HyDelta

WP1A– Safety and hydrogen

D1A.2 – Design of QRA, effect of ventilation in case of small leaks and recommendations for measures

Status: Final

Dit project is medegefinancierd door TKI Nieuw Gas | Topsector Energie uit de PPS-toeslag onder referentie nummer TKI2020-HyDelta.

Document summary

Corresponding author

Corresponding author	Albert van den Noort
Affiliation	DNV
Email address	Albert.vandenNoort@dnv.com

Document history

Version	Date	Author	Affiliation	Summary of the main changes
1	04-01-2022	AvdN	DNV	Eerste draft
2	18-03-2022	AvdN	DNV	Draft voor review EAG
3	8-04-2022	AvdN	DNV	Verwerkt commentaar EAG; voor review brede reviewgroep en supervisory board
4	29-4-2022	AvdN	DNV	Verwerkt commentaar brede review group; voor review supervisory board
5	1-5-2022	AvdN	DNV	Final

Dissemination level

PU	Public	X
R1	Restricted to • Partners including Expert Assessment Group • Other project participants including Sounding Board • External entity specified by the consortium (please specify)	
R2	Restricted to • Partners including Expert Assessment Group • Other project participants including Sounding Board	
R3	Restricted to • Partners including Expert Assessment Group	

Document review

Partner	Name
Alliander	P. te Morsche / P. Verstegen / E. Rikken
Enexis	R. van Hooijdonk / W. de Rooij
Stedin	R. van den Brink / F. van Alphen
Coteq	S. Buruma
Westland Energie	R. den Hartog
N-tra	B. Meijer
Gasunie	M. van Agteren
NIPV	M. Spoelstra
Kiwa Technology	R. v. Aerde; H. Salomons; K. Pulles, P. Postma; S. Delnooz; H. Rijpkema
DNV	J. Knijp
NBNL, Gasunie, Kiwa, DNV, TNO, NEC	HyDelta Supervisory Group

Summary

To estimate the risks associated with the use of hydrogen in the distribution network and the built environment compared to the use of natural gas, it is important to know the differences in chances and consequence. The chance relates in particular to the probability of a dangerous situation occurring; the consequences can be expressed in damage caused by that hazardous situation (typically fire or explosion). Mitigating measures are aimed at reducing the chance of a dangerous situation arising or lowering its consequences.

To this end, the Hydelta programme defines the 'Hydrogen and Safety' work package in which the main objective is formulated as:

Identifying the risks of hydrogen leaks in homes and in the distribution network and defining mitigating measures on the basis of the risks.

To answer this main question, this report relies heavily on previously published work from the United Kingdom (UK) where similar research has been conducted. In the first phase of the research, an analysis was made of the work from the UK and a translation was made to the Dutch situation. To give insight in the risks of hydrogen in the English distribution network, a quantitative risk analysis was made (QRA). Supporting experimental research was carried out to improve this QRA model. Based on the results of the model, recommendations have been made for mitigating measures for the UK, that ensure that the risk of the hydrogen infrastructure does not exceed the risks of the current natural gas infrastructure.

In the Hydelta work package, the same approach was followed to make an initial assessment of the risks in the Dutch situation. In the first deliverable of the work package, [1] the studies in the UK were analysed and differences with the Dutch situation were identified. Based on this analysis and existing questions about the safety of hydrogen in the built environment from the Dutch grid operators, a start was made in the second phase of the research in the work package with a QRA model for the Dutch (hydrogen) distribution network. In addition, an experimental programme has been set up to provide insight into the effect of ventilation on the accumulation of dangerous concentrations in the event of small leaks. It should be noted that this is an initial exploration: given the time available within the Hydelta programme, further research in next phases of Hydelta will be needed to further validate and fine-tune the models with additional research.

The report is divided into three coherent parts. Part I describes the setup of the QRA model. The effect of ventilation on small leaks is described in Part II, based on a set of experiments that have been carried out. Finally, Part III provides an overview of mitigating measures that can be considered in the pilot projects.

Part I 'Quantitative risk analysis'

The model that has been developed considers the gas distribution system for pressures up to and including 8 bar, as operated by the distribution grid operators. More specifically, in the model we focus on the underground mains in the distribution network and the service pipes between the mains and the meter setup in the houses. The model is based on the composition of the Dutch distribution network, with different pressure regimes, material types, diameters and lengths, as well as on the failure data of recent years for the corresponding natural gas network. This report describes the model. The assumptions used for the Dutch situation and the associated results of the quantitative risk analysis will be further described in the next phase of HyDelta.

Part II "Effect of mitigating measures on hydrogen accumulation"

It is known from the studies from the UK that the greatest risk for the use of hydrogen in the built environment is caused by an explosion due to accumulation of hydrogen at concentrations above 10 vol%. To prevent this build-up of the concentration, ventilation is an important parameter. The workshops held with the Dutch grid operators showed that the dispersion of hydrogen in the event of leaks inside homes and the associated influence of ventilation require additional recommendations for the implementation of pilots in the short term. To provide more insight into this issue, a test set-up has been built in a container that measures the effect of (low) ventilation rates on the accumulation in different rooms in the event of small leaks. In the experiments, both the outflow of hydrogen (up to 20 dm^3/hour) and methane (up to 15 dm^3/hour [1]) were investigated. The current limit for permitted leaks for natural gas is 5 dm^3/hour. The results lead to the following conclusions:

1. *Build-up of concentrations remains well below the LEL in the largest tested room (36m^3).* The LEL[2] for hydrogen is 4 vol% gas in air. In the experiments in the entire space of the container (36 m^3), maximum concentrations of 6% LEL (= 0.24 vol% H2 in air) are measured. For both hydrogen and methane, the concentration at the top of the container is the highest. In none of the experiments a dangerous concentration was measured (near or above LEL).
2. *Opening a door or ventilation opening is an efficient way to reduce concentration.* We tried to make the container as gas-tight as possible in order to simulate a very poorly ventilated room. When the ventilation rate is greater than 5 times per hour, it may be considered "Good" (NPR7910-1). In homes the ventilation rate often does not exceed 2 times per hour, where it should be considered moderate (NPR7910-1). In cases where the ventilation rate is less than 1 time per hour it is referred to as "no ventilation" (NPR7910-1). By measuring how fast the concentration decays after an outflow test, the ventilation rate of the container was determined. For hydrogen, it was 0.2 /hour. Opening a vent on the side of the container results in a ventilation rate of 1 /hour, while opening the door of the container leads to a ventilation rate of 15-20 / hour. Opening the door halves the concentration in about 1-2 minutes. Ventilation by opening a vent, it takes about half an hour, while with no ventilation the concentration halves in a few hours after stopping the supply.
3. *Leakage in a meter cupboard also results in concentrations lower than the LEL.* In the second phase of the experiments, the container was divided into 2 compartments (10 and 26 m^3) with a meter cupboard with door with ventilation grills in the smallest compartment. The 10 m^3 thus represents a typical hall. The outflow of the gas is always at the bottom of the meter cupboard. It is observed that the largest increase in concentration is in the upper part of the meter cupboard, but that it levels during the experiments. The concentration in the adjacent room then increases by the gas dispersing through the opening of the meter cupboard door to this room. The highest hydrogen concentration in the meter cupboard is achieved when both the ventilation grills in the meter cupboard door and the ventilation opening in the container are closed, with the concentration levelling off to a value of approximately 45 %LEL in the hydrogen tests. Opening the ventilation in the meter cupboard door leads to a significant decrease in the average hydrogen concentration in the meter cupboard (43% to 20% of the LEL). A decrease in the outflow rate from 20 dm^3/hour to 15 dm^3/hour also results in a decrease in the average hydrogen concentration in the meter cupboard. Only if the

[1] In this report dm^3/hr refers to normal dm3/hr. In the experiments, a mass flow controller is used that has a slightly higher maximum flow rate for hydrogen than for methane.

[2] LEL refers to the lower explosion limit of gas in air and can also be translated LFL (lower flammability limit). For hydrogen the LEL is 4vol%, for methane 5% vol. is used.

ventilation grills in the door of the meter cupboard are closed and the maximum gas supply is used, the safety value of 50% LEL set for the experiments is reached and the experiment is aborted. In the experiments, this only occurred with methane with an outflow of 15 dm^3/hour. The maximum concentration at the top of the meter cupboard is generally lower for hydrogen compared to methane.

4. *Closing the gas supply leads to a rapid decay, followed by normal ventilation.* In both the experiments with hydrogen and methane, it is observed that as soon as the gas supply in the meter cupboard is closed, the concentration in the meter cupboard drops rapidly. The gas disperses quickly, even with closed ventilation openings in the door, to the adjacent room. This seems to happen faster with hydrogen than with methane. As soon as the concentrations in the meter cupboard and adjacent room are equal, the ventilation of the adjacent small space is leading in a further reduction of the concentration.
5. *The measured concentrations could be detected by H_2 sensors or odorization.* The concentrations of hydrogen measured in the experiments are generally very low, far below the LEL. In the analysis it appears that with the small leaks up to 20 dm^3/hour no dangerous situations arise. However, to be sure that such small leaks are noticed and do not extend over much longer periods of time than the hours used in these experiments, it is important to know whether detection mechanisms are effective. Based on previous research, an estimate has been made of the limits at which CO sensors, which can be used as hydrogen sensors, will alarm, as well as when the gas can be smelled. The figure below shows the average concentration in the meter cupboard (left) and in the larger room (right). It also shows the concentration bands in which the H_2 sensors are expected to react and the limits for smellability of the gas.

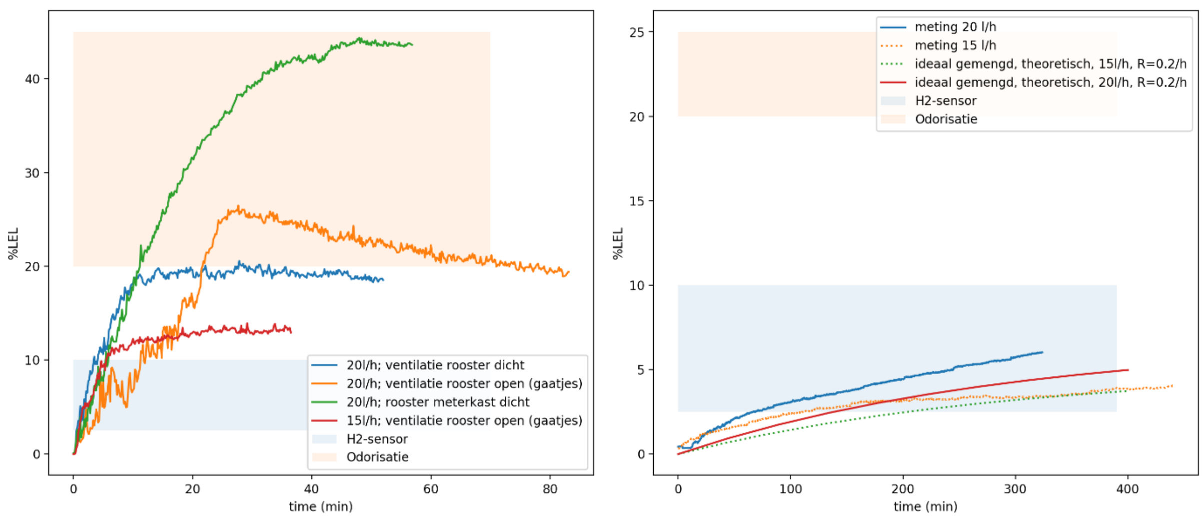


Figure 1 Measured average concentrations of hydrogen and lower concentration limits at which H2 sensors alarm or odorantly detect the concentrations. The meter cupboard (left) and the 36 m³ space (right)

It is likely that gas air will already be detectable at concentrations below 20 %LEL . It could be recommended to place sensors at the top of the room, where the higher concentrations prevail. With this, a small leak will be noticed in time and the risk can be further reduced.
In case of leakage, ventilation by means of a grid or opening a door is an effective way to reduce concentration.

Part III "Safety recommendations for hydrogen pilot projects"

During the Hydelta programme, several pilot projects will be set up in the Netherlands to gain experience with hydrogen in the built environment. It is of great importance to execute these pilots and demonstration projects in a safe manner. Based on the results of this work and the knowledge already gained in various pilot projects, an overview has been made of the mitigating measures that can be considered for future pilots. We focus on measures for an infrastructure with a maximum working pressure of 8 bar in transition from natural gas to a hydrogen, for pilot projects and for permanent installations. Initially, the focus is on the pilot projects and these measures are conservatively inclined. Basis for this set of recommendations is that the majority of the methods that are used for the design/construction and operation of the natural gas infrastructures are also suitable for hydrogen. Extra attention is required to limiting "large leaks". The recommendations are grouped around the different phases of the project: preparation, design, implementation and operation. Both measures for the distribution network and 'behind the meter' in the homes are mentioned. Based on the experiences from the pilots and future insights, we need to re-assess at a later stage to what extent these measures should also be applied in a future regular hydrogen distribution network.

Table of contents

1 Introduction

Hydrogen has different properties than natural gas. The difference in physical and chemical properties are well known. What is lacking, however, is the specific knowledge on the difference in safety risk for gas distribution and transport. On this topic there is extensive knowledge for natural gas which can serve as a reference.

To be able to estimate the risks associated with the use of hydrogen in the distribution network and transmission network compared to natural gas, it is important to know the differences in probability and the subsequent consequences. The probability relates in particular to the possibility of a dangerous situation occurring; the consequences can be expressed in damage caused by a fire or explosion. Mitigating measures are aimed to reduce the chance of a dangerous situation arising or mitigate its consequences .

To this end, the Hydelta programme defines the 'Hydrogen and Safety' work package in which the main objective is formulated as:

Identifying risks regarding hydrogen leakages in homes and in the distribution network and defining mitigating measures based on these risks.

The question of the extent of the relative safety risks (hydrogen vs natural gas) can be divided into the following sub-questions:

- To what extent is there a difference in the probability of a dangerous situation arising in the event of free outflow due to leakage or during maintenance of the grid?
- To what extent is there a difference in dispersion (or possibly accumulation) of the gas clouds?
- To what extent is there a difference in the probability of ignition?
- To what extent is there a difference in the consequences of fires and explosions?
- To what extent is there a difference in the necessary mitigating measures?

With the help of (existing) risk models, probabilities and consequences can be quantitatively modelled for both natural gas and hydrogen. However, for hydrogen, the model has not yet been developed far enough to be able to make the quantitative estimate for the Dutch situation [2]. In Hydelta, a first step is made.

The analysis of the current international literature shows that the question of whether the risks of natural gas and hydrogen are comparable is situation-dependent. Within the H21 and Hy4heat projects in the UK, various experiments have been carried out, including: the build-up of concentration of hydrogen in houses, dispersion through the underground, and the ignition by various sources. Both projects translate the results of the experiments into quantitative risk models (Quantitative Risk Models; QRA). A combined model for the risk of hydrogen from the distribution network (H21) and for the home (Hy4heat) is currently being developed, but is not yet available. HyDelta deliverable D1a.1 summarizes these studies and compares them with the Dutch situation. The report concludes, among others, that: [1]

1. The low-pressure distribution network in the United Kingdom (UK) is made up of mostly the same materials as in the Netherlands, but different in proportions in terms of lengths, diameters and pressures. To calculate the risk, the QRA model for the

Netherlands must be adjusted for the materials, pressures, diameters and pipe lengths used.

2. The typical layout of Dutch houses differs from those in England. The location of the meter cupboard in the house is often different. In the UK there are relatively more old houses compared to the Netherlands: less mechanical ventilation and more natural ventilation. Ventilation has a major impact on the overall risk.
3. Accumulation of hydrogen in confined spaces has been investigated in hy4heat, Hyhouse and the Gas Dispersion Analysis report; this is primarily based on indoor leaks in the indoor piping installation. In the event of a hydrogen leakage, higher gas concentrations (gas stratification) first form at the top of the room. The volume flow of hydrogen released from a leak is 1.2 to 1.8 times greater than methane. The influence of natural ventilation is considerably larger than, for example, mechanical ventilation. At the highest leakage rate (78.6 m^3/h) used in the experiments, room ventilation reduces the concentration at the top of the room from a rich mixture (~ 60 % vol) to stoichiometric mixture (~ 40% vol). If hydrogen spreads to other rooms, the hydrogen concentration also decreases rapidly: the formation of an explosive mixture is unlikely for small leaks with natural ventilation. In the event of a hydrogen leak in a room without ventilation and closed doors/windows, an explosive mixture can form. The most effective measures to prevent an explosive mixture is a combination of cabinet ventilation (e.g. air vent in meter cupboard) and room ventilation. With these measures the ignition limit in the room where the leakage occurs is not exceeded and room ventilation further reduces the probability of explosive mixtures. In addition, in the UK it is recommended for the time being - as with natural gas - not to place a hydrogen installation in a basement, because the chance of insufficient ventilation (and therefore faster accumulation) is considerable. This situation is less common in the UK.
4. In natural gas, most leaks are detected by the smelling the odorant and action is taken to prevent an ignition. Research from the UK therefore recommends using odorization in addition to a flow protection such as an EFV or gas stopper adjusted to the maximum consumption of a device.

In order to answer the main research question, this report translates these findings into the Dutch situation, using the method described below.

2 Method

To map the risks regarding the behaviour of hydrogen in the event of leaks in homes and in the distribution network and to define mitigating measures on the basis of the risks, the schematic approach as shown in Figure 2 is usedFigure 2. In this approach, two processes can be recognized: a vertical process in which recommendations are made via a quantitative risk analysis to arrive at an acceptable risk, and a horizontal process that is aimed at improving the risk model for the given situation.

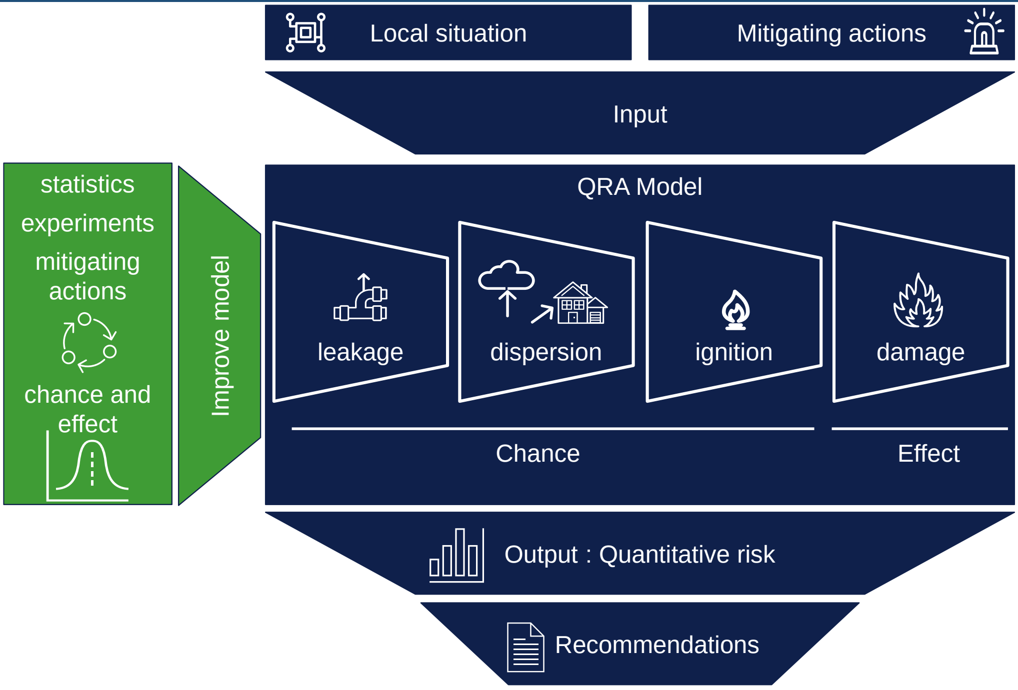


Figure 2 Model-based approach to risk analysis

The model needs to be adapted for the given situation, the Dutch hydrogen distribution network, before it can be applied. The original model was developed for the characteristics in the UK and has been validated for the risks of natural gas. In order to demonstrate the applicability of such a model to the Dutch situation, an initial step was set in this phase of HyDelta to translate the model towards the Dutch situation. The focus was mainly on the components that have a major effect on the risk and that differ in the Netherlands compared to the situation in the UK. The design of this analysis is described in **Part I "Quantitative risk analysis"**. The results of the quantitative risk analysis will be further described in the next phase of HyDelta.

