV, V, VI and VII (measurements 34 to 37 and 44 to 47).

Sub-conclusions:

For an application in a hydrogen pipeline with a diameter greater than 110 mm, the single stoppers from IPCO and Kleiss are not suitable as a sealing for situations where the stopper is placed at a large distance from the outlet opening [2].

Single inflatable gas stoppers in a pipe with a diameter of 110 mm are resistant to unexpected ignition.

3.3 Installing a stopper after hydrogen or natural gas has been ignited

The tests described in this section are intended to determine how a gas stopper behaves when extinguishing a gas fire as a result of the ignition of freely flowing gas. See Figure 7 for a further description of the measuring method and the test setup used. An overview of all measurements performed in this setup is shown in Figure 7. The green frames indicate that the stoppers were not affected during the measurements. These frames also contain the measurement number and the gas flow rate.

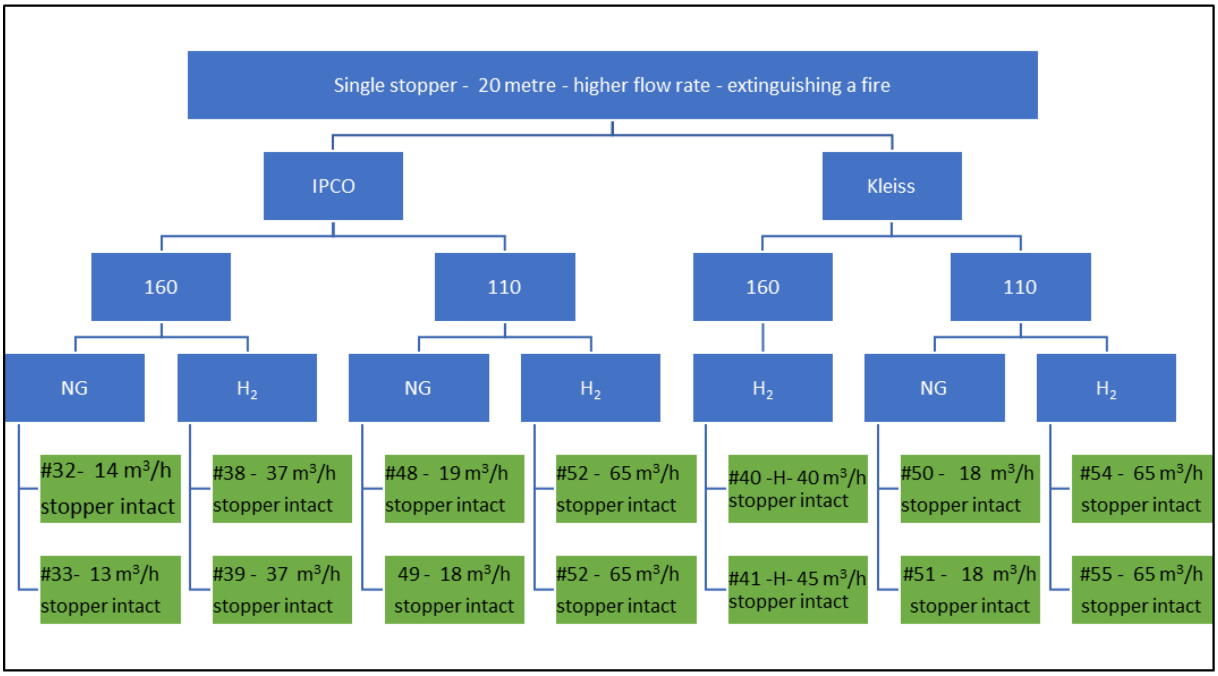


Figure 7 Overview of measurements with a single stopper in a pipe length of 20 meters, extinguishing a flame

The flow rate was the maximum achievable flow rate in the setup used, at a supply pressure of 100 mbar, before the inflatable gas stoppers were inflated.

3.3.1 Stopper in case of fire of freely flowing natural gas

These measurements were performed six times, with the gas flowing from the pipe being ignited with a spark igniter. The Kleiss stoppers were not tested in a pipe with a diameter of 160 mm, because these measurements were already performed in HyDelta 2.

[2] *This was already known from HyDelta 2 based on the measurements of the Kleiss stoppers. This led to a recommendation "block & bleed".*

The stoppers are not affected. There has been no increase in temperature near the stopper. For further details see Appendices IVand VII(measurements 32, 33 and 48 to 51).

Sub-conclusion
A gas fire in a natural gas pipeline can be stopped without any problems with both IPCO and Kleiss inflatable gas stoppers.

NB. This is on condition that the stopper remains pressurized.

3.3.2 Stopper in case of free flowing hydrogen fire

These measurements were performed eight times, with the gas flowing from the pipe being ignited with a spark igniter.

The stoppers are not affected. There has been no increase in temperature near the stopper. For further details see Appendices IV and VII (measurements 38 to 41 and 52 to 55).

Sub-conclusion
A gas fire in a hydrogen pipe can be stopped without any problems with both IPCO and Kleiss inflatable gas stoppers.

NB. This is on condition that the stopper remains pressurized.

NB. Tests were conducted with a flow rate of 65 $m^3{}_n$/h (pipe with a diameter of 110 mm) and a flow rate of 40 $m^3{}_n$/h (pipe with a diameter of 160 mm). This corresponds to velocities of 2.4 m/s and 0.7 m/s respectively. The flow velocity will be many times greater in the event of an actual leak. This study investigated the effect of stopping the burning hydrogen. If in practice the gas outflow is stopped with an inflatable gas stopper, the velocity will decrease and eventually reach the outflow velocity of 0.7 m/s. At further inflation of the stopper the outflow velocity will be reduced even further. This study assessed whether possible backflash of the flame has a negative effect on the functioning of the stopper. Backflash of a flame can only occur at lower gas outflow velocities.

In a hydrogen network, the flow rate may be three times higher than the flow rate in a natural gas network. Whether an inflatable gas stopper can be placed at these high speeds will have to be investigated.

3.4 The effectiveness of double stoppers

In the report “ HyDelta 2” the application of double stoppers is proposed as an additional measure when using inflatable gas stoppers in a long length (for incident response distance from stopper to outlet opening can be 20 meters). In this case, two inflatable gas stoppers are placed in series. The space between the stoppers is in contact with the atmosphere so undesired leakage gas from the outer stopper can be discharged into the atmosphere. In this setup, it is also possible to start making the pipe section between the inner stopper and the outlet opening hydrogen-free by purging with nitrogen. This paragraph presents the results in which the effects of unexpected ignitions during the placement of double stoppers are assessed, even before nitrogen purging has started.

3.4.1 Ignition after two stoppers have been placed

These measurements were performed to gain insight into the effect of an ignition when two stoppers are placed. A leakage flow rate was chosen that, from a completely air-filled pipe, ultimately caused severe ignitions (see paragraph 3.2.2).

See 2.3.1 for a further description of the measurement method and the test setup used. An overview of all measurements performed in this configuration is shown in Figure 8. This concerns measurements 56 to 59 and 72 to 75. These are shown in table form in Appendix III.

Where the stopper is not affected, the relevant frame is shown in green. If one of the two stoppers in series is damaged or ruptured, this frame is colored orange. If both are ruptured the frame is colored red. The green, orange and red colored frames contain the measurement number, the gas flow rate and a short description of the condition of the stoppers.

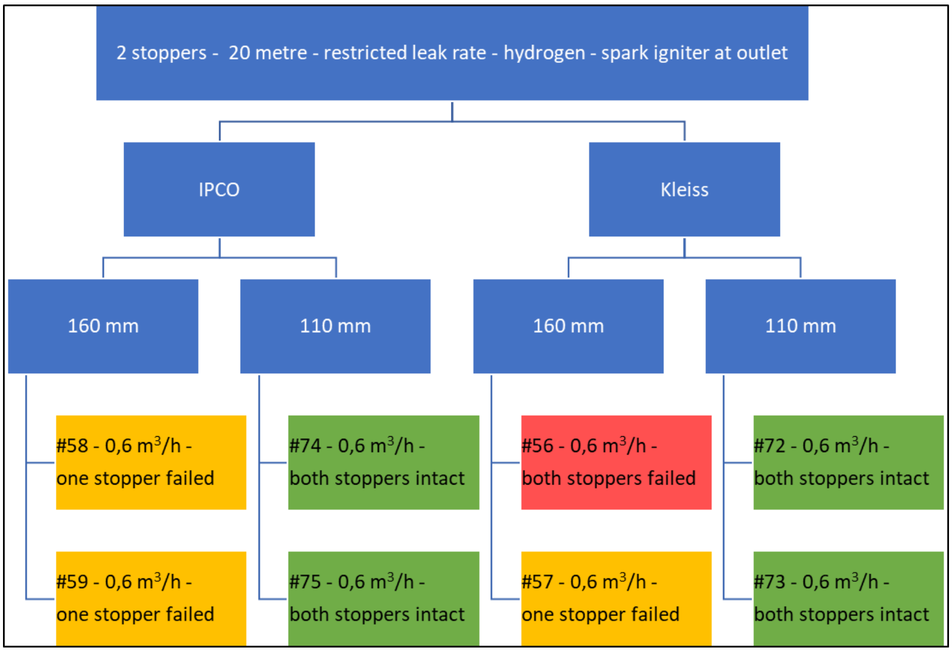


Figure 8 Overview of measurements with double stoppers in a pipe length of 20 meters

Both the IPCO and Kleiss inflatable gas stoppers remain intact in the 110 mm diameter pipe, despite the powerful ignitions. This was also somewhat expected based on the results of the measurements on a single stopper (see paragraph 3.2.2).

In the pipe with a diameter of 160 mm the ignition is noticeably more intense. In three of the four measured situations one of the two stoppers burst in the other situation both stoppers burst.

In the two measurements with the IPCO stoppers the outer stoppers hold and the inner stoppers burst. The outer stoppers are not affected.
In one measurement with Kleiss stoppers the outer stopper holds and the inner stopper bursts. The outer stopper is not affected. In the other measurement with Kleiss stoppers, both stoppers burst as a result of the powerful ignition.

For further details of the measurements, see Appendices IV, V, VI and VII.

Sub-conclusions

- In a pipe with a diameter of 110 mm and a length of 20 meters, two stoppers placed in series hold. This applies to both the IPCO and the Kleiss inflatable stoppers.
- In a pipe with a diameter of 160 mm, two stoppers placed in series can both fail.

3.4.2 Ignition after placement of outer stopper and the effect on the inner stopper-inlet-saddle and inner lance

These measurements were performed to gain insight into the effect of an ignition if one of the two stoppers is placed. In these tests, only the outer stopper is placed and the inner stopper is not yet. Whereby the saddle of the inner stopper is placed and the cap of this attachment is loosened. In other words; the mechanic is about to insert the lance concerning the inner stopper.

See 2.3.2for a further description of the measurement method and the test setup used. An overview of all measurements performed in this configuration is shown in Figure 9. This concerns measurements 60 to 71 and 76 to 81. These are shown in table form in Appendix III.

Where the stopper-inlet-saddle or lance is not damaged and where no flame has come out of the stopper-inlet-saddle, the frame is shown in green. If an undesirable situation has occurred, the frame is colored red. The green and red colored frames contain;

- the measurement number,
- the component subject to ignition (stopper-inlet-saddle or lance),
- the concentration of hydrogen at a certain distance from the stopper where the ignition is located.

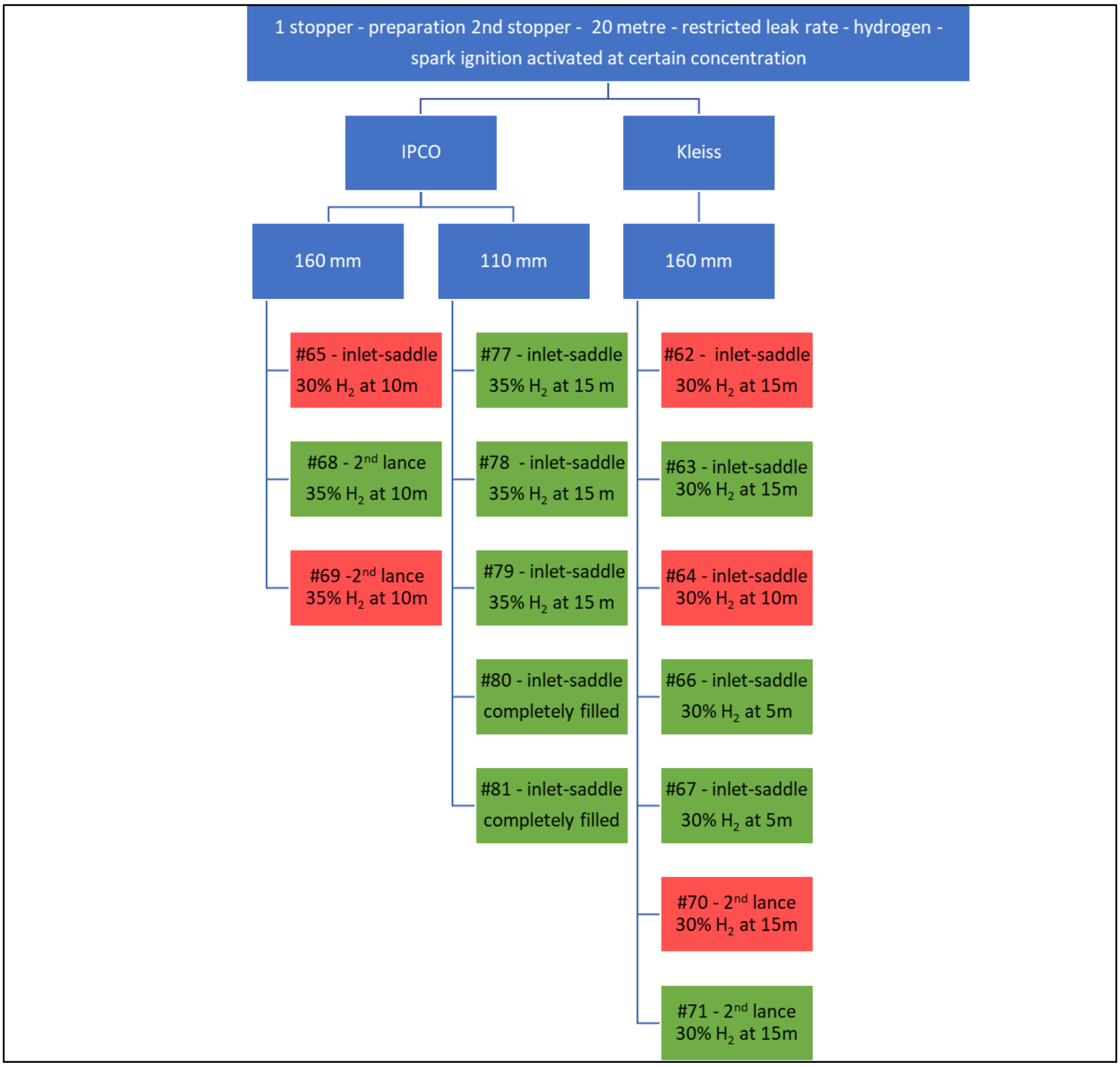


Figure 9 Overview of measurements with preparations for double stoppers in a pipe length of 20 meters

Due to the more specific execution of the measurements, an explanation per measurement follows below.

<u>Measurements 60 & 61 – pipe 160 mm</u>

These concentration measurements determined how the concentration in the pipe decreased and whether there was still an outflow of a flammable mixture. It appears that in the pipe with a diameter of 160 mm, a flammable mixture flows out for a long time at the location of the outflow opening. See the graphs in appendix VI. For this reason, ignition tests were carried out on the pipe with a diameter of 160 mm at the moment that gas concentrations were 30% at 15, 10 and 5 metres from the stopper respectively. See the results for measurements 62 to 67.

Measurements 62 & 63 – 160mm pipe – ignition at 30% at 15m from the stopper – Kleiss stopper

In measurement 62 the stoper-inlet-saddle pops out, in measurement 63 it does not. In both cases the stoppers remain intact.

Measurements 64 & 65 – 160mm pipe – ignition at 30% at 10m from stopper – Kleiss & IPCO stopper

This appears to be the most critical amount of hydrogen. This circumstance was therefore tested with an IPCO stopper and Kleis stopper. Both the inflatable gas stoppers and the stoper-inlet-saddle blow out with both IPCO and Kleiss stoppers. This circumstance was also tested with a not fully tightened 2nd lance. See the explanation below (measurements 68 to 71).

These ignitions where the most powerful of all observed ignitions in this study. This is probably because the rubber non-return valve is not fully closed by the gas pressure. This allows hydrogen to escape and air to enter at two places in the pipe; near the stoper-inlet-saddle and near the work pit.

Measurements 66 & 67 – 160 mm pipe – ignition at 30% at 5 meters from the stopper– Kleiss stopper

No strong ignition. The stopper and the stoper-inlet-saddle remain intact during these two measurements.

Measurements 68 & 69 – 160mm pipe – ignition at 30% at 10m from the stopper – IPCO lances

The inner lance (provided with a stopper) is tightened one full turn. At 4 turns this lance is fully tightened. In these two measurements, an ignition of the hydrogen is observed within 5 seconds after the activation of the spark ignition.

In one measurement the outer stopper is damaged (measurement 69) in the other measurement not. In both cases the inner lance remains in its normal position in which it was inserted. The uninflated stopper had already been inserted. After measurement 68 it was still intact, but after measurement 69 the outside of the stopper appeared to be torn. The stopper could be pressurized and kept under pressure. The inner stopper was apparently still intact.

Measurements 70 & 71 – 160mm pipe – ignition at 30% at 10m from the stopper – Kleiss lances

The inner lance (equipped with a vacuum-sucked stopper) is tightened one full turn. At 2.5 turns this lance is fully tightened. With these two measurements an ignition of the hydrogen is observed within 5 seconds after the activation of the spark ignition.

In one measurement the outer stopper is ruptured (measurement 70) in the other measurement it is not. In both cases the inner lance, despite a powerful ignition of the hydrogen, remains in the position in which it was applied. The inner stopper remains intact.

Measurement 76 – pipe 110 mm

These concentration measurements determined how the concentration in the pipe decreased and whether there was still an outflow of a flammable mixture. For a decrease in concentrations (without ignition) see the graphs in appendix VI belonging to measurement 76.

Measurement 77 & 78 – pipe 110 mm

In these two measurements, a concentration of 30% hydrogen in air was found after approximately 2.5 minutes at 15 m from the stopper. After this, the ignition was activated. There appeared to be no ignition, but after an assessment of the video images from the work pit, one non-explosive ignition was observed in both of these measurements. These ignitions had no effect on the stopper or the inner inlet-saddle. Hydrogen does visibly flow from the inlet-saddle with the cap open (prior to ignition). This is because the gas in the pipe between the stopper and the outlet opening in the work pit is more or less depressurized. The rubber flap (valve) drops down due to its own weight and the lack of gas pressure.

Because measurements 77 and 78 did not appear to indicate ignition and because the readings of the hydrogen concentration near the outlet opening indicated a concentration of 0% quite quickly after the gas supply was stopped, it was decided that it was not useful to perform measurements in which the spark igniter was activated at the moment that the concentration at 10 and 5 meters from the stopper was 30%. After all, the gas could no longer be ignited and there is less gas in the pipe because the outflow had been able to take place for a longer period of time.

<u>Measurement 79 – pipe 110 mm</u>
In this measurement, a concentration of 30% hydrogen in air was reached at 15 m from the stopper three minutes after the gas supply was stopped. After this, the ignition was activated. One minute later, the cap was loosened on the inlet-saddle (for the inner stopper). No ignition of hydrogen occurred.

<u>Measurement 80 & 81 – pipe 110 mm</u>
After the pipe was filled with 100% H2, the supply was stopped and the continuous sparking spark igniter was activated. In both of these measurements, an ignition of hydrogen was immediately observed in the work pit (and also from a distance). Not all of the hydrogen was burned, because even after the ignition of hydrogen, hydrogen still flows out of the inlet-saddle. The ignitions had no effect on the inlet-saddle or the inflatable gas stoppers.
Based on the results of measurements 80 and 81 (direct ignition of the fully hydrogen-filled line) it was decided not to perform measurements in which a second lance was placed, since there was no observable effect on the stopper-inlet-saddle. Because there was no explosive ignition in the line, there is no effect on the stopper used. In this case, the measurement was performed with IPCO stoppers. This was a random choice. The make of the stopper is of secondary importance in these measurements.

For further details of the measurements, see Appendices IV, V, VI and VII.

<u>Sub-conclusions</u>

An undesired ignition during the placement of the inner stopper can lead to unwanted consequential damage. These include, for example, a part coming loose from the stopper-inlet-sadle or an outer stopper that fails. This only applies to the pipe with a diameter of 160 mm and is independent of the make. In particular, the part coming loose from the stopper-inlet-sadle with considerable force can lead to injury to a mechanic.

A lance that is not fully tightened in a pipe with a diameter of 160 mm will not cause the lance to shoot loose. If the uninflated (inner) stopper has already been inserted, it can be damaged in the event of an unexpected ignition of the hydrogen that is still present.

In the case of a pipe with a diameter of 110 mm combined with an undesired ignition near the outlet opening, no adverse consequences are to be expected from inserting an inner stopper after the outer stopper has already been inserted and inflated.

4. Conclusions

4.1 Overall conclusions

Based on the experiments carried out, it has been shown that the use of single placed inflatable gas stoppers is not always safe.

4.1.1 Application with natural gas

When applied in a pipe with a diameter of 110 mm, no bursting inflatable gas stoppers were observed with natural gas. When applied in a pipe with a diameter of 160 mm, this was the case. The latter with direct ignition of leaking gas in a pipe with a length of 1 meter. It should be noted that there are some important differences between these measurements and the situations in daily practice. During the measurements, there was a permanent ignition source near the outlet opening and the leakage was directed at the gas stopper. There are no known incidents with natural gas in which leaking gas ignited and led to failure of the gas stopper.

Extinguishing a natural gas fire in a pipe with a diameter of 110 mm and 160 mm is possible with both the IPCO and the Kleiss stoppers without damaging the stoppers.

4.1.2 Application with hydrogen

When applied to a pipe with a diameter of 110 mm and a diameter of 160 mm, failure of inflatable gas stoppers have been observed at pipe lengths of 1 meter and 20 meters with hydrogen.

Extinguishing a hydrogen fire in a pipe with a diameter of 110 mm and 160 mm is possible with both the IPCO and the Kleiss stoppers without damaging the stoppers.

4.2 Answering research questions

Based on the experiments performed, the research questions as stated in paragraph 1.3 are to be answered as follows.

4.2.1 IPCO stoppers as a temporary shut-off device in hydrogen distribution networks

IPCO stoppers can be used as a temporary closing device in hydrogen distribution networks. There are specific recommendations depending on the diameter and length of the pipe in which the stoppers are used. These recommendations apply not only to IPCO stoppers, but also to Kleiss stoppers. See chapters 5 and 6 of this report.

4.2.2 Effects of unexpected ignitions in pipes with a diameter smaller than 160 mm

A small leak rate of hydrogen ignited near the outlet of a 1 meter long, 110 mm diameter pipe causes the gas stoppers of both IPCO and Kleiss to burst . This has also been observed with 160 mm diameter pipes.

A gas/air mixture ignited near the outlet of a 20-meter long, 110-mm diameter pipe does not cause the single-inserted stoppers to fail. This applies to IPCO and Kleiss stoppers for both natural gas and hydrogen. For this reason, inserting double stoppers in pipes with a diameter of 110 mm or smaller is not necessary.

4.2.3 Block & bleed in combination with nitrogen as a mitigating measure

Stopping the gas supply by means of block & bleed and starting the nitrogen purging will quickly dissipate the hydrogen present, which reduces the chance of hydrogen ignition. This has already been shown in previous studies [2] [3].

The placement of double stoppers increases the chance of maintaining the stopped gas flow. However, failure of both stoppers, in the absence of nitrogen purging, cannot be ruled out.

Should hydrogen ignition occur during the preparatory activities for placing the inner stopper, after the outer stopper has been placed and before the nitrogen flush has started, the following undesirable events may occur;

- The inflated outer stopper may burst;
- A part of the inner stopper inlet attachment may come loose;
- The uninflated inner stopper may fail

5. Mitigating measures

Based on the measurements performed, in the event of a “small” hydrogen leak (< 0.6 m^3_n/h) at the location of a gas stopper, the stopper may be affected if an ignition source is present near the outlet opening in the work pit. The stopper could burn (in the case of a stopper at approximately 1 meter from the outlet opening) or the stopper could burst (in the case of a stopper at 20 meters from the outlet opening).
The presence of hydrogen downstream of the placed stopper is conceivable due to the limited permissible leakage according to Gastec QA inspection requirements 194 and 214, due to contamination or damage to the pipe causing some leakage or because after the free gas flow has stopped there is hydrogen in the pipe. This gas flows slowly out of the pipe with air flowing into the pipe. A flammable gas/air mixture will be present in the pipe for a longer period of time. With hydrogen the period is simply longer compared to natural gas due to the wider flammability limits of hydrogen. In the event of an unexpected ignition, the impact with hydrogen has proven to be greater compared to natural gas.

Measures to reduce the risk of stopper damage will focus on preventing;

- A gas leak (the passage of gas from an inflatable gas stopper);
- The formation of a flammable mixture;
- An ignition.

Based on previous research [1], the current measures when using gas stoppers in the natural gas distribution network do not appear to lead to burning of the stopper. The **current** measures include ;

1. Check stopper tightness in advance.
2. Checking whether the stopper remains pressurized after placement.
3. Prevent ignition in the work pit by cordoning off the work pit, not using tools that generate sparks and wearing antistatic clothing.
4. Measuring the gas concentration in the work pit. If a person is present in the work pit, this is done using the gas detector of that person.