In addition to adjusting the local situation and statistics, the studies from the UK show that the largest risk originates from the large effect of an explosion due to accumulation of hydrogen to concentrations above 10 vol%. To prevent this accumulation, the effect of ventilation in closed rooms is an important parameter. Workshops with Dutch grid operators learned that the accumulation of hydrogen from leaks in homes and the associated influence of (poor) ventilation require additional recommendations for the implementation of pilots in the short term. To provide more insight, an experimental set-up has been developed in the project that allows to measure the effect of (low) ventilation rate on the accumulation in different rooms in the event of small leaks. The experiments are described in **Part II "Effect of mitigating measures on hydrogen accumulation"** of this report.

Parallel to the execution of the Hydelta project, a number of pilot projects are developed in the Netherlands to gain experience with hydrogen in the built environment. It is of great importance to execute out these pilots and demonstration projects in a safe manner. The described risk model in Part I and the additional information from the experiments as reported in Part II form input for determining the necessary measures in the pilots. As the model is currently under development and does not yet fully describe the Dutch situation, we used insights from the pilot projects to gain an even better understanding of the risks. In **Part III "Safety recommendations for hydrogen pilot projects**" of this report, we provide a set of recommendations for the mitigating measures for distribution infrastructures with a maximum working pressure of 16 bar, pilot projects and for permanent installations. Initially, the focus is on the pilot projects and these measures are set conservatively. Based on the experiences from the pilots and progressive insight, it can be determined at a later stage to what extent these measures should also be applied in a future regular hydrogen distribution network.

Finally, it is noted that due to delays in the release of the reports in the UK, the analysis from the first phase of the work package has been delayed. In this report, therefore, a first step has been made for both the risk model and the experiments. In the next phase of the Hydelta project, both the model and the experiments will be further developed in order to give an even better picture of how hydrogen can be used in a safe way in the built environment. The aforementioned pilot projects play a major role in this. After all, the necessary experience will be gathered on the applicability of hydrogen and statistics will be collected on associated around risks in the same way as risk knowledge has been build up in the last built decades for the safe application of natural gas.

Quantitative risk analysis model

3 Introduction

To be able to make an initial assessment of the risks of hydrogen in the Dutch distribution network, a quantitative risk analysis (QRA) was made. It compares the risk between the current natural gas distribution system and the future hydrogen distribution system. The results of such an analysis provide a quantitative basis for whether the hydrogen distribution poses more risk to society and, if so, which measures have the largest influence to reduce this risk. The QRA model developed by DNV for a similar analysis in the UK forms the basis for this analysis.

In Hydelta, an initial version been made to translate the UK model for the Dutch situation. This report describes the methodology and structure of this analysis. In the next phase of Hydelta, the assumptions and outcomes used will be further described.

3.1 Preconditions of the model

The model developed in Hydelta considers the gas distribution system for pressures up to and including 8 bar, as operated by the regional grid operators. Gasunie's regional and high-pressure transport network is excluded in this analysis. More specifically, in this first version of the model, we focus on the

- Underground mains in the distribution network
- Services between the main and the meter connection in the house (and excluding the indoor installation).

The model is based on the composition of the Dutch distribution network, with different pressure regimes, material types, diameters and lengths, as well as on the failure data of recent years for the natural gas network.

4 Methodology

4.1 Background

In a quantitative risk analysis, the chances of leakage and the consequences thereof are calculated for a given situation or configuration of the network and connected homes. The developed model takes into account a number of parameters for the distribution network:

- Pressure
- Variation in diameter of the mains
- Materials used in the mains (e.g. steel or PE)
- Construction method of the mains (e.g. wall thickness)
- PE connections (e.g. electro fusion)
- Depth of the pipes in the ground
- Construction of the services
- Permeability of the underground

In the QRA model developed for the Netherlands, the above parameters are estimated. Initially, the focus was mainly on the variation in pressures, diameters and materials and the distance from the houses to the main pipeline.

4.2 Description Risk model

Within DNV, a standardised risk analysis method has been developed for calculation of risks in the distribution network (CONIFER: Calculation of Networks and Installations Fire and Explosions Risk). The model was originally developed as a risk analysis model for the UK's natural gas network to determine the prioritisation in replacing cast iron pipes with polyethylene (PE). The model has been further developed over the years. The model is based on incident data, measurement data (specific to the model) and validated model data. As part of the H21 project in the UK, the model is currently adapted and validated for hydrogen transport systems. To this end, additional experiments have been carried out in the UK and the results have been implemented in modules in the model.

Details for the model and its development is given in the QRA reports for H21. The modules in the model are developed in a software package by DNV [3] [4] [5] and offer the possibility to model the risk given the following input parameters:

- Metal and polyethylene (PE) pipes.
- Natural gas, full hydrogen and all blends in between
- Various causes of leakage: Spontaneous and damage by third parties (external interference).[3] The failure frequency for these causes is input for the model.
- Physical phenomena such as outflow, dispersion and accumulation of gases
- Services and gas pipes behind the meter (indoor installation)
- Different compositions of dwellings, such as type of dwellings (bungalows, terraced houses, semi-detached houses and detached houses) including different sizes of rooms, presence of cellars and presence of residents
- Outcomes, including explosions and fires, translated into individual or social risks.

The model can be used for both leaks due to external interference and leaks due to failure of the infrastructure itself. Even though these causes are treated differently, both can lead to above-ground fires, or dispersion of the gas through the subsurface to closed spaces (e.g. houses) and possibly lead to explosions there. The results of the model are risks for personal accidents but also chances of fires or explosions.

The model is modular and consists of several individual models, as shown in Figure Figure 3, Figure Figure 4 and Figure Figure 5. Each of the numbered steps in the figures contain detailed submodels that go beyond a single (set of) equation (s). Details about these submodels are given in [3], below a brief summary is given.

[3] Damage caused by third parties or external interference is caused by human interaction such as excavation damage in which a pipe is accidentally hit. Spontaneous damage refers to damage without direct human interaction. Examples include, for example, the failure of couplings or corrosion.

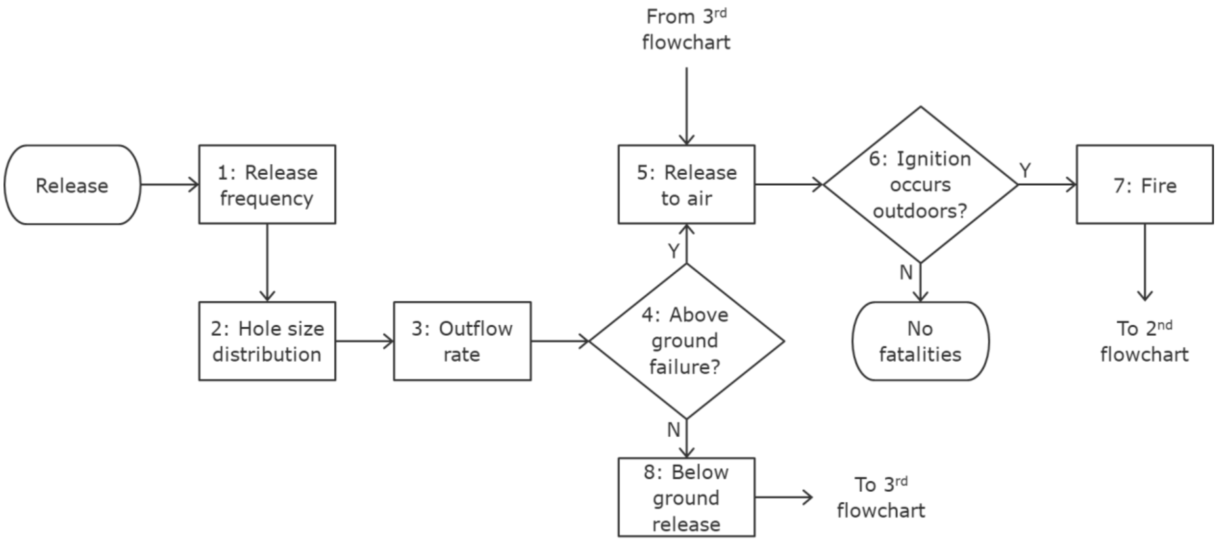


Figure 3 Structure of the QRA model: probability of leakage. (first flowchart)

The model starts with an outflow of gas, in which the failure frequency, the number and size of the leaks and the outflow quantity are determined in the first steps. Based on the materials, pressures and diameters used in the natural gas system, an estimate can be made based on incident data for the failure frequencies in the pipe fracture model. In the Netherlands, leaks and incidents in the distribution network are registered in the registration database 'Nestor'. The vast majority of these have been detected in the services and were classified as urgent. The nature of the leaks in terms of size and speed of development varies. Aging and corrosion are often smaller leaks that slowly increase while the failure of couplings, saddles, loosening of connections due to sinking soil, and fractures in brittle materials occur suddenly and directly result in a significant gas outflow. Due to differences in materials used, and layout of the distribution network, the data used in the model for the UK will not be applicable 1-to-1 for the Netherlands.

In the Dutch version of the QRA model developed for Hydelta, the following steps are followed based on Dutch historical leak data and the structure of the distribution network.

- The frequency of each leak is determined by pipe properties (such as pressure, diameter and construction details) and failure mode (interference and/or spontaneous). Each error mode is considered successively in the following steps.
- Based on the same data used in the first step, the probability is determined over a range of leak sizes. Specific data for the hole distribution is rare, in case of incidents it is often not registered how large the leak is. In the model, a set of assumptions has been made for natural gas, it is assumed that this distribution also applies to hydrogen.
- The outflow is determined for each leak size. The differences between the amount of hydrogen and natural gas released at a given pressure and leak size have been validated in practice in H21.

The amount of gas flowing from a leak is determined by the leak size, the gas pressure (30 mbar, 100 mbar, 4 bar and 8 bar), the back pressure that the outflowing gas experiences, whether and what kind of ground cover and top layer (tiles, clinkers, asphalt, grass) is used and how to gas can flow to other places (e.g. crawl space, basement, meter cupboard, house, ground surface).

From the statistical data for natural gas, the underground behavior and the chance of ingress to a basement can be approximated. There are models available that simulate the behaviour of flow through different soil types, indoors and in the open air. These can be used to obtain a good indication of the possible differences in behaviour between hydrogen and natural gas.

It is important to determine which soil types form the coverage of pipes and which cover is present, what volume basements, crawl spaces, meter cupboards and other indoor spaces have. Based on the experimental program of H21 (phase 1b), an adapted model has been developed for the travel of hydrogen through the soil towards a house. For the Dutch situation, it is possible to make adjustments to the typical layout of homes.

In Figure Figure 3, step 4, a distinction is made for outflow to the open air resulting in a fire, and underground ingress of the gas to closed spaces. This last step is further elaborated in Figure Figure 5. From the data described above, the model calculates what concentrations can occur depending on weather conditions (moist soil is less permeable; wind changes the size and concentration in the gas "cloud") and how these can be detected, for example during leak detection.

The ignition energy for hydrogen and natural gas varies with the concentration. The model estimates a probability of ignition based on the presence of potential ignition sources, but also on the duration of presence of persons in the home and their response to detecting a leak. On the one hand, the probability of the presence of residents determines the potential damage to persons, as described in the following flowchart (Figure Figure 4Figure 4). On the other hand, residents can reduce the risk of damage by, for example, taking action by smelling odorant, such as opening windows and doors and warning the emergency services.

Should an ignition lead to a fire, Figure Figure 4 the steps followed to determine the risk. From the heat load of the ignited hydrogen, in the event of a fire, the chance is determined that the house will also catch fire and that residents will be trapped in the house. Starting from the heat load, these probabilities are no different for hydrogen than for natural gas, so that the existing model for natural gas can also be applied here. The model assumes that 10% of the residents do not leave the house, which is a conservative assumption and whose sensitivity to the results should be further investigated. Because most fires as a result of excavation damage take place during the day, in practice this chance appears to be smaller.

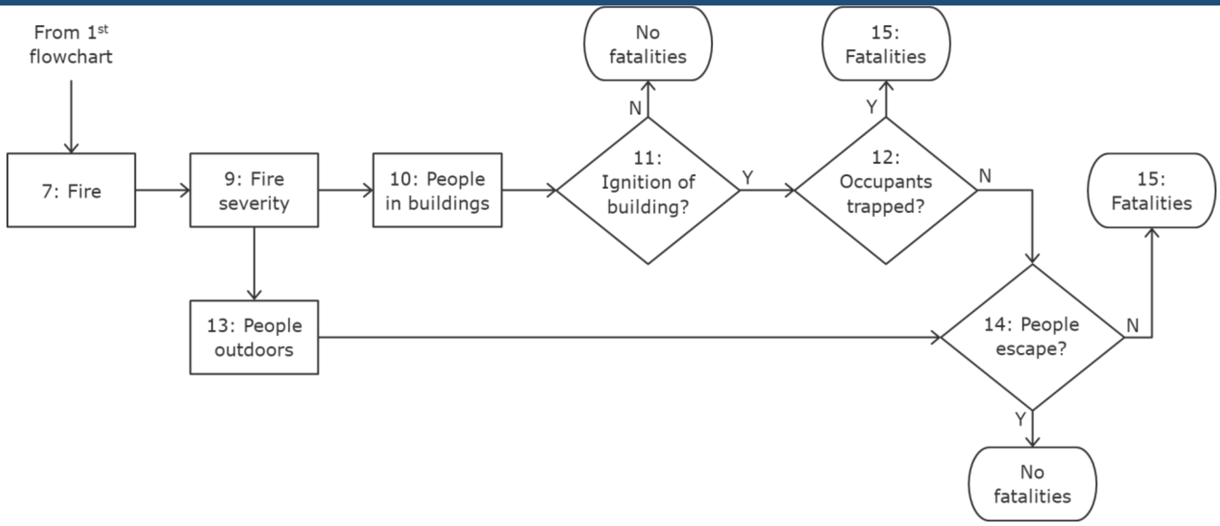


Figure 4 Structure of the QRA model: effects of fires. (second flowchart)

In the case of a gas flow, which originates outside the house and moves to a closed environment, there is a chance of an explosion. Figure Figure 5 shows the steps that are followed.

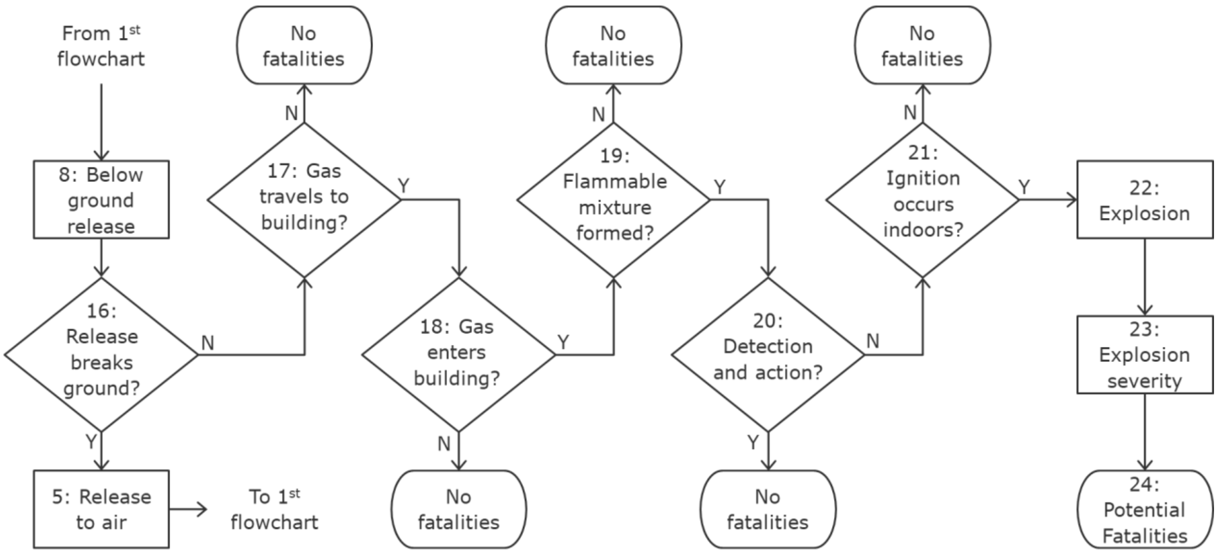


Figure 5 Structure of the QRA model: effects of explosions (third flowchart)

With the accumulation of hydrogen in the house (step 19), the effect of ventilation in the house and the migration of hydrogen to different rooms in the house is taken into account. Based on experimental research in H21, these models have been validated for hydrogen. Depending on the presence of people in the home, who can notice a leak by smelling odorized gas or alarms from sensors, the probability that potential ignition sources cause an explosion in the home is estimated. The concentration of hydrogen at the time of ignition is included in the models. Especially for explosions, the overpressure is very dependent on the concentration of hydrogen. Potentially, hydrogen explosions are much more harmful than natural gas explosions, if the mixture is stoichiometric. At lower concentrations (between 5 and 10 vol%) this does not have to be the case.

For explosions, the overpressure is included in the model. For hydrogen, it is larger than for natural gas. Based on the overpressure, an estimate is made of the number of victims, whereby a distinction is made in the type of home. As with the fires, this estimate for victims at a given overpressure for hydrogen is the same as for natural gas.

5 Continuation

In the study, a first test run was carried out for a QRA model for the Dutch distribution system based on a first set of assumptions for, in particular, the composition of the distribution network. A further validation of the input parameters as well as of the results will still be carried out. The results of the model will be compared with the practice for natural gas, after which statements can be made with more certainty about the risks of converting this grid to hydrogen. In the follow-up research within Hydelta 2.0, the input parameters and outcomes of the model will be described in more detail.

Effect of mitigating measures on hydrogen accumulation

6 Introduction and objective

Based on a survey with the Expert Assessment Group of the work package, consisting of, among others, the Dutch grid operators, we concluded that the accumulation of hydrogen in the event of leaks in homes and the associated influence of ventilation requires additional recommendations for the implementation of pilots in the short term.

Recently released reports from the UK describe experiments on the accumulation of hydrogen in (typically English) homes and translate these results into risk models. Based on the analysis of these reports, it is concluded that the accumulation of hydrogen in enclosed areas can potentially lead to greater risks compared to natural gas. In the context of the Hydelta project and the Dutch pilot projects under development, there is an urgent question of demonstrating the effectiveness of a number of mitigating measures, independent of other studies. In very well insulated homes, the ventilation rate is generally low. When the ventilation rate is greater than 5 times per hour, it may be considered "Good" (NPR7910-1). Since within homes the ventilation rate often does not exceed 2 times per hour, it should be considered moderate (NPR7910-1) or as "no ventilation" when the rate of refreshment is less than 1 time per hour (NPR7910-1). Insight into the effect of ventilation (or lack thereof) on the build-up of dangerous concentrations in the event of leaks is therefore necessary.

Mitigating measures proposed within pilot projects include H2 sensors, excess flow valves (EFV or “gas stoppers”) and sensors coupled to valves, but also ventilation openings between, for example, the meter cupboard and surrounding rooms. For each of these measures, it is recommended to demonstrate effectiveness in a controlled, independent environment before deploying them in pilots. In this way, stakeholders can be convinced of the effectiveness of the relevant mitigating measure.

The proposal is to make a distinction between large leaks, for which the excess flow valves is seen as a measure, and small leaks. The effectiveness of the excess flow valves in the event of a complete loss of gas pressure is demonstrated in the context of the 'Kenniscentrum Gasnetbeheer'[4] programme that is being carried out on behalf of Netbeheer Nederland. Hydelta's experimental programme focuses on small leaks (< 20 dm^3/h) with associated measures (sensors, ventilation openings, etc.).

The objective of the test program is to build a conditioned room, in which the various mitigating measures developed for small leaks in the home can be tested for effectiveness and functionality. The aim is to simulate a 'worst-case' scenario with the smallest possible ventilation rate (< 1 /hour as mentioned above). The experiments show how the ventilation rate in (adjacent) rooms has an effect on the build-up of concentrations in the event of small leaks and thus the effect of ventilation as a mitigating measure. Additional mitigating measures are, in addition to odorization of the gas, sensors that may be linked to valves to detect and stop the outflow.

7 Experimental set-up

To study hydrogen leaks, a standard office unit container was used that can be flexibly re-arranged in different rooms. In this way, the measuring system and layout of the container can be modified in an easy way in future research.

The internal dimensions of the container are 600 cm x 250 cm x 250 cm (lxwxh) with a working volume of about 36 m^3. The advantage of this office unit container is that all walls are flat and the unit is insulated, making the container easy to set up and uncontrolled external influences

[4] https://www.kenniscentrumgasnetbeheer.nl/

(temperature, wind, etc.) are kept to a minimum. External variables such as the outside temperature and wind speed, wind direction, solar radiation are measured during the experiments.

Figure 6 Photo of the container used in the experiments

7.1 Layout of the container

The purpose of the container is to be able to simulate hydrogen and methane leaks in indoors and to determine the outflow profile. The container can be flexibly arranged in different rooms. Wooden rasters are mounted to the walls, floor and ceiling, to be able to divide the interior space (both vertically and horizontally) into compartments. Against the wooden raster, plates can be mounted in order to divide the interior into compartments of 10, 20 or 30 m^3 (see also Figure 7).
In these compartments, objects to be studied such as a meter cupboard, kitchen cupboard, taps, etc. can be placed. The meter cupboard from the previous research for Alliander is reused [6]. Prior to the experiments, the container is heated to 20°C. If necessary, the container will be shielded from direct sunlight.

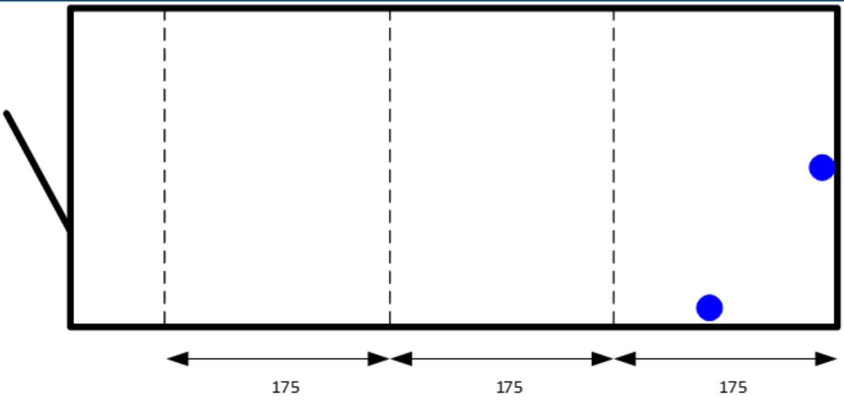


Figure 7 Layout of the container (top view) with the rooms of 10-20-30m3 to be set up (right to left) and with the location of the outflow (blue points)

To follow the accumulation of gas in the container, a matrix of 50 gas sensors has been placed that monitor the methane or hydrogen concentration at different places. The sensors are calibrated in the container by the supplier. During the tests, a number of sensors was randomly tested with calibration gases of known composition. These tests showed that the sensors do indeed measure the correct concentrations.

Brand	GDS Technologies XDI-F6
Type of sensor	Catalytic gas sensor
Methane measuring range	0-5 vol% (0-100% LEL)
Measuring range hydrogen	0-4 vol% (0-100% LEL)

Table 1: Data gas sensors

The gas sensors are distributed throughout the room using a steel wire grid (see Figure Figure 8). For each experiment, the location of the sensors can be adjusted.

Figure 8 Matrix of sensors on the inside of the container

7.2 Simulation of a gas leak

The scheme for simulating a gas leak in the container isFigure 99. During the experiments, the methane or hydrogen gas flows are controlled with a Bronkhorst EL-FLOW mass flowcontroller. The outflow of gas ranges between 0-20 dm^3/hour, well above the norm for natural gas leaks in a meter cupboard (5 dm^3/hour).[5] The maximum flow for hydrogen is 20 dm^3/hour and for methane 15 dm^3/hour. The gas flows into the container using a gas ball valve (Figure Figure 10). To ensure safe operation during the experiments, a limit value of 50%LEL has been assigned for 49 gas sensors. If this value is exceeded, the voltage of the mass flow controller will drop, causing the control valve (NC)[6] to close and stop gas flowing to the container. As an additional safety measure, a sensor has been placed that, independently of the other sensors, gives a signal to the NC valve when the LEL is exceeded by 60%. In both cases, the operator will be alerted so that the container can be vented. Furthermore, a pressure of 30mbar is used during the experiments.

[5] NEN 8078:2004

[6] The NC valve is a normally closed valve, that is, in the event of a power failure, the valve closes automatically

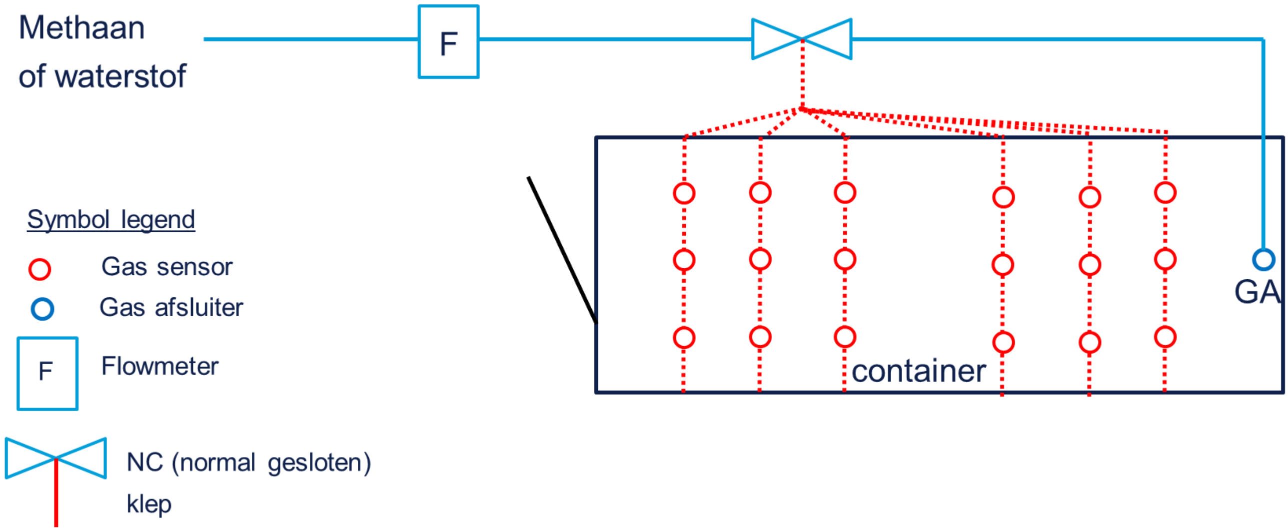


Figure 9 Schematic overview of gas outflow

Figure 10 Gas valve with opening for outflow

7.3 Ventilation

The ventilation in the container should be controlled in order to be able to make statements about the effect of ventilation on the accumulation of hydrogen in the adjacent rooms in the container. As shown in Figure Figure 11 , 6 ventilation openings (50 cm x 2 cm) have been installed on both sides of the container; three openings at a height of 200 cm and three openings at a height of 90 cm.

Figure 11 Photo of side of the container with the 6 vents

Wire ends are welded around the openings so that they can be easily closed with flange connections or provided with a plate with the desired outlet.

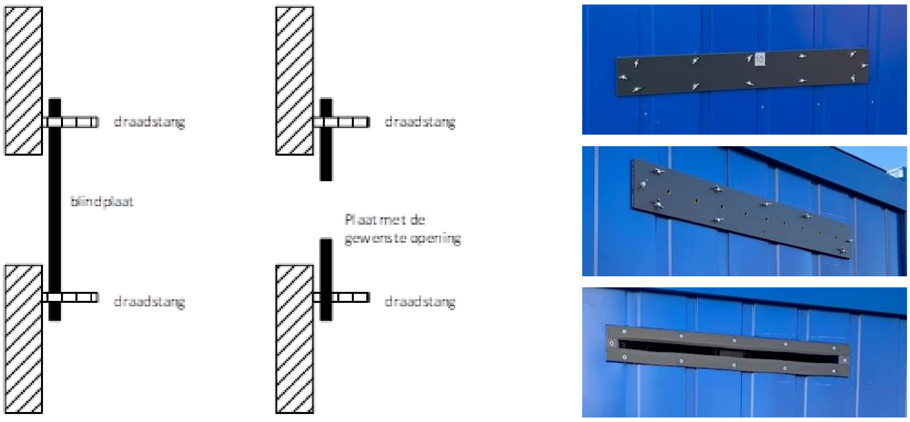


Figure 12 Vents; top to right: closed, with 9 holes and open

The vents are 50x2cm (lxb) at full opening. For a number of experiments, a plate was made with 9 holes with a diameter of 1cm.

8 Gas outflow experiments in container

The experiments are divided into two phases:

- Phase 1: measurements in the container without compartments (36 m^3), focusing on the functionality of the set-up (flow profile, LEL values and ventilation rate).
- Phase 2: the interior space is divided into two compartments of 10 m^3 and 26 m^3 by placing a partition wall with a door. This simulates a meter cupboard placed in the hall where the hall

is connected to a larger room. In both compartments and in the meter cupboard, the outflow profiles for hydrogen and natural gas are measured.

The table below shows an overview of the tests. The duration of the tests varied depending on the concentration achieved and possibility of venting (no outflow experiments can take place outside office hours).

Measurement series	**Setup**	**Type of gas**	**Leak size (dm^3/h)**	**Variation:**
Phase 1: 1.1-1.3 and 1.9	36 m^3	Methane	10-15	Determine ventilation rate at: no ventilation, vents open and door open. Initially at maximum leak size
Phase 1: 1.4-1.8	36 m^3	Hydrogen	15-20	Determine ventilation rate at: no ventilation, vents open and door open. Initially at maximum leak size
Phase 2: 2.1-2.7 and 3.6-3.7	10+26 m^3	Hydrogen	15-20	Meter cupboard door open/closed; grills meter cupboard open / closed; vents open/holes/closed
Phase 2: 3.1-3.5	10+26 m^3	Methane	10-15	Meter cupboard door open/closed; grills meter cupboard open / closed; vents open/holes/closed

Table 2: Overview of experiments

This chapter describes the measurements from both phases. In the next chapter, the different measurements are compared and further discussed.

8.1 Phase 1. Outflow experiments without compartments

8.1.1 Concentration profile in container

In this phase, the entire interior of the container is used. Figure Figure 13 shows the positions of the gas sensors in the container.

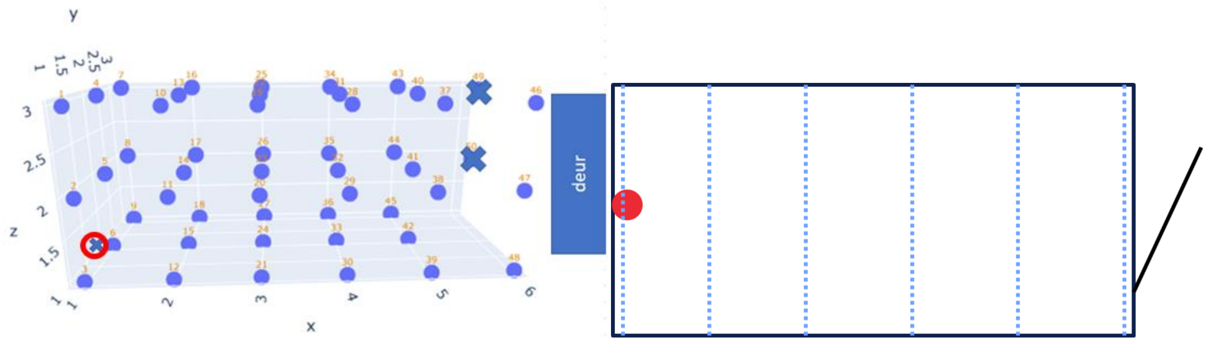


Figure 13 Left: position of the gas sensors in the container. Gas sensor 50 has been used as an extra protection (with limit value of 60% of the LEL). Right: top view of the gas sensors (blue dotted lines) and gas outflow point (red dot)

Before starting the outflow experiments, the container is conditioned at room temperature (20°C) using an electric heater. During the outflow experiments, the heating is switched off for safety reasons and the gas supply to the container is opened. At the end of the day, the gas supply is closed. The measurements continued until the next morning. Figure 14 shows the measurement results of the sensors from a hydrogen outflow experiment with a closed container (H_2 outflow of 15 dm^3/h). Each row shows the measurements of the 9 sensors in 1 plane in the x-direction, as shown in Figure Figure 13. The results show that the maximum hydrogen concentration is about 6% of the LEL (0.24 vol% H_2 in air) for leakage that lasts about 7.5 hours. For methane, similar values were found for the same leakage outflow (max. 0.22 vol% CH_4 in air) as shown in Figure 15 Measurement results of the sensors (methaan, outflow rate of 15 dm3/h, gas flow for ~7.5 hours on, closed container). The displayed time is in minutes.Figure 15. Figure 14 also shows the effect of switching off the gas supply to the container: the measured concentration decreases after switching off the gas flow.

To gain insight into the concentration build-up during the outflow experiments, the measurement results of the gas sensors and the location of the sensors in the container were combined using software (Python) into a 3D image with planes of equal concentration (isosurfaces). Figure 16 shows the result, a time series for a hydrogen outflow experiment from the moment the gas supply to the container is opened (left) and closed (right). After the gas supply is opened, the lighter gas moves upwards and disperses towards the back of the containes.

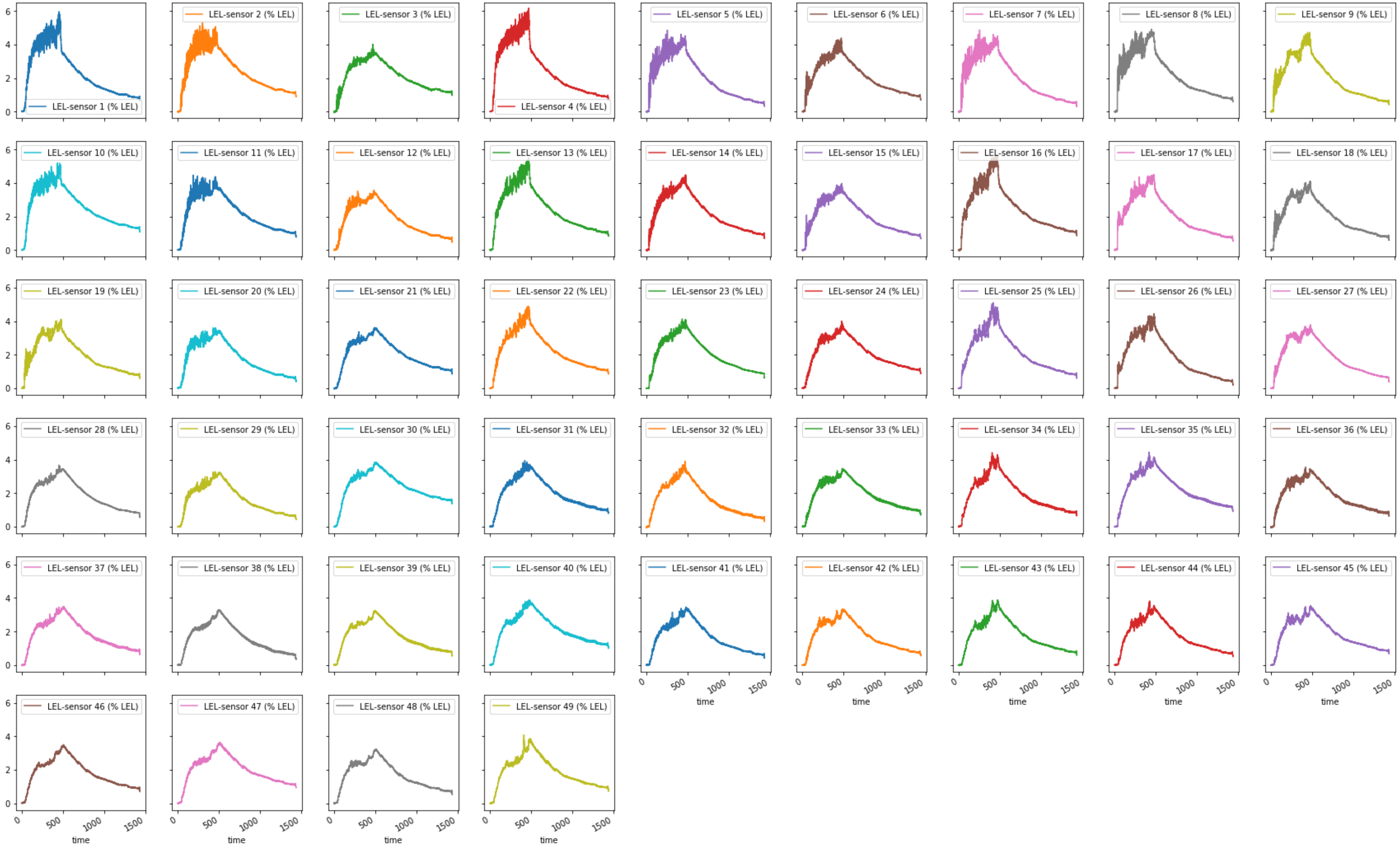


Figure 14 Measurement results of the sensors (hydrogen, outflow rate of 15 dm³/h, gas flow for 7.5 hours on, closed container). The displayed time is in minutes.

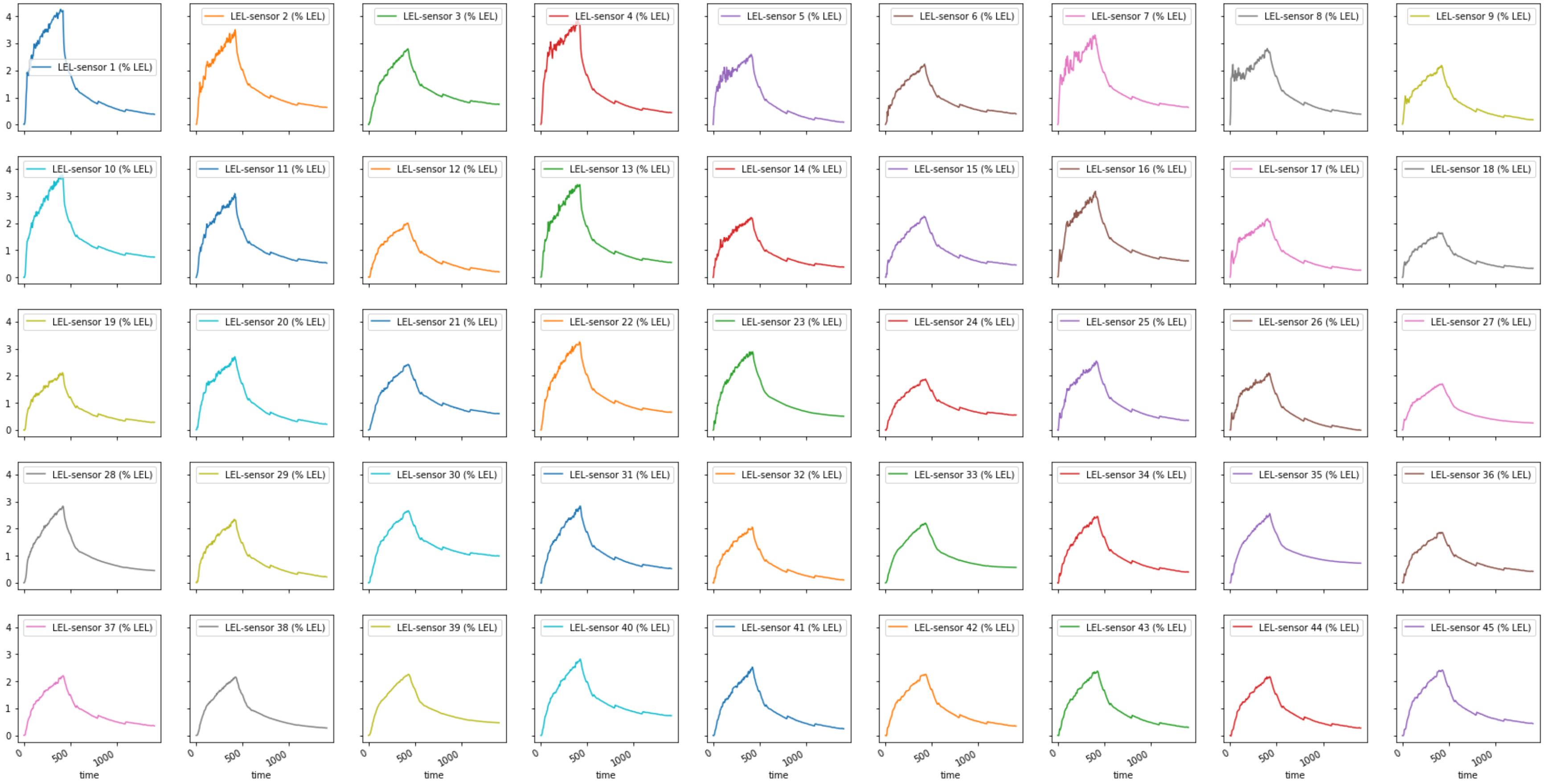


Figure 15 Measurement results of the sensors (methaan, outflow rate of 15 dm3/h, gas flow for ~7.5 hours on, closed container). The displayed time is in minutes.