For other measures see G-24 (www.beiviag.nl).

For stoppers placed **approximately 1 meter** from the end of the pipe:

1. Forced ventilation of the work pit;
2. Measuring the gas concentration at the pipe end (top of the pipe);
3. After the inflatable gas stoppers have been set and the section of pipe on which work is planned has been depressurised , degas the section in question by purging it with nitrogen.

When placing a gas stopper at a distance of 1 meter from the pipe end in a hydrogen network, the expectation is that the current measures are sufficient to ensure safe application. In particular in pilot projects, it is useful to consider and/or validate the proposed additional measures.

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

1. Applying a type of stopper with a more solid construction than those tested. This requires the application of another type of stopper or a modification of the current types that should be realized by the manufacturers.
2. Applying double stoppers with degassing between the stoppers (block & bleed)
3. Applying a single stopper with a ventilation outlet behind the stopper (air-moving)
4. Forced ventilation of the work pit.
5. Measuring the gas concentration at the pipe end (top of the pipe)
6. After a single stopper or double stoppers has been placed, degas the area between the stopper and the outlet opening by purging with nitrogen.

The measures mentioned can be applied independently of each other, with the understanding that by applying air-moving (measure 3) the work pit will also be additionally ventilated (measure 4) by the admission of air into the interrupted pipe. The disadvantage of measures 3 and 4 is that the hydrogen gas concentration will decrease, but that a flammable mixture will be created over a certain period. Given the wider flammability limits for hydrogen, that period is longer for hydrogen than in a comparable situation for natural gas.

In this report, the measure of block & bleed has been further investigated and points of attention emerge with regard to the implementation. See chapter 6.

6. Recommendations

Based on the research carried out, the following recommendations are made:

1. For pipes with a diameter larger than 110 mm, it is advisable to use two stoppers in the event of an uncontrolled gas outflow. The chance that the gas outflow will start again after an unexpected ignition of a hydrogen/air mixture is then reduced. Bursting of both stoppers cannot be completely ruled out. This shows the added value of purging with nitrogen.
2. When installing double stoppers (in case of a pipe with a diameter > 110 mm), the choice can be made to install the outer stopper first and then start preparing the second (inner) stopper. However, in the event of an unexpected ignition of the present hydrogen, a part of the inner stopper-inlet-saddle can come loose and cause injury to the fitter. The retaining ring of the rubber non-return valve is particularly critical. It is therefore advisable to have fully completed the preparations for both stoppers (including inserting the lances with stoppers). It is advisable not to open the degassing tap yet, in order to limit the ingress of air into the work pit. Then the outer stopper can be inflated, shortly afterwards the inner stopper can be inflated and subsequently the nitrogen injection must be started. This complete procedure has the following advantages;
    - It reduces the risk of injury to the technician due to a loose part of the stopper-inlet-saddle.
    - It reduces the chance of hydrogen leaking from the inner stopper-inlet-saddle via a non-sealing check valve.
    - It reduces the chance of a flammable mixture forming because the outer and inner stoppers can be inflated in quick succession, allowing the nitrogen purge to start more quickly.

    After pressurizing both stoppers, the space between the stoppers must be reduced in pressure to a pressure approximately equal to the atmosphere. Then the valve in question is closed again. The pressure between the stoppers must be monitored. If the pressure increases, it must be blown off again. Another application that prevents the ingress of air is also possible.
3. It is advisable to bring this report to the attention of manufacturers of inflatable gas stoppers so that they can adapt their inflatable gas stoppers, lance sets, operating instructions and other accessories to the above procedure.
4. In a hydrogen network, the flow rate may be three times higher compared to the flow rate in a natural gas network. It is recommended to investigate whether an inflatable gas stopper can be placed at these high speeds. The current Gastec QA criteria (KE 194) assume a maximum gas velocity of 80 m/s.
5. It is advisable to bring this report to the attention of the College of experts Gastec QA. This with the aim of aligning KE 194 and KE 214 where necessary with the findings from this report [3].
6. Consider, especially for diameters larger than DN 100, the use of other methods of sectioning in a hydrogen distribution network. This includes squeezing, stoppling and/or the installation of fixed valves.

[3] *At the time of writing this report, both inspection requirements are under revision.*

Based on the findings as described in this report and in the inflatable gas stoppers report " HyDelta 2" [1]the use of inflatable gas stoppers is as follows;

Table 2 Application of single or double stoppers depending on activity and pipe diameter

Description of activity		Diameter of the pipe		
		≤ DN 100	DN 150	≥ DN 200
Planned work (distance inflatable gas stopper to opening ≤ 1m)	Extension on an offshoot	single	single	double
	Installing T-piece	single	single	double
	Repairing a leak after above-ground leak detection	single	single	double
Incident response (distance inflatable gas stopper to opening > 1 m)	Extinguish gas fire	single	single	double
	Stop gas outflow	single	double	double

For natural gas, according to the Dutch VWI G-24, two inflatable gas stoppers must be placed in series at;

- *pipes with diameter ≥ DN 150 in case of application of inflatable gas stoppers without QA*
- *pipes with diameter > DN 300*

For hydrogen, the starting point is that inflatable gas stoppers are selected with a QA quality mark. In addition, the limit for the use of inflatable gas stopper when used in a hydrogen network has been lowered from > DN 300 for natural gas to ≥ DN 200 because the outflow of gas in the event of unexpected inflatable gas stopper failure is greater with hydrogen than with natural gas.
Placing double inflatable gas stoppers involves purging with nitrogen.

To keep the application simple, it is possible to choose to use of double inflatable gas stoppers where this is not strictly necessary according to the table above.

References

[1] Kiwa Technology, "HyDelta: D6B.2A & D6B.2B Report on ignition scenarios and experiments during the use of inflatable gas stoppers to mitigate natural gas and hydrogen leaks in the low pressure gas distribution grid," 2023. [Online]. Available: https://zenodo.org/records/8112254.

[2] Kiwa Technology, "Spoelen van waterstofleidingen_GT-200289," 2021.

[3] S. Lueb, "Beproeving block & bleed - Het zetten van gasblazen onder waterstofcondities in een gasdistributienet (Enexis)," 2023.

Attachments

I. Background Block & bleed in combination with nitrogen purging

In order to determine how the mitigating measure "block & bleed in combination with nitrogen purging" would be investigated to determine whether it was effective, the measure was discussed extensively with the EAG. This was done on the basis of a study commissioned by Enexis [2] and an exchange of experiences from the grid operators. Below follows a further explanation of the method of testing.

When placing two stoppers in series (block & bleed) the entire gas supply to the leak is stopped. Immediately after stopping the gas supply the gas concentration will decrease due to the ingress of air (in case of a large leak). Based on the results obtained with HyDelta 2 a low concentration of hydrogen has proven to be critical. At a leak rate of 0.6 m^3/h hydrogen in an air-filled 160 mm pipe and an ignition source at the outlet opening the Kleiss stopper failed in two of the three measurements. In these two measurements the explosive ignitions occurred after approximately 10 minutes. The 20 meter pipe has a capacity of 315 liters. In 10 minutes 60 liters of hydrogen was supplied. The average concentration (it will not have been a homogeneous mixture) is 19% gas in air. At some places in the pipe there will be an ideal mixture (30% hydrogen in air). The fact that after stopping the gas supply and after starting the purging with nitrogen, the hydrogen present is expelled does not need to be investigated further according to the EAG. This has already been shown in previous studies[3]

Questions raised during an EAG meeting;

1) Will the two stoppers hold (in a block & bleed configuration) after an unexpected ignition?

This situation can occur, for example, if nitrogen purging is started later than expected and/or if air ingress has already occurred before nitrogen purging has started. Note that in practice, the choice of whether or not to open the blow-off valve is an important factor in the degree of air ingress.

2) What happens at the saddle (with the cap of the other stopper-inlet-saddle open) where the stopper with nitrogen purging must be applied if an unexpected inflammation occurs after the outer stopper has been inserted?

During an EAG meeting prior to the experiments, the order of placing inflatable gas stoppers in the event of a hydrogen incident was discussed. It was indicated that, as with natural gas, preference is given to starting with the outer stoppers (see Appendix II). This is because the outer stoppers sometimes do not settle properly due to the high flow rate. In the event of a small leak, air will not enter quickly because the contained amount of hydrogen flows away slowly. In the event of a large leak, the overpressure will have decreased quickly and air may enter before nitrogen purging via the inner stoppers has started. In order to investigate what the consequences could be, it was decided to carry out the following series of measurements.

Measurement series – do the two stoppers hold up under strong ignition?

In order to determine whether at least one stopper will hold when using two stoppers, measurements are carried out in which a hydrogen leak of 0.6 m^3/h is created downstream after the two stoppers have been placed . The starting point is a pipe completely filled with air. This is a simulation of the situation in which a limited amount of hydrogen is present in the pipe after the supply via two stoppers has been completely stopped. After the leakage has started, the spark igniter at the outlet opening is energised. It is expected that, as with HyDelta 2, a violent ignition will take place after approximately 10 minutes.

Measurement series – inflammation after placing the outer stopper and opened cap on the other attachment

In a block & bleed setup , only the outer stopper is applied. The downstream line is completely filled with hydrogen. The seal at the attachment is the rubber flap. The ignition is energized after the hydrogen concentration has dropped from 100% to 30% at a distance of 15, 10 and 5 meters from the stopper, respectively.

This measures the concentration in the middle of the pipe. At the top of the pipe, there will be a long-term concentration of 100% hydrogen at any distance from the gas stopper, and at the bottom, 0% hydrogen for a long time. This measurement series focuses on the effect on the opened attachment (for example, is there a flash flame from the attachment?) with the rubber flap as the only seal.

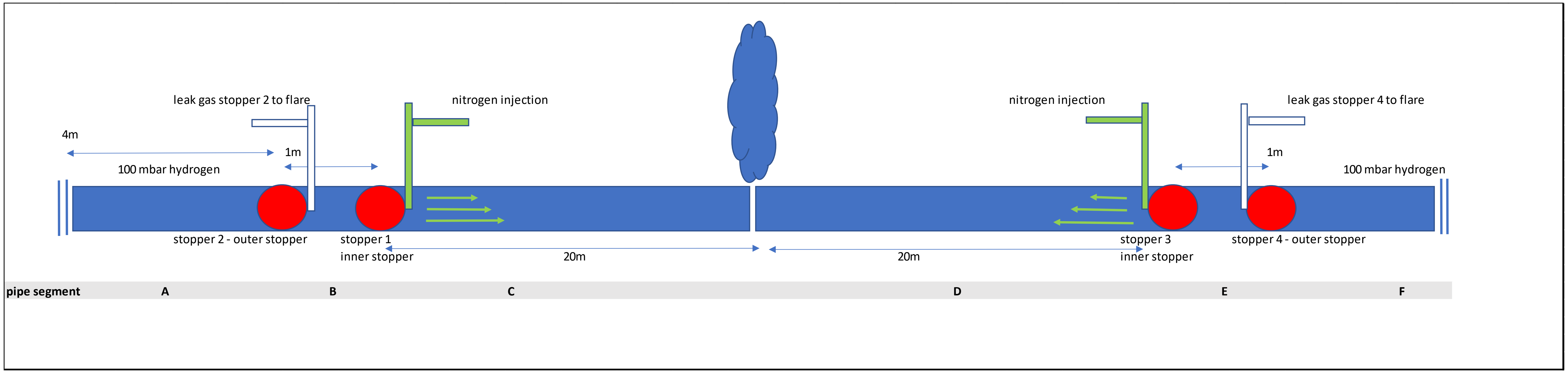
Measurement series – ignition after insertion of outer stopper and incomplete insertion of inner lance.

In practice, it is possible that a mechanic has placed an outer stopper and then starts to apply the lance for the inner stopper. What are the consequences of an unexpected ignition at the moment that the mechanic has inserted the lance but has not yet fully tightened? The situation of the most powerful ignitions as observed in the measurement series mentioned above are also carried out with a lance that is not fully tightened.

II. Schematic representation of the use of inflatable gas stoppers in hydrogen incidents

During an EAG meeting, the methodology of using inflatable gas stoppers with hydrogen incidents was discussed. After exchanging arguments and experiences, the approach below emerged as a correct option.

The stoppers at the greatest distance from the outflow opening are called the outer stoppers. The other stoppers are referred to as the inner stoppers.



Description of the various events and actions;

- A leak is detected by above-ground leak detection or by smell (small leak) or during excavation work (large leak, excavation damage)
- The leak is located.
- At a distance where a concentration of less than 10% LEL is measured, inflatable gas stoppers are placed (on both sides of the leak)
- Stopper 2 and 4 are set.
- Stopper 1 and 3 are set, nitrogen purging is started
- The position of the leak is approached with a personal protective equipment (gas detector)
- The leak is being dug up
- Once the leak is approachable, it is measured whether the concentration is less than 10% LEL
- If the concentration is less than 10% LEL, the nitrogen supply is stopped.

In the Dutch Safety Work Instruction G36 a distinction is made between combating a major leak (excavation damage) and a small leak (detected with above-ground leak detection). In practice, stoppers 2 and 4 will always be set first (the outer stoppers). Then stoppers 1 and 3. The outer stoppers will have to endure the greatest flow. They may therefore not set as well as desired. The inner stopper is then easier to set. This ensures a complete seal because any leak gas between the stoppers is discharged. The EAG considers this more important than being able to start purging nitrogen more quickly (in the case that stoppers 1 and 3 are set first).

Major leak (excavation damage); Nitrogen inlet from both sides. Hydrogen discharge via the leak.

Small leak (a leak still covered by the soil); Purging with nitrogen from one inner stopper to the other inner stopper.

III. Overview of measurements performed

The measurement numbers as listed in the table below do not follow each other in order of execution. This had various practical causes. In the table below, measurements of equal lengths and diameters are clustered as much as possible.

No.	Date	Length (m)	Diameter (mm)	Gas	Flow rate (m^3_n/uur)	Igntion	Stopper	Performed in HyDelta 2?
1	15/04/2024	1	160	natural gas	0,15	direct	IPCO	no
2	15/04/2024	1	160	natural gas	0,20	direct	IPCO	no
3	15/04/2024	1	160	natural gas	0,30	direct	IPCO	no
4	15/04/2024	1	160	natural gas	0,30	direct	IPCO	no
5	15/04/2024	1	160	hydrogen	0,35	direct	IPCO	no
6	15/04/2024	1	160	hydrogen	0,35	direct	IPCO	no
7	15/04/2024	1	160	hydrogen	0,35	direct	Kleiss	no
8	15/04/2024	1	160	hydrogen	0,35	direct	Kleiss	no
9	15/04/2024	1	160	hydrogen	0,45	direct	Kleiss	yes
10	08/07/2024	1	160	natural gas	0,075	direct	IPCO	no
11	08/07/2024	1	160	natural gas	0,075	direct	IPCO	no
12	08/07/2024	1	160	hydrogen	0,160	direct	IPCO	no
13	08/07/2024	1	160	hydrogen	0,160	direct	IPCO	no
14	08/07/2024	1	160	natural gas	0,075	direct	Kleiss	no
15	08/07/2024	1	160	natural gas	0,075	direct	Kleiss	no
16	08/07/2024	1	160	hydrogen	0,160	direct	Kleiss	no
17	08/07/2024	1	160	hydrogen	0,160	direct	Kleiss	no
18	05/07/2024	1	110	natural gas	0,075	direct	IPCO	no
19	05/07/2024	1	110	natural gas	0,075	direct	IPCO	no
20	05/07/2024	1	110	hydrogen	0,160	direct	IPCO	no
21	05/07/2024	1	110	hydrogen	0,160	direct	IPCO	no
22	05/07/2024	1	110	hydrogen	0,100	direct	IPCO	no
23	05/07/2024	1	110	hydrogen	0,100	direct	IPCO	no
24	05/07/2024	1	110	natural gas	0,075	direct	Kleiss	no
25	05/07/2024	1	110	natural gas	0,075	direct	Kleiss	no
26	05/07/2024	1	110	hydrogen	0,160	direct	Kleiss	no
27	05/07/2024	1	110	hydrogen	0,160	direct	Kleiss	no
28	05/07/2024	1	110	hydrogen	0,100	direct	Kleiss	no
29	05/07/2024	1	110	hydrogen	0,100	direct	Kleiss	no
30	16/04/2024	20	160	natural gas	0,20	direct	IPCO	no
31	16/04/2024	20	160	natural gas	0,20	direct	IPCO	no
32	22/04/2024	20	160	natural gas	14	after ± 1 min	IPCO	no
33	22/04/2024	20	160	natural gas	13	after ± 1 min	IPCO	no
34	16/04/2024	20	160	hydrogen	0,60	direct	IPCO	no
35	16/04/2024	20	160	hydrogen	0,60	direct	IPCO	no
36	16/04/2024	20	160	hydrogen	0,60	direct	Kleiss	yes
37	16/04/2024	20	160	hydrogen	0,60	direct	Kleiss	yes
38	22/04/2024	20	160	hydrogen	37	after ± 2 min	IPCO	no
39	22/04/2024	20	160	hydrogen	37	after ± 2 min	IPCO	no
40	22/04/2024	20	160	hydrogen	40	after ± 3 min	Kleiss	yes
41	22/04/2024	20	160	hydrogen	45	after ± 3 min	Kleiss	yes
42	17/04/2024	20	110	natural gas	0,20	direct	IPCO	no
43	16/04/2024	20	110	natural gas	0,20	direct	Kleiss	no
44	16/04/2024	20	110	hydrogen	0,60	direct	IPCO	no
45	16/04/2024	20	110	hydrogen	0,60	direct	IPCO	no
46	16/04/2024	20	110	hydrogen	0,60	direct	Kleiss	no
47	16/04/2024	20	110	hydrogen	0,60	direct	Kleiss	no
48	22/04/2024	20	110	natural gas	19	after ± 2,5 min	IPCO	no
49	22/04/2024	20	110	natural gas	18	after ± 2,5 min	IPCO	no
50	22/04/2024	20	110	natural gas	18	after ± 2,5 min	Kleiss	no
51	22/04/2024	20	110	natural gas	18	after ± 2,5 min	Kleiss	no
52	22/04/2024	20	110	hydrogen	65	after ± 2,5 min	IPCO	no
53	22/04/2024	20	110	hydrogen	65	after ± 2,5 min	IPCO	no
54	22/04/2024	20	110	hydrogen	65	after ± 2,5 min	Kleiss	no
55	22/04/2024	20	110	hydrogen	65	after ± 2,5 min	Kleiss	no

Measurement 10 t/m 29 are done at Kiwa facilities, other measurements at the Twente Safety Campus.

No.	Date	Diameter (mm)	Flow rate (m^3_n/uur)	Configuration	Igntion	Stoppers
56	18/04/2024	160	0,6	2 stoppers	direct	Kleiss
57	18/04/2024	160	0,6	2 stoppers	direct	Kleiss
58	18/04/2024	160	0,6	2 stoppers	direct	IPCO
59	18/04/2024	160	0,6	2 stoppers	direct	IPCO
60	18/04/2024	160	n/a	1 stopper + inlet	**none***	Kleiss
61	18/04/2024	160	n/a	1 stopper + inlet	**none***	Kleiss
62	19/04/2024	160	n/a	1 stopper + inlet	when conc. 30% at 15m away from stopper is reached	Kleiss
63	19/04/2024	160	n/a	1 stopper + inlet	when conc. 30% at 15m away from stopper is reached	Kleiss
64	19/04/2024	160	n/a	1 stopper + inlet	when conc. 30% at 10m away from stopper is reached	Kleis
65	19/04/2024	160	n/a	1 stopper + inlet	when conc. 30% at 10m away from stopper is reached	IPCO
66	19/04/2024	160	n/a	1 stopper + inlet	when conc. 30% at 5m away from stopper is reached	Kleiss
67	19/04/2024	160	n/a	1 stopper + inlet	when conc. 30% at 5m away from stopper is reached	Kleiss
68	19/04/2024	160	n/a	1 stopper + 1 lance	when conc. 35% at 10m away from stopper is reached	IPCO + 2nd lance
69	19/04/2024	160	n/a	1 stopper + 1 lance	when conc. 35% at 10m away from stopper is reached	IPCO + 2nd lance
70	19/04/2024	160	n/a	1 stopper + 1 lance	when conc. 35% at 10m away from stopper is reached	Kleiss + 2nd lance
71	19/04/2024	160	n/a	1 stopper + 1 lance	when conc. 35% at 10m away from stopper is reached	Kleiss + 2nd lance
72	17/04/2024	110	0,6	2 stoppers	direct	Kleiss
73	17/04/2024	110	0,6	2 stoppers	direct	Kleiss
74	17/04/2024	110	0,6	2 stoppers	direct	IPCO
75	17/04/2024	110	0,6	2 stoppers	direct	IPCO
76	17/04/2024	110	n/a	1 stopper + inlet	**none***	IPCO
77	18/04/2024	110	n/a	1 stopper + inlet	15 m of stopper 30%	IPCO
78	18/04/2024	110	n/a	1 stopper + inlet	15 m of stopper 30%	IPCO
79	18/04/2024	110	n/a	1 stopper + inlet	15 m of stopper 30%	IPCO
80	18/04/2024	110	n/a	1 stopper + inlet	directly after stopping flow (= extra)	IPCO
81	18/04/2024	110	n/a	1 stopper + inlet	directly after stopping flow (= extra)	IPCO

*Measurements 60, 61 en 76 are concentration measurements. Decrease of hydrogen concentration in the pipe strongly depends on windconditions. Therefore decided to activate the spark not after a setted period, but to monitor the concentrations during ignition experiments.

IV. Findings per measurement

Table 1 Results measurements 1 to 4

Measurement	1	2	3	4
Manufacturer inflatable stopper [-]	IPCO	IPCO	IPCO	IPCO
Medium [-]	Natural gas	Natural gas	Natural gas	Natural gas
Diameter [mm]	160	160	160	160
Length of pipe [m]	1	1	1	1
Flow rate [m^3_n/h]	0.15	0.2	0.3	0.3
Sound - LAFmax [dB]	88	86.8	114.6	80.1
Max. concentration at outlet opening [%]	3.6	2.7	3.7	3,3
Max. temperature at inflatable stopper [°C]	85	84	204	99
Ambient temperature [°C]	10.1	10.1	10.1	8.7
Wind speed [m/s]	8	8	8	6
Observations [-]	Based on temperature measurements at the stopper; per measurement, ignition of natural gas several times followed by extinguishing of the flame.			
Inflatable stopper condition [-]	Intact	Intact	Failed	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes	No	Yes

Table 2 Results measurements 5 and 6

Measurement	5	6
Manufacturer inflatable stopper [-]	IPCO	IPCO
Medium [-]	Hydrogen	Hydrogen
Diameter [mm]	160	160
Length of pipe [m]	1	1
Flow rate [m^3_n/h]	0.35	0.35
Sound - LAFmax [dB]	99.1	107.7
Max. concentration at outlet opening [%]	0.2	1
Max. temperature at inflatable stopper [°C]	51	82
Ambient temperature [°C]	9	9
Wind speed [m/s]	7	7
Observations [-]	Ignition of gas within 30 sec.	Ignition of gas within 30 sec.
Inflatable stopper condition [-]	Failed	Failed
Inflatable stopper remains pressurised [-]	No	No

Table 3 Results measurements 7 to 9

Measurement	7	8	9
Manufacturer stopper[-]	Kleiss	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	160	160	160
Length of pipe [m]	1	1	1
Flow rate [$m^3{}_n$/h]	0.35	0.35	0.45
Sound - LAFmax [dB]	84.8	122.8	127.3
Max. concentration at outlet opening [%]	0	0	0
Max. temperature at stopper[°C]	69	59	- (moisture in the meter)
Ambient temperature [°C]	9	4	6
Wind speed [m/s]	7	7	6
Observations [-]	Ignition of gas within 30 sec.	Ignition of gas within 30 sec.	Ignition of gas within 15 sec.
Stoppercondition [-]	Failed	Failed	Failed
Keep stopperunder pressure [-]	No	No	No

Table 4 Results measurements 10 to 13

Measurement	10	11	12	13
Manufacturer stopper[-]	IPCO	IPCO	IPCO	IPCO
Medium [-]	Natural gas	Natural gas	Hydrogen	Hydrogen
Diameter [mm]	160	160	160	160
Length of pipe [m]	1	1	1	1
Flow rate [$m^3{}_n$/h]	0.075	0.075	0.16	0.16
Sound - LAFmax [dB]	78	ng .	93	97.3
Max. concentration at outlet opening [%]	7.9	1.0	6.4	5.8
Max. temperature at stopper[°C]	64	54	43	47
Ambient temperature [°C]	18	18	18.5	19
Wind speed [m/s]	0	0	0	0
Observations [-]	Some gas ignitions audible. Small pop by stopper bursting.	After about 1 minute the stopper burst. Visible damage to the outer part of the stopper. The inner part is also damaged.	First a small pop, then the stopper bursts with a louder bang.	Ignition audible within 1 minute. Stopper bursts audibly and continues to burn.
Stoppercondition [-]	Failed	Failed	Failed	Failed
Keep stopperunder pressure [-]	No	No	No	No

Table 5 Results measurements 14 to 17

Measurement	14	15	16	17
Manufacturer inflatable stopper [-]	Kleiss	Kleiss	Kleiss	Kleiss
Medium [-]	Natural gas	Natural gas	Hydrogen	Hydrogen
Diameter [mm]	160	160	160	160
Length of pipe [m]	1	1	1	1
Flow rate [$m^3{}_n$/h]	0	0.075	0.16	0.16
Sound - LAFmax [dB]	78.1	73.4	121.8	122.4
Max. concentration at outlet opening [%]	3.4	3.6	6.1	6
Max. temperature at inflatable stopper [°C]	122	56	60	66
Ambient temperature [°C]	22	22	22	22
Wind speed [m/s]	0	0	0	0
Observations [-]	Multiple ignitions of natural gas. Smoke visible. Stopper remained pressurized.	Stopper was leaking at the start. During measurement kept under pressure by pumping. Multiple ignitions audible. Smoke in the pipe.	Audible ignition, then louder pop of stopper bursting.	Audible ignition, then louder pop of stopper bursting.
Inflatable stopper condition [-]	Melting damage at connection.	Melting damage at connection.	Failed	Failed
Inflatable stopper remains pressurised [-]	Yes	Yes	No	No