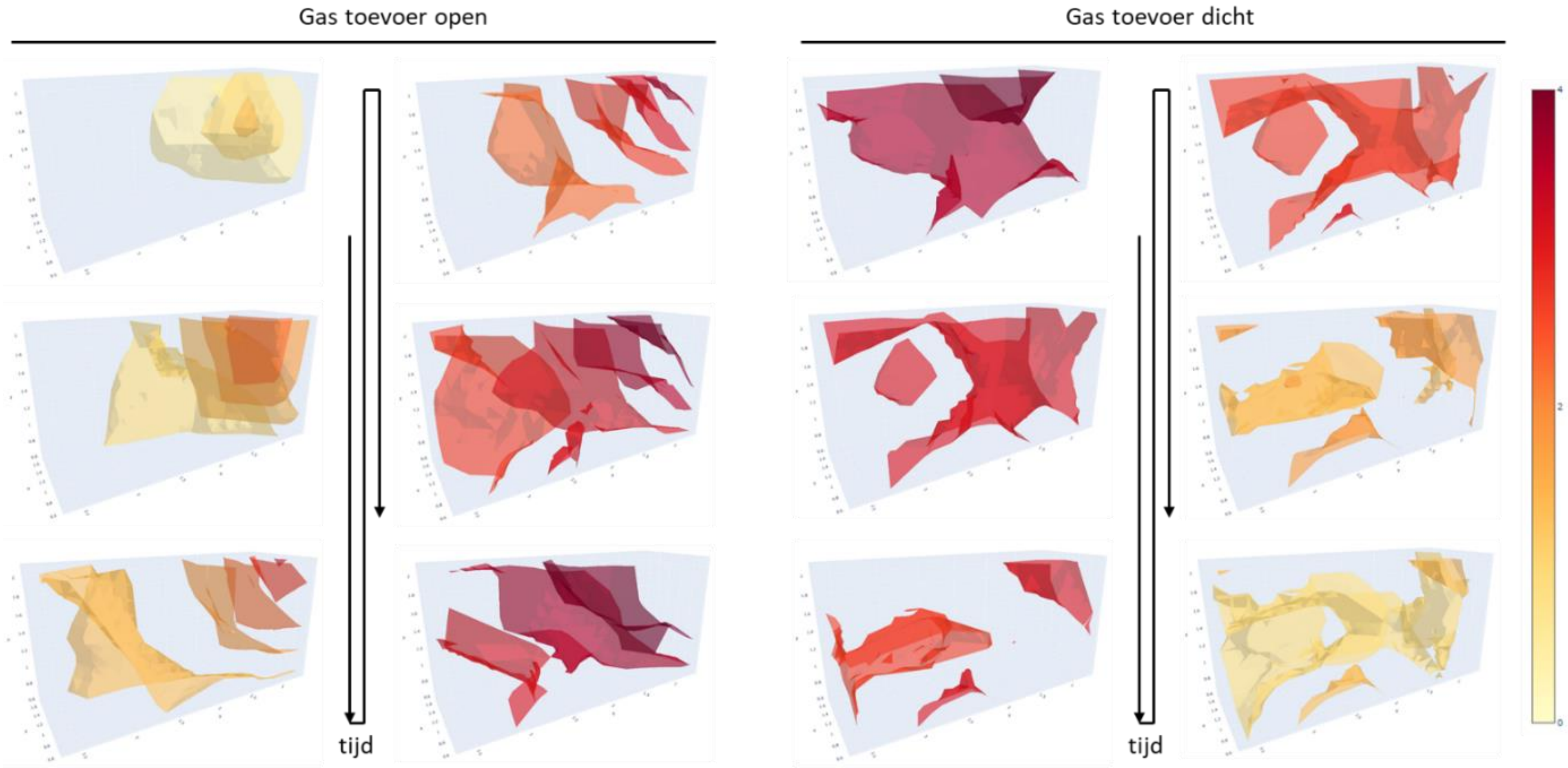


Figure 16 Flow profile of hydrogen as isosurfaces in a closed container with the gas supply to the container open (left) and closed (right). Outflow rate of 15 dm3/h, with the gas flow on for 7.5 hours. The outflow location is located in the back right of the container.

The moment the gas flow is closed, stratification occurs in the gas concentration, at with the highest hydrogen concentration is found at the top of the container. The concentration of gas then slowly decreases throughout the container depending on the degree of ventilation. Without opening the vents or the door, the gas seems to escape the container in the middle, in the front and back of the container the concentration remains a fraction higher. Similar trends are observed in the tests with methane, no visible difference in stratification is seen between the methane as hydrogen situation.

8.1.2 Ventilation rate

Figure 14 already shows that the container used is not completely airtight. It is therefore inevitable that there is a (small) influx of outside air. To determine how large this flow is, the ventilation rate is determined by stopping the gas supply and monitoring the decrease of the concentration. The ventilation rate is calculated on the basis of a calculation model [7], originally intended for the description of the exhaust of flue gases in an air treatment room. This report uses a simplified version of the model, assuming that the gases mix homogeneously with the air. In that case, when the gas supply to the container is stopped, the gas concentration will decrease according to:

$$Cg(t) = Cg(t_s)e^{-Rt} + Cg_f \qquad (1)$$

Wherein:

- $Cg(t)$ = concentration at time t [% LEL]
- Cg_f = final concentration [% LEL]
- t = time [hour]
- t_s = time of stopping gas supply [hour]
- R = ventilation rate [1/hour], this is the number of times per hour that the air in the container is refreshed

Figure 17 shows the concentration process after the opening and closing of the gas supply for the 50 sensors (same conditions as inFigure 14). Even though all sensors start with the same initial value, we observe a variation in the concentration between the sensors. At night, the container cooled down (10 degrees or more). The temperature dependence of the sensors differs per sensor, which results in differences in measured values. It is advisable to keep the temperature of the room as constant as possible in a next phase of the experiments (HyDelta 2) in order to minimize these differences by keeping the heating on during the measurements. However, it should be noted that the differences are very small (1% LEL spread, or 0.04 vol% H_2 in air). These differences have also been observed for the methane outflow experiments. [7]

[7] Later additional tests confirm that if the heating is turned on again at the end of the described experiment, the measurements of the various sensors will converge (around 0%LEL). However, the dependence on the temperature seems to be different for each sensor.

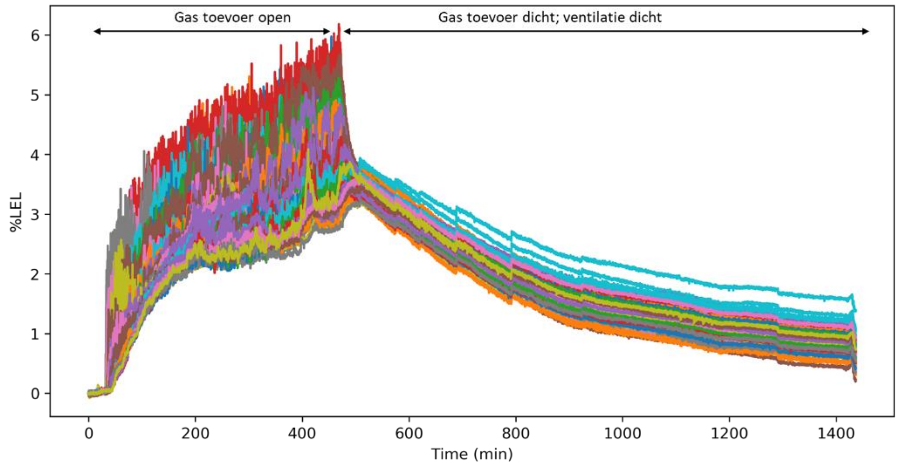


Figure 17 Measured concentration profiles of a hydrogen outflow (15 dm^3/h) in a closed container with the gas supply to the container open and closed. The gas supply was open for 7.5 hours

In Figure Figure 18 , the concentration course as a function is time (above). This gradient is fitted to equation (1) to determine the ventilation rate R.

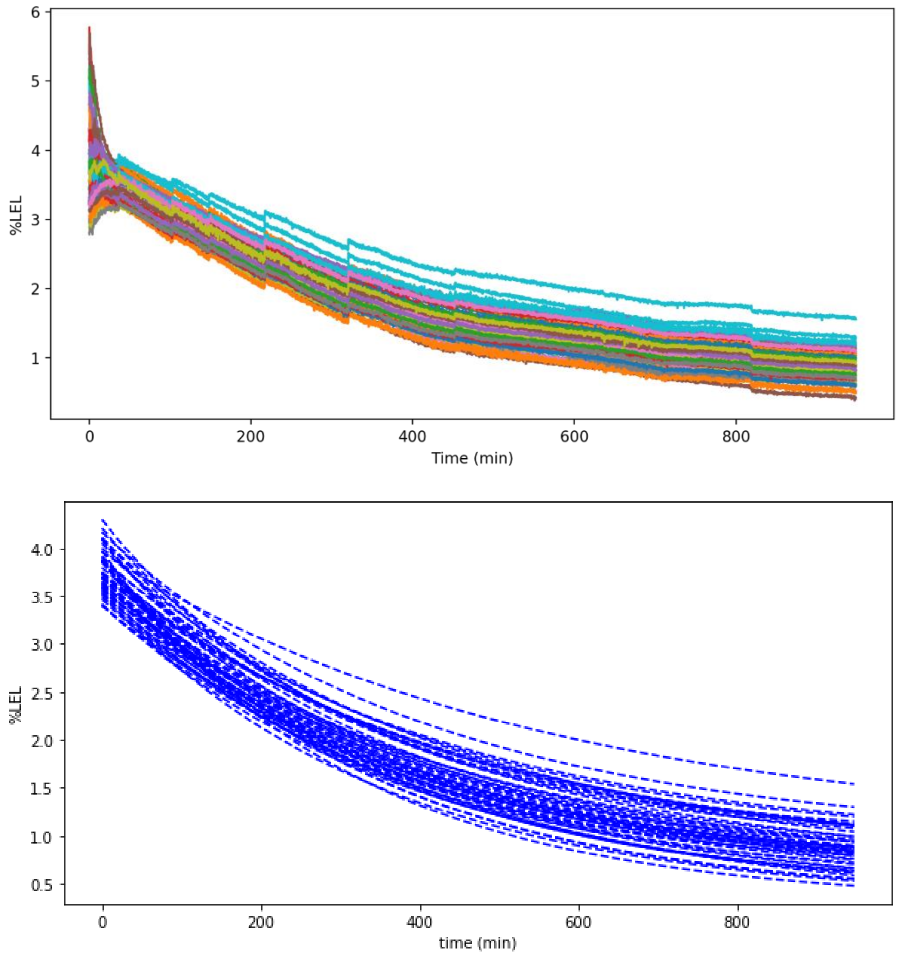


Figure 18 Measured hydrogen concentration gradient (top) and fits according to equation (1) (bottom) . This is a hydrogen experiment in a closed container without ventilation.

For a similar experiment with the same outflow (15 dm^3/hour) with methane, the concentration build-up and decrease is shown in Figure 19.

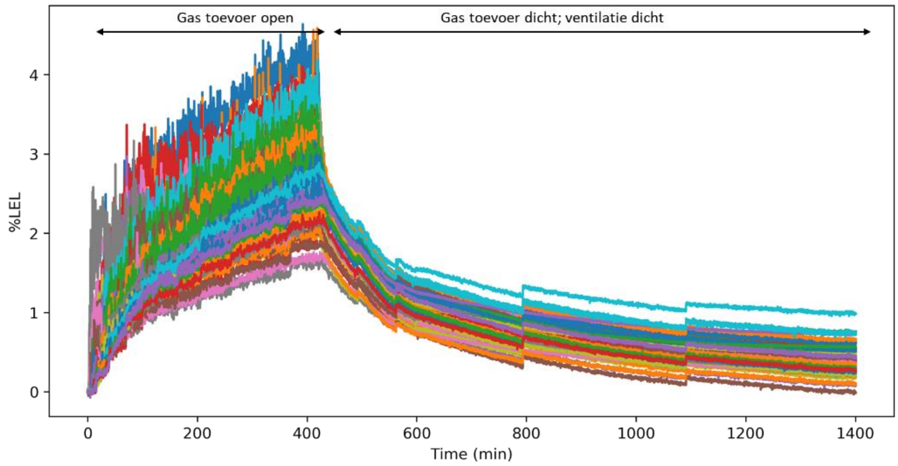


Figure 19 Measured concentration profiles of a methane outflow (15 dm3/h) in a closed container with the gas supply to the container open and closed. The gas supply was open for ~7.5 hours.

The results per sensor for hydrogen and methane are shown in Figure Figure 20. It is striking that in these tests (carried out twice for both natural gas and hydrogen) the ventilation rate of methane is higher than that of hydrogen. This is in contrast to the expectation that hydrogen will diffuse faster due to a higher diffusion coefficient. Also, with methane, the ventilation rate for the sensors further away from the leak (sensors 30-50) seems to be lower than for sensors closer to the leak. A direct explanation for this phenomenon has not been found. A possible cause of this difference could be the influence of the wind on the container during measurement, which allows more natural ventilation in the container and thus flow of the gas in the room. The assumption for equation (1) of a homogeneous distribution of the concentration is not entirely true in these cases, resulting in a deviation due to a different initial concentration per sensor. This needs additional research in follow-up research. Nevertheless, in both cases the ventilation rate is very low and in the same order of magnitude.

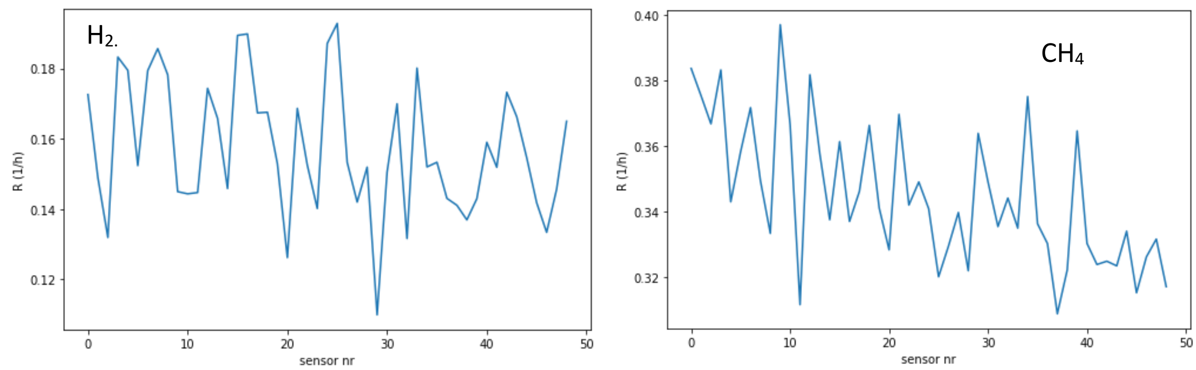
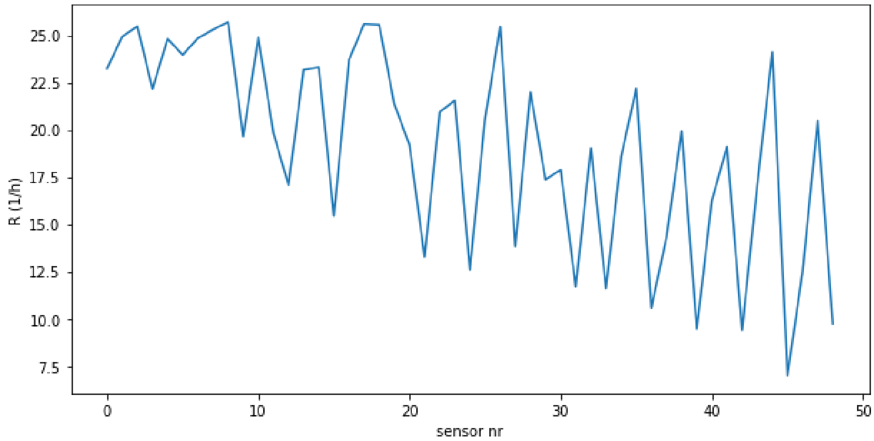


Figure 20 Calculated ventilation rate for a hydrogen outflow (left) and a methane outflow (right) for a closed container (outflow rate of 15 dm^3/h).

Next, we looked at the ventilation rate when opening the door in the container. The result for hydrogen is shown in Figure Figure 21. Also in this measurement, a lower ventilation rate is measured at the sensors further away from the leak and in this case closer to the opening of the door.



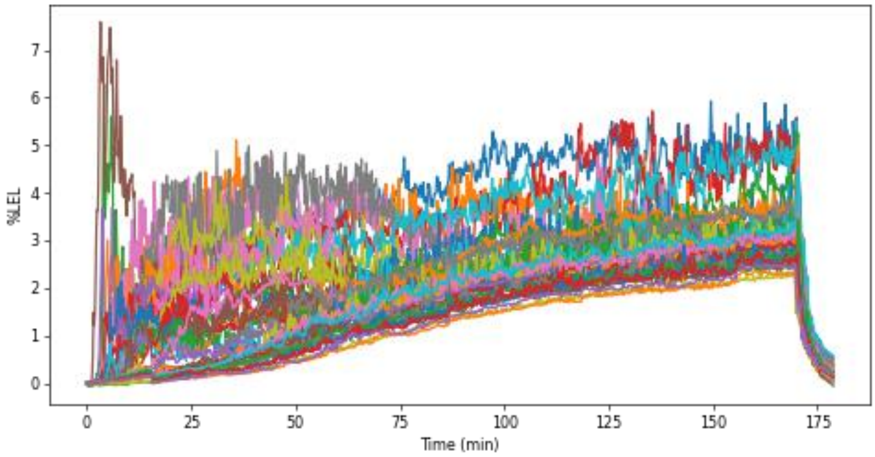


Figure 21 Calculated ventilation rate for a hydrogen outflow (15 dm³/h) for a container with an open door. The figure below shows the build-up and decay of the concentration during gas outflow and opening of the door respectively.

The ventilation rate with an open door in the container is two orders higher than with a closed door. Opening a door can be a safe method to vent the room. The concentration in these cases drops to almost 0% in the order of minutes. In the experiment with natural gas in which the door was opened, a similar ventilation rate was found.

Finally, we looked at the ventilation rate when one of the vents on the side of the container is opened. First, the hydrogen gas flow to the heated container is opened (20 dm^3/hour) until about 5% of the LEL is reached. The gas supply is then closed and vent nummer 8 (see Figure Figure 22) is opened.

Figure 22 Numbered vents. In the described experiment, vent 8 is opened (right-middle-top)

The hydrogen concentration over time measured by the installed sensors is shown in Figure Figure 23 . Based on the decrease in concentration and following equation (1), the ventilation rate was determined (see Figure Figure 24).