Table 6 Results measurements 18 to 19

Measurement	18	19
Manufacturer inflatable stopper [-]	IPCO	IPCO
Medium [-]	Natural gas	Natural gas
Diameter [mm]	110	110
Length of pipe [m]	1	1
Flow rate [$m^3{}_n$/h]	0.075	0.075
Sound - LAFmax [dB]	70	69.1
Max. concentration at outlet opening [%]	7.1	24.4
Max. temperature at inflatable stopper [°C]	45	151
Ambient temperature [°C]	16	16
Wind speed [m/s]	0	0
Observations [-]	Ignition was observed.	Ignition was observed.
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 7 Results measurements 20 to 23

Measurement	20	21	22	23
Manufacturer inflatable stopper [-]	IPCO	IPCO	IPCO	IPCO
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	110	110	110	110
Length of pipe [m]	1	1	1	1
Flow rate [$m^3{}_n$/h]	0.16	0.16	0.1	0.1
Sound - LAFmax [dB]	87.2	91.2	90	89.8
Max. concentration at outlet opening [%]	2.2	4.2	1.8	1.4
Max. temperature at inflatable stopper [°C]	85	58	102	57
Ambient temperature [°C]	17	17	16	16
Wind speed [m/s]	0	0	0	0
Observations [-]	Almost immediate ignition. Stopper failed almost immediately.	Almost immediate ignition. Stopper failed almost immediately.	Ignition within 1 minute. Stopper failed almost immediately.	Gas outflow had already started before spark was energized. After energizing spark immediate ignition and bursting of stopper.
Inflatable stopper condition [-]	Failed	Failed	Failed	Failed
Inflatable stopper remains pressurised [-]	No	No	No	No

Table 8 Results measurements 24 and 25

Measurement	24	25
Manufacturer inflatable stopper [-]	Kleiss	Kleiss
Medium [-]	Natural gas	Natural gas
Diameter [mm]	110	110
Length of pipe [m]	1	1
Flow rate [$m^3{}_n$/h]	0.075	0.075
Sound - LAFmax [dB]	72.8	75.9
Max. concentration at outlet opening [%]	3.1	6.5
Max. temperature at inflatable stopper [°C]	84	92
Ambient temperature [°C]	17	17
Wind speed [m/s]	0	0
Observations [-]	Multiple ignitions observed.	Multiple ignitions observed.
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 9 Results measurements 26 to 29

Measurement	26	27	28	29
Manufacturer inflatable stopper [-]	Kleiss	Kleiss	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	110	110	110	110
Length of pipe [m]	1	1	1	1
Flow rate [$m^3{}_n$/h]	0.160	0.160	0.100	0.100
Sound - LAFmax [dB]	88.8	87.3	112.9	114.2
Max. concentration at outlet opening [%]	3.3	2.6	0.3	2
Max. temperature at inflatable stopper [°C]	169	45	166	140
Ambient temperature [°C]	17	17	17	17
Wind speed [m/s]	0	0	0	0
Observations [-]	After about 3 minutes ignition and stopper failed.	Ignition within 1 minute. Stopper not broken at first ignition, later it is. Melting damage to connection hose, had to be sawn loose because of that.	Fast ignition. Smoke visible. Stopped manually after 10 minutes. Melting damage to connection hose, had to be sawn loose.	Fast ignition. Smoke visible. Stopped manually after 10 minutes. Melting damage to connection hose, had to be sawn loose.
Inflatable stopper condition [-]	Failed	Failed	Melting damage at connection.	Melting damage at connection.
Inflatable stopper remains pressurised [-]	No	No	No	No

Table 10 Results measurements 30 and 31

Measurement	30	31
Manufacturer inflatable stopper [-]	IPCO	IPCO
Medium [-]	Natural gas	Natural gas
Diameter [mm]	160	160
Length of pipe [m]	20	20
Flow rate [m^3_n/h]	0.20	0.20
Sound - LAFmax [dB]	88.4	80
Max. concentration at outlet opening [%]	4	4.5
Max. temperature at inflatable stopper [°C]	- (moisture in the meter)	- (moisture in the meter)
Ambient temperature [°C]	7	8
Wind speed [m/s]	6	5
Observations [-]	In video footage in the work pit, an ignition was observed once.	In video footage in the work pit, an ignition was observed once.
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 11 Results measurements 32 and 33

Measurement	32	33
Manufacturer inflatable stopper [-]	IPCO	IPCO
Medium [-]	Natural gas	Natural gas
Diameter [mm]	160	160
Length of pipe [m]	20	20
Flow rate [m^3_n/h]	14	13
Sound - LAFmax [dB]	78	75.4
Max. concentration at outlet opening [%]	2.9	2.5
Max. temperature at inflatable stopper [°C]	20	18
Ambient temperature [°C]	9	9
Wind speed [m/s]	5	5
Observations [-]	At each measurement, the visible flame can be extinguished by inflating the stopper.	
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 12 Results measurements 34 to 37

Measurement	34	35	36	37
Manufacturer inflatable stopper [-]	IPCO	IPCO	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	160	160	160	160
Length of pipe [m]	20	20	20	20
Flow rate [m^3_n/h]	0.6	0.6	0.6	0.6
Sound - LAFmax [dB]	134	133.7	133.4	134.6
Max. concentration at outlet opening [%]	3.2	3.5	3.8	3.5
Max. temperature at inflatable stopper [°C]	150	188	46	22
Ambient temperature [°C]	11	11	11	8
Wind speed [m/s]	4	4	4	4
Observations [-]	Intens ignition observed.	Intens ignition observed.	Intens ignition observed.	Intens ignition observed.
Inflatable stopper condition [-]	Intact	Stopperpops out	Stopperpops out	Stopperpops out
Inflatable stopper remains pressurised [-]	Yes	No	No	No

Table 13 Results measurements 38 to 41

Measurement	38	39	40	41
Manufacturer inflatable stopper [-]	IPCO	IPCO	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	160	160	160	160
Length of pipe [m]	20	20	20	20
Flow rate [m^3_n/h]	37	37	40	45
Sound - LAFmax [dB]	103.1	98.2	102.9	97.6
Max. concentration at outlet opening [%]	3.3	2.3	3.4	3.3
Max. temperature at inflatable stopper [°C]	23	22	22	26
Ambient temperature [°C]	9	9	9	6
Wind speed [m/s]	6	6	6	6
Observations [-]	At each measurement, the visible flame can be extinguished by inflating the stopper.			
Inflatable stopper condition [-]	Intact	Intact	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes	Yes	Yes

Table 14 Results measurements 42 and 43

Measurement	42	43
Manufacturer inflatable stopper [-]	IPCO	Kleiss
Medium [-]	Natural gas	Natural gas
Diameter [mm]	110	110
Length of pipe [m]	20	20
Flow rate [$m^3{}_n$/h]	0.2	0.2
Sound - LAFmax [dB]	70.6	84.2
Max. concentration at outlet opening [%]	7.2	7.2
Max. temperature at inflatable stopper [°C]	10	16
Ambient temperature [°C]	8	9
Wind speed [m/s]	4	3
Observations [-]	Multiple ignitions observed, no flame flash back. Total measurement length approximately 30 minutes.	Multiple ignitions observed, no flame flash back. Total measurement length approximately 30 minutes.
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 15 Results measurements 44 to 47

Measurement	44	45	46	47
Manufacturer inflatable stopper [-]	IPCO	IPCO	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	110	110	110	110
Length of pipe [m]	20	20	20	20
Flow rate [$m^3{}_n$/h]	0.6	0.6	0.6	0.6
Sound - LAFmax [dB]	128.9	130.2	131.2	131.4
Max. concentration at outlet opening [%]	16	7.1	5.5	5.1
Max. temperature at inflatable stopper [°C]	17	20	20	18
Ambient temperature [°C]	9	9	9	9
Wind speed [m/s]	2	2	4	4
Observations [-]	Intens ignition observed.	Intens ignition observed.	Intens ignition observed.	Intens ignition observed.
Inflatable stopper condition [-]	Intact	Intact	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes	Yes	Yes

Table 16 Results measurements 48 to 51

Measurement	48	49	50	51
Manufacturer inflatable stopper [-]	IPCO	IPCO	Kleiss	Kleiss
Medium [-]	Natural gas	Natural gas	Natural gas	Natural gas
Diameter [mm]	110	110	110	110
Length of pipe [m]	20	20	20	20
Flow rate [m^3_n/h]	19	18	18	18
Sound - LAFmax [dB]	85	82.9	64.4	68.3
Max. concentration at outlet opening [%]	4.2	4	3.8	4
Max. temperature at inflatable stopper [°C]	19	19	21	21
Ambient temperature [°C]	8	8	8	8
Wind speed [m/s]	4	4	4	4
Observations [-]	At each measurement, the visible flame can be extinguished by inflating the stopper.			
Inflatable stopper condition [-]	Intact	Intact	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes	Yes	Yes

Table 17 Results measurements 52 to 55

Measurement	52	53	54	55
Manufacturer inflatable stopper [-]	IPCO	IPCO	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	110	110	110	110
Length of pipe [m]	20	20	20	20
Flow rate [m^3_n/h]	65	65	65	65
Sound - LAFmax [dB]	102.1	100.3	100.4	101.4
Max. concentration at outlet opening [%]	4.1	5.7	5.7	4.9
Max. temperature at inflatable stopper [°C]	17	16	14	13
Ambient temperature [°C]	7	7	7	7
Wind speed [m/s]	5	5	5	5
Observations [-]	At each measurement, the visible flame can be extinguished by inflating the stopper.			
Inflatable stopper condition [-]	Intact	Intact	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes	Yes	Yes

Table 18 Results measurements 56 to 59

Measurement	56	57	58	59
Manufacturer inflatable stopper [-]	Kleiss	Kleiss	IPCO	IPCO
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	160	160	160	160
Length of pipe [m]	20	20	20	20
Flow rate [$m^3{}_n$/h]	0.6	0.6	0.6	0.6
Sound - LAFmax [dB]	134.5	133.5	133.1	134.3
Max. concentration at outlet opening [%]	7.6	3	4.2	4.3
Max. temperature at inflatable stopper [°C]	77	148	159	154
Ambient temperature [°C]	11	11	10	10
Wind speed [m/s]	5	5	4	4
Observations [-]	Intens ignition observed.	Intens ignition observed.	Intens ignition observed.	Intens ignition observed.
Inflatable stopper condition [-]	Inner and outer stopper both failed.	Inner stopper is ruptured - outer stopper remains intact	Inner stopper is ruptured - outer stopper remains intact	Inner stopper is ruptured - outer stopper remains intact
Inflatable stoppers remains pressurised [-]	No (neither inner or outer)	Outside yes, inside no	Outside yes, inside no	Outside yes, inside no

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Table 19 Results measurements 60 and 61

Measurement	60	61
Manufacturer inflatable stopper [-]	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen
Diameter [mm]	160	160
Length of pipe [m]	20	20
Flow rate [$m^3{}_n$/h]	n/a	n/a
Sound - LAFmax [dB]	n/a	n/a
Max. concentration at outlet opening [%]	n/a	n/a
Max. temperature at inflatable stopper [°C]	n/a	n/a
Ambient temperature [°C]	11	11
Wind speed [m/s]	5	5
Observations [-]	Measurement for the purpose of concentration determination.	
Inflatable stopper condition [-]	n/a	n/a
Inflatable stopper remains pressurised [-]	n/a	n/a

Table 20 Results measurements 62 and 63

Measurement	62	63
Manufacturer inflatable stopper [-]	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen
Diameter [mm]	160	160
Length of pipe [m]	20	20
Flow rate [$m^3{}_n$/h]	n/a	n/a
Sound - LAFmax [dB]	132.3	133.1
Max. concentration at outlet opening [%]	88	78
Max. temperature at inflatable stopper [°C]	210	211
Ambient temperature [°C]	7	7
Wind speed [m/s]	6	6
Observations [-]	Intlet piece on pipe pops out.	Intlet piece remains intact.
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 21 Results measurements 64 and 65

Measurement	64	65
Manufacturer inflatable stopper [-]	Kleiss	IPCO
Medium [-]	Hydrogen	Hydrogen
Diameter [mm]	160	160
Length of pipe [m]	20	20
Flow rate [$m^3{}_n$/h]	n/a	n/a
Sound - LAFmax [dB]	134.4	135.5
Max. concentration at outlet opening [%]	70	86
Max. temperature at inflatable stopper [°C]	187	49
Ambient temperature [°C]	0	0.3
Wind speed [m/s]	8	8
Observations [-]	See description in 3.4.2	See description in 3.4.2
Inflatable stopper condition [-]	Failed	Failed
Inflatable stopper remains pressurised [-]	No	No

Table 22 Results measurements 66 and 67

Measurement	66	67
Manufacturer inflatable stopper [-]	Kleiss	Kleiss
Medium [-]	Hydrogen	Hydrogen
Diameter [mm]	160	160
Length of pipe [m]	20	20
Flow rate [m^3_n/h]	n/a	n/a
Sound - LAFmax [dB]	ng .	82.6
Max. concentration at outlet opening [%]	72	85
Max. temperature at inflatable stopper [°C]	23	15
Ambient temperature [°C]	9	11
Wind speed [m/s]	7	7
Observations [-]	See description in 3.4.2	See description in 3.4.2
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

Table 23 Results measurements 68 to 71

Measurement	68	69	70	71
Manufacturer inflatable stopper [-]	IPCO + 2nd lance	IPCO + 2nd lance	Kleiss + 2nd lance	Kleiss + 2nd lance
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	160	160	160	160
Length of pipe [m]	20	20	20	20
Flow rate [m^3_n/h]	n/a	n/a	n/a	n/a
Sound - LAFmax [dB]	130.9	134.9	134.2	134.5
Max. concentration at outlet opening [%]	73	72	90	46
Max. temperature at inflatable stopper [°C]	191	23	45	178
Ambient temperature [°C]	9	9	9	9
Wind speed [m/s]	8	8	9	9
Observations [-]	See description in 3.4.2	See description in 3.4.2	See description in 3.4.2	See description in 3.4.2
Inflatable stopper condition [-]	Intact	Outer stopper failed - tear in stopper of inner lance	Outer stopper failed - uninflated inner stopper intact	Outer stopper failed - uninflated inner stopper intact
Inflatable stopper remains pressurised [-]	Yes	Stopper in lance yes, outer stopper no	stopper in lance yes, outer stopper no	Yes, both stoppers

Table 24 Results measurements 72 to 75

Measurement	72	73	74	75
Manufacturer inflatable stopper [-]	Kleiss	Kleiss	IPCO	IPCO
Medium [-]	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	110	110	110	110
Length of pipe [m]	20	20	20	20
Flow rate [$m^3{}_n$/h]	0.6	0.6	0.6	0.6
Sound - LAFmax [dB]	130.7	130.2	131.8	130.8
Max. concentration at outlet opening [%]	6.5	6.3	4.9	6.7
Max. temperature at inflatable stopper [°C]	16	13	20	10
Ambient temperature [°C]	6	7	7	0
Wind speed [m/s]	4	2	3	5
Observations [-]	Ignition with considerable force.	Ignition with considerable force.	Ignition with considerable force.	Ignition with considerable force.
Inflatable stopper condition [-]	Both remain intact	Both remain intact	Both remain intact	Both remain intact
Inflatable stopper remains pressurised [-]	Yes, both	Yes, both	Yes, both	Yes, both

Table 25 Results measurement 76

Measurement	76
Manufacturer inflatable stopper [-]	IPCO
Medium [-]	Hydrogen
Diameter [mm]	110
Length of pipe [m]	20
Flow rate [$m^3{}_n$/h]	n/a
Sound - LAFmax [dB]	n/a
Max. concentration at outlet opening [%]	n/a
Max. temperature at inflatable stopper [°C]	n/a
Ambient temperature [°C]	6
Wind speed [m/s]	5
Observations [-]	Measurement for the purpose of concentration determination.
Inflatable stopper condition [-]	n/a
Inflatable stopper remains pressurised [-]	n/a

Table 26 Results measurements 77 to 79

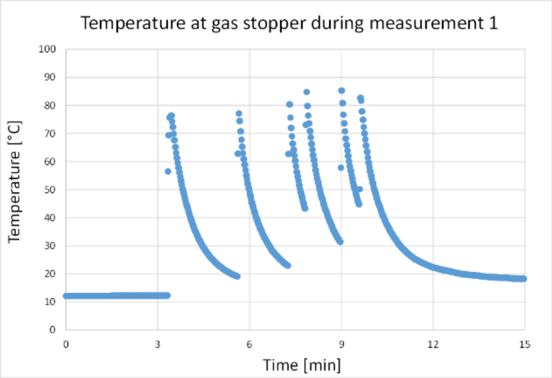
Measurement	77	78	79
Manufacturer inflatable stopper [-]	IPCO	IPCO	IPCO
Medium [-]	Hydrogen	Hydrogen	Hydrogen
Diameter [mm]	110	110	110
Length of pipe [m]	20	20	20
Flow rate [$m^3{}_n$/h]	n/a	n/a	n/a
Sound - LAFmax [dB]	75	ng .	77.7
Max. concentration at outlet opening [%]	86	52	81
Max. temperature at inflatable stopper [°C]	No ignition detected on site, data not saved		
Ambient temperature [°C]	9	11	11
Wind speed [m/s]	3	3	3
Observations [-]	See description in 3.4.2	See description in 3.4.2	See description in 3.4.2
Inflatable stopper condition [-]	Intact	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes	Yes

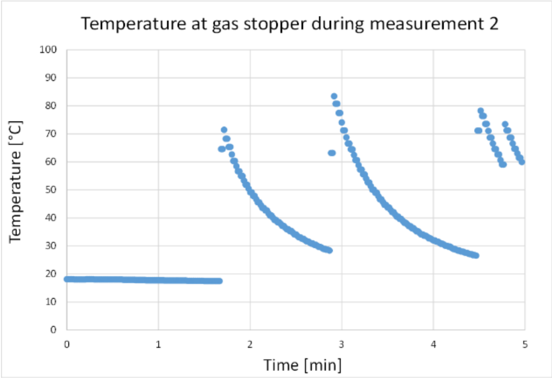
Table 27 Results measurements 80 and 81

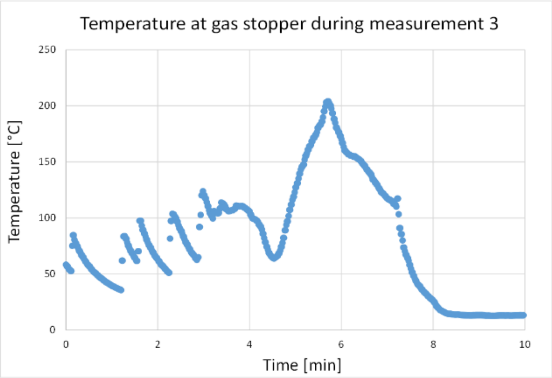
Measurement	80	81
Manufacturer inflatable stopper [-]	IPCO	IPCO
Medium [-]	Hydrogen	Hydrogen
Diameter [mm]	110	110
Length of pipe [m]	20	20
Flow rate [$m^3{}_n$/h]	n/a	n/a
Sound - LAFmax [dB]	49.5	90.8
Max. concentration at outlet opening [%]	77	67
Max. temperature at inflatable stopper [°C]	21	21
Ambient temperature [°C]	11	11
Wind speed [m/s]	3	3
Observations [-]	See description in 3.4.2	See description in 3.4.2
Inflatable stopper condition [-]	Intact	Intact
Inflatable stopper remains pressurised [-]	Yes	Yes

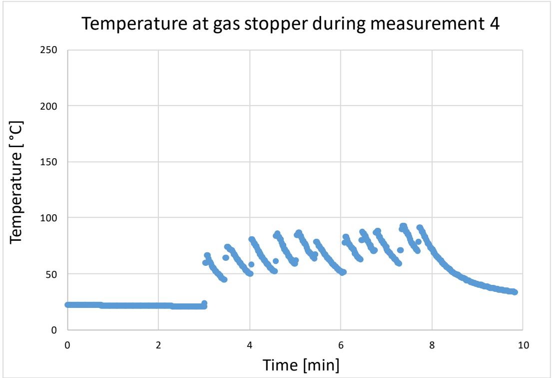
V. Temperature measurements ignition tests

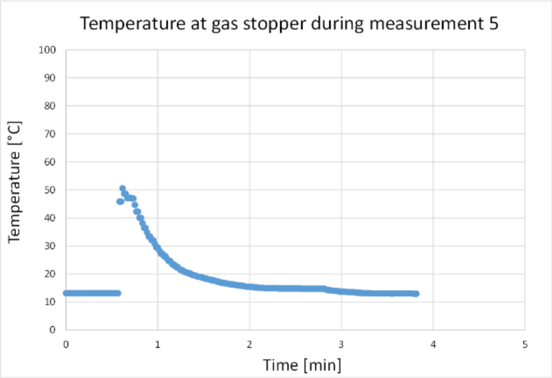
Where temperatures rise during the measurement, graphs are included per measurement.

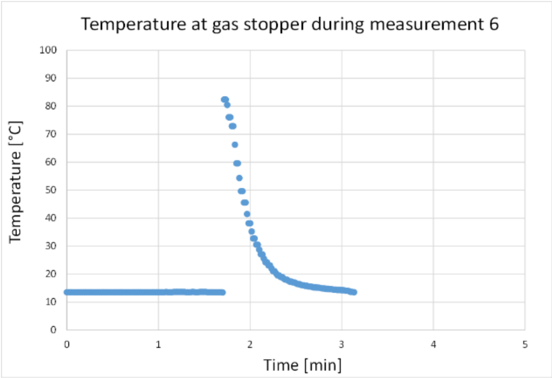


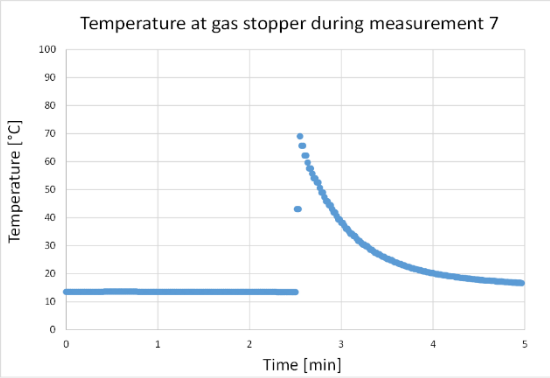


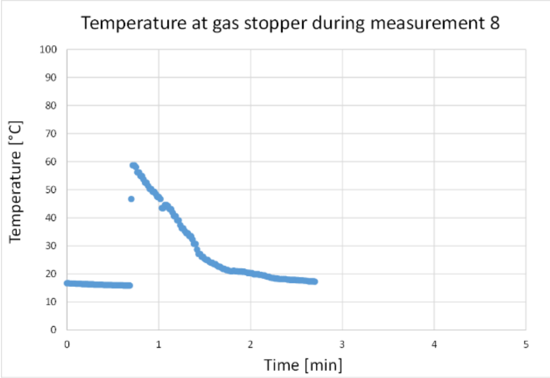


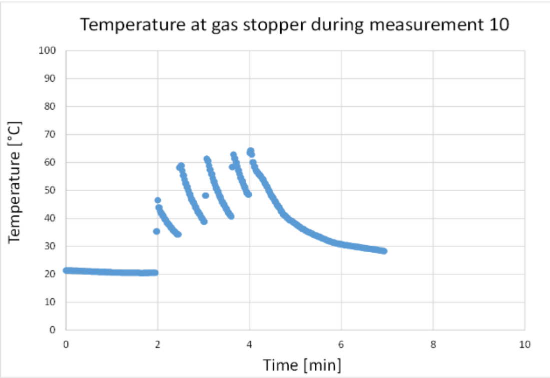


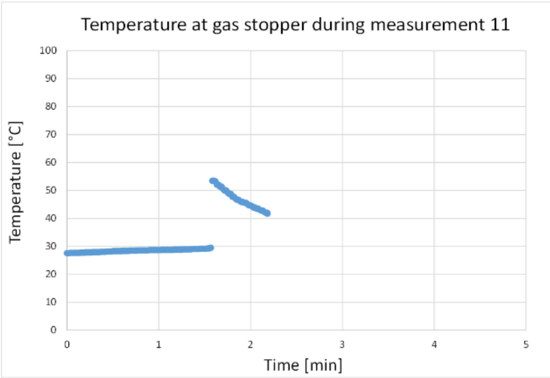


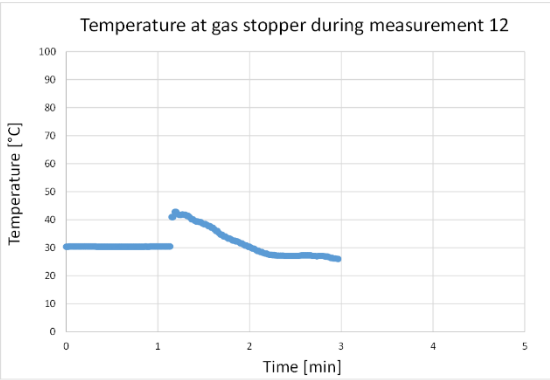


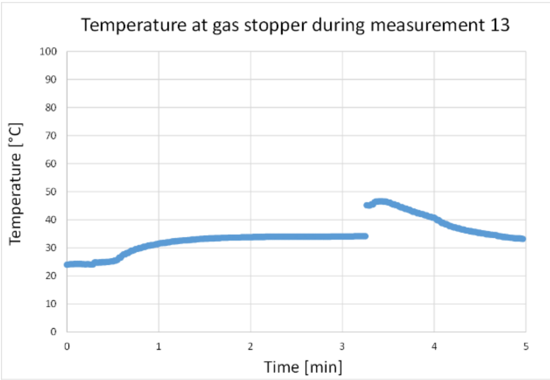

Temperature at gas stopper during measurement 7
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Time [min]

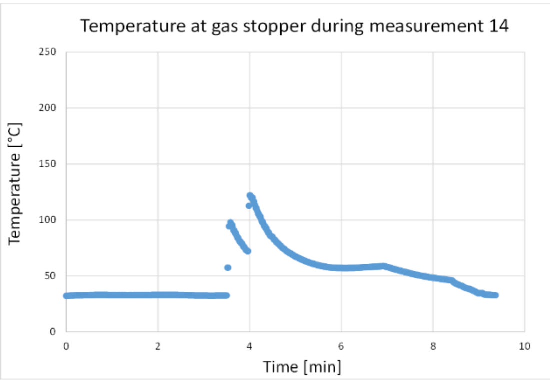

Temperature at gas stopper during measurement 8
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Time [min]

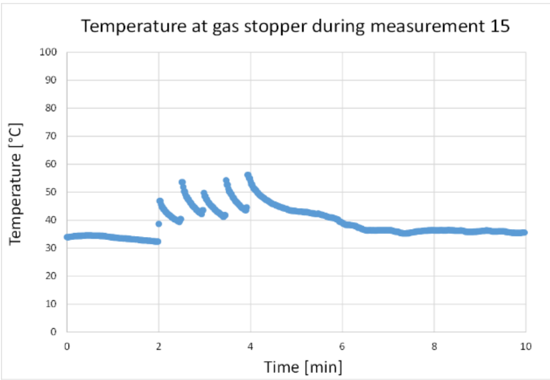

Temperature at gas stopper during measurement 10
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
Time [min]

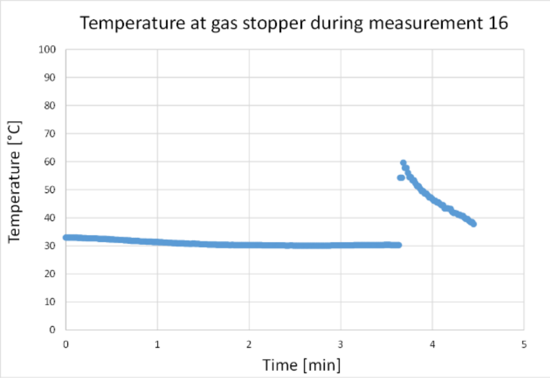

Temperature at gas stopper during measurement 11
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Time [min]

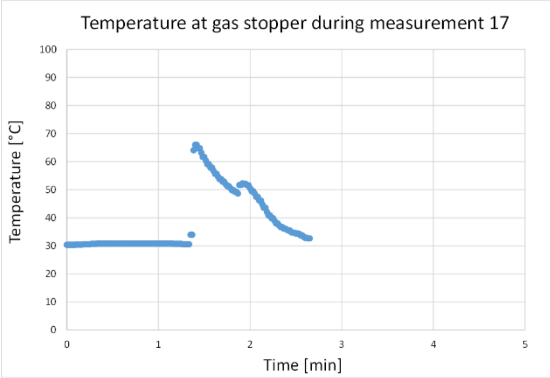

Temperature at gas stopper during measurement 12
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Time [min]

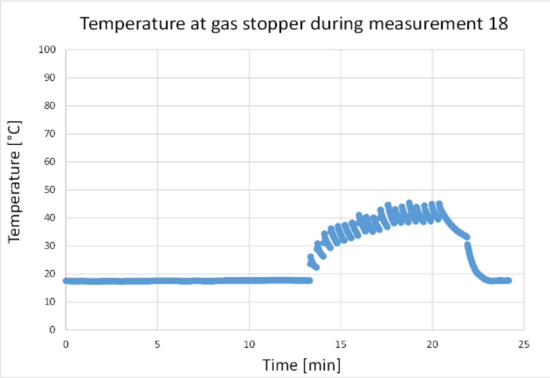

Temperature at gas stopper during measurement 13
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
Time [min]

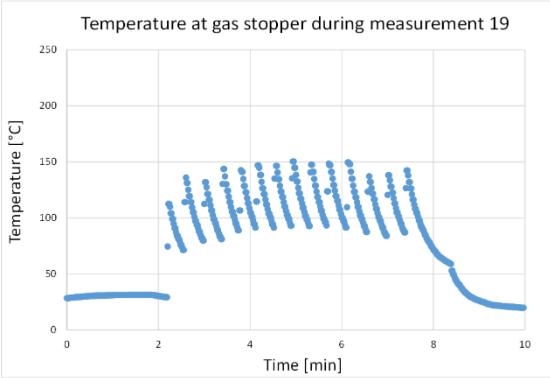

Temperature at gas stopper during measurement 14
Temperature [°C]
0
50
100
150
200
250
0
2
4
6
8
10
Time [min]

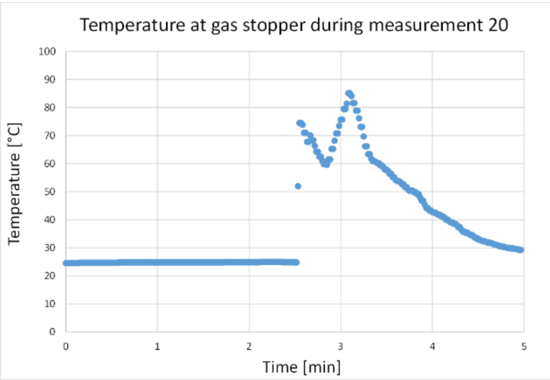

Temperature at gas stopper during measurement 15
Temperature [°C]
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
Time [min]

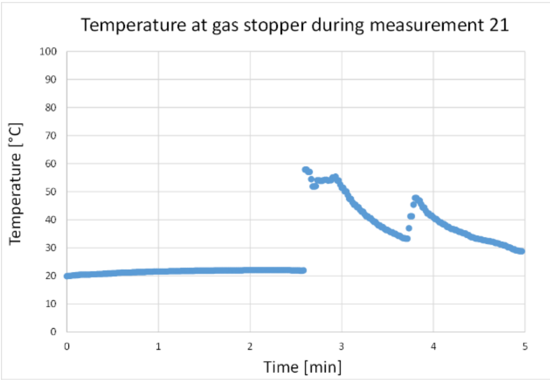

Temperature at gas stopper during measurement 16
Temperature [°C]
Time [min]
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5

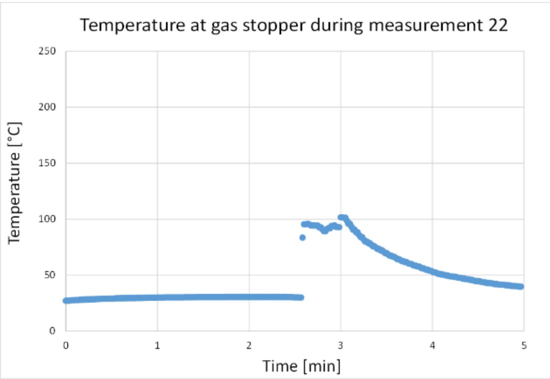

Temperature at gas stopper during measurement 17
Temperature [°C]
Time [min]
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5

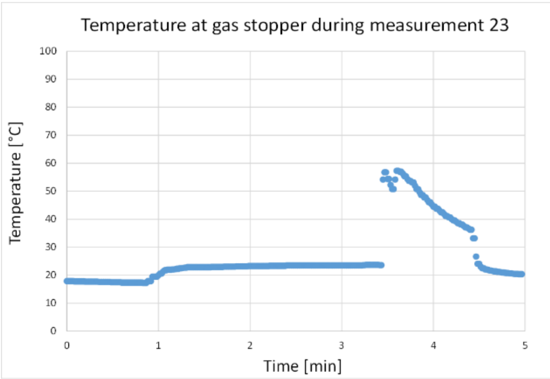

Temperature at gas stopper during measurement 18
Temperature [°C]
Time [min]
0 10 20 30 40 50 60 70 80 90 100
0 5 10 15 20 25

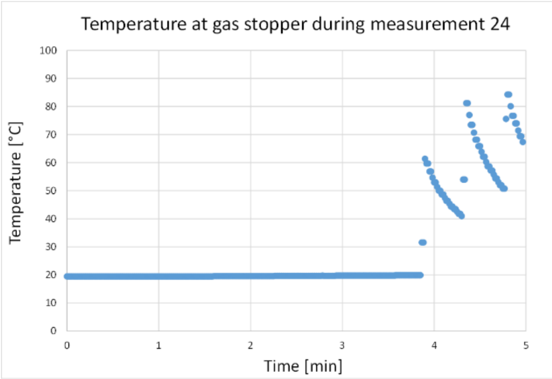

Temperature at gas stopper during measurement 19
Temperature [°C]
Time [min]
0 50 100 150 200 250
0 2 4 6 8 10

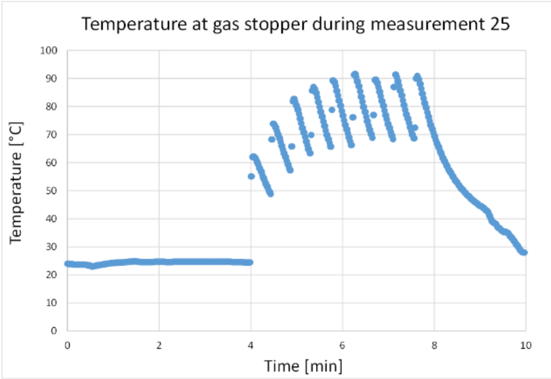

Temperature at gas stopper during measurement 20
Temperature [°C]
Time [min]
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5

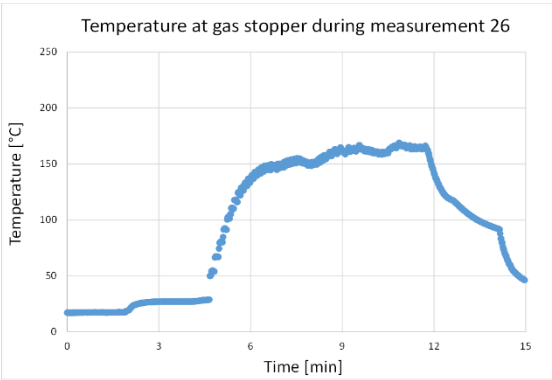

Temperature at gas stopper during measurement 21
Temperature [°C]
Time [min]
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5

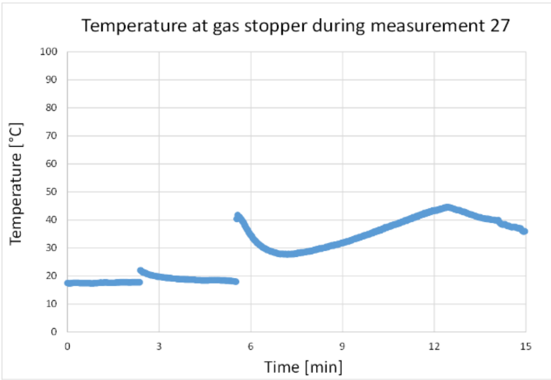

Temperature at gas stopper during measurement 22
Temperature [°C]
Time [min]
0 50 100 150 200 250
0 1 2 3 4 5

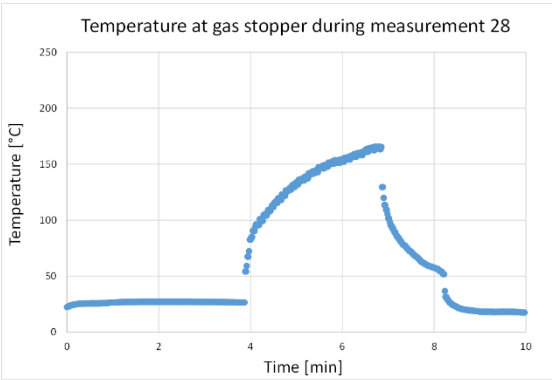

Temperature at gas stopper during measurement 23
Temperature [°C]
Time [min]
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5

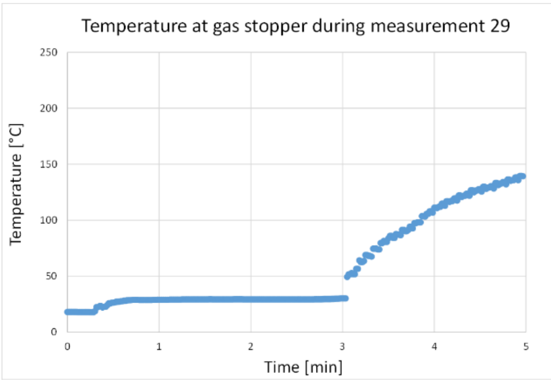

Temperature at gas stopper during measurement 24
Temperature [°C]
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5
Time [min]

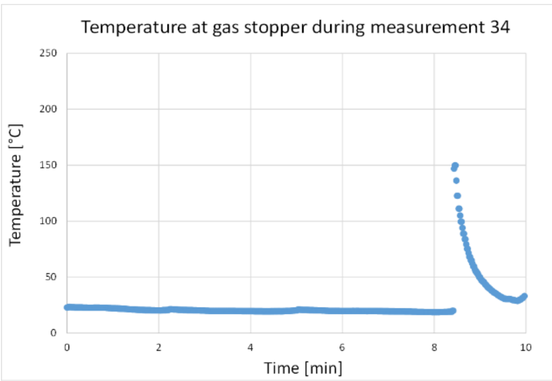

Temperature at gas stopper during measurement 25
Temperature [°C]
0 10 20 30 40 50 60 70 80 90 100
0 2 4 6 8 10
Time [min]

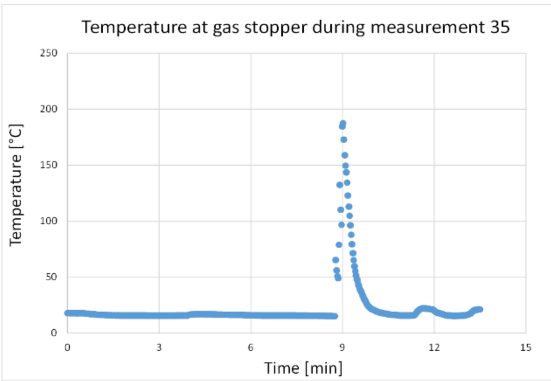

Temperature at gas stopper during measurement 26
Temperature [°C]
0 50 100 150 200 250
0 3 6 9 12 15
Time [min]

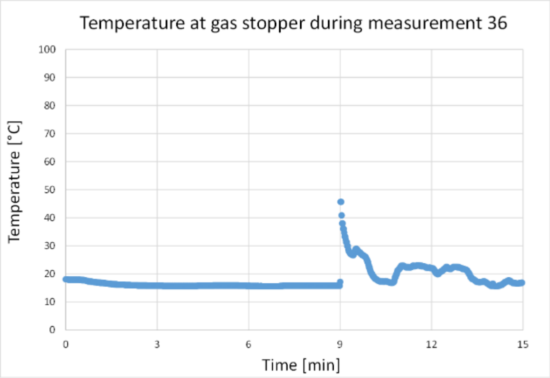

Temperature at gas stopper during measurement 27
Temperature [°C]
0 10 20 30 40 50 60 70 80 90 100
0 3 6 9 12 15
Time [min]

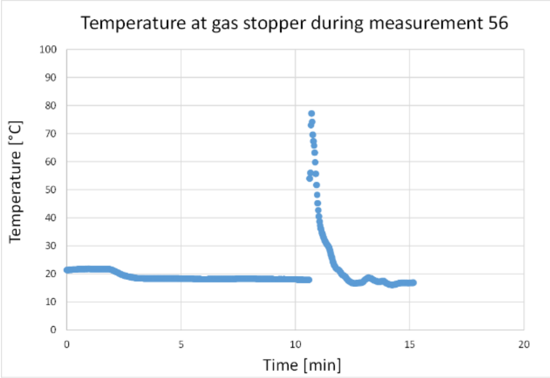

Temperature at gas stopper during measurement 28
Temperature [°C]
0 50 100 150 200 250
0 2 4 6 8 10
Time [min]

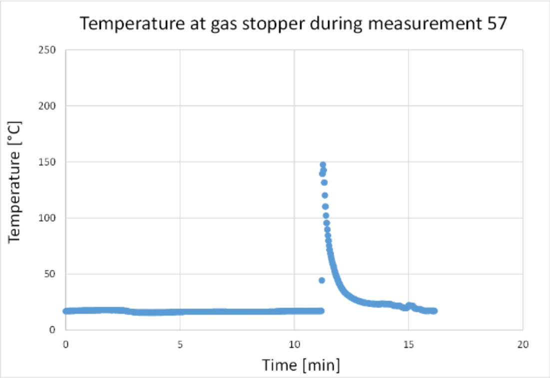

Temperature at gas stopper during measurement 29
Temperature [°C]
0 50 100 150 200 250
0 1 2 3 4 5
Time [min]

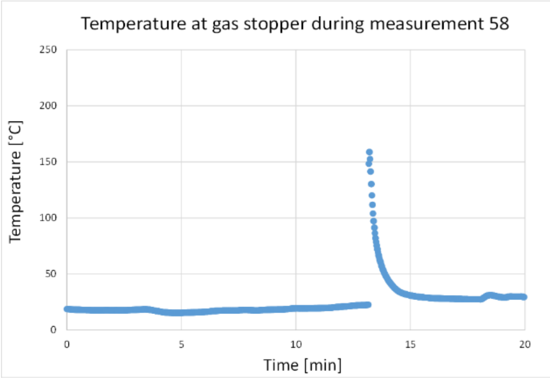

Temperature at gas stopper during measurement 34
Temperature [°C]
0 50 100 150 200 250
0 2 4 6 8 10
Time [min]

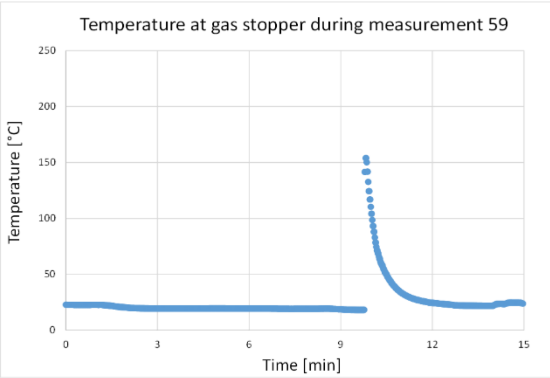

Temperature at gas stopper during measurement 35
Temperature [°C]
0 50 100 150 200 250
0 3 6 9 12 15
Time [min]

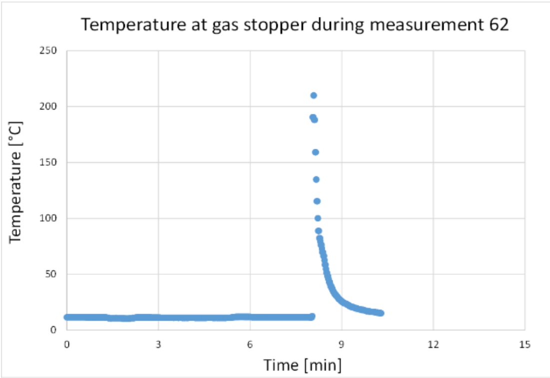

Temperature at gas stopper during measurement 36
Temperature [°C]
Time [min]

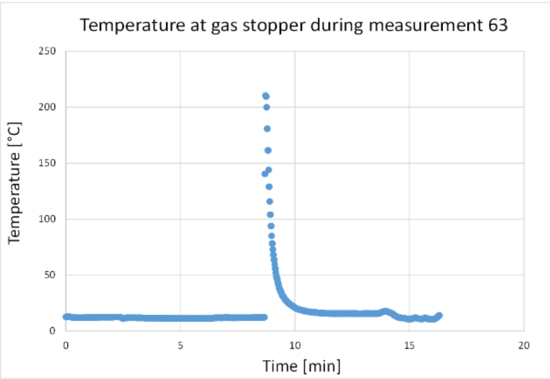

Temperature at gas stopper during measurement 56
Temperature [°C]
Time [min]

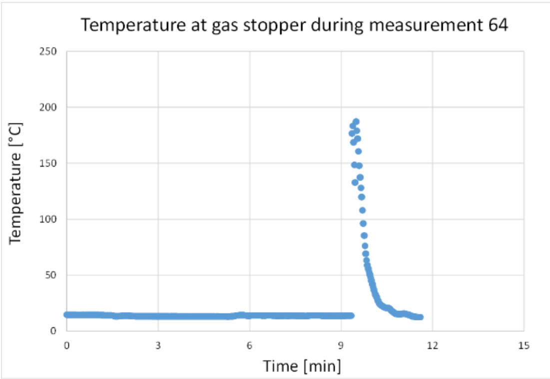

Temperature at gas stopper during measurement 57
Temperature [°C]
Time [min]

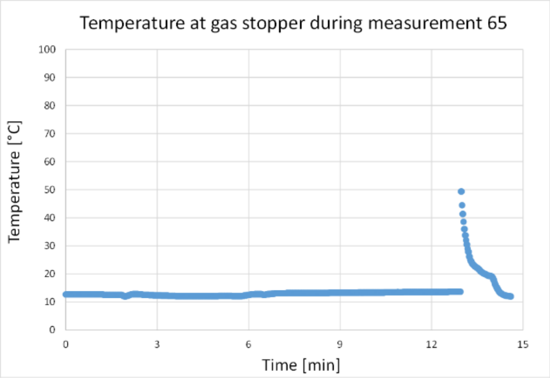

Temperature at gas stopper during measurement 58
Temperature [°C]
Time [min]

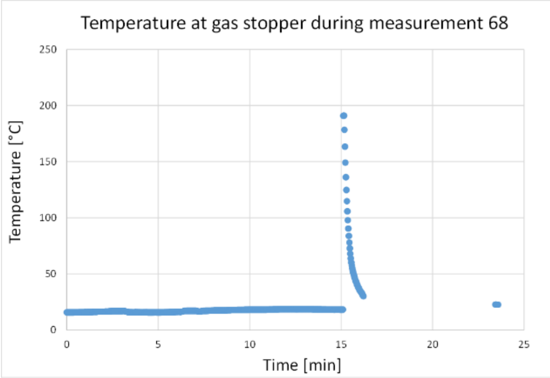

Temperature at gas stopper during measurement 59
Temperature [°C]
Time [min]

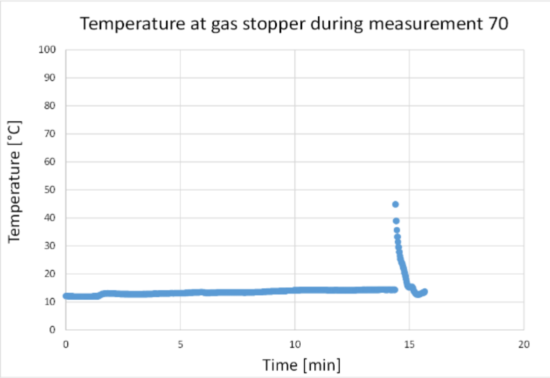

Temperature at gas stopper during measurement 62
Temperature [°C]
Time [min]

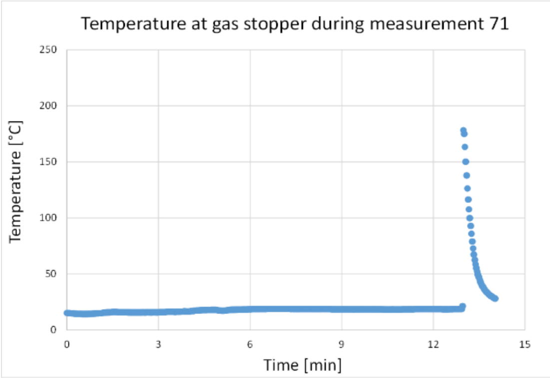

Temperature at gas stopper during measurement 63
Temperature [°C]
Time [min]


Temperature at gas stopper during measurement 64
Temperature [°C]
Time [min]


Temperature at gas stopper during measurement 65
Temperature [°C]
Time [min]


Temperature at gas stopper during measurement 68
Temperature [°C]
Time [min]


Temperature at gas stopper during measurement 70
Temperature [°C]
Time [min]

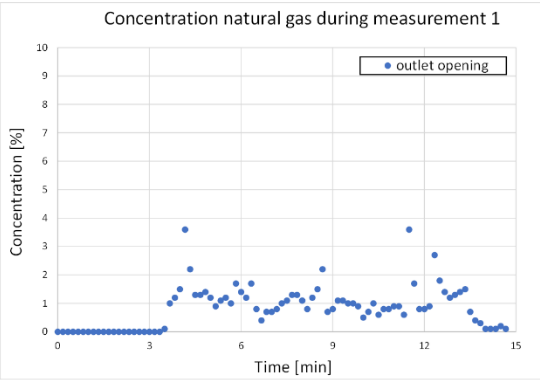

Temperature at gas stopper during measurement 71
Temperature [°C]
Time [min]

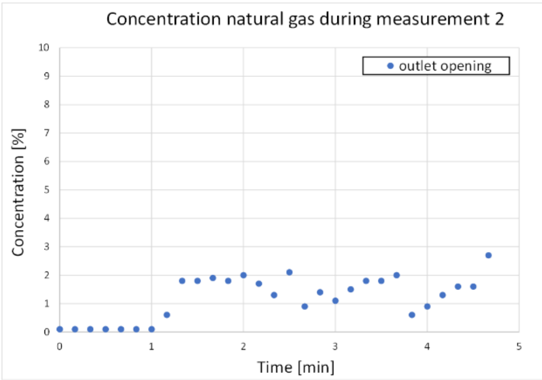
VI. Concentration measurements ignition tests

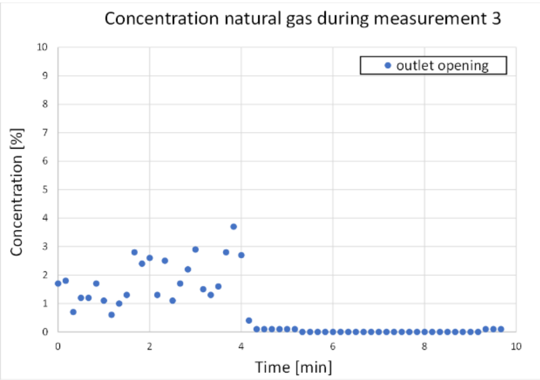
In this appendix, depending on the type of measurement, the results of the concentration measurements;

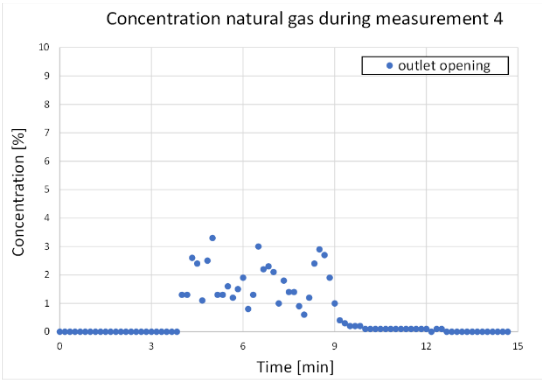
- near the outlet opening;
- 0.5 metres below the edge of the work pit (left and right);
- or at a specific point in the pipe with a length of 20 meters.