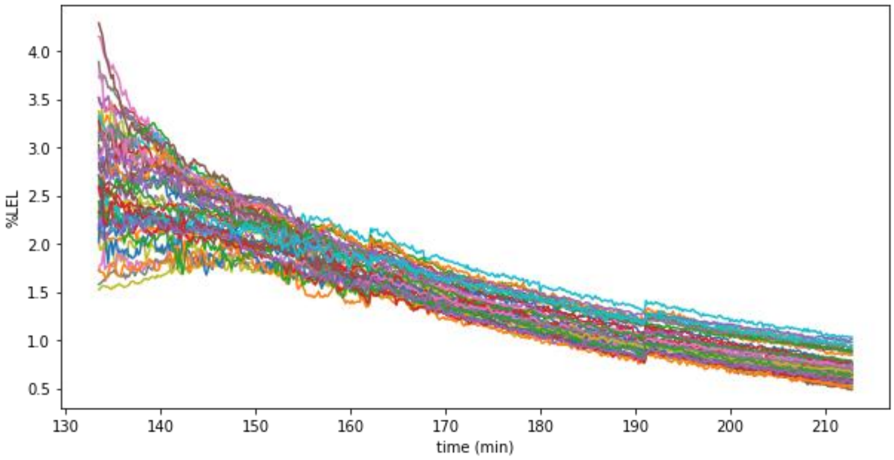


Figure 23 Measured hydrogen concentration after opening vent no.8 (door closed).

The ventilation rate value obtained is between a closed container (Figure Figure 20) and an open door (Figure Figure 21). To determine the effect of opening the vent on the concentration build-up , the hydrogen gas flow to the container was opened again.

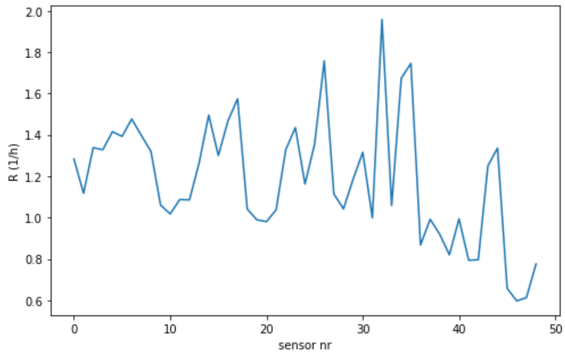


Figure 24 Calculated ventilation rate R for a hydrogen outflow (15 dm³/h) in the container with vent no.8 open (door closed).

Figure Figure 25 shows that the hydrogen concentration in the container increases again after reopening, but that the maximum concentration by opening the ventilation opening is lower than the value in a closed container. At a ventilation rate of about 1, which corresponds to poorly ventilated homes, the build-up of the concentration of hydrogen is therefore very low. The difference between the situation without ventilation (R= ~0.2 /hour) and with poor ventilation (R = ~1 /hour) is that in the first hour after opening the flow the concentration is about a factor two lower. In the experiments, even without ventilation, no equilibrium situation is achieved in the entire container in the time available for the experiments (max 8 hours).

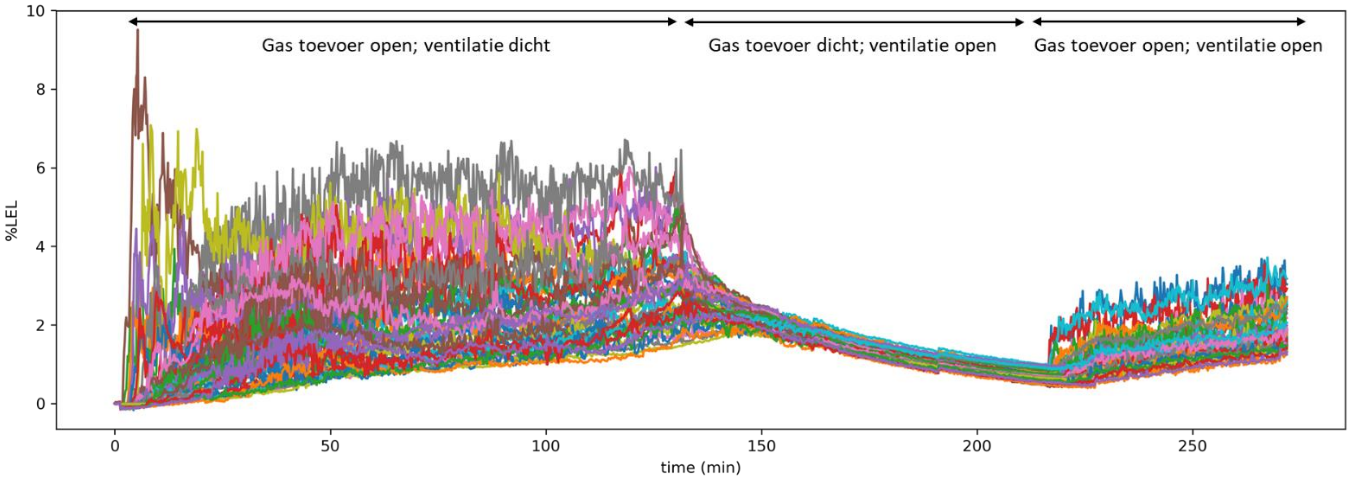


Figure 25 Measured concentration profiles of a hydrogen outflow (20 dm3/h) with and without vents open.

8.2 Phase 2: Outflow experiments with meter cupboard, 10m3 and 26m3 compartments

In the second phase, the interior is divided into two compartments of 10 m^3 and 26 m^3 by placing a partition wall with a door. This simulates a meter cupboard placed in the hall where the hall is connected to a larger room. The meter cupboard is placed in the smallest compartment and equipped with three sensors (down, middle and top of the meter cupboard). The room of 10 m^3 contains 24 sensors, the remainder sensors are located in the room of 26 m^3. Figure Figure 26 shows the interior of the comparted container and the locations of the sensors.

Figure 26 Photos of the setup for phase 2.

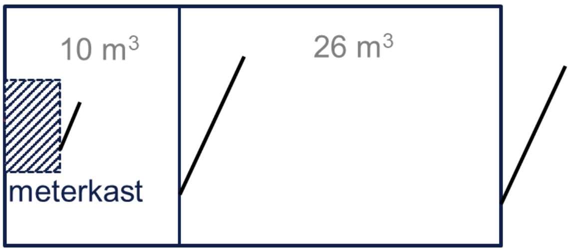


Figure 27 Top view of container with layout for phase 2 experiments

In this phase, the gas outflow takes place in the meter cupboard and the effect of the meter cupboard door (open/closed), ventilation grilles in meter cupboard door and the effect of ventilation in the container on the concentration in the various rooms (meter cupboard, 10m^3 and 26m3 space) is examined. In the experiments, the door between the two compartments is kept closed.

8.2.1 Distribution from the meter cupboard

Figure Figure 28 shows the measured hydrogen concentration profiles of the sensors in the meter cupboard and in the 10 and 26 m^3 compartment. The door of both the meter cupboard and the door between the 10m3 and 26m3 compartment were closed during the experiment. When the hydrogen supply is opened (20 dm^3/hour), the concentration in the cabinet increases towards the 25% of the LEL (0.8 vol% gas in air). In line with the observations in phase 1, a higher concentration at the top of the cabinet can be observed. The concentration build-up at the top of the meter cupboard flattens over time and reaches a plateau value. Remarkable are the values of the lower sensor: after an initial comparable increase as the two other sensors higher in the meter cupboard, the concentration at the bottom of the meter cupboard decreases over time. The hydrogen concentration in the meter cupboard measured by the upper sensors equalizes because hydrogen travels to the 10 m^3 space which can be seen from the increase in the hydrogen concentration of the sensors in the 10m3 compartment. It is likely that the hydrogen flows through the upper ventilation grille in the meter cupboard door to the other room, while air from outside the meter cupboard is drawn in through the lower grille. This was also observed in previous research. [6] The profile of the concentration in the 10m^3 compartment is shown inFigure 29. This clearly shows that the concentration builds up from the top of the room to the bottom. Due to this (ventilation) flow in the meter cupboard, a lower concentration is measured at the bottom of the meter cupboard. The sensors in the 26m^3 compartment did not detect hydrogen during the experiment. The moment the gas supply is closed, a sharp decline in the hydrogen concentration can be observed in the meter cupboard. The sensors in the 10 m^3 compartment also show a decrease in the hydrogen concentration. At the end of the experiment, the door of the container is opened and the concentration quickly drops to 0 %LEL.

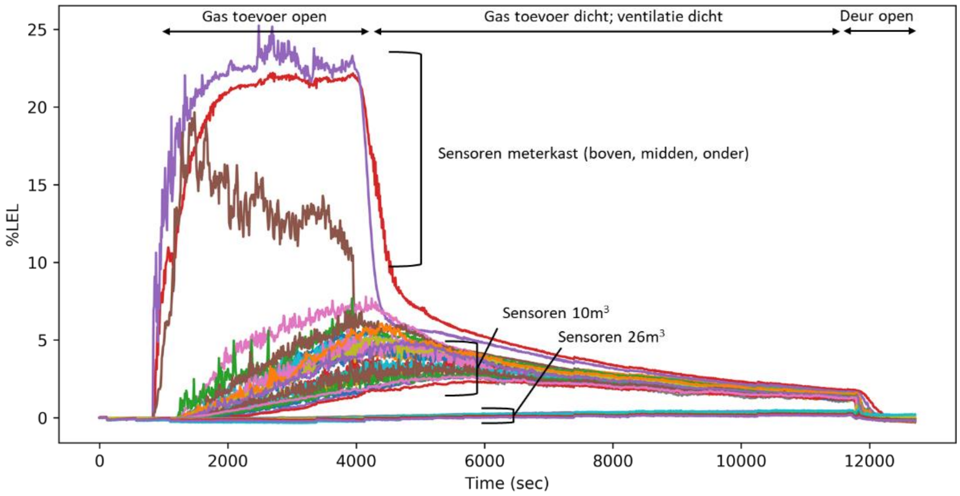


Figure 28 Measured concentration profiles of hydrogen when the meter cupboard door is closed, but the grills in the meter cupboard door are open (hydrogen outflow of 20 dm3/hour).

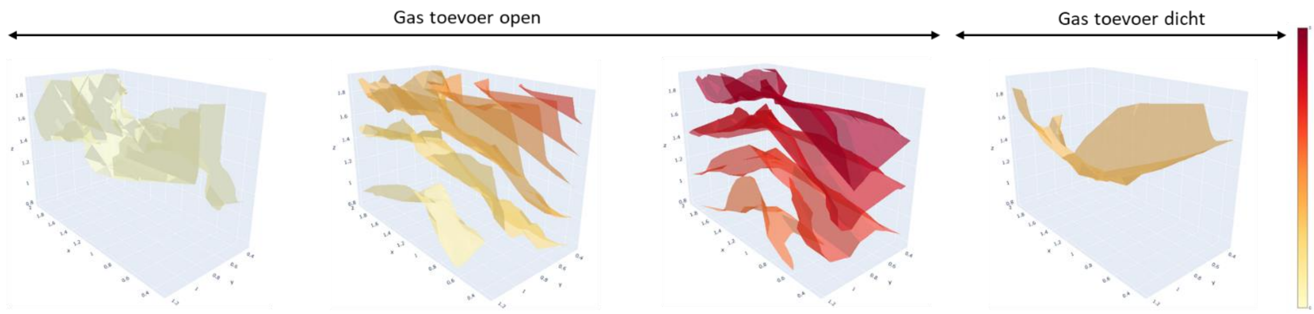


Figure 29 Concentration profiles in the room next to the meter cupboard (10m3). The color scale is displayed in %LEL. The meter cupboard is located at the back right of this room (long side).

The tests with methane show similar trends as with hydrogen (Figure Figure 30):

- Increase in methane concentration in the upper part of the meter cupboard
- Flattening of the methane concentration due to flow to the 10m^3 compartment
- Rapid decay at the moment the gas supply is closed.

Also in these experiments, the top and middle sensors in the cabinet measure the highest concentrations, while the lower sensor shows a much lower concentration. This can be explained by the stratification that occurs in the meter cupboard, but also in the space next to it. The methane 'escapes' the meter cupboard at the top and then accumulates at the top of the adjacent room. In comparison with hydrogen, it is striking that the concentrations of methane at the bottom of the meter cupboard remain much lower.

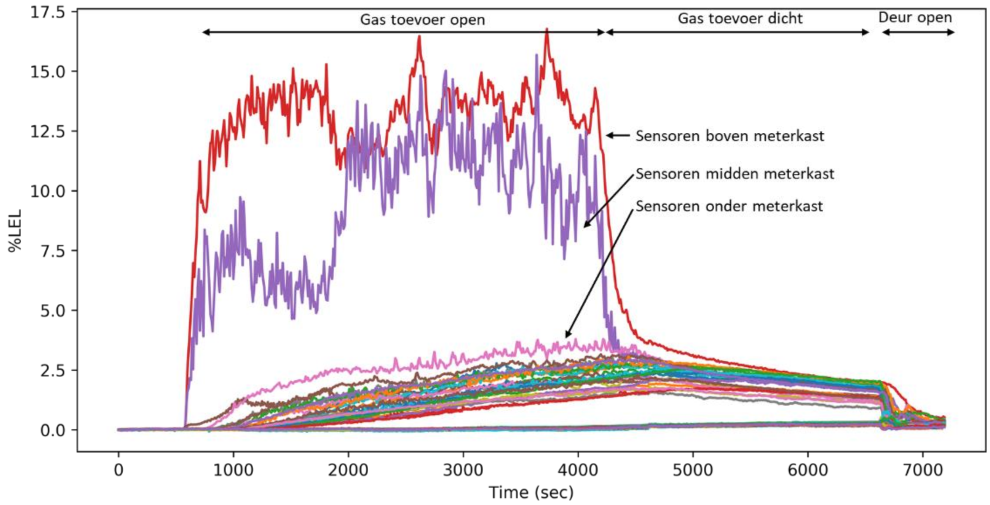


Figure 30 Measured concentration profiles of methane with the meter cupboard door closed (15 dm³/h).

Based on the decrease in hydrogen and methane concentrations after the gas supply was closed, a ventilation rate of the space of 10m^3 has been determined. In these experiments, there is no ventilation in the room (vents and doors closed) and the gas will disappear through natural ventilation through crevices. The measurements of the sensors in the meter cupboard and the 10m3 compartment were used. The results are shown in Figure Figure 31 and show an equal ventilation rate for both gases. The ventilation rates in both cases are less than 1 time per hour, lower than in the measurements in phase 1 in the 36m^3 space. This could be explained by the fact that, in addition to the ventition from the container, the gas also disappears into the compartment of 26m^3. Figure 28 and Figure 30 show a (very slight) increase in the concentration of the sensors in this room, which confirms this assumption. Nevertheless, it can be concluded that the measured ventilation rates represent a 'poor' ventilation of the room next to the meter cupboard and that by placing grills in the door of the meter cupboard, it can be prevented that the concentration in the meter cupboard for these leaks comes close to the LEL.

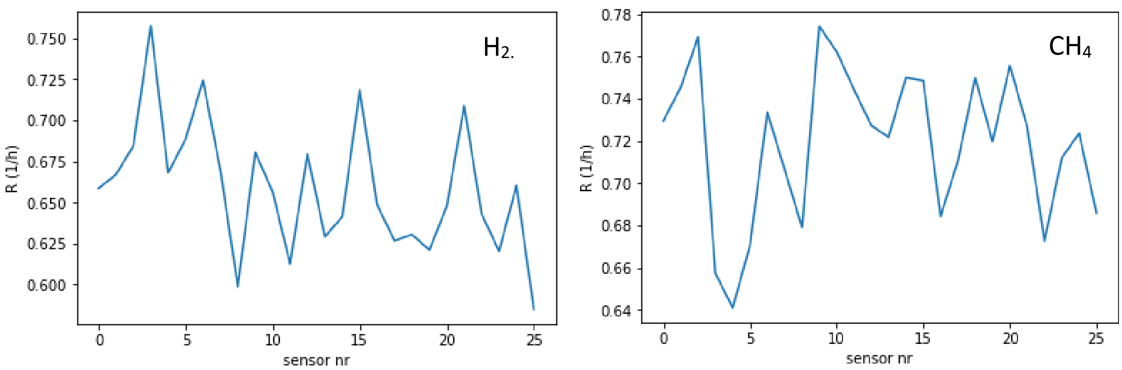


Figure 31 Calculated ventilation rate for hydrogen (left) and methane outflow (right) in the meter cupboard and the adjacent room.

8.2.2 Effect of ventilation grilles in meter cupboard door

In the next experiment, the ventilation grilles in the meter cupboard door (see also Figure Figure 26) were closed by tape. During the experiment both the meter cupboard door and the door between the 10m^3 and 26m^3 were kept closed. Figure Figure 32Figure 32 shows the hydrogen concentration over time for the sensors in the meter cupboard, 10 m^3 and 26 m^3 compartments. After opening the

hydrogen supply (20 dm^3/hour), the hydrogen concentration in the meter cupboard increases rapidly. Because the ventilation grilles are closed, the maximum measured hydrogen concentration in the meter cupboard is higher than with open grilles (43% of LEL with closed grilles and 24% of the LEL with open grilles in Figure 28). This result shows that the ventilation grille has a major influence on concentration build-up in the meter cupboard. In this situation, the lower sensor in the meter cupboard shows a similar profile as the top two sensors. In this test, there is no draught through the meter cupboard as seemed to be the case in the tests with open grills. Nevertheless, the concentration for all three sensors flattens out at a value of around 40 % LEL. No flammable mixture was observed in the meter cupboard even when the ventilation grilles are closed by tape.
The sensors in the $10m^3$ compartment also show an increase in the hydrogen concentration over time (max 8% of the LEL) suggesting that part of the hydrogen escapes to the 10m3 room (through cracks and holes). No hydrogen was observed in the 26m3 compartment in this experiment either. After closing the hydrogen supply, a rapid decrease in the hydrogen concentration can be observed by all sensors. At the end of the experiment, a second sharp drop can be observed when the doors in the container are opened.

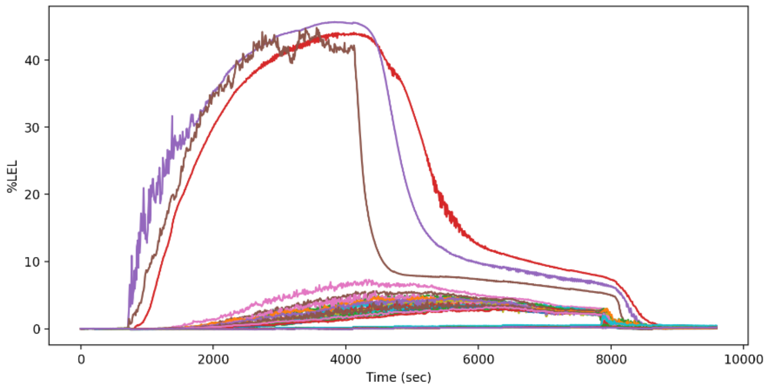


Figure 32 Measured concentration profiles of hydrogen in which the ventilation grilles in the meter cupboard door were closed. After about 4000 sec the supply is closed (20 dm^3/hour), after about 8000 sec the door is opened.

8.2.3 Effect of ventilation in the container

To study the effect of the ventilation in the container on the concentration accumulation, a ventilation opening on the side of the container was opened. The experiments considered two situations: a fully open vent and one in which the vent is equipped with a slot with 9 holes. Figure Figure 33 shows the ventilation opening used with a slot with holes.

In the first experiment, the vent with holes was placed and the hydrogen concentration profile in the container was measured. The meter cupboard door and the door between the two compartments are kept closed. The ventilation grilles in the meter cupboard door were kept open during the experiment. Figure Figure 34 shows the hydrogen concentrations measured by the sensors.

Figure 33 Photo of ventilation opening in the container with a slot with 9 holes.

The same trends as with a closed vents in the container can be observed (see Figure Figure 28):

- Increase in concentration in the upper part of the meter cupboard
- Flattening of the concentration due to flow to the $10m^3$ compartment
- Rapid decrease at the moment the gas supply is closed.