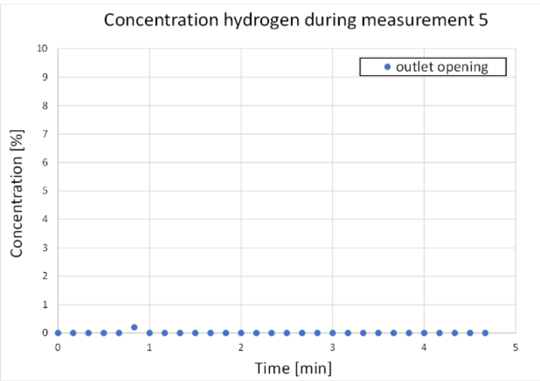
Note: the natural gas and hydrogen detectors take a measurement every 10 seconds. Because of this and because of the length of the suction line, it is possible that a flammable mixture is created at the outlet opening, while this is not apparent from the graphs below.

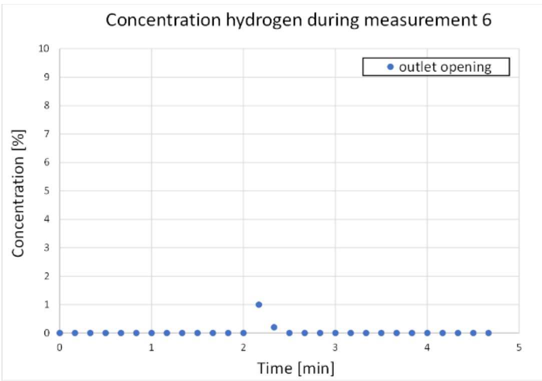


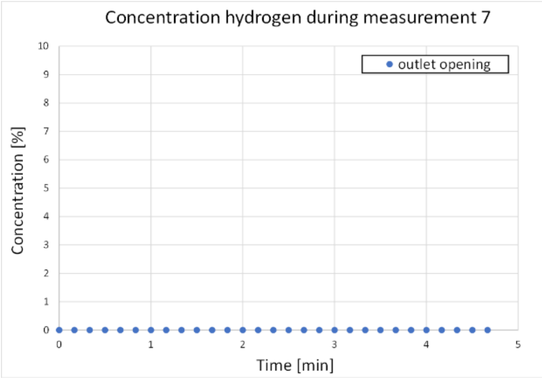


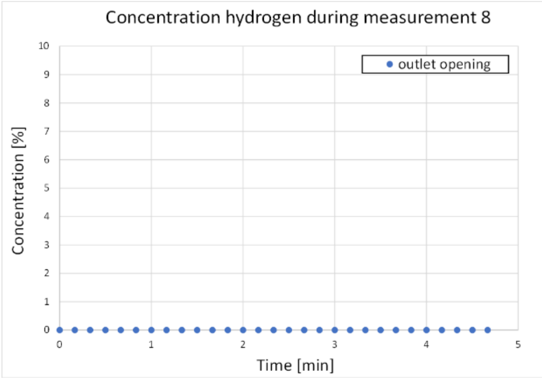


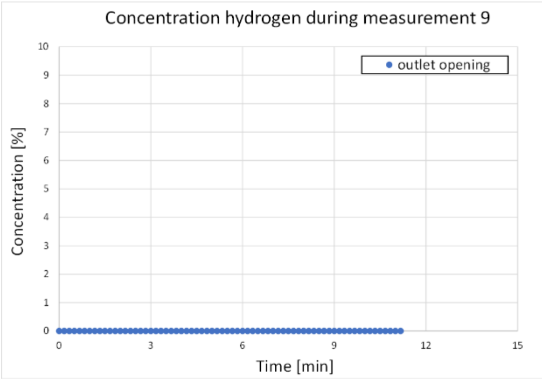


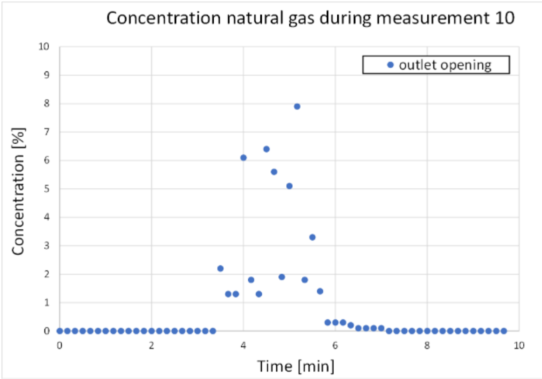


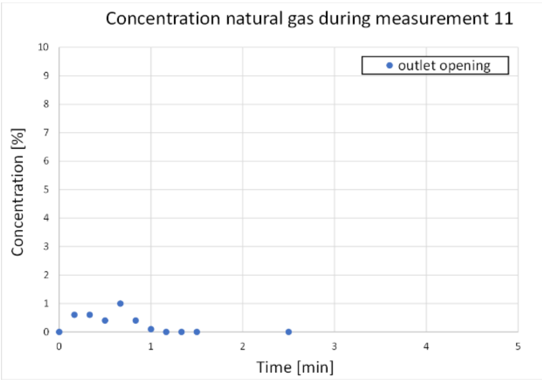


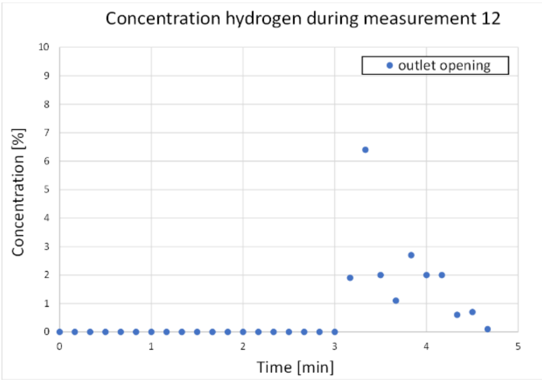

Concentration hydrogen during measurement 7
outlet opening
Concentration [%]
Time [min]

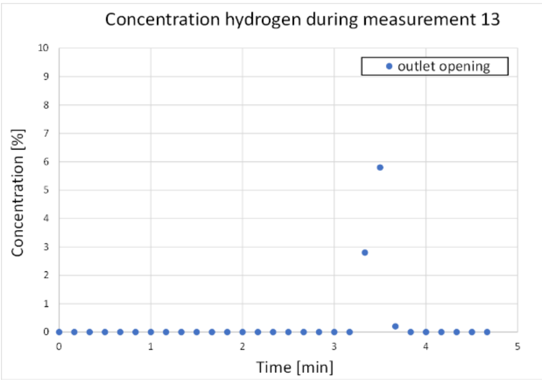

Concentration hydrogen during measurement 8
outlet opening
Concentration [%]
Time [min]

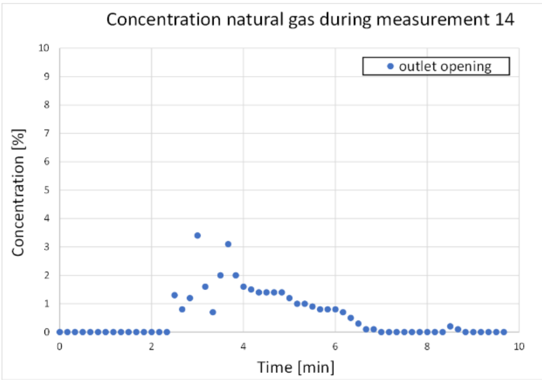

Concentration hydrogen during measurement 9
outlet opening
Concentration [%]
Time [min]

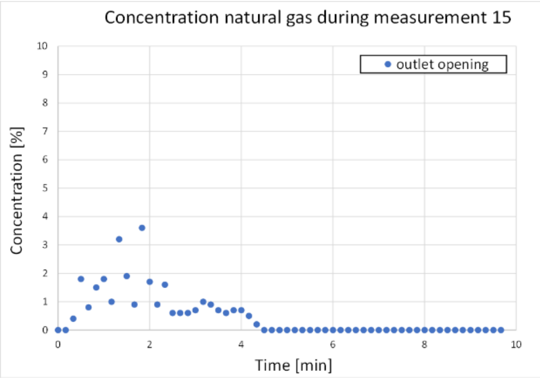

Concentration natural gas during measurement 10
outlet opening
Concentration [%]
Time [min]

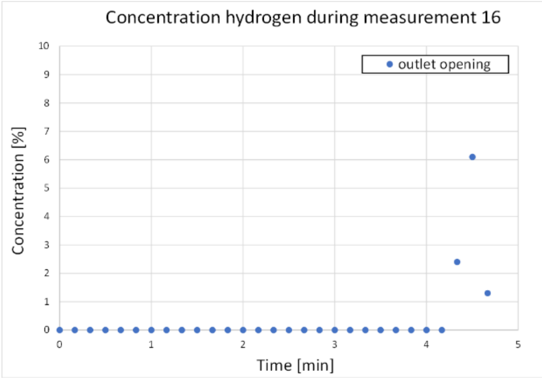

Concentration natural gas during measurement 11
outlet opening
Concentration [%]
Time [min]

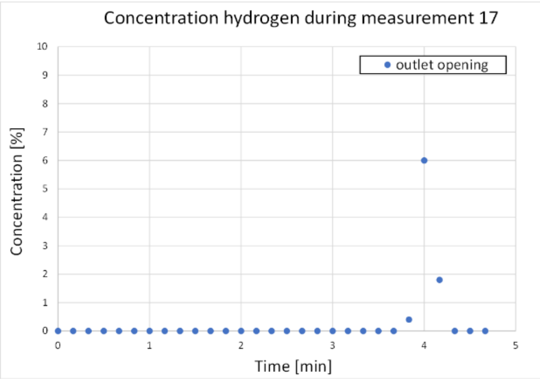

Concentration hydrogen during measurement 12
outlet opening
Concentration [%]
Time [min]

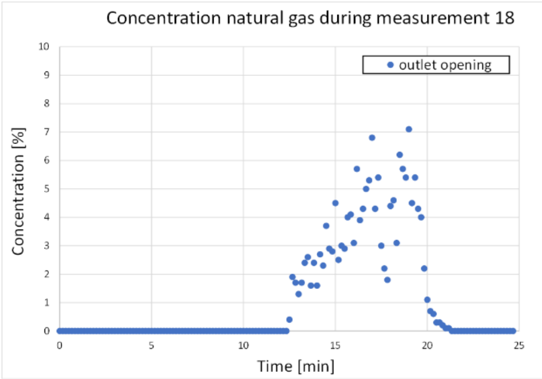

Concentration hydrogen during measurement 13
outlet opening
Concentration [%]
Time [min]

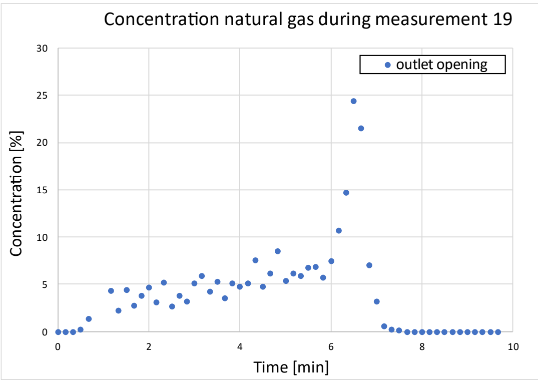

Concentration natural gas during measurement 14
outlet opening
Concentration [%]
Time [min]

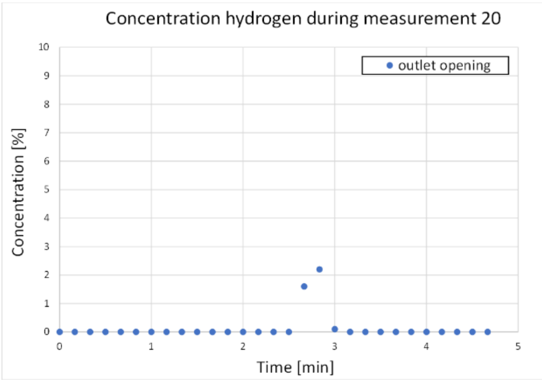

Concentration natural gas during measurement 15
outlet opening
Concentration [%]
Time [min]

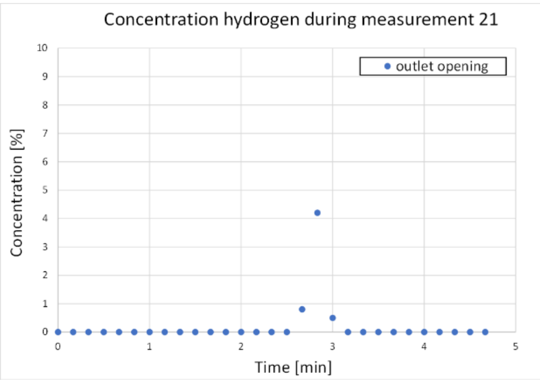

Concentration hydrogen during measurement 16
outlet opening
Concentration [%]
Time [min]

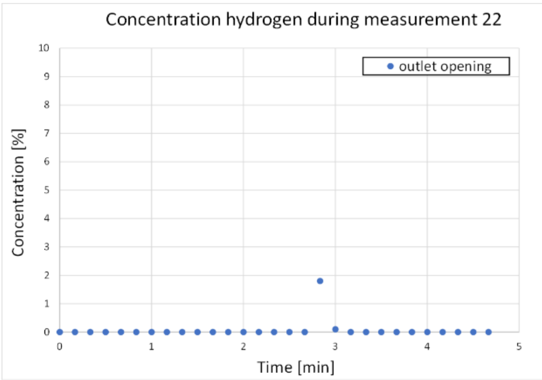

Concentration hydrogen during measurement 17
outlet opening
Concentration [%]
Time [min]

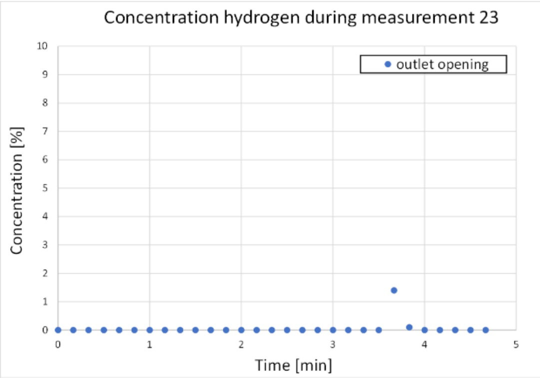

Concentration natural gas during measurement 18
outlet opening
Concentration [%]
Time [min]

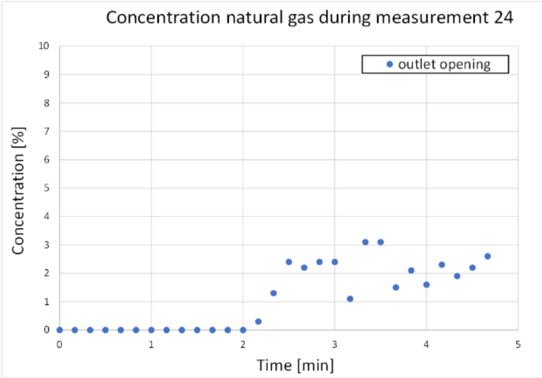

Concentration natural gas during measurement 19
outlet opening
Concentration [%]
Time [min]

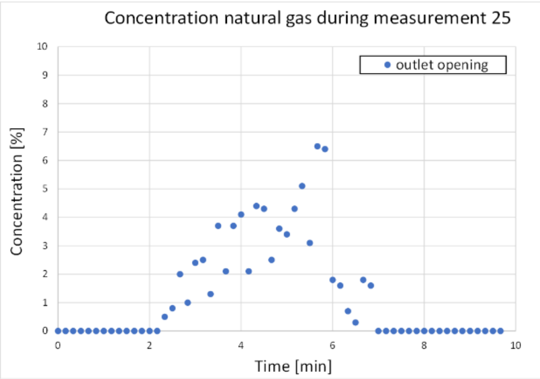

Concentration hydrogen during measurement 20
outlet opening
Concentration [%]
Time [min]

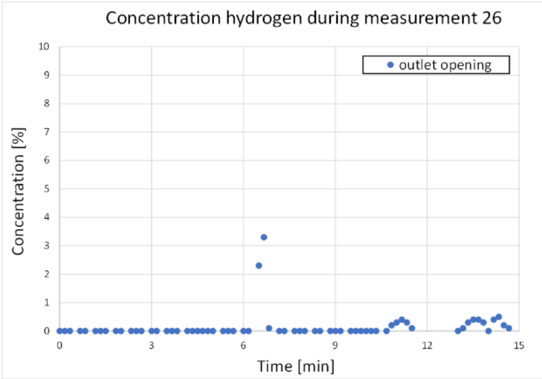

Concentration hydrogen during measurement 21
outlet opening
Concentration [%]
Time [min]

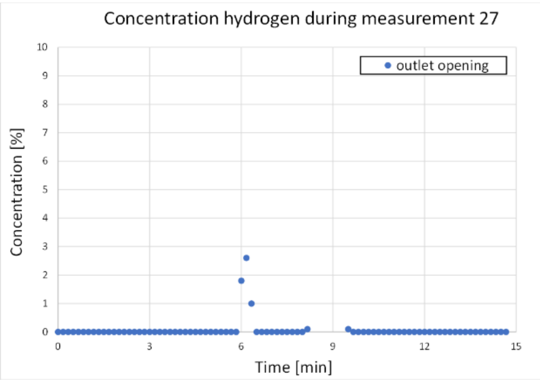

Concentration hydrogen during measurement 22
outlet opening
Concentration [%]
Time [min]

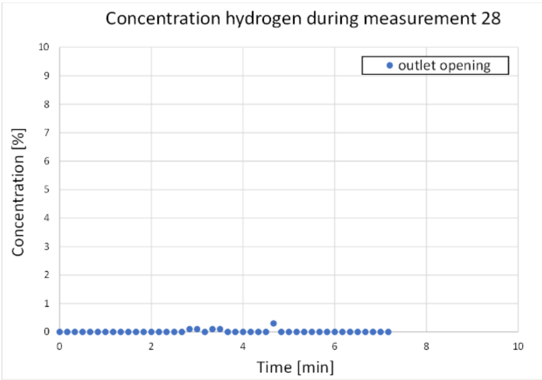

Concentration hydrogen during measurement 23
outlet opening
Concentration [%]
Time [min]

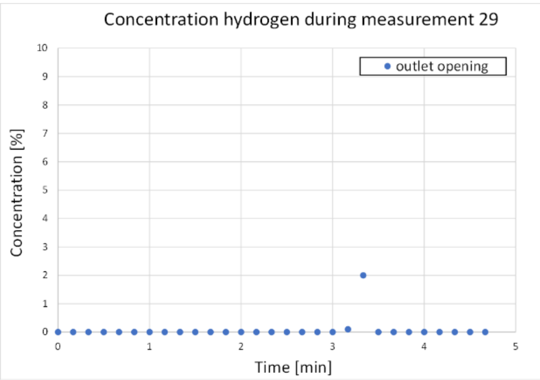

Concentration natural gas during measurement 24
outlet opening
Concentration [%]
Time [min]

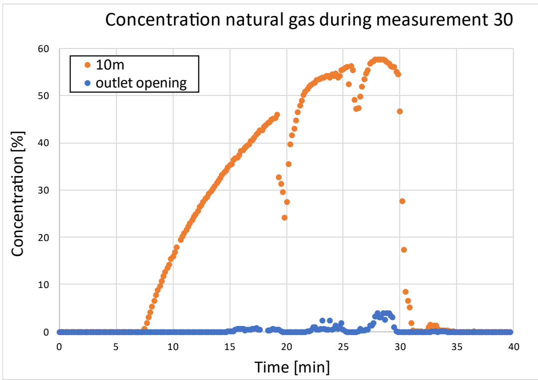

Concentration natural gas during measurement 25
outlet opening
Concentration [%]
Time [min]

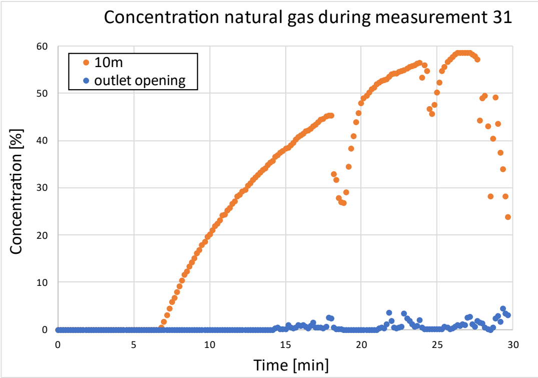

Concentration hydrogen during measurement 26
outlet opening
Concentration [%]
Time [min]

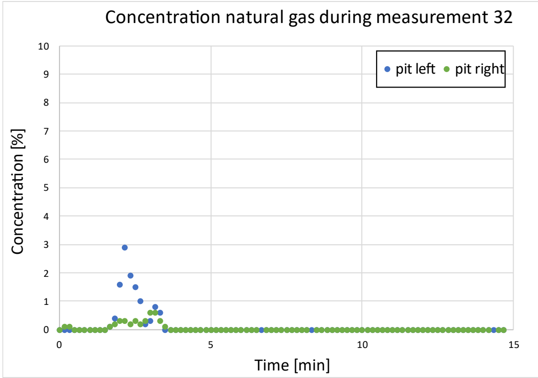

Concentration hydrogen during measurement 27
outlet opening
Concentration [%]
Time [min]

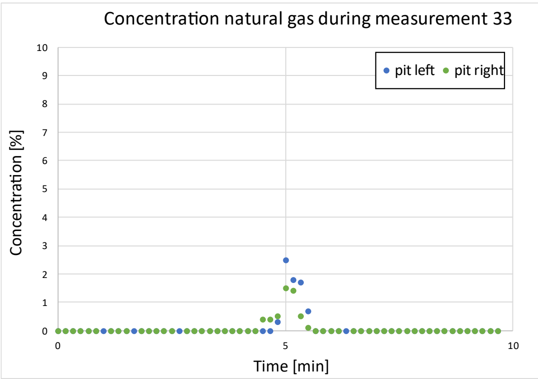

Concentration hydrogen during measurement 28
outlet opening
Concentration [%]
Time [min]

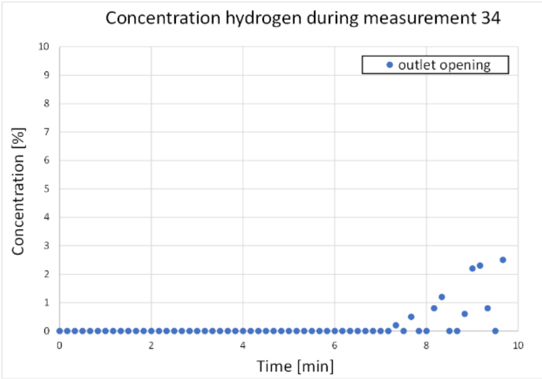

Concentration hydrogen during measurement 29
outlet opening
Concentration [%]
Time [min]

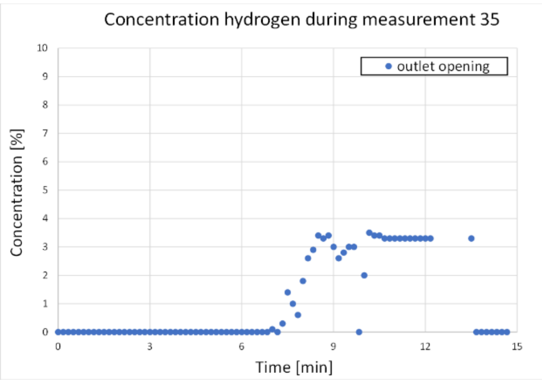

Concentration natural gas during measurement 30
10m
outlet opening
Concentration [%]
Time [min]

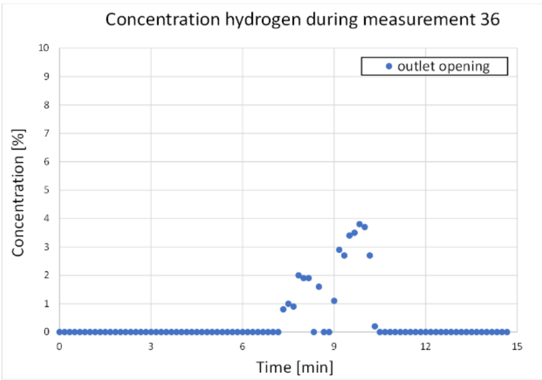

Concentration natural gas during measurement 31
10m
outlet opening
Concentration [%]
Time [min]

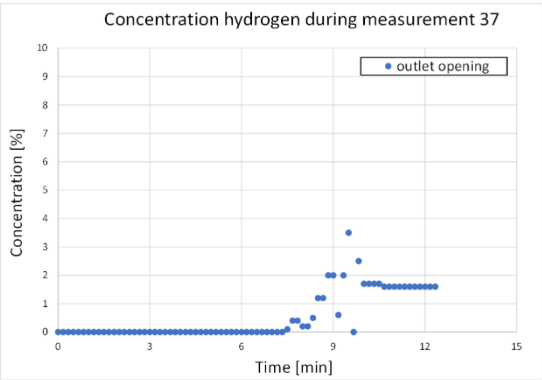

Concentration natural gas during measurement 32
pit left
pit right
Concentration [%]
Time [min]

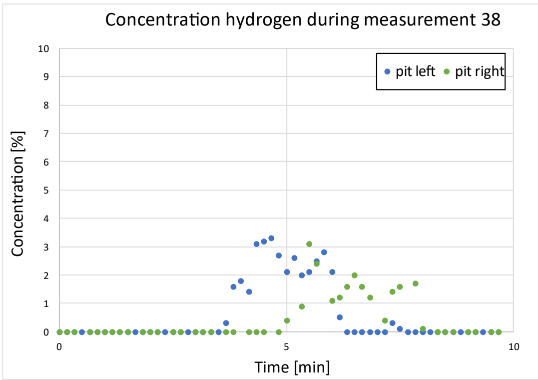

Concentration natural gas during measurement 33
pit left
pit right
Concentration [%]
Time [min]

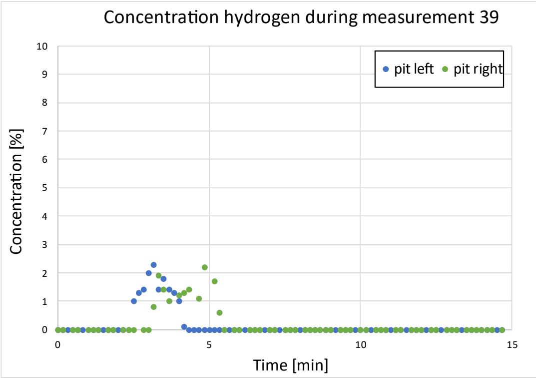

Concentration hydrogen during measurement 34
outlet opening
Concentration [%]
Time [min]

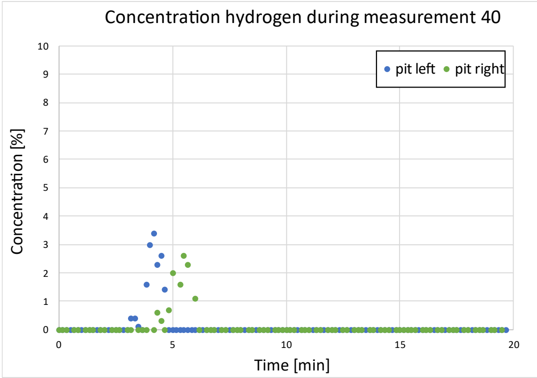

Concentration hydrogen during measurement 35
outlet opening
Concentration [%]
Time [min]

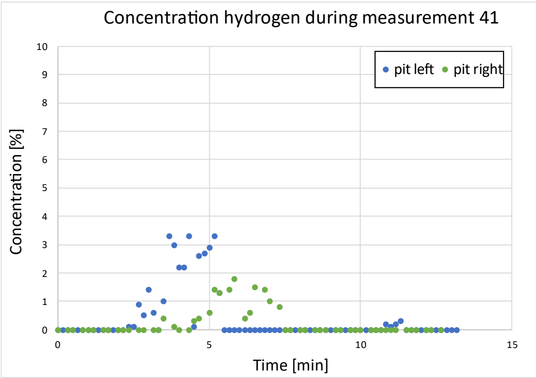

Concentration hydrogen during measurement 36
outlet opening
Concentration [%]
Time [min]

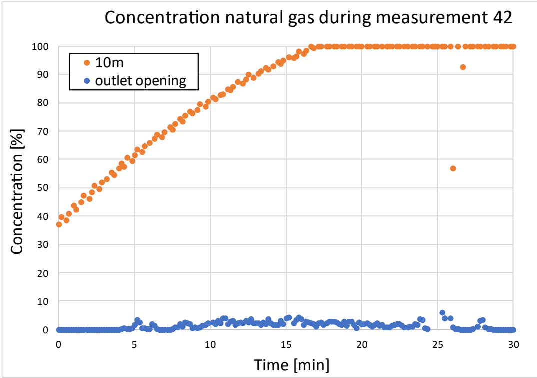

Concentration hydrogen during measurement 37
outlet opening
Concentration [%]
Time [min]

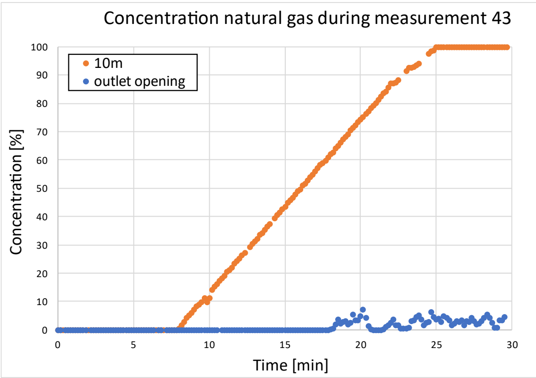

Concentration hydrogen during measurement 38
pit left
pit right
Concentration [%]
Time [min]

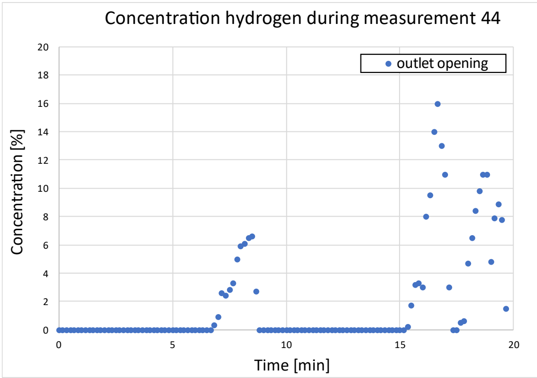

Concentration hydrogen during measurement 39
pit left
pit right
Concentration [%]
Time [min]

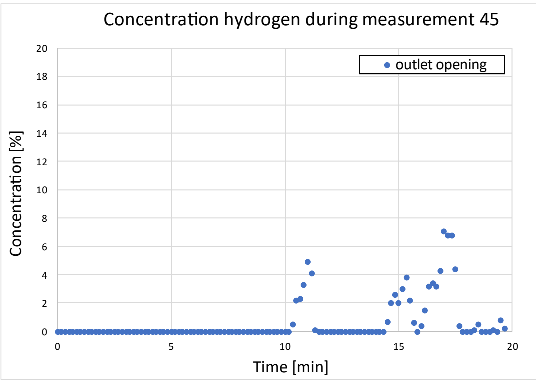

Concentration hydrogen during measurement 40
pit left
pit right
Concentration [%]
Time [min]

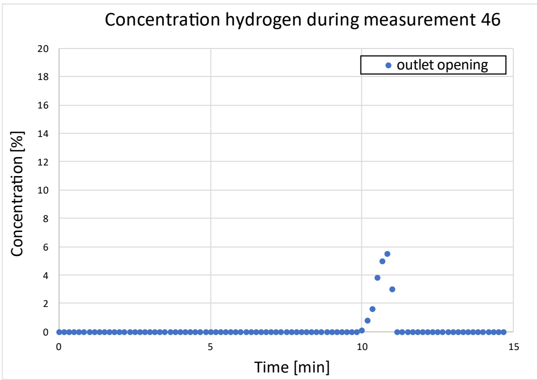

Concentration hydrogen during measurement 41
pit left
pit right
Concentration [%]
Time [min]

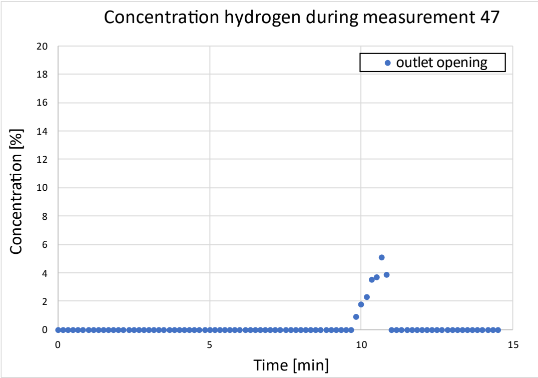

Concentration natural gas during measurement 42
10m
outlet opening
Concentration [%]
Time [min]

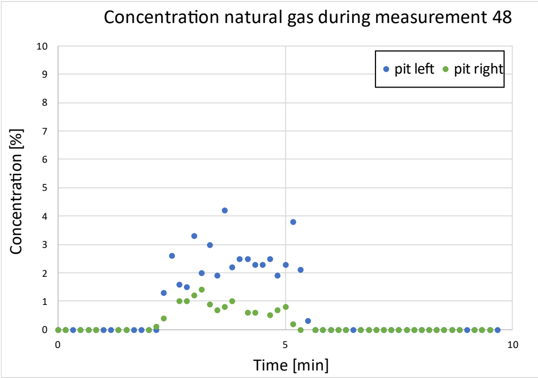

Concentration natural gas during measurement 43
10m
outlet opening
Concentration [%]
Time [min]

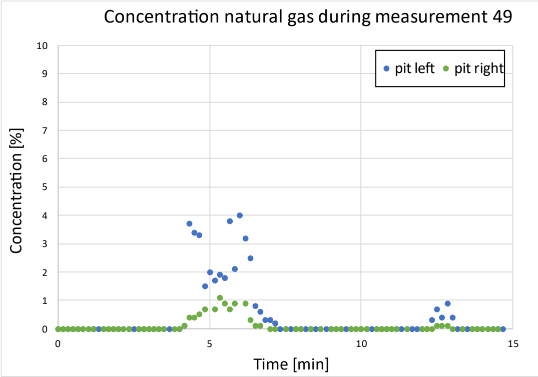

Concentration hydrogen during measurement 44
outlet opening
Concentration [%]
Time [min]

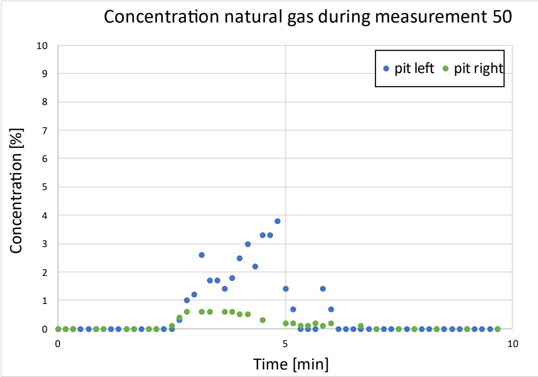

Concentration hydrogen during measurement 45
outlet opening
Concentration [%]
Time [min]

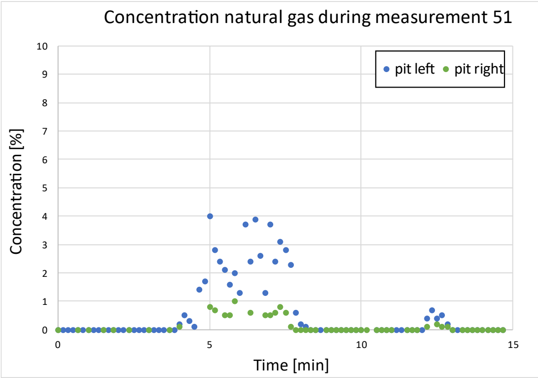

Concentration hydrogen during measurement 46
outlet opening
Concentration [%]
Time [min]

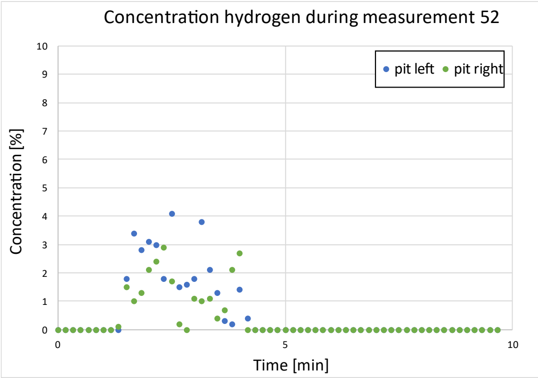

Concentration hydrogen during measurement 47
outlet opening
Concentration [%]
Time [min]

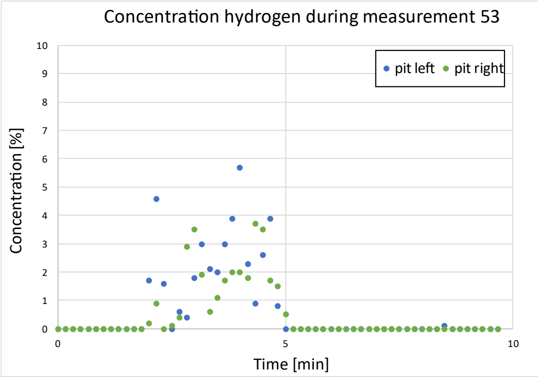

Concentration natural gas during measurement 48
pit left
pit right
Concentration [%]
Time [min]

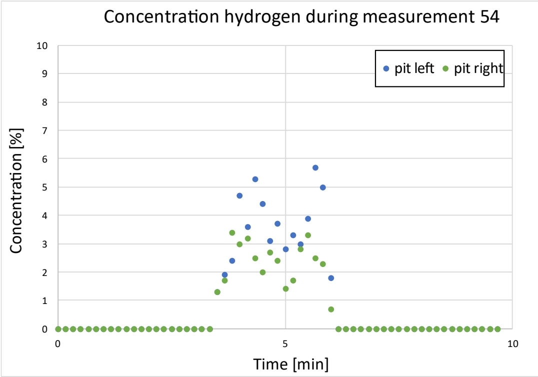

Concentration natural gas during measurement 49
pit left
pit right
Concentration [%]
Time [min]

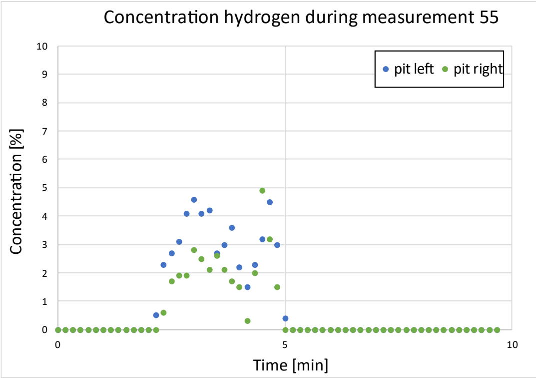

Concentration natural gas during measurement 50
pit left
pit right
Concentration [%]
Time [min]

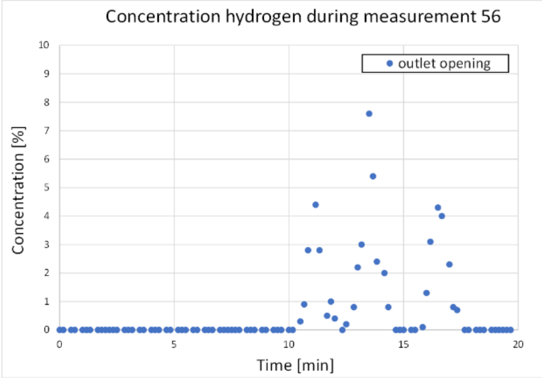

Concentration natural gas during measurement 51
pit left
pit right
Concentration [%]
Time [min]

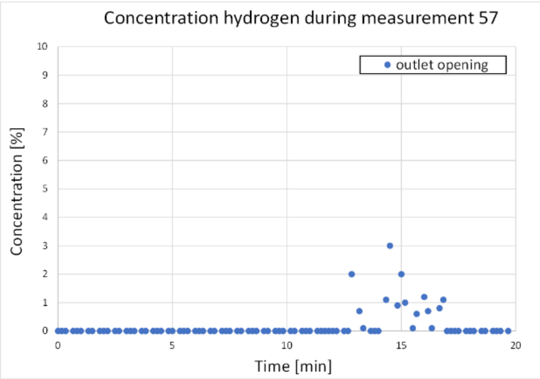

Concentration hydrogen during measurement 52
pit left
pit right
Concentration [%]
Time [min]

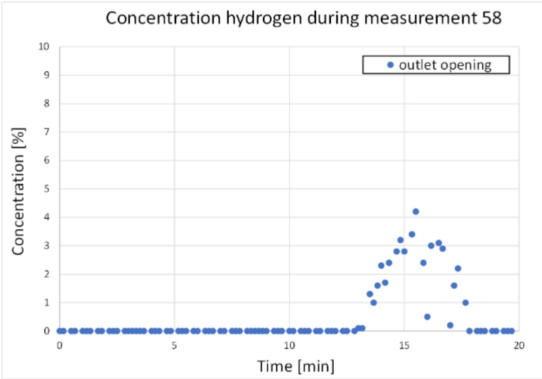

Concentration hydrogen during measurement 53
pit left
pit right
Concentration [%]
Time [min]

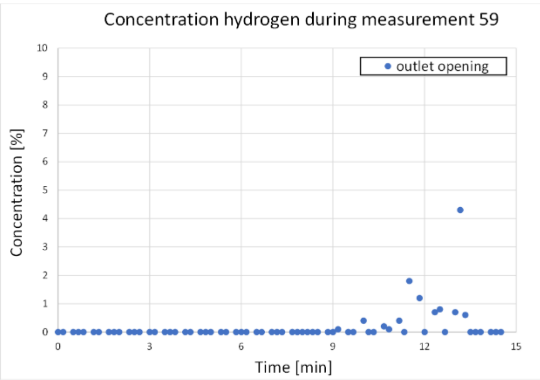

Concentration hydrogen during measurement 54
pit left
pit right
Concentration [%]
Time [min]

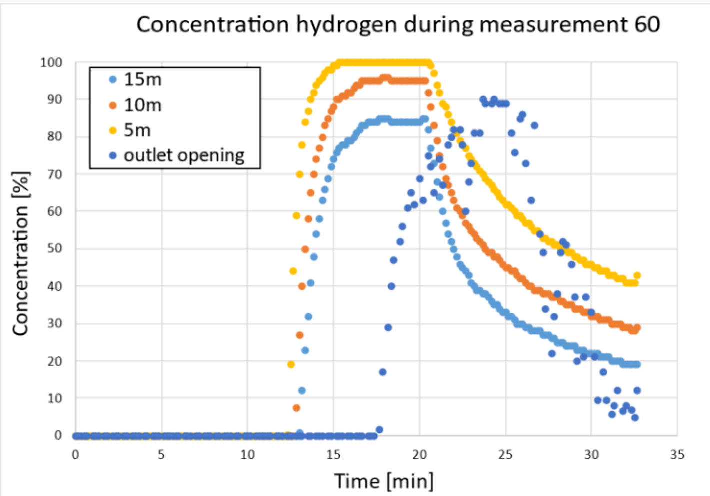

Concentration hydrogen during measurement 55
pit left
pit right
Concentration [%]
Time [min]

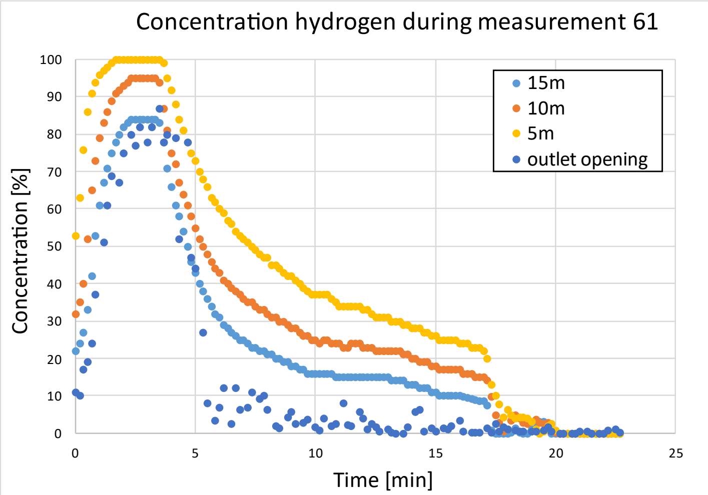

Concentration hydrogen during measurement 56
outlet opening
Concentration [%]
Time [min]

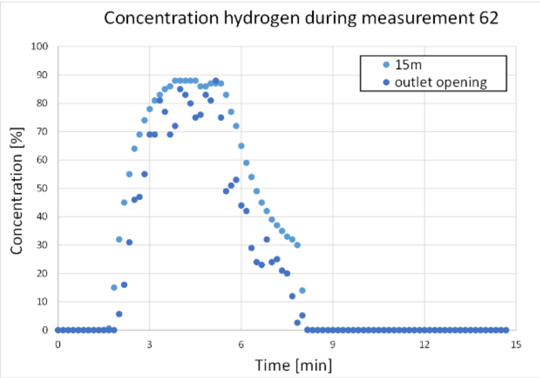

Concentration hydrogen during measurement 57
outlet opening
Concentration [%]
Time [min]

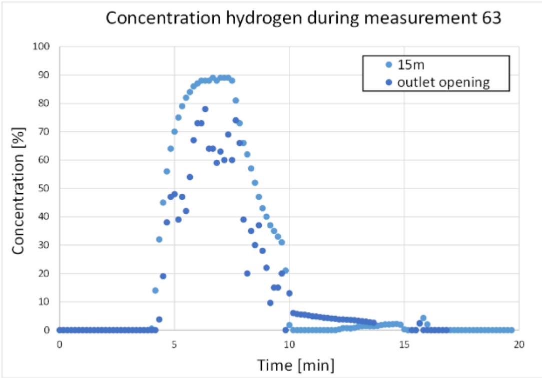

Concentration hydrogen during measurement 58
outlet opening
Concentration [%]
Time [min]

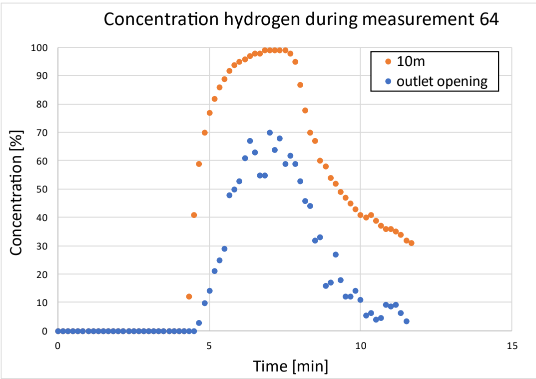

Concentration hydrogen during measurement 59
outlet opening
Concentration [%]
Time [min]

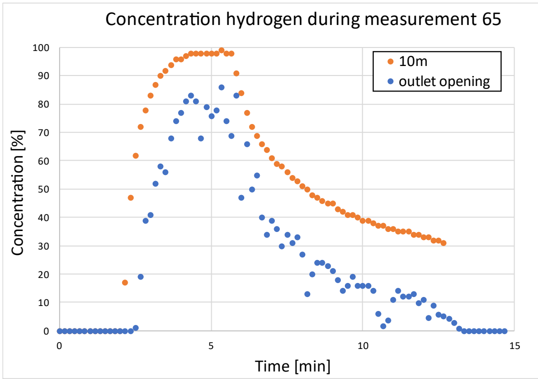

Concentration hydrogen during measurement 60
15m
10m
5m
outlet opening
Concentration [%]
Time [min]

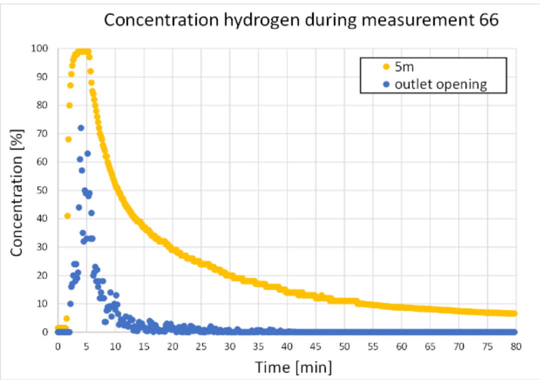

Concentration hydrogen during measurement 61
Concentration [%]
Time [min]
15m
10m
5m
outlet opening

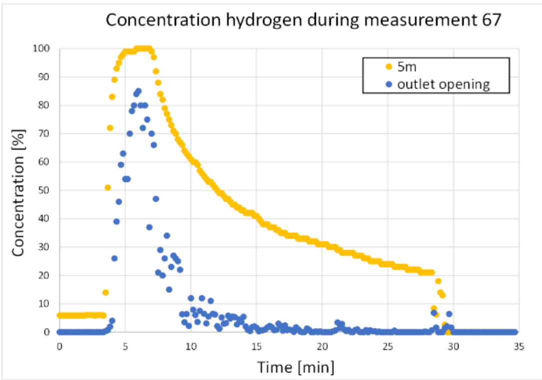

Concentration hydrogen during measurement 62
Concentration [%]
Time [min]
15m
outlet opening