The maximum measured hydrogen concentration also corresponds fairly well with the value found with experiments with closed vents, respectively 28% and 24% of the LEL. A difference with the situation without ventilation in the room of $10m^3$ is that the concentration at the top of the meter cupboard, decreases over time, where it remained constant in the situation without ventilation. A (small) ventilation in the room next to the meter cupboard seems to cause a slightly lower concentration in the meter cupboard. This is in line with expectations: the ventilation allows the hydrogen to escape faster from the container.

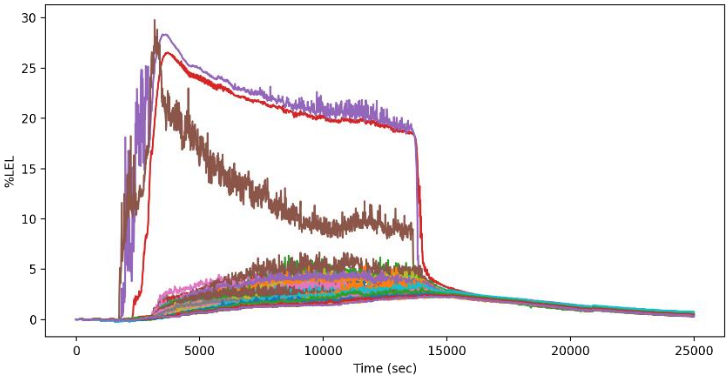


Figure 34 Measured concentration profiles of hydrogen where the meter cupboard door is closed and the ventilation opening in the container is provided with a slot with 9 holes (hydrogen outflow of 20 dm3/hour).

Figure 35 shows the measured concentration profile when the meter cupboard door is opened during the experiments. All sensors in the meter cupboard and the 10m3 compartment show an increase in the hydrogen concentration, but with a lower maximum value than when the meter cupboard door is closed (14% of LEL when the door is open).

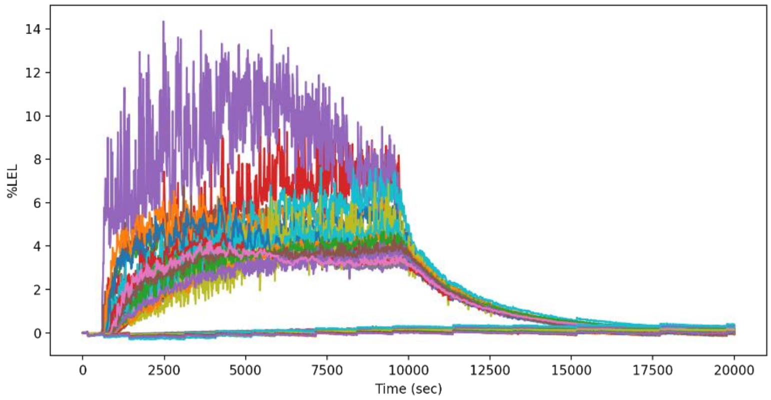


Figure 35 Measured concentration profiles of hydrogen in which the meter cupboard door is open and the ventilation opening in the container is provided with a slot with 9 holes (hydrogen outflow of 20 dm3/hour).

In a subsequent experiment, one vent of the container was fully opened as well as the meter cupboard door. Also in this situation, the maximum hydrogen concentration is lower than with a closed door as shown in Figure Figure 36 . When the gas supply is closed, the concentration decreases more quickly due to the larger ventilation opening.

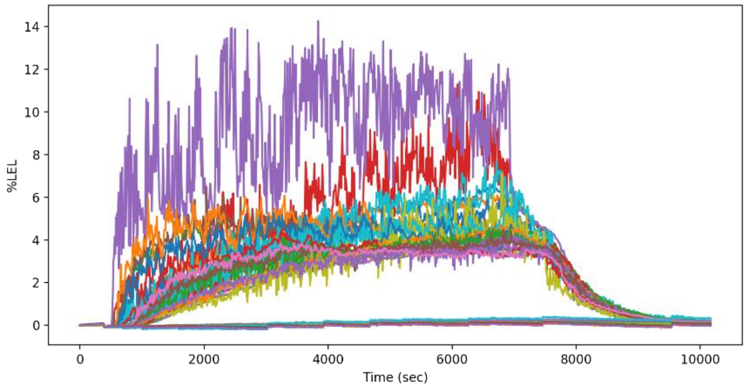


Figure 36 Measured concentration profiles of hydrogen in which the meter cupboard door and ventilation opening in the container is fully opened (hydrogen outflow of 20 dm3/hour).

To determine the effect of the ventilation opening (with and without slot), the ventilation rates for the three situations have been determined. Figure Figure 37 shows an overview of the calculated ventilation rates. The full opening of the vent gives a 10x higher ventilation rate in the room. The calculated ventilation rate (~6/hour) can be qualified as good ventilation in a home. Opening a vent with 9 holes, results in a ventilation rate of about 1.7 /hour (moderate ventilation) and is therefore a factor of 3 better than no ventilation and roughly a factor of 3 worse than a fully opened grid. This means that the test container can be used for representative measurements with ventilation rates that also occur in typical homes.

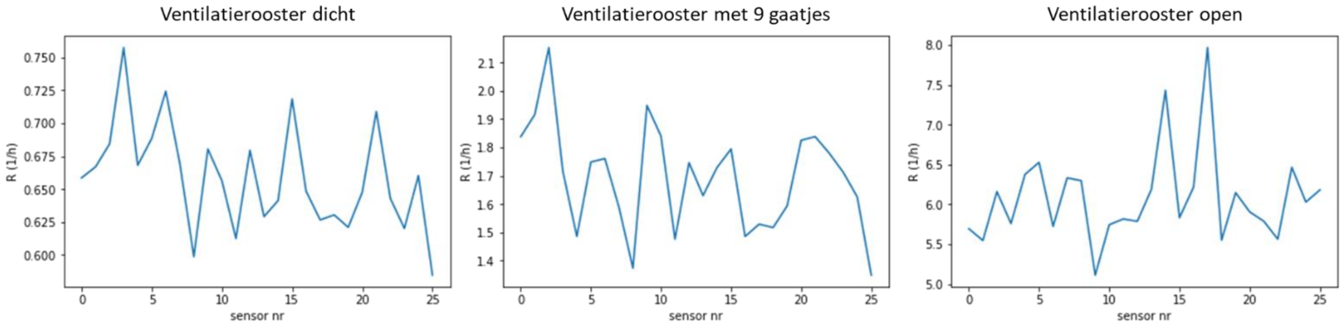


Figure 37 Calculated ventilation rate for hydrogen outflow of 20 dm3/hour in space of 10m3 with different ventilation opening settings.

9 Discussion of the results of the experiments

9.1.1 Build-up of concentrations in the large space remains well below the LEL

In this study, outflow experiments were carried out in an empty container and a container equipped with a meter cupboard in a 10m^3 compartment. The results of the measurements show that for outflow rates up to 20 dm^3/hour, all measured hydrogen concentrations remain below 100% of the LEL.

For the experiments in the un-comparted but closed container (phase 1), the following trends could be observed for both hydrogen and methane:

- After opening the gas supply, the gas mainly travels via the top of the container.
- After closing the gas supply, a layering occurs in which the highest concentration is found at the top of the container.

If the average concentration, averaged over all sensors, is plotted against time, in the various experiments in which no ventilation was applied, it appears that it flattens but does not yet reach a plateau value. Due to the maximum time for the outflow tests in the empty container (~8 hours), no plateau value was found in these experiments. The relatively small outflow in combination with the volume of the container ensures that the average concentrationin the container rises only slowly, even with no ventilation. Theoretically, it can be estimated what the final concentration will be given a certain outflow, volume of the container and ventilation rate. The flattening can theoretically be approximated by equation (2).

$$\frac{Cg(t)}{LEL_{H2}} = \frac{Q_g}{Q_g+VR}\left(1-e^{-\frac{Q_g+VR}{V}t}\right) \quad (2)$$

With:

$Cg(t)/LEL_{H2}$ = concentration at time t [% LEL]

Q_g = gas supply [m^3/h]

t = time

R = ventilation rate [1/hour]

V = volume of space [m^3]

In Figure Figure 38 ,three measurements with an outflow of 20 dm^3/h and a measurement with an outflow of 15 dm^3/hour are plotted against the approximation according to equation (2). From the theoretical approximation, we learn that the stationary concentration ($Q_g/(Q_g+VR)$) is 6.7 %LEL and 5.0 %LEL respectively for an outflow of 20 dm^3/h and 15 m^3/h. The curve fit is fitted with a ventilation rate of 0.2 /hour and the volume of the empty container. For smaller leaks, the final concentration will be even lower. Therefore, it can be concluded that in case of leaks up to 20 dm3/hour combined with a very limited ventilation rate of 0.2 /hour, concentrations near the LEL are never reached.

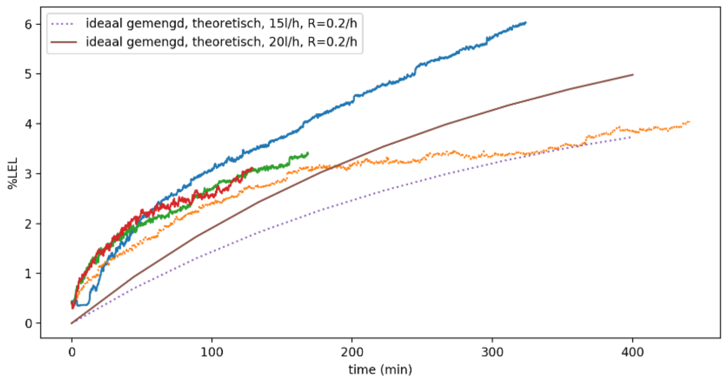


Figure 38 Mean concentration build-up for hydrogen (20 dm³/h and 15 dm³/h) for both the different measurements and a theoretical approach

9.1.2 Effect of ventilation

Opening a vent in the container and opening the container door leads to an increase in the ventilation rate and a faster decay in the measured hydrogen concentration. This can also be seen in Figure Figure 39 where the relative hydrogen and methane concentration profiles are shown starting when the gas supply is closed. The hydrogen decrease in the container takes the longest with a fully closed container and has the shortest time with an open container door. Opening a door halves the concentration in about 1-2 minutes, the corresponding ventilation rate is then ~15/hour. Ventilation by opening a vent (R= ~1/hour) takes about half an hour, while with no ventilation in the container (R=~0.2 /hour) the concentration halves in a couple of hours. When the ventilation rate is greater than 5 times per hour, it may be considered "Good" (NPR7910-1). Since within homes the ventilation rate often does not exceed 2 times per hour, it is considered as moderate (NPR7910-1) or as "no ventilation" when the rate of refreshment is less than 1 time per hour (NPR7910-1).
The natural ventilation in the closed container is much lower than the 'no ventilation' situation and therefore represents a worst-case scenario. There seems to be is a difference between the decrease in methane and hydrogen concentration. Despite the fact that the diffusion coefficient of hydrogen is higher compared to methane, the concentration decrease for hydrogen takes longer than for methane. Additional research is required to show what causes this difference.
In the experiments with the empty container, opening one vent yields a ventilation rate of about 1/hour. The difference between the situation without ventilation (R= ~0.2 /hour) and with poor ventilation (R = ~1 /hour) is that in the first hour after opening the leakage the concentration is about half lower. Both situations represent poorly ventilated space in homes. Even a small increase in (poor) ventilation seems to give a decrease in concentration by a factor of 2. Given the low concentrations measured in these tests and the long duration of the experiments, a follow-up phase of the study will have to look more closely at the effect on larger outflow flows or smaller spaces. The ratio between the leak flow and the size of the room should have to be varied.

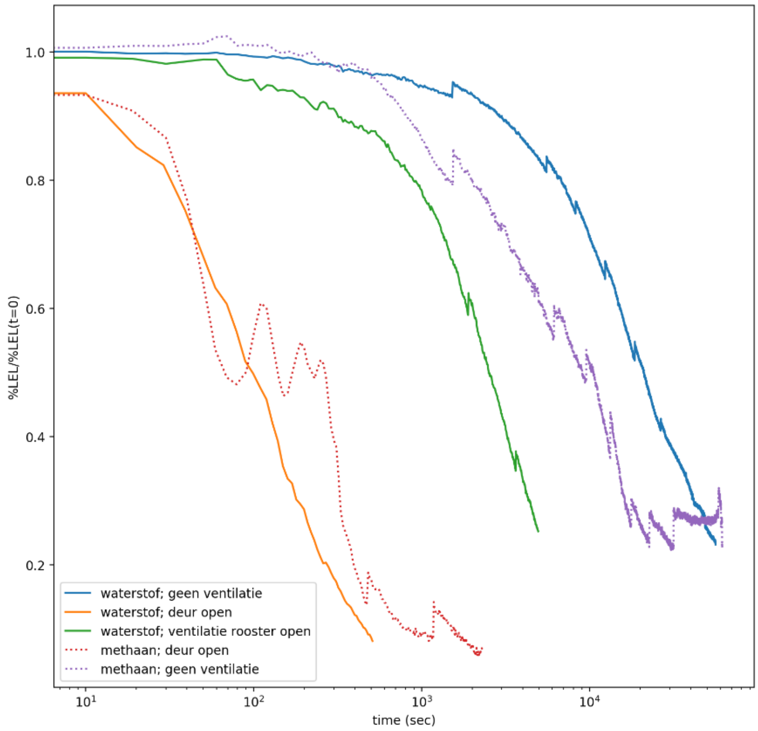


Figure 39 Relative decrease of hydrogen and methane concentrations in an open container (phase 1) at the time the gas supply is closed.

9.1.3 Leakage in a meter cupboard also leads to concentrations lower than the LEL.

For the experiments with a meter cupboard (phase 2), the following trends can be observed for both hydrogen and methane outflows in the meter cupboard:

- Increase in concentration in the upper part of the meter cupboard, but still lower than the LEL;
- Flattening of the concentration due to flow to adjacent 10m^3 compartment;
- Rapid decrease when the gas supply is closed;
- With a closed door between the two compartments, no hydrogen is measured in the 26m^3 space.

Figure 40 summarises the effect of gas supply flows, ventilation grilles in the meter cupboard door and vents in the container on the measured hydrogen concentrations in the meter cupboard where the meter cupboard door is closed. It should be noted that this is an average of the three sensors in the meter cupboard. The highest hydrogen concentration is achieved when both the ventilation grilles in the meter cupboard door and the ventilation opening in the container are closed. Opening the ventilation grilles in the meter cupboard door leads to a significant decrease in the average hydrogen concentration in the meter cupboard (43% to 20% of the LEL). A decrease in the outflow flow from 20 dm^3/hour to 15 dm^3/hour also results in a decrease in the average hydrogen concentration in the meter cupboard.

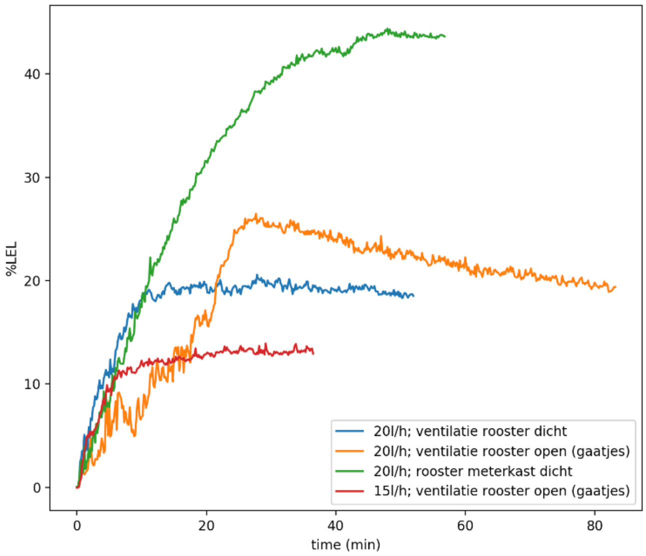


Figure 40 Measured average hydrogen concentrations in the meter cupboard in different configurations

Figure 41 shows the average methane concentration in the meter cupboard when the gas supply is open for different configurations. For reference, a corresponding hydrogen measurement has been added to the figure. Also in these measurements we find that the concentration flattens when the grilles in the door of the meter cupboard are open. Similar concentrations are measured between hydrogen and methane at the top of the meter cupboard. As noted earlier, the lower sensor shows a lower value for methane, which means that the average for methane in the graph below is lower. Only if the grilles in the door of the meter cupboard are closed by tape and the maximum gas supply flow is used, the safety value of 50%LEL is reached and the experiment is stopped. In the experiments, this only occurred with methane.

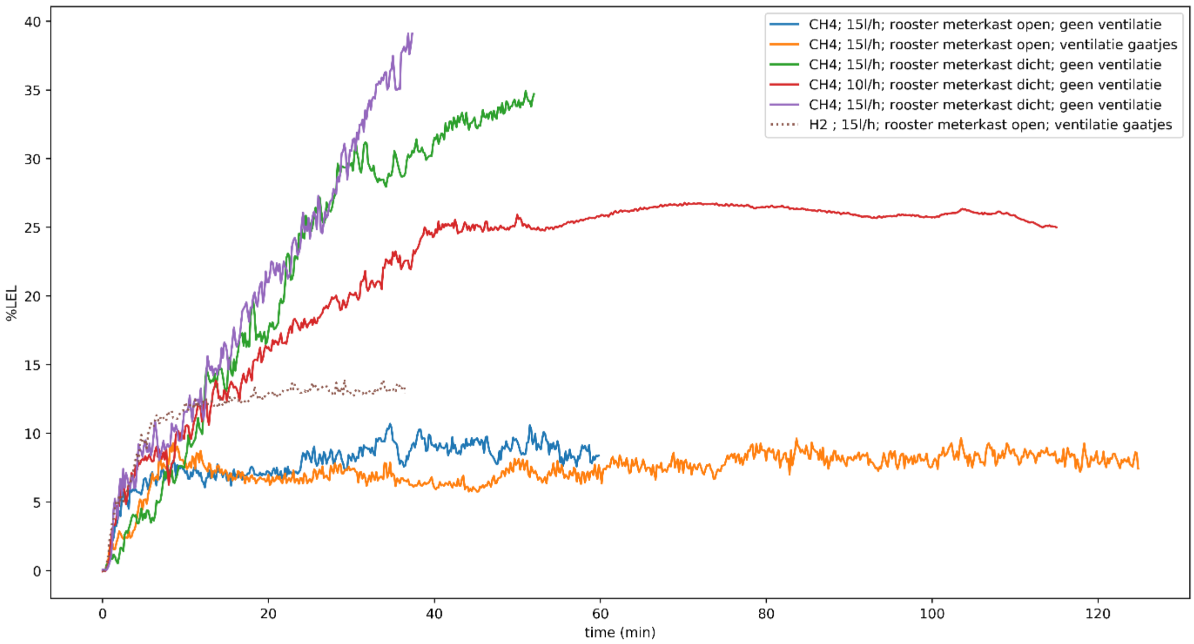


Figure 41 Measured average methane concentrations in a meter cupboard at different configurations. A hydrogen measurement has been added as a reference.

9.1.4 Closing the gas supply leads to a rapid decrease, followed by normal ventilation

As described above, closing the gas supply is an effective method to reduce the concentration in the meter cupboard. In all experiments with the meter cupboard, it is noticed that the concentration in the meter cupboard decreases rapidly as soon as the gas supply is cut off. This is also shown in Figure Figure 42: first a rapid decrease can be seen, followed by a slow one through ventilation (which is equal to the decrease in the room of 10m3).