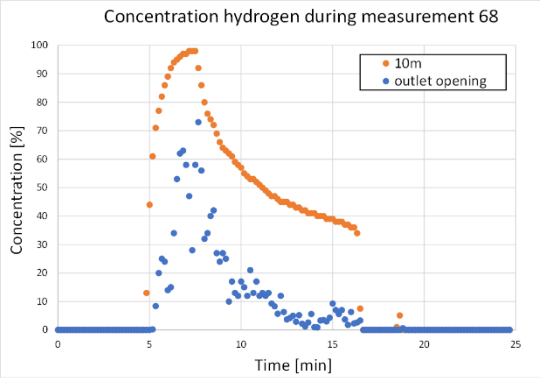

Concentration hydrogen during measurement 63
Concentration [%]
Time [min]
15m
outlet opening

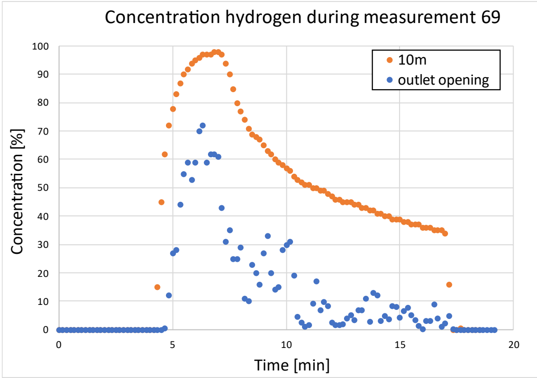

Concentration hydrogen during measurement 64
Concentration [%]
Time [min]
10m
outlet opening

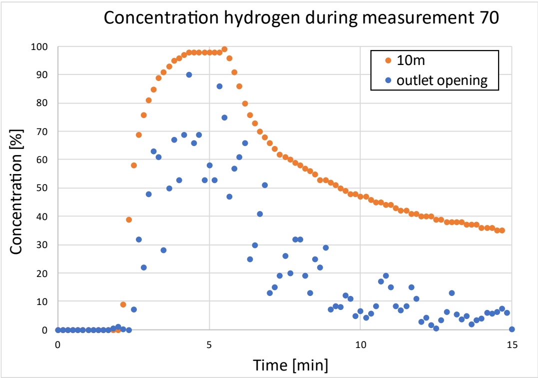

Concentration hydrogen during measurement 65
Concentration [%]
Time [min]
10m
outlet opening

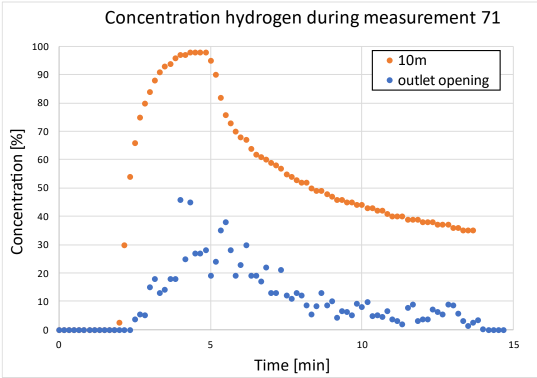

Concentration hydrogen during measurement 66
Concentration [%]
Time [min]
5m
outlet opening

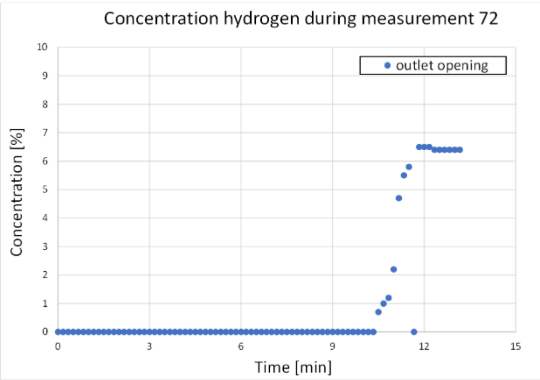

Concentration hydrogen during measurement 67
Concentration [%]
Time [min]
5m
outlet opening

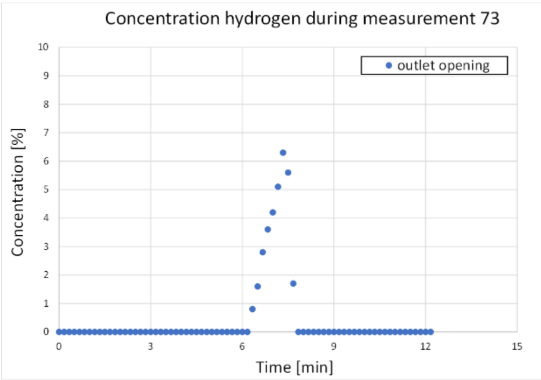

Concentration hydrogen during measurement 68
10m
outlet opening
Concentration [%]
Time [min]

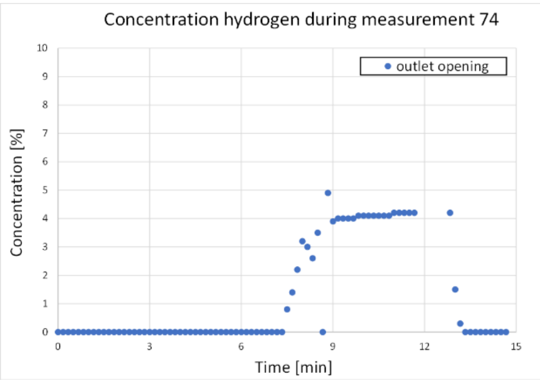

Concentration hydrogen during measurement 69
10m
outlet opening
Concentration [%]
Time [min]

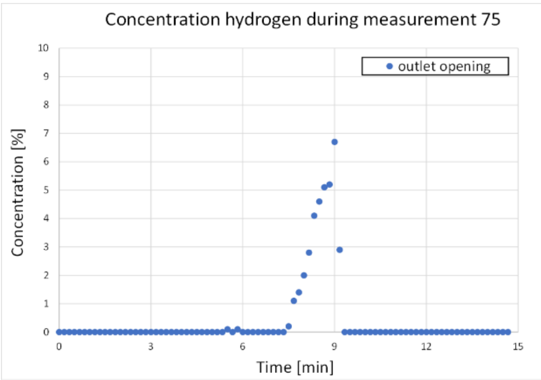

Concentration hydrogen during measurement 70
10m
outlet opening
Concentration [%]
Time [min]

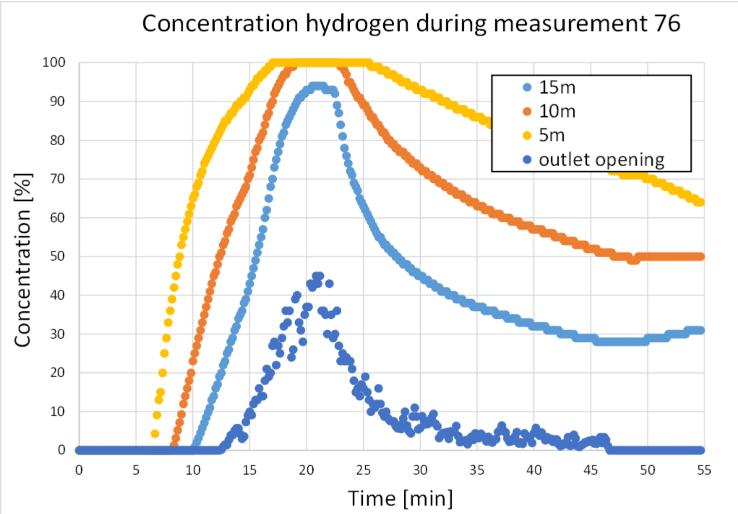

Concentration hydrogen during measurement 71
10m
outlet opening
Concentration [%]
Time [min]

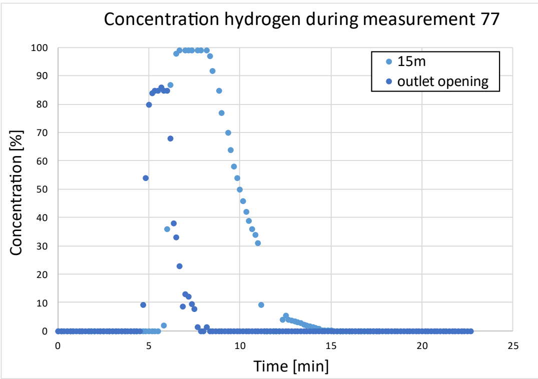

Concentration hydrogen during measurement 72
outlet opening
Concentration [%]
Time [min]

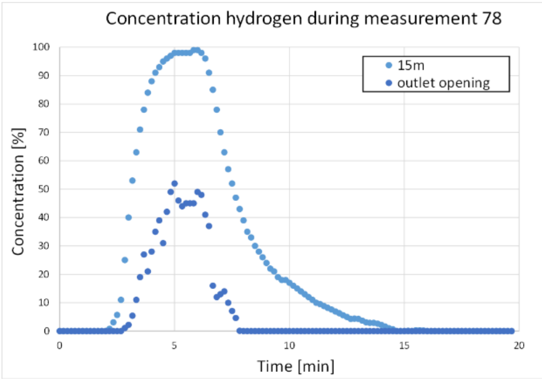

Concentration hydrogen during measurement 73
outlet opening
Concentration [%]
Time [min]

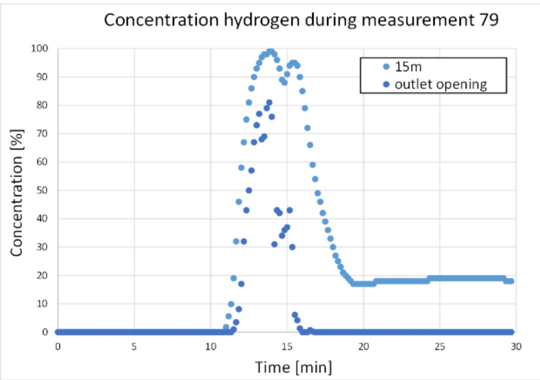

Concentration hydrogen during measurement 74
outlet opening
Concentration [%]
Time [min]

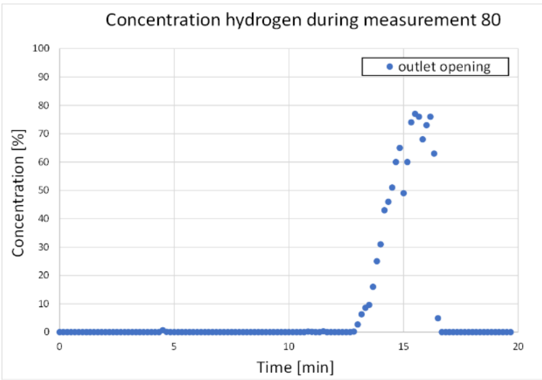

Concentration hydrogen during measurement 75
outlet opening
Concentration [%]
Time [min]

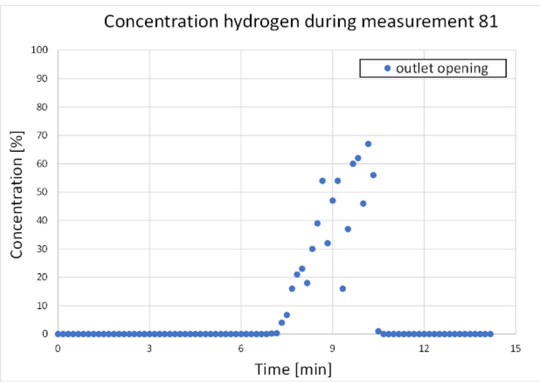

Concentration hydrogen during measurement 76
15m
10m
5m
outlet opening
Concentration [%]
Time [min]


Concentration hydrogen during measurement 77
15m
outlet opening
Concentration [%]
Time [min]


Concentration hydrogen during measurement 78
15m
outlet opening
Concentration [%]
Time [min]


Concentration hydrogen during measurement 79
15m
outlet opening
Concentration [%]
Time [min]


Concentration hydrogen during measurement 80
outlet opening
Concentration [%]
Time [min]


Concentration hydrogen during measurement 81
outlet opening
Concentration [%]
Time [min]

VII. Evaluation of used inflatable gas stoppers

After the experiments the inflatable gas stoppers were assessed. This assessment consisted of

1) A visual assessment for the presence of damages
2) A leak tightness check

The tables on the following pages show these findings. The subsequent pages show photographs of the inflatable gas stoppers with abnormalities.

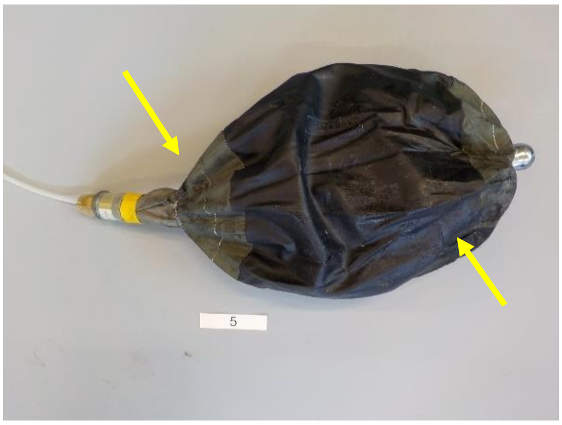
The very last page contains photos of IPCO's lance constructions and photos of some of Kleiss' lance constructions .

No.	Date	Length (m)	Diameter (mm)	Gas	Brand	Encoding manufacturer	Visual examination stopper	Tightness (3 minutes on testpressure*)	Examination connection stopper	Remarks
1	15/04/2024	1	160	AG	IPCO	**see 3**	-	-	-	-
2	15/04/2024	1	160	AG	IPCO	**see 3**	-	-	-	-
3	15/04/2024	1	160	AG	IPCO	04-241902.35	fire damage	could not be pressurized	fire damage	-
4	15/04/2024	1	160	AG	IPCO	**see 5**	-	-	-	-
5	15/04/2024	1	160	H2	IPCO	04-241902.25	fire damage and a tear	could not be pressurized	no deviations	-
6	15/04/2024	1	160	H2	IPCO	04-241902.31	tear	could not be pressurized	no deviations	-
7	15/04/2024	1	160	H2	Kleiss	16-03-24/08 - MDS B500 D3 (P3)	fire damage and a tear	could not be pressurized	melt damage	-
8	15/04/2024	1	160	H2	Kleiss	05-09-22/82 - MDS B500 D3 (P3)	fire damage and a tear	could not be pressurized	melt damage	-
9	15/04/2024	1	160	H2	Kleiss	16-03-24/03 - MDS B500 D3 (P3)	fire damage and a tear	could not be pressurized	melt damage	-
10	08/07/2024	1	160	AG	IPCO	04-241902.38	no deviations	could not be pressurized	no deviations	-
11	08/07/2024	1	160	AG	IPCO	04-241902.34	fire damage	could not be pressurized	fire damage	-
12	08/07/2024	1	160	H2	IPCO	04-241902.44	minor fire damage and two tears	could not be pressurized	no deviations	-
13	08/07/2024	1	160	H2	IPCO	04-241902.37	fire damage	could not be pressurized	fire damage	-
14	08/07/2024	1	160	AG	Kleiss	04-05-24/13 - MDS B500 D3 (P3)	no deviations	remains pressurized	melt damage	-
15	08/07/2024	1	160	AG	Kleiss	04-05-24/18 - MDS B500 D3 (P3)	no deviations	remains pressurized	melt damage	-
16	08/07/2024	1	160	H2	Kleiss	04-05-24/11 - MDS B500 D3 (P3)	burning hole	could not be pressurized	melt damage	-
17	08/07/2024	1	160	H2	Kleiss	04-05-24/04 - MDS B500 D3 (P3)	burning hole	could not be pressurized	melt damage	-
18	05/07/2024	1	110	AG	IPCO	04-241902.08	no deviations	remains pressurized	no deviations	-
19	05/07/2024	1	110	AG	IPCO	04-241902.01	no deviations	remains pressurized	no deviations	-
20	05/07/2024	1	110	H2	IPCO	04-241902.02	fire damage and a tear	could not be pressurized	fire damage and a tear	-
21	05/07/2024	1	110	H2	IPCO	04-241902.16	fire damage	could not be pressurized	no deviations	-
22	05/07/2024	1	110	H2	IPCO	04-241902.20	fire damage	could not be pressurized	fire damage	-
23	05/07/2024	1	110	H2	IPCO	04-241902.13	fire damage	could not be pressurized	fire damage	-
24	05/07/2024	1	110	AG	Kleiss	16-03-24/18 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
25	05/07/2024	1	110	AG	Kleiss	16-03-24/03 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
26	05/07/2024	1	110	H2	Kleiss	16-03-24/16 - MDS B500 D2 (P3)	burning hole	could not be pressurized	melt damage	-
27	05/07/2024	1	110	H2	Kleiss	16-03-24/05 - MDS B500 D2 (P3)	burning hole	could not be pressurized	melt damage	sawn loose to get it out of the lance
28	05/07/2024	1	110	H2	Kleiss	16-03-24/09 - MDS B500 D2 (P3)	no deviations	could not be pressurized	melt damage - filling tube (inner) melted	sawn loose to get it out of the lance
29	05/07/2024	1	110	H2	Kleiss	16-03-24/04 - MDS B500 D2 (P3)	no deviations	could not be pressurized	melt damage - filling tube (inner) melted	sawn loose to get it out of the lance

No.	Date	Length (m)	Diameter (mm)	Gas	Brand	Encoding manufacturer	Visual examination stopper	Tightness (3 minutes on testpressure*)	Examination connection stopper	Remarks
30	16/04/2024	20	160	AG	IPCO	***see 31***	-	-	-	-
31	16/04/2024	20	160	AG	IPCO	04-241902.39	no deviations	remains pressurized	no deviations	-
32	22/04/2024	20	160	AG	IPCO	***see 33***	-	-	-	-
33	22/04/2024	20	160	AG	IPCO	04-241902.24	no deviations	remains pressurized	no deviations	-
34	16/04/2024	20	160	H2	IPCO	04-241902.27	no deviations	remains pressurized	no deviations	-
35	16/04/2024	20	160	H2	IPCO	04-241902.40	torn	could not be pressurized	torn at transition	-
36	16/04/2024	20	160	H2	Kleiss	16-03-24/07 - MDS B500 D3 (P3)	torn	could not be pressurized	no deviations	-
37	16/04/2024	20	160	H2	Kleiss	16-03-24/01 - MDS B500 D3 (P3)	torn	could not be pressurized	no deviations	-
38	22/04/2024	20	160	H2	IPCO	**see 39**	-	-	-	-
39	22/04/2024	20	160	H2	IPCO	04-241902.41	no deviations	remains pressurized	no deviations	-
40	22/04/2024	20	160	H2	Kleiss	***see 70 & 71 (in lance)***	-	-	-	-
41	22/04/2024	20	160	H2	Kleiss	***see 70 & 71 (in lance)***	-	-	-	-
42	17/04/2024	20	110	AG	IPCO	04-241902.03	no deviations	remains pressurized	no deviations	-
43	16/04/2024	20	110	AG	Kleiss	16-03-24/02 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
44	16/04/2024	20	110	H2	IPCO	04-241902.12	no deviations	remains pressurized	no deviations	-
45	16/04/2024	20	110	H2	IPCO	04-241902.18	no deviations	remains pressurized	no deviations	-
46	16/04/2024	20	110	H2	Kleiss	16-03-24/11 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
47	16/04/2024	20	110	H2	Kleiss	16-03-24/08 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
48	22/04/2024	20	110	AG	IPCO	**see 49**	-	-	-	-
49	22/04/2024	20	110	AG	IPCO	04-241902.07	no deviations	remains pressurized	no deviations	-
50	22/04/2024	20	110	AG	Kleiss	***see 51***	-	-	-	-
51	22/04/2024	20	110	AG	Kleiss	16-03-24/13 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
52	22/04/2024	20	110	H2	IPCO	***see 53***	-	-	-	-
53	22/04/2024	20	110	H2	IPCO	04-241902.05	no deviations	remains pressurized	no deviations	-
54	22/04/2024	20	110	H2	Kleiss	***see 55***	-	-	-	-
55	22/04/2024	20	110	H2	Kleiss	16-03-24/06 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	-
56	18/04/2024	20	160	H2	Kleiss	05-09-22/76 - MDS B500 D3 (P3)	ruptured	could not be pressurized	threaded coupling broken off the hose	outer stopper
56	18/04/2024	20	160	H2	Kleiss	05-09-22/60 -MDS B500 D3 (P3)	ruptured	could not be pressurized	no deviations	outer stopper
57	18/04/2024	20	160	H2	Kleiss	05-09-22/72 - MDS B500 D3 (P3)	ruptured	could not be pressurized	threaded coupling broken off the hose	inner stopper
57	18/04/2024	20	160	H2	Kleiss	16-03-24/05 - MDS B500 D3 (P3)	no deviations	remains pressurized	no deviations	outer stopper
58	18/04/2024	20	160	H2	IPCO	04-241902.32	ruptured	could not be pressurized	torn at transition	inner stopper
58	18/04/2024	20	160	H2	IPCO	04-241902.88	no deviations	remains pressurized	no deviations	outer stopper
59	18/04/2024	20	160	H2	IPCO	04-241902.42	ruptured	could not be pressurized	torn at transition	inner stopper
59	18/04/2024	20	160	H2	IPCO	04-241902.30	no deviations	remains pressurized	no deviations	outer stopper
60	18/04/2024	20	160	H2	Kleiss	***see 62***	-	-	-	-
61	18/04/2024	20	160	H2	Kleiss	***see 62***	-	-	-	-

No.	Date	Length (m)	Diameter (mm)	Gas	Brand	Encoding manufacturer	Visual examination stopper	Tightness (3 minutes on testpressure*)	Examination connection stopper	Remarks
62	19/04/2024	20	160	H2	Kleiss	16-03-24/09 - MDS B500 D3 (P3)	no deviations	remains pressurized	no deviations	-
63	19/04/2024	20	160	H2	Kleiss	***see 71***	-	-	-	-
64	19/04/2024	20	160	H2	Kleiss	16-03-24/02 - MDS B500 D3 (P3)	fulling tube through stopper	could not be pressurized	no deviations	-
65	19/04/2024	20	160	H2	IPCO	04-241902.23	ruptured	could not be pressurized	torn at transition	-
66	19/04/2024	20	160	H2	Kleiss	***see 70***	-	-	-	-
67	19/04/2024	20	160	H2	Kleiss	***see 70***	-	-	-	-
68	19/04/2024	20	160	H2	IPCO	***see 58 outer stopper***	-	-	-	-
69	19/04/2024	20	160	H2	IPCO	04-241902.33	ruptured	could not be pressurized	torn at transition	outer stopper
69	19/04/2024	20	160	H2	IPCO	04-241902.36	tears outer layer	remains pressurized	no deviations	at inner lance
70	19/04/2024	20	160	H2	Kleiss	16-03-24/06 - MDS B500 D3 (P3)	ruptured	could not be pressurized	no deviations	outer stopper
71	19/04/2024	20	160	H2	Kleiss	16-03-24/10 - MDS B500 D3 (P3)	no deviations	remains pressurized	no deviations	outer stopper
70 & 71	19/04/2024	20	160	H2	Kleiss	16-03-24/04 - MDS B500 D3 (P3)	no deviations	remains pressurized	no deviations	at inner lance
72 & 73	17/04/2024	20	110	H2	Kleiss	16-03-24/12 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	outer stopper
73 & 73	17/04/2024	20	110	H2	Kleiss	16-03-24/07 - MDS B500 D2 (P3)	no deviations	remains pressurized	no deviations	inner stopper
74 & 75	17/04/2024	20	110	H2	IPCO	04-241902.19	no deviations	remains pressurized	no deviations	outer stopper
75 & 75	17/04/2024	20	110	H2	IPCO	04-241902.10	metal cap a bit skew, no further deviations	remains pressurized	no deviations	inner stopper
76	17/04/2024	20	110	H2	IPCO	***see 81***	-	-	-	-
77	18/04/2024	20	110	H2	IPCO	***see 81***	-	-	-	-
78	18/04/2024	20	110	H2	IPCO	***see 81***	-	-	-	-
79	18/04/2024	20	110	H2	IPCO	***see 81***	-	-	-	-
80	18/04/2024	20	110	H2	IPCO	***see 81***	-	-	-	-
81	18/04/2024	20	110	H2	IPCO	04-241902.22	no deviations	remains pressurized	no deviations	
* testpressure		IPCO inflated to 0,6 bar			Kleiss 110mm inflated to 0,4 bar			Kleiss 160 mm inflated to 0,2 bar		

Stopper measurement 3; The stopper is almost completely burned.



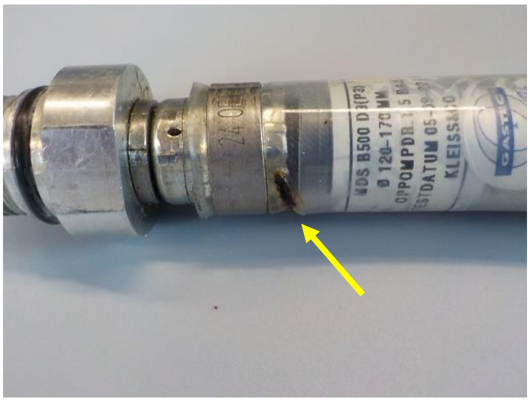
Stopper measurement 5; Burn damage to the stopper and a tear in the stopper.

Stopper measurement 6; The stopper is ruptured.

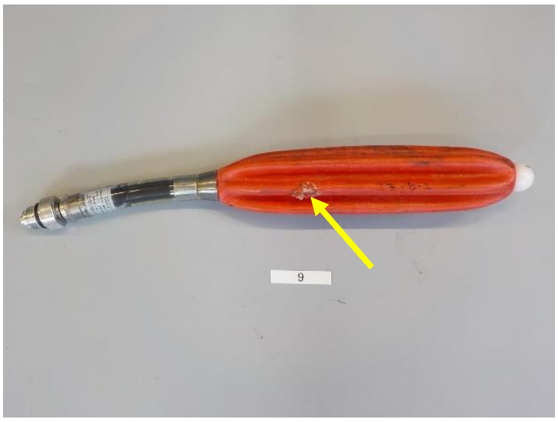
Stopper measurement 7; Burn damage to the stopper and a tear.

Stopper measurement 7; Melting damage to the stopper connection

Stopper measurement 8; Burn damage to the stopper and a tear.



Stopper measurement 8; Melting damage at the stopper connection.

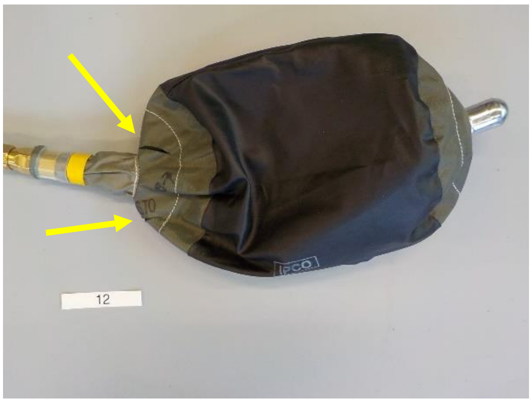


Stopper measurement 9; Burn damage to the stopper and a tear.

Stopper measurement 9; Melting damage at the stopper connection.

Stopper measurement 11; Fire damage to the stopper or connecting line.

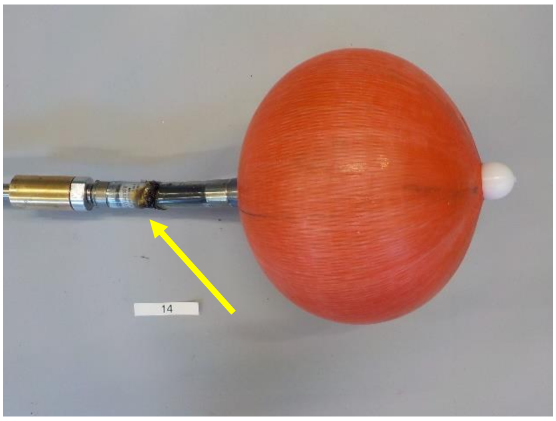
Stopper measurement 11; Fire damage to the stopper or connecting line.



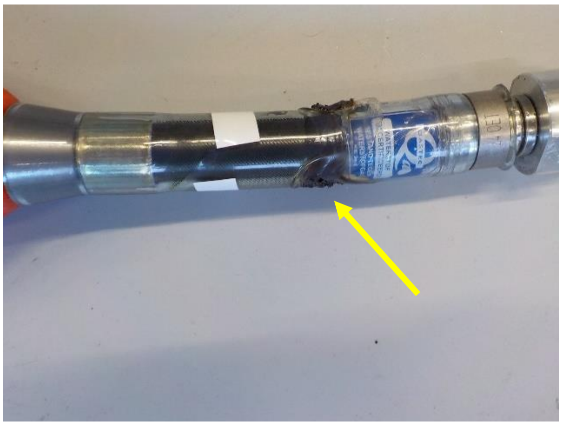
Stopper measurement 12; Fire damage leading to a rupture.

Stopper measurement 12; Fire damage leading to a rupture.

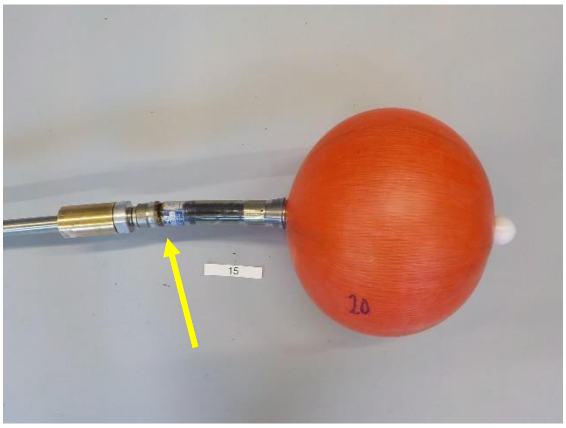
Stopper measurement 13; Completely ruptured stopper due to fire.



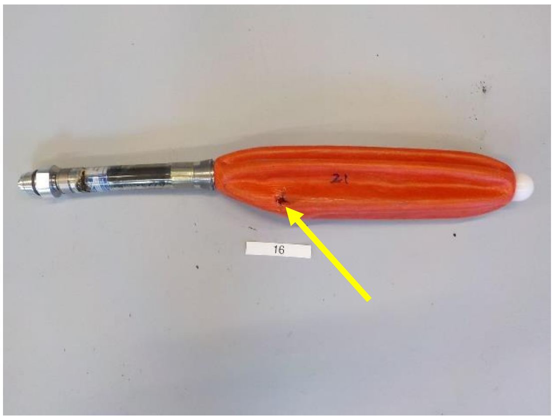
Stopper measurement 14; Melting damage at the stopper connection.



Stopper measurement 14; Melting damage at the stopper connection.

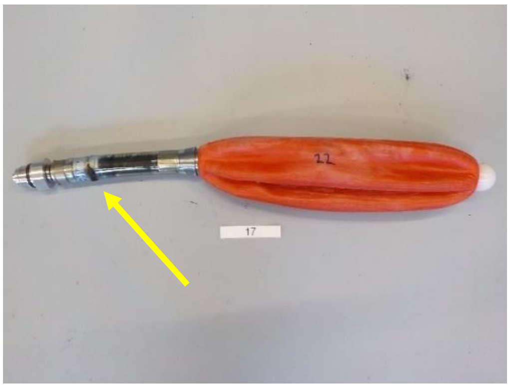


Stopper measurement 15; Melting damage at the stopper connection.

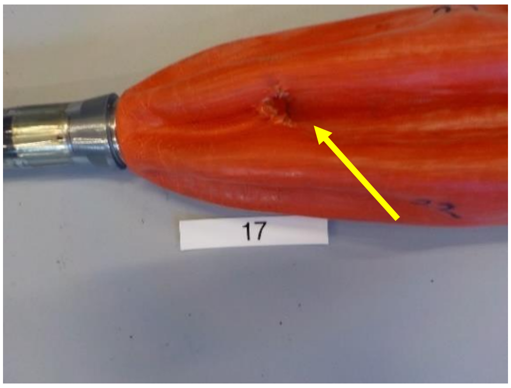


Stopper measurement 16; Burn damage and tear in the stopper.

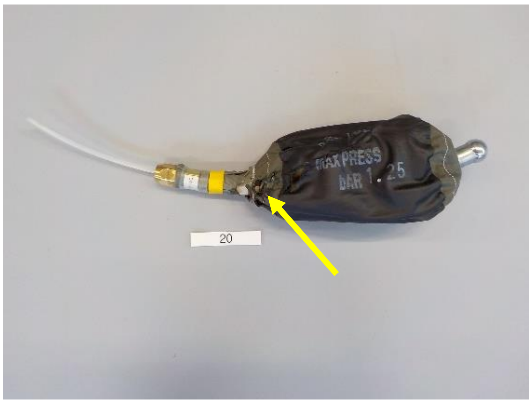
Stopper measurement 16; Melting damage at the stopper connection.



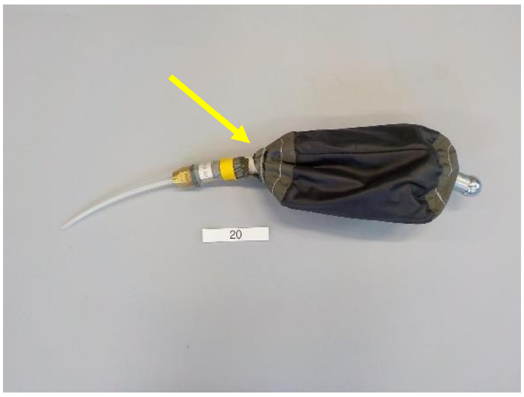
Stopper measurement 17; melt damage at the stopper connection



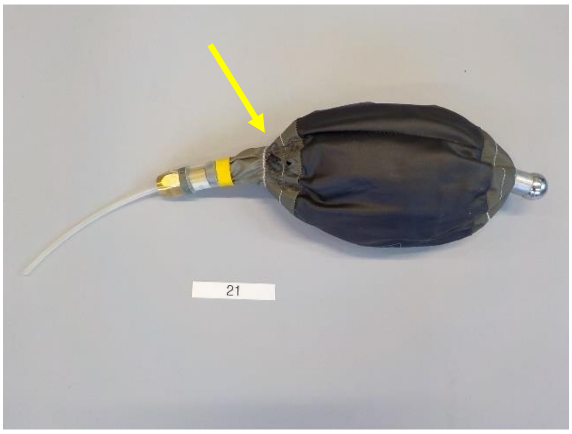
Stopper measurement 17; Burn damage and tear in the stopper.



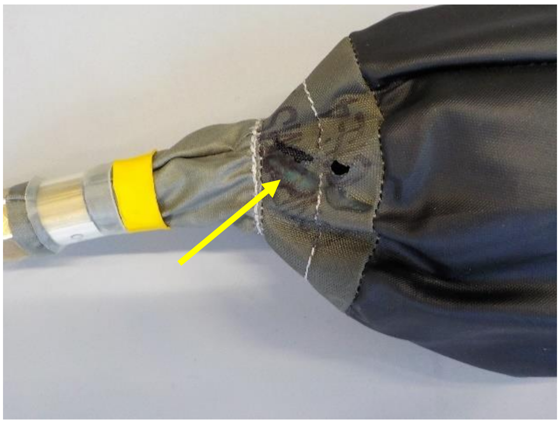
Stopper measurement 20; Burn damage and tear in the stopper.



Stopper measurement 20; Burn damage and tear in the stopper.



Stopper measurement 21; Burn damage and hole in the stopper.

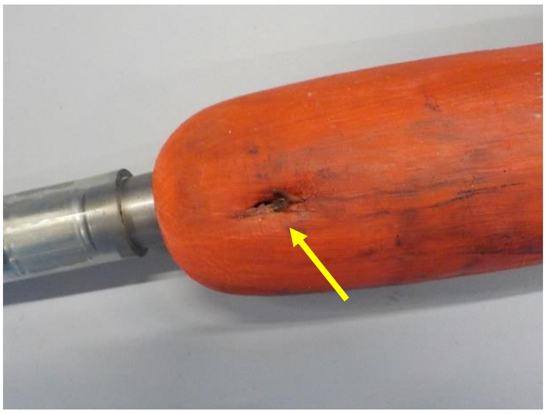


Stopper measurement 21; Burn damage and hole in the stopper.

Stopper measurement 22; Completely ruptured stopper due to fire (shaped this way when removed).

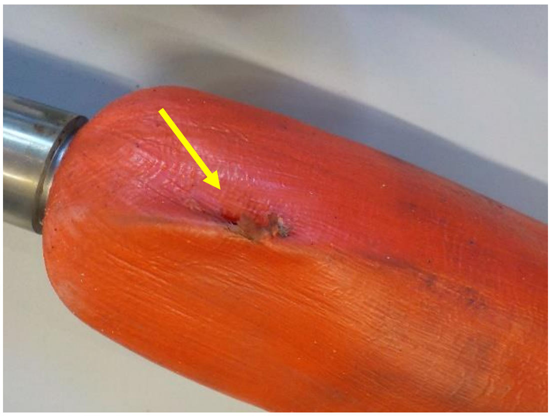
Stopper measurement 23; Completely ruptured stopper due to fire (shaped this way when removed).

Stopper measurement 26; melt damage at the stopper connection.

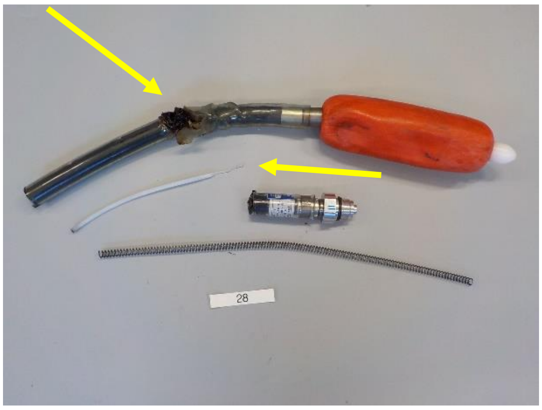


Stopper measurement 26; Burn hole in the stopper.

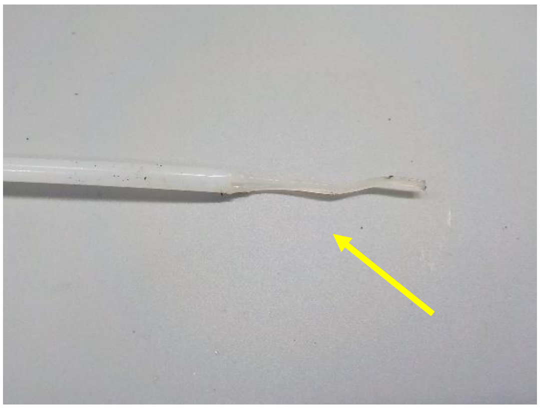
Stopper measurement 27; Melting damage to the stopper connection. This had to be sawn loose to get it out of the lance and pipe.



Stopper measurement 27; Burn hole in the stopper.

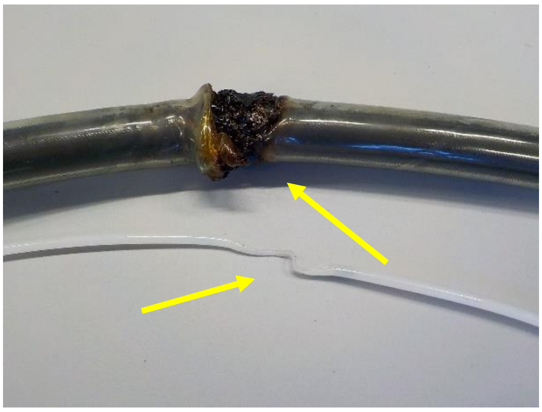


Stopper measurement 28; Melting damage to the stopper connection. This had to be sawn loose to get it out of the lance and pipe.



Stopper measurement 28; melt damage - filling tube (internal) melted

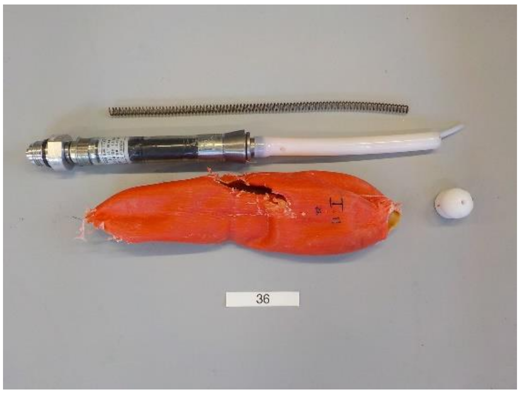
Stopper measurement 29; Melting damage to the stopper connection. This had to be sawn loose to get it out of the lance and pipe.



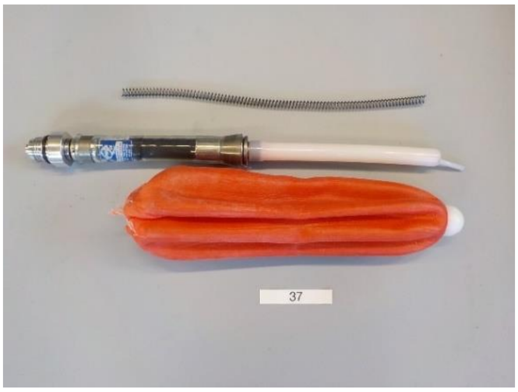
Stopper measurement 29; melt damage (filling tube melted)

Stopper measurement 35; The stopper is completely ruptured

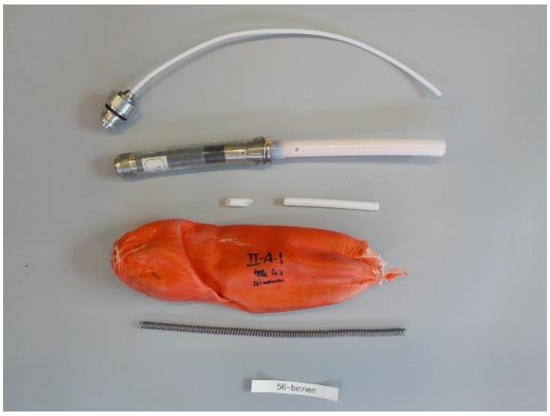
Stopper measurement 35; Detail of the tear.



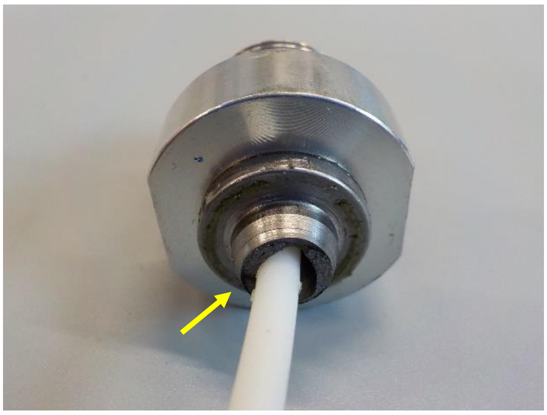
Stopper measurement 36; The stopper is ruptured and become detached from the connection.



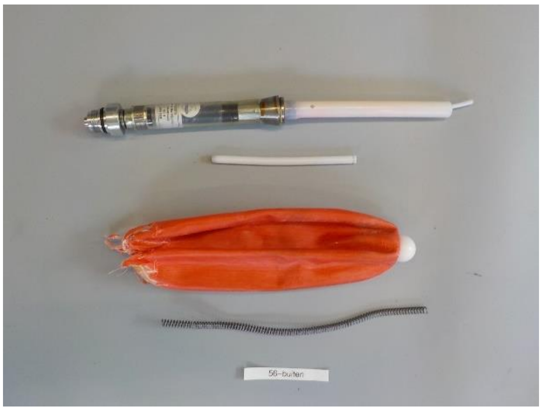
Stopper measurement 37; The stopper is ruptured and become detached from the connection.



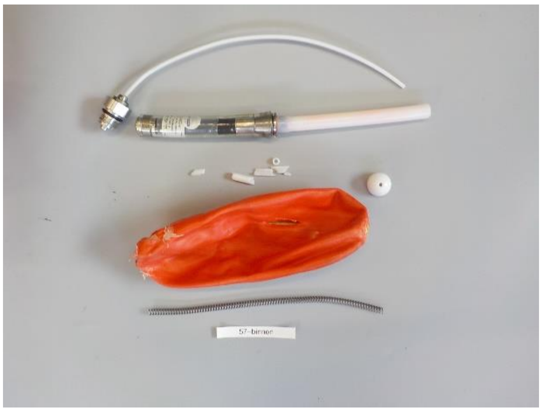
Inner stopper measurement 56; The stopper is ruptured and become detached from the connection.



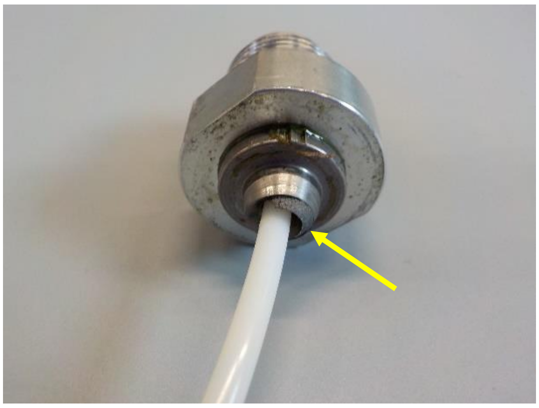
Inner stopper measurement 56; The threaded coupling has broken off the hose.



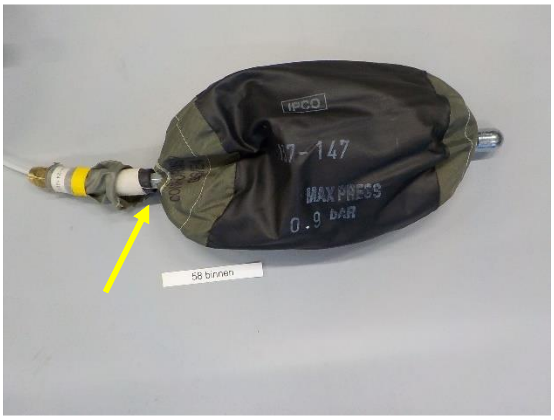
Outer stopper measurement 56 ; The stopper is ruptured and become detached from the connection.



Inner stopper measurement 57; The stopper is torn and detached from the connection. A part of the filling line is broken.



Inner stopper measurement 57; The threaded coupling has broken off the hose.



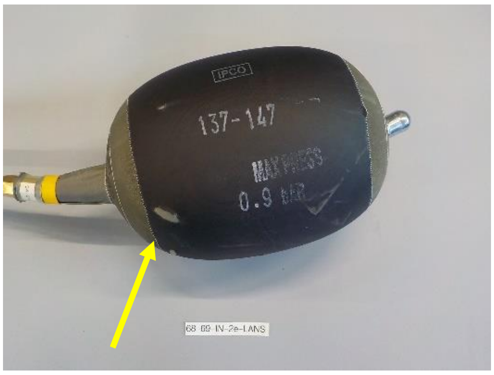
Inner stopper measurement 58; The stopper is completely ruptured.

Inner stopper measurement 59; The stopper is completely ruptured (formed as a result of removal from the lance).

Stopper measurement 64; The filling measuring tube is inserted through the stopper.

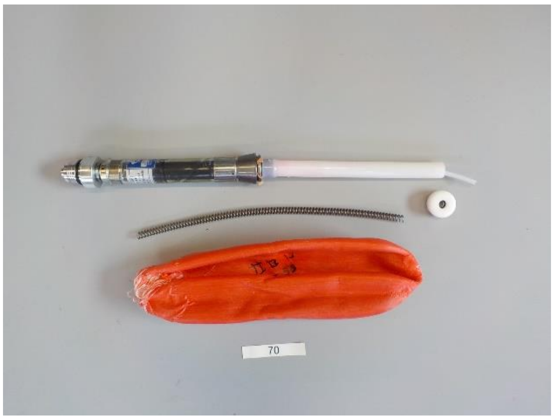
Stopper measurement 65; The stopper is completely ruptured

Outer stopper measurement 69; The stopper is completely torn. The connection has become detached from the stopper.

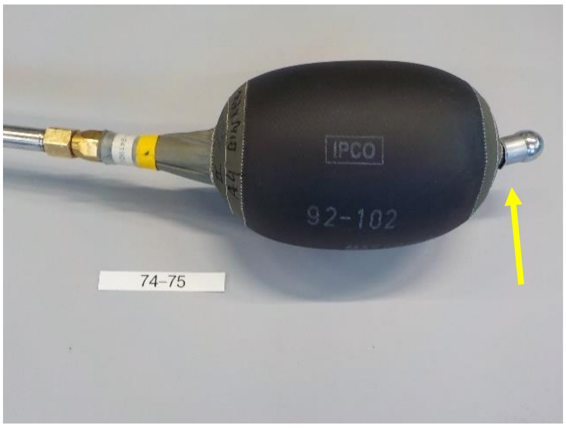


Stopper measurement 69 in inner lance; Cracks in outer layer (at the time of the experiment the stopper was not inflated).

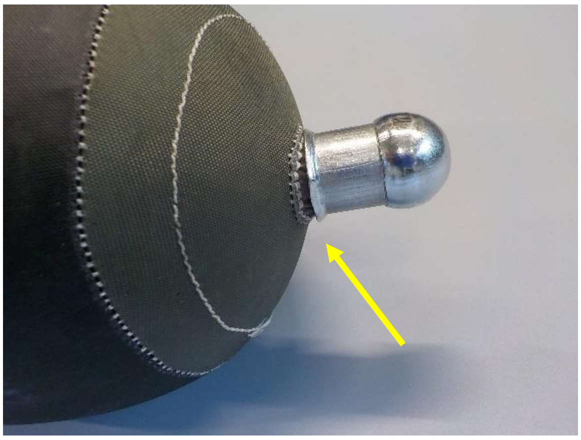

Stopper measurement 69 in inner lance; Cracks in outer layer (at the time of the experiment the stopper was not inflated).



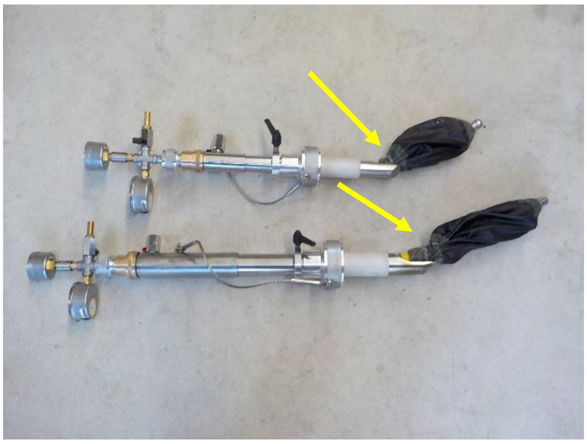
Stopper measurement 70; The stopper is ruptured and become detached from the connection.



Stopper measurements 74 &75; The metal cap is slightly crooked.


Stopper measurements 74 &75; The metal cap is slightly crooked.

Part of the Kleiss lance constructions for the stoppers in the 110 mm and 160 mm pipes. With the larger stopper, a short connection line to the stopper is possible, because the threaded coupling extends further into the lower part of the lance. The yellow arrows indicate the melt damage as it has been found several times. This is also the place where the stopper connection line comes out of the lance.



The IPCO lance constructions for the stoppers in the piopes 110 mm and 160 mm. The stopper itself starts almost immediately after it comes out of the lance.