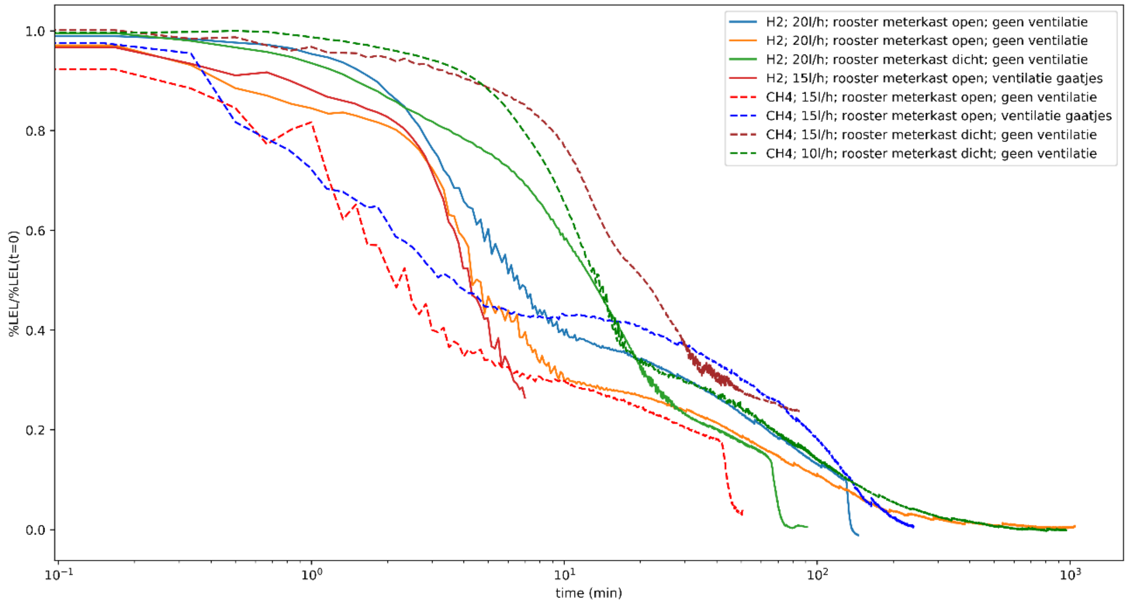


Figure 42 Decrease in the average hydrogen and methane concentrations of the meter cupboard in different configurations.

The figure above shows that when the ventilation grilles in the meter cupboard door are opened, the average methane concentration in the meter cupboard decreases faster than the average hydrogen concentration. The moment the ventilation grilles are closed, it is the other way around: the average hydrogen concentration decreases faster than the average methane concentration. A greater draught through the grills in methane relative to hydrogen could explain this effect. With the closed grills, hydrogen seems to be able to escape more easily through cracks. Further investigation should further confirm this assumption.

For some curves, a sudden decrease in the measured concentration can be observed at the end of the measurements. This is caused by the fact that the door of the container was opened.

9.1.5 The measured concentrations can be detected by H2 sensors or odorization

The concentrations of hydrogen measured in the experiments are generally very low, far below the LEL. In the analysis it appears that with the small leaks up to 20 dm^3/hour no dangerous situations arise. However, to ensure that such small leaks are noticed and do continue over much longer periods of time than the hours used in these experiments, it is important to know whether detection mechanisms are effective. In the current set of experiments, no time was available to measure the effect of sensors and odorization. However, previous studies have been carried out into the detection of (low) hydrogen concentrations with CO sensors [8] [9]. These studies show that CO detectors, for consumer use, are also sensitive for hydrogen. There seems to be a fairly large spread in sensitivity, but each of the 8 meters tested reacts quickly to concentrations of 10%LEL, the most sensitive meter will already go off at a concentration of 1-2%LEL. Odorization of the hydrogen will allow residents to smell low concentrations of hydrogen gas. For natural gas, the standard is that 1vol% (= 20%LEL) must be easy to smell. Figure Figure 43 shows the previously discussed measurements of hydrogen in the meter cupboard and in the large space again, with the addition of the concentration bands in which the H_2 sensors are expected to react and the limits for smellability of the gas. In the event of leaks in the meter cupboard, a gas smell will probably already be perceptible in the meter cupboard itself at lower concentrations. Both in the empty container and in the compartment next to the meter cupboard, the hydrogen concentration remains well below 20 % LEL (1vol%). In first pilot projects, it could be considered to place sensors at the top of the meter cupboard, where the higher concentrations are measured. With this, a small leak will be noticed in time and the risk can be reduced even further. In follow-up research, the effectiveness of these sensors will be further investigated.

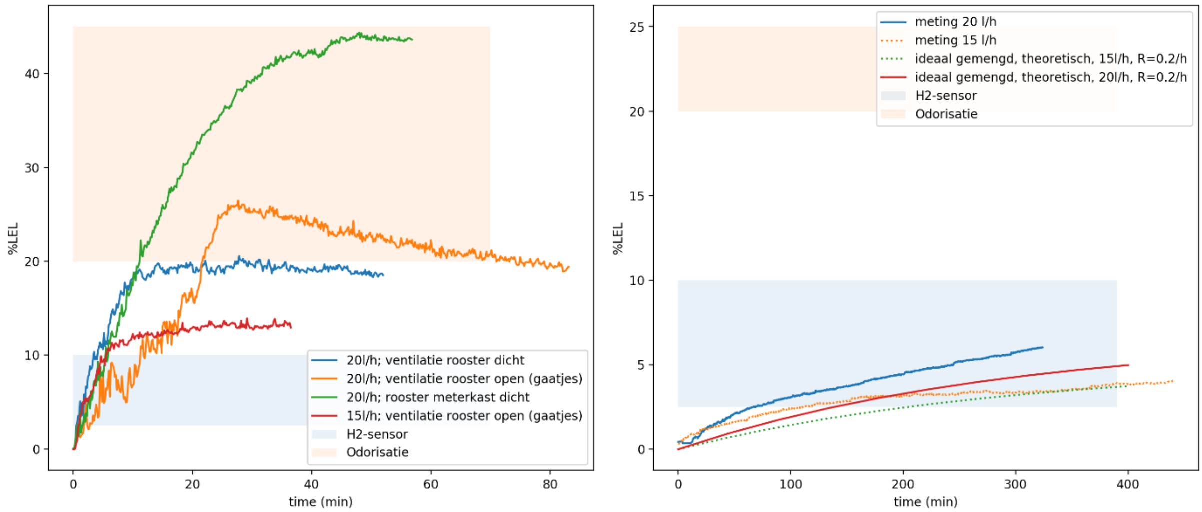


Figure 43 Measured average concentrations of hydrogen and lower concentration limits where H2 sensors alarm or odorant could be smelled. The meter cupboard (left) and the 36m3 container (right)

10 Conclusions and recommendations from the experiments

In summary, in the experiments with leaks up to 20 dm^3/h for hydrogen, no concentrations were measured near the LEL. The minimum ventilation rate in the container was 0.2/hour, which corresponds to a very poorly ventilated area in a dwelling. The container therefore represents a worst-case scenario, each additional opening in the container will show an increased ventilation rate and thus a smaller concentration build-up. Because dangerous concentrations are not measured in these experiments, it is expected that they will not occur in practice in homes at these leak rates. It has been shown that by opening a vent or door, the concentration can be quickly reduced again.

The highest concentrations were measured at the top of the meter cupboard in the situation where the ventilation grilles in the door of the meter cupboard are closed by tape. Also in this situation, the concentration of hydrogen levels at about 40%LEL. By placing two grills in the door of the meter cupboard, as required by NEN 2768 for a gas connection, this concentration is approximately 20%LEL. In order to detect leaks up to 20 dm^3/hour in time and to prevent the build-up of concentration, it is therefore advisable to place grills in the door of the meter cupboard. Placing an H2 sensor (CO detector) at the top of the meter cupboard will most likely respond to such small leaks. To detect small leaks, before they are detected by odorization, it could be considered to use such sensors in pilot projects.

10.1.1 Recommendations for additional experimental research

This report describes the first measurements for the accumulation of hydrogen in small compartments in the event of small leaks and the effect of ventilation on them. The used container has the flexibility to allow additional experiments in the next phase of the project.

During the experiments, it turned out to be difficult to keep the temperature in the container constant. The temperature dependence of the sensors may differ per sensor, so that a constant temperature is desired. It is therefore advisable to keep the temperature in the container constant by, for example, applying insulation and placing a radiator in the unit that can remain on during the measurements.

A number of experiments also gave unexpected results. For example, in the empty container, the ventilation rate for methane appears to be greater than under similar conditions for hydrogen. The stratification of methane also appears to be stronger in the meter cupboard than for hydrogen. Both observations are not expected based on the physical properties. In follow-up experiments, these phenomena could be investigated further.

In addition, the effect of opening a single ventilation opening in the container on the concentrations in the container was examined. Opening multiple vents or partially opening the vent and the associated difference in ventilation rate could be further investigated.

It is also advisable to carry out measurements with suitable hydrogen detection sensors (CO sensors) in follow-up experiments in order to further investigate this option as a mitigating measure.

The current set of experiments was limited to a configuration of the container with a meter cupboard in a room of 10m3. The flexibility of the container makes it possible to also examine other room layouts. This could include, for example, gas leakages in a crawl space or a kitchen.

Finally, in the current set of experiments, small leaks up to 20 dm^3/h were examined. Only low concentrations of hydrogen were measured, far below the LEL. In follow-up experiments, the outflow flow can be further increased, in order to explore to which leaks ventilation and other mitigating measures such as sensors are effective.

Safety recommendations for hydrogen pilot projects

11 Introduction

The introduction of hydrogen into the gas distribution network and into inhouse installation connected to it, may entail a change in the risks compared to the current situation for natural gas. In particular, the increased concentrations of hydrogen in an enclosed space (above 10vol%) can lead to increased risks due to the greater reactivity of hydrogen. Moreover, even if the risks of the current gas distribution network are limited and acceptable, it is important to know how big the differences are if hydrogen is distributed through the same network. Research is currently being carried out in various places in the world into these risks with hydrogen. Based on insights from the UK, the work package 1a of the Hydelta programme makes an analysis of the differences in the Dutch situation.

In the Netherlands, several pilot projects are being developed to gain experience with hydrogen in the built environment. It is of great importance to execute these pilots and demonstration projects in a safe manner. This document therefore describes the recommendations for mitigating measures to be taken for the infrastructure with a maximum working pressure between 100 mbar and 16 bar, for the transition of natural gas to hydrogen distribution, for pilot projects and for permanent installations. It is stressed that the measures listed in this document are initially proposed for pilot projects. These measures are conservative. Based on the experiences from the pilots and progressive insights, it can be decided/determined at a later stage to what extent these measures should also be applied in a regular hydrogen distribution network. Required permits for projects are outside the scope of this project.

This document is a collection report / advice list with an inventory of possible measures and points of attention. It contains a first set of recommendations and points of attention for hydrogen pilot projects, but each pilot project will have to assess whether this set is sufficiently complete and sufficiently effective based on the specific situation and risks.

Starting points for this set of recommendations and points of attention are:

1) that most of the working methods as they are known in the design/construction and management of the natural gas infrastructure are also suitable for the hydrogen infrastructure to be built in the future, with extra attention to limiting "large leaks".

2) that the safety assessments of pilot projects have been included in these recommendations and points of attention.[8]

The safety risk of hydrogen, in accordance with the definition of 'risk', can be determined by the probability that an amount of hydrogen is released in a leak or otherwise, this amount accumulates to a dangerous concentration and is ignited, multiplied by the consequences of this ignition.

Mitigating measures make it possible to reduce the various probabilities and their effects. The starting point for these measures is that the risk of leaks must be prevented during the design/construction/management. Next they are aiming to reduce accumulation, the chance of ignition and finally the effects in the event of possible ignition of the hydrogen.

In this document we use these steps in the following chapters:

1) Generic recommendations, including risk of ignition and consequences (Chapter 12)

2) Leakage (Chapter 13)

[8] Pilot Rozenburg; Conversion Uithoorn; Green Village; Hydrogreenn; City on 't Haringvliet; Pilot Wagenborgen

3) Dispersion (Chapter **Error! Reference source not found.**)

The generic recommendations and points of attention are included in chapter 12 , in order to prevent too many repetitive topics in the other chapters.

For each chapter, the recommendations are organized based on project life cycle phases:

a) Preparation

b) Design

c) Realisation

d) Operational

For phases not mentioned in a chapter, no specific recommendations and points of attention have been identified. These are included in the generic recommendations and points of attention in Chapter 12.

12 Generic recommendations

12.1 Preparation phase

12.1.1 Designate responsibilities in line with VIAG

The VIAG (safety instruction natural gas) provides rules for the safe working in gas distribution systems. Within the VIAG structure, it is clearly defined by whom and how work should be carried out on gas distribution systems. Netbeheer Nederland is preparing a hydrogen version of the VIAG system, with adjustments based on input from the HyDelta studies. By applying this methodology for the hydrogen distribution system (with some adjustments), it is ensured that work can be carried out with sufficient knowledge and level of safety.

12.1.2 Additional measures related to nitrogen

The maintenance and installation procedures are based on work on the natural gas infrastructure that does not use nitrogen for purging. In order to prevent an explosive mixture from forming in the pipeline with hydrogen, the installation must be purged with an inert gas. Nitrogen is an inert gas with other characteristics and properties. The procedures will have to be adapted to the use of nitrogen, when purging hydrogen.

Recommendation: Establish procedures for venting of pipelines with nitrogen.

12.1.3 Inspection inhouse installation

An inspection is required of the existing inhouse installation(s) to gain knowledge about the state of construction and maintenance of the inhouse installation. For the transition from natural gas to hydrogen, it is required that the inhouse installation (again) meets the applicable natural gas standard. The responsibility for this inspection must be defined. For natural gas, it is the homeowner.

Recommendation: Perform inspections on the state of construction and maintenance of the inhouse installation well before the conversion.

Recommendation: Investigate whether current standards for natural gas installations can also be applied for hydrogen installations

12.1.4 Determining safety distance around the pressure control and measuring stations and pipe(s)

The pipe routing and the location of pressure control and measuring stations must be chosen in such a way (by determining the safety distances by means of a QRA) that in the event of an escalation (fire, explosion) as a result of a leak , no or minimal damage will occur to the other installation components and/or environment.

12.1.5 Periodic inspection of the potential sources of leaks

Periodic inspection on leaks should be performed in the case of newly constructed pipelines as well as the reuse of natural gas infrastructure, before, during and after the start of the operation of the pipeline with hydrogen.

Investigate whether the procedures regarding leak detection in the (distribution) pipelines, NEN7244, VIAG safety work instruction(s) and of the installation sector, should be adjusted when applying them to the hydrogen infrastructure.

N.B.: HyDelta is investigating whether pressure and leak tightness tests will deviate from the criteria as formulated in the NEN7244 and the VIAG safety work instructions. For this, reference is made to HyDelta WP1c "Pipes and indoor installations" in which recommendations are made for adjustments to the VIAG.

Recommendation: investigate if a periodic leak check is also necessary and feasible for the indoor installation during a pilot and/or the normal operation and by whom it should be carried out. Determine the effective frequency of these checks.

Periodic leak check could be combined with the periodic maintenance of the end-user equipment.

12.2 Design

12.2.1 Odorized hydrogen

Hydrogen, like natural gas, is an odorless gas. By odorizing hydrogen, hydrogen leakage is perceptible to the human nose, like natural gas.

Recommendation: Use odorized hydrogen or provide alternative detection methods.

12.2.2 Design/construction/management of inhouse installation in line with NEN1078 (new construction)

The design/construction and management of gas installation for natural gas must comply with NEN1078 for new construction of the installation. Previous tests and research[9] have shown that the main standard NEN1078 can also be used for the installation for hydrogen.

12.2.3 Design/construction/management of inhouse installation in line with NEN8078 (existing building)

The design/construction and management of gas installations for natural gas must comply with NEN8078 for existing buildings. Previous tests and research (see footnote) have shown that the main standard of the NEN8078 can also be used for the installation for hydrogen (see also advice chapter 'Inspection indoor installation')

[9] See HyDelta work package WP1C "Piping and indoor installations (components)"; Report D1C5- risks when using hydrogen instead of natural gas. The main standards 1078 and 8078 are good to use, the corresponding NPR parts may need to be adjusted.

12.2.4 Equip installation(s) with fire-resistant pipelines

If there is a leak with ignition (fire), a "fire-resistant/heat-insulating PE pipe" will not be an accelerating component for the incident. Due to these fire-resistant properties, this type of pipes are preferred for construction or modifications of existing installations.

The same standards regarding fire resistance should apply to the piping up to the gas meter as with natural gas.

N.B. The meter cupboard can be seen as a weak spot in the fire safety of the house. The increasing use of electronic devices in the meter cupboard and the use of the meter cupboard as storage (resulting in limitation in ventilation), increases the risk of a fire in this room.

Recommendation: Consider (during pilots) higher fire resistance requirements for the meter cupboard and for the equipment installed in this room.

12.2.5 Installation of (additional) intermediate valves (segmentation of the transport and distribution network)

By segmenting the transport and distribution network, it is possible to shut down sub-systems in the event of maintenance, incidents, or calamities. As a result, it is not always necessary to evacuate/depressurize the entire installation and thus limit the amount of gas that has lost.

Recommendation: Explore the possibility of segmenting the transmission and distribution network in order to be able to isolate parts of the network in the event of maintenance, incidents or calamities

12.2.6 Inserting purging points into the pipe for repair and adjustments (for nitrogen purging)

No oxygen may be present in a hydrogen pipeline together with hydrogen. To not always evacuate the entire pipe during adjustment or maintenance work, it is good that (sub)sections can be inerted (hydrogen and oxygen free). To achieve this, the pipes (transport, distribution, and connection pipes) will have to be equipped with purging points (e.g. nipples) at suitable points. Via these points, the pipe can be filled and evacuated of nitrogen without outflow to the environment, so that the work can be carried out safely.

Recommendation: For each pipe section, make sure you have purging points at the beginning and end of the pipe.

12.2.7 Use suitable materials for construction, replacement and modifications

For modifications to pipes, in the event of replacement (due to aging) and in the new construction of pipes and installations, materials that are suitable for hydrogen are required. This could include pipes and materials with the so-called GASTEC QA quality mark, for which increasingly more materials are approved for hydrogen. Although more hydrogen certified materials are introduced on the market, it will not always be possible to have hydrogen-certified materials available during pilot(s). During the pilots it will be necessary to look carefully at the risks posed by the use of these materials. (See also Kiwa report GT-170272 "Future-proof gas distribution networks").

Recommendation: Research in (pilot) projects which materials suitable for hydrogen are available (with applicable quality approval, or substantiation if these are not yet available).

12.2.8 Install ATEX installations and equipment

If any leaks occur within the transport or distribution network, these leaks must not lead to escalations or calamities. By installing ATEX IIC certified installations and equipment, in ATEX-marked areas within the installation(s), it is prevented that this equipment will serve as an ignition source.

This is applicable for ATEX-marked areas as they currently exist at, for example, gasstations, and not the meter cupboard or other spaces in homes.

N.B. For guidelines regarding ATEX see: NPR7910-1 and/or NEN-EN-IEC 60079-10-1

12.2.9 Install certified end-user equipment

Install only hydrogen-certified end user equipment. As long as, there is only a temporary certification (for projects or limited series of test devices), the manufacturer/supplier will have to demonstrate that the device is specifically suitable for full hydrogen (> 98%). A recommendation is to define requirements for appliances that no flashback can occur from the boiler towards the inner pipe. As an additional safety measure, it may be considered to install a flame arrester directly in front of or in the device.

12.2.10 Assess materials in existing installations for suitability

The existing gas infrastructure has been constructed for the use of natural gas. The infrastructure needs to be assessed per project to check if the materials used are suitable for hydrogen or whether they will have to be replaced or decommissioned. Previous research results and experiences can be used for this, as stated in previous KIWA reports and the report "Future-proof gas distribution networks" of Netbeheer Nederland. Aspects that need to be considered include service life, permeation, leak tightnessand strength. If necessary, perform additional tests for these aspects.

12.2.11 Restrict access to installations

Where necessary, the number of people in the vicinity of the installation locations can be limited by access restrictions such as:

1) lockable entrance doors, possibly with locks that can only be opened by approved persons.

2) provide the location with fencing.

12.2.12 Installation of crash protection for installations

In places where it is possible that vehicles can cause damage to the gas-carrying installations (pressure control and measuring stations), the installation must be protected by a crash protection system, as is the case with natural gas (NEN 1059).

12.2.13 Leakage detection

During the construction and service life of installations, small or large leaks can occur. Early detection of these leaks is important to prevent a possible escalation. Large leaks have a flow over 20 dm^3/hour.

Small leaks

Small leaks are sometimes difficult to detect due to their size. Part II of this report examines the extent to which the risks give rise to the need to use the above measures (or combinations thereof). A distinction is made between the different types of locations (meter cupboard, adjacent rooms) and ventilation options. In these experiments, leak sizes up to 20 dm^3/hour for hydrogen are examined. In the experiments, no concentrations were observed above the LEL, even in very poorly ventilated rooms. To detect and stop/repair these leaks in a timely manner, the following measures or combinations thereof could be considered:

1) Odorization (detection);

By applying odorant, persons can detect any leaks with his / her nose and initiate the necessary actions.

2) Pressure loss detection (detection/control);

By using periodically performed pressure loss detection, even small leaks can be detected by an acoustic and / or optical alarm and the necessary actions (for example: closing the source) can be taken to prevent escalation.

3) Leak indicators (detection)

Applying tape or stickers that change colour at contact with hydrogen.

4) Installation of sensors (detection/control);

By applying sensors, the presence can already be detected at a small concentration of hydrogen, so that the necessary actions can be taken to prevent escalation. (The number of sensors and the mounting location, will vary per location / installation)

5) Periodic monitoring (prevention);

Periodic monitoring of the infrastructure for leakage can prevent a minor leakage from being unnoticed and escalating.

6) Ventilation.

Ventilation of the rooms through which the hydrogen pipeline passes will ensure that no accumulation of hydrogen can take place and escalation can be prevented.

Large leaks
In order to detect and stop large leaks in time, the following measures or combinations of these measures can be considered:

1) Odorization (detection);

By applying odorant, persons can smell any leaks and initiate the necessary actions.

2) Excess Flow Valve ("Gas stopper") (control);

By applying an excess flow valve in the service pipe, only a limited amount of gas can flow freely before the outflow is stopped.

3) Installation of sensors (combined with valves) (detection/control).

By applying sensors, the presence can already be detected at a low concentration of hydrogen, so that the necessary actions (for example: ventilation by opening windows and doors, closing gas supply) can be taken to prevent escalation.

N.B. The functionality of excess flow valves is currently being tested by Kiwa within the 'Gas Network Management Knowledge Centre'. HyDelta is investigating to what extent the risks give rise to the need to use the above measures (or combinations thereof). A distinction is made between the different types of locations and whether it concerns existing or new infrastructure.

12.3 Implementation phase

12.3.1 Construction and maintenance by qualified technicians/installers (e.g. by clear instructions)

During the first pilots, there is no (or few) certified personnel for the construction and testing of hydrogen infrastructure outside and inside homes. The basis for natural gas technicians to be allowed to work on a hydrogen network is that they have at least knowledge / training and experience in working on the natural gas and completed the associated VIAG training courses.

During or in the process to the implementation of the pilot projects, the mechanics/installers will need to be sufficiently trained and/or instructed and have knowledge of the specific properties and working methods regarding hydrogen to be able to carry out their planned and unplanned work properly and safely.

When more pilot projects are realized, the training requirements with regard to the technicians will be better defined, after which further requirements may and can also be set for the training. As a result, it is not yet possible to "demand" certified mechanics in the first pilots.

There are already several pilot projects active where experience can be learned for operational activities. Examples are: Rozenburg, Uithoorn, Stad aan 't Haringvliet, The Green Village, Entrance and the demonstration house at Kiwa.

Recommendation: Make sure that requirements are listed for training for technicians / installers and that training and teaching programs are developed on the basis of this. In the training courses, attention must be paid to attitude and behavior when working with another gas such as hydrogen.

Recommendation: As soon as hydrogen training is available, training and certification of technicians and installers should start as soon as possible

12.3.2 Information before the start of work (Explanation of dangers)

When working on and near transport and distribution pipelines, it is good that everyone involved in this work has the same starting points and that the risks are known to everyone. The risks and starting points will be included in the safety work instructions, a 'Toolbox meeting' or a work plan/operating plan will be part of these safety work instructions for hydrogen.

12.3.3 At the start of work in the morning 'start-up work consultation'

When working on and near transport and distribution pipelines, it is good that everyone involved in this work has the same starting points and knows which work will be carried out that day. In the "start-up work consultation" the safety work instructions will be reviewed.

12.3.4 PPE: Gas and oxygen detection equipment

Hydrogen and nitrogen are by themselves odorless gases. Provide personnel with specific hydrogen and oxygen detection equipment. Any leaks of the gases can be detected at an early stage before it becomes a risk.

The oxygen detection is necessary in relation with any nitrogen emissions, which could cause a low oxygen level. In the presence of an electrolyzer, a high concentration of oxygen can also arise due to the release of pure oxygen from the electrolyzer. Both situations are not desirable.

Recommendation: Current CO sensors are very sensitive to hydrogen. Investigate whether the current gas leak detection equipment is sufficiently selective.

Recommendation: Make sure people have the right PPE and are well instructed.

12.3.5 PPE: Clothing

The current protective clothing (antistatic and flame retardant) used within the current natural gas infrastructure also suffices for hydrogen.

12.3.6 Material

It needs to be determined which equipment needs to be adapted for use within a hydrogen infrastructure. As a basis, the natural gas tools will be used during the hydrogen work and as soon as 10%LEL is measured, the gas supply will be closed.

Among others, the torch installation will have to be adapted. These shall be fitted with a flame arrester suitable for hydrogen (gas group IIC). Kiwa has already conducted research into the applicability of the natural gas flare.

Research is also needed into inflatable gas stoppers. According to the K194 standard, gas stoppers may have 300 dm^3/hour leakage. This may be too large to close a hydrogen pipeline. For example, a valve or a combination of shut-off means (double gas stopper with ventilated gap). In Hydelta 2.0, further research will conducted into the suitability of inflatable gas stoppers.

Recommendation: Check whether the tools used are suitable use in a hydrogen infrastructure

12.3.7 Provide clear instructions for the Network Operator/Users/Environment/Emergency Services

Hydrogen in the built environment is new for everyone, in the event of use or incidents it must be clear to network operator / users / environment / emergency services who has which tasks / roles / responsibilities and what actions must be taken. A clear (documented) instruction will ensure that communication to and training can be done in an unambiguous way to all parties involved (network operator / users / environment / emergency services). This allows all parties involved to take in the right information and respond in a safe way. This could include the necessary communication and escalation lines (Grip1/2/..) and having a clear and trained emergency plan.

12.3.8 Perform pressure and leak tightness test after installation and modification(s)

After construction or modifications of the infrastructure, a pressure and leak test will have to be carried out and it will be determined that the installation is leak-tight in accordance with the limits set for this purpose.

12.3.9 Install fire extinguishing equipment

If a fire occurs due to leaks during the work of a mechanic, the hydrogen supply must first be closed and afterwards the fires need to be extinguished. Extinguishing a fire while there is still pressure on the pipe causes an uncontrolled hydrogen outflow, resulting in a possible accumulation and explosion. The latter is more dangerous than a fire. To extinguish the fires, fire extinguishers will have to be available.

12.4 Operational phase

12.4.1 Use of odorized gas

Hydrogen, like natural gas, is an odorless gas. By odorizing hydrogen, hydrogen leakage is perceptible to the human nose, like odorized natural gas.

12.4.2 Periodic above-ground leak search

By means of periodic above-ground leak searches, with hydrogen-suitable detection equipment, (small) leaks can be detected before they reach such a size that they pose a danger to the environment.

The current practice is that a natural gas pipeline is inspected for leakage approximately once every five years.

A frequency for such a check of hydrogen pipelines needs to be determined. A possible frequency could initially be annual. When more experience of the infrastructure has been collected, the frequency can be adjusted at a later stage.

Recommendation: Determine a frequency for above-ground leak detection for hydrogen pipelines.

12.4.3 Detecting leakage due to uncontrolled pressure drop

Investigate whether it is possible to periodically (automatically) check whether there is a leak in the gas infrastructure. If a pressure drop occurs during the test period, the root cause needs to be found by for example leak searching. This solution is currently being tested in the pilot "Stad aan 't Haringvliet".

Recommendation: Investigate whether periodic pressure drop control is possible

12.4.4 Provide clear instructions for the residents/environment/emergency services

Hydrogen in the built environment is new for everyone, in the event of incidents it must be clear to residents / environment / emergency services which actions must be taken. A clear (documented) instruction will ensure that it is possible to communicate and train in an unambiguous way to all parties involved (network operator / residents / environment / emergency services). This allows all parties involved to take in the right information and respond in a "safe" way.

Adjustments to the hydrogen infrastructure and installations may only be made (during the pilots) by authorized companies.

Recommendation: Investigate whether it is possible that hydrogen infrastructure and installations can and may be worked on by competent and approved installation companies

13 Leakage

13.1 Leakage in general - distribution network and stations

13.1.1 Preparation phase

Assess if the installation must comply with the Industrial Emissions Directive

On the basis of the Industrial Emissions Directive, governments check permit applications, such as the environmental permit. Permit applications from large companies must comply with best available techniques (BAT).

In order to obtain an environmental permit, the authorities can ask to comply with the directive. The permit application must indicate the measures taken for prevention and control to prevent pollution (soil, water, air).

Inventory of whether QRA (Quantitative Risk Analysis) is required

By means of a quantitative risk analysis (or: QRA) a statistical determination is made of the risks for the environment and those involved as a result of risky activities. A QRA is generally requested by the authorities to be able/willing to issue a permit.

13.1.2 Design

Design/construction/management in line with NEN1059

The NEN1059 contains relevant functional requirements for the design, materials, construction, testing, operation and maintenance of gas pressure control and measurement stations of gas pressure control and/or measurement setups that are part of a gas transport and gas distribution system.

Previous tests have shown that when the installations are gas tight for natural gas, they are also not leaking hydrogen. This makes it plausible that the principles of the NEN1059 can also be used for the hydrogen gas pressure control and measurement stations. The operation of the regulator and safety features have partly been tested within the HyDelta project, which is why it will have to be checked per pilot which stationstype is used and whether it is sufficient.

Design/construction/management in line with NEN7244 (pipelines and meter setups)

The NEN7244 is the guideline for the design/construction and management of natural gas distribution pipelines, service pipes and meter setups. Previous tests and research have shown that the principles of the NEN7244, taking into account the different characteristics of the medium, can also be used for the hydrogen distribution pipelines.

Inventory depth of (existing) pipes

The existing distribution pipelines are covered underground at a depth in accordance with NEN7244.

Extra attention is required for existing pipes that have been installed in the past (in accordance with the then applicable standard) with less ground cover than the current regulations indicate or have received a different coverage due to ground level change. For each situation, it will have to be assessed whether, in the case of a pipeline with too little ground cover or zoning changes, adjustments must be made to guarantee safety during excavation work. One option may be that the pipe will have to be laid deeper into the ground to prevent excavation damage.

Identifying whether design principles/measures are sufficient for construction in floodplains

An inventory will have to be made of whether the current design principles/measures are sufficient in the event that the distribution pipeline is constructed in a possible flood zone. If this is not the case, the design principles/measures will have to be adapted.

Recommendation: make an inventory of whether starting points/measures are sufficient for use within flood areas.

Identifying whether design principles/measures are sufficient for construction in earthquake areas

An inventory will have to be made of whether the current design principles/measures are sufficient in the event that the distribution pipeline is constructed in a possible earthquake area. If this is not the case, the design principles/measures will have to be adapted.

Recommendation: make an inventory of whether principles/measures are sufficient for use in earthquake areas.

Hydrogen pipeline through the crawl space

In relation to possible leaks, it is desirable that a gas-carrying pipe is as limited as possible placed in the crawl space, to prevent accumulation in case of leakages. In case the pipe is placed in the crawl space, leakage can be detected early, and the necessary actions are taken to prevent escalation.

Possible options are:

1) Install a jacket pipe or Peko through crawl space as with natural gas;
2) Ensure gas detection in the crawl space with acoustic and optical alarm and follow-up (removal of source);
3) Ensure adequate ventilation of the crawl space.

Recommendation: Research which solution is the best solution to prevent gas accumulation in the crawl space.

13.1.3 Implementation phase

Output pressure and leak tightness test after construction and modifications

Pressure and leak tightness tests of natural gas pipelines are carried out in accordance with the NEN7244 and the VIAG safety instructions. Previous tests and research have shown that the principles of the NEN7244 and VIAG safety work instructions, taking into account the various characteristics of the medium and minor adjustments such as the use of nitrogen and deviating criteria for pressure and leak tightness tests, can also be used well for the hydrogen infrastructure.

N.B.: HyDelta is investigating whether it is possible to deviate from the criteria as formulated in the NEN7244 and the VIAG safety work instructions regarding pressure and leak tightness tests.

Hydrogen pipeline marking

A hydrogen pipeline can be marked in various ways as being a hydrogen pipeline. This is necessary to have clarity about the medium inside the pipeline during work or an incident. Both pipes will be yellow and in both gases THT is the applied odorant. It is important to identify whether it is a hydrogen or natural gas pipeline, especially when pipelines are laid next to each other or crossing and one of the two is leaking. Some options for this are:

1) In the case of new construction or modifications, warning tape above the pipe may be considered. In this way, the agitator is alerted in during the work to the presence of the relevant pipe.

2) The cap of the saddle can be manufactured in a different color or the symbol of hydrogen can be engraved in the hood.

3) Where possible, a hydrogen markings can be applied/clamped to the pipes.

Recommendation: investigate how existing pipelines can be easily marked when hydrogen is transported as a medium.

Pipes included in GIS system

When laying cables and pipes, they must be included in a GIS system. It is important that the GIS system indicates that it is a hydrogen pipeline. In this way, during excavation works, it can be checked whether there are any cables or pipes in the route to be dug. Through this mandatory check of the GIS system (Klic notification) and the 'precautionary measure requirement', prior to the excavation work, excavation incidents can be kept to a minimum.

13.1.4 Operational phase

Detection and repair of leaks in the event of a pressure drop, in the case of pressure and leak tests in line with the NEN 7244 and VIAG.

In the event of detected leaks, these will have to be found and repaired. In the NEN7244 and VIAG safety work instructions, these activities are defined for natural gas. When using hydrogen, these activities will have to be carried out via a similar method as described in the NEN7244 and the VIAG safety work instructions. For this, a 24/7 management organisation will have to be set up for the hydrogen infrastructure, just as for the management of the natural gas infrastructure.

Work is only allowed on the basis of Work Plan

Work on a gas-carrying installation may only be carried out with a working plan. By requesting a work plan / operating plan, ad hoc work is avoided and various people / agencies assess the work to be carried out.

Measures in line with VIAG with additional measures related to hydrogen and nitrogen

The VIAG safety work instructions are based on work on the natural gas infrastructure. In order to prevent explosive mixtures in installations, it is recommended to purge with nitrogen at hydrogen installations. Hydrogen and nitrogen are gases with different characteristics and properties. The VIAG safety work instructions need to be adapted for the use of hydrogen and nitrogen.

Recommendation: Develop safety work instructions for working with hydrogen and nitrogen.

Procedure in line with CROW500

The CROW500 directive is about preventing excavation damage to cables and pipes. A central notification (Klic) checks whether cables or pipes are present in the excavation route. When the CROW-500 procedure is followed prior to the work, excavation incidents can be kept to a minimum. Consideration could be given to requiring supervision of excavation work near a hydrogen (distribution) pipeline or ensure that the network operator exposes existing hydrogen pipelines.

Recommendation: Ensure the presence of a network operator during excavation work near a hydrogen (distribution) pipeline.

Pipes leakage into the ground

The installed distribution pipelines are located outside in the ground, so small emissions will not directly lead to incidents because the gas can escape into the open air via the ground.

If the gas cannot escape to the outside air, there is a risk of accumulation in, for example, a crawl space and it is necessary that the leak is detected in time by smell detection or leak detection.

Periodic above-ground leak detection will find small leaks, taking into account the composition of the cover of the pipeline in relation to gas permeability of the soil (composition of soil, foundation, paving, etc.)

13.2 Leakage in general – Inhouse installation

13.2.1 Operational phase

Detection and repair of leaks in the event of a pressure drop, pressure and leak test

In the event of detected leaks, these will have to be found and repaired. In the NEN1078 and NEN8078 directives, these activities are defined for natural gas. When using hydrogen, these activities will have to be carried out via a similar method as described in the NEN1078 and NEN8078 directives (see also chapter 'Detecting leakage due to uncontrolled pressure drop').

14 Dispersion

14.1 Gas leaks to building - Distribution network

14.1.1 Design

Seal wall penetrations gas-tight

Leaks allow leaked gases to travel through the ground towards any existing buildings. In line with NEN7244, the wall penetration need to be gas-tight and prevent the gases entering the buildings via this route.

14.1.2 Operational phase

Periodic above-ground leak search

By means of a periodic above-ground leak search program, (small) leaks can be detected before they reach such a size that they pose a danger to the environment. A frequency for such a check needs to be determined. A possible frequency could be annual. When more experience of the infrastructure and the medium has been gathered, the frequency can be adjusted at a later stage.

14.2 Gas enters building - Inhouse installation (behind the meter)

14.2.1 Design

Ventilation

Ventilation can prevent a flammable or explosive mixture from forming. When the ventilation rate is greater than 5 times per hour, it may be considered "Good" (NPR7910-1). Since within homes the ventilation rate often does not exceed 2 times per hour, the rate is considered to be moderate (NPR7910-1) or as "no ventilation" when the rate of refreshment is less than 1 time per hour (NPR7910-1). It needs to be investigated which degree of ventilation is realistic within a home or in certain spaces within a home.[10]

For example: in accordance with the NEN2768 , the meter cupboard door needs to be equipped with ventilation grilles for new construction. It may be considered/recommended to apply the requirement to existing buildings if they are converted to hydrogen.

[10] For new homes the regulations refer to the NEN 1087. This dictates a minimum requirement for each type of space in dm^3/sec. This translates to ventilation rates in the order of magnitude between 1-2 /hour.

15 References

[1] KIWA, DNV, "Hydelta D1a_1 Uitkomsten onderzoeken Verenigd Koninkrijk Hy4Heat en H21 vertaald naar Nederlandse situatie," 2022.

[2] DNV, "Gedrag van waterstof bij lekkages in het distributienet," 2020.

[3] DNV, "H21, QRA model for hydrogen gas distribution networks," DNV report 10078380-2 Rev 0, 2020.

[4] DNV, "H21, Risk predictions for hydrogen gas distribution networks," DNV report 10078380-2 Rev 0, 2020.

[5] M. Acton, A. Halford and A. Phillips, "Quantification of the Risks Associated with a Hydrogen Gas Distribution Network," in *Hazards 30 (paper accepted)*, Manchester, November 2021.

[6] DNV GL, "Rapport proefopstelling verspreiding waterstof in de meterkast," 2020.

[7] H. Top, "Onderzoek aan een Rinnai RC 204 W-1 afvoerloze kachel met geforceerde convectie," N.V. Nederlandse Gasunie, Rapport TP/M 92.R.1008, 1992.

[8] DNV, "Investigation into the cross-sensitivity of domestic carbon monoxide alarms to hydrogen," in *ICHS*, 2021.

[9] DNV, "Verkennend metingen naar gebruik CO melders voor waterstof detectie - Hydrogreenn," 2019.

[10] IEEE, "IEEE Citation Guidelines," [Online]. Available: https://ieee-dataport.org/sites/default/files/analysis/27/IEEE%20Citation%20Guidelines.pdf. [Accessed 19 03 2021].

[11] KIWA Technology, "Betrouwbaarheid van gasdistributienetten in Nederland," Netbeheer NL, 2018.

[12] M. Acton and B. Smith, "The Development and Application of Risk Assessment Techniques for Gas Distribution Pipelines”,," in *Rio Oil & Gas Conference, IBP24000*, 2000.

[13] DNV GL, "Thermal radiation properties of large hydrogen leaks from gas distribution networks," in *ICHS*, Adelaide, 2019.

[14] M. Acton, A. Halford, P. A., R. Oxley and D. Evans, "Quantification of the risks associated with a hydrogen gas distribution network," in *Hazards 31 Conference*, 2021.