HyDelta 2

WP6a – Hydrogen safety in the distribution network and built environment

D6a_4 – Additional recommendations: applicability of QRA tools, detection of hydrogen fires, effectiveness odorization and effect permeation

Status: final

Dit project is medegefinancierd door TKI Nieuw Gas | Topsector Energie uit de PPS-toeslag onder referentienummer TKI2022-HyDelta.

Document summary

Corresponding author

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

Document historie

Version	**Date**	**Author**	**Affiliation**	**Summary of main changes**
1	4-5-2023	Albert van den Noort	DNV	Merge 4 documents in 1 deliverable
		John Zevenbergen	TNO	Chapter Applicability of QRA tools
		Rob van Aerde	KIWA	Chapter Detection of hydrogen fires, effectiveness odorization and effect permeation

Verspreidingsniveau

PU	Public	X
RE	Limited to • Project partners including Expert Assessment Group • External entity with whom a Non-Disclosure Agreement exists	

Document review

Partner	**Name**
	EAG:
Enexis	Raymond van Hooijdonk;
Alliander	Pascal te Morsche
Rendo	Johan Jonkman, Roy Scholten
Stedin	Gilles de Kok
NetbeheerNL	Tom Eijsackers
NBNL, Gasunie, Kiwa, DNV, TNO, NEC, Hanze	HyDelta Supervisory Group

Summary

In Hydelta 2.0's work package "Safety of hydrogen in the distribution network and the built environment", research has been conducted on the risks of hydrogen through a quantitative risk model and additional experiments around the effect of ventilation on the accumulation of gas in a home. In addition to these two main tasks, a number of smaller topics related to the same main objective were conducted. These knowledge gaps were identified during Hydelta's scoping phase and may lead to additional measures in the pilot projects. They are:

1. Are existing QRA tools applicable for hydrogen gas pressure regulating stations?
2. Is flame detection necessary for hydrogen fires?
3. To what extent is the effectiveness of barrier odorization affected by, for example, adsorption and/or absorption of the odorant?
4. What is the effect on safety and gas quality of the permeation of nitrogen, oxygen and water from outside the pipeline to the inside?

Based on literature review, these 4 questions were answered.

Applicability of existing QRA tools for hydrogen gas pressure regulating stations

The most common and available tools for performing a so-called Quantitative Risk Assessment (QRA) were assessed and compared. For the comparison, it was specifically examined which tools would be suitable for determining the risk contours around a so-called gas pressure regulating stations operating on hydrogen.

The application area and scope of each tool were analysed. From the analysis it was concluded that the software tools Safeti-NL and Conifer are suitable for determining the risk contours around a gas pressure regulating station, with the former being accepted by the Dutch competent authorities as an unequivocal calculation method for facilities for performing a QRA. Conifer is less well-known in the Netherlands and at this point in time does not have the option of being licensable but has been specifically developed for that part of the gas network from the gas pressure regulating station (<8 barg) to the gas meter (20 – 25 mbar). Taking into account the validation programs of both tools, it is expected that the risk contours of both tools around a gas pressure regulating station will largely overlap. Both tools have been validated for use with natural gas and the validation with hydrogen is steadily being expanded. Based on the current validation datasets, the risk contours for the same situation for hydrogen are greater than those for natural gas. It should be noted that for both software tools - in case of hydrogen - worst case scenarios are used with the calculations. For example, the ignition probability of hydrogen is set to 100% by default. Such parameters have a clear influence on the risk contours. Knowing that the validation process is still in full swing, it is therefore not appropriate to make a statement about how the risk contours of hydrogen and natural gas relate to each other in terms of size. Comparing the first results, it is expected that after full validation the difference will be limited.

Detection of hydrogen fires

A hydrogen flame may be less visible depending on the circumstances. Reduced visibility may result in injury to persons when they get too close to the flame. Currently, there is a lack of experience with hydrogen flame visibility under various conditions. Because the experience is lacking, it is recommended that tools be made available for service technicians in pilot projects to detect a hydrogen flame and make them aware of the possible presence of a hydrogen flame. With the

experience gained during the pilot projects and additional research, it can be determined whether future flame detection tools should be available for work on hydrogen grids. Gathering of information on the visibility of burning odorized hydrogen and the visibility of flames during incidents is recommended.

Determining the effectiveness of THT odorant

Based on the literature review, it was determined that, in specific situations, the effectiveness of odorization by THT can be negatively affected. Despite this influence, the effectiveness of odorization of hydrogen by THT is comparable to that of natural gas. With this, there is no reason to take additional control measures when distributing hydrogen odorized with THT.

Determining the effect on safety and gas quality due to permeation of nitrogen, water and oxygen

Permeation is a natural phenomenon that occurs in both natural gas and hydrogen distribution. As long as there is gas flow through the pipelines, the effect with respect to safety and quality is negligible. In situations where there is a isolated pipeline section, based on a theoretical consideration, there will be an effect with respect to safety and quality over time. This consideration considered the permeation of individual components, oxygen, nitrogen and water, from outside the pipeline to inside the pipeline. In order to understand the total process of permeation and its effect on safety and gas quality, it is recommended that pilot projects monitor the gas composition especially in situations where there is long-term shutdown of hydrogen in pipelines.

	Knowledge gap	Recommendation
Detection of hydrogen flame	Experience with the visibility of a hydrogen flame	Availability of tools for detection of hydrogen flames to service technicians. Gather information on visibility of odorized hydrogen and flame visibility during incidents.
Effectiveness of THT odorant	None	None
Effect of permeation	Understanding the overall process of permeation of multiple components	Monitor gas composition when there is prolonged stoppage of hydrogen in pipelines.

Contents

1 Introduction

For the application of hydrogen in houses and the distribution grid, it is important to know the associated risks and mitigate them where necessary. To estimate the risks in using hydrogen in the distribution network compared to natural gas, it is important to know the differences in probability and consequence. The probability refers to the possibility of a hazardous situation occurring; the consequence can be expressed in terms of damage that occurs in the event of a fire or explosion. Mitigation measures are then aimed at reducing the probability of a hazardous situation occurring or its consequences.

To this end, the HyDelta program defined the work package "Hydrogen and Safety" in which the main objective is formulated as follows:

Identify risks regarding the behavior of hydrogen in case of leaks in houses and in the distribution network and define mitigating measures based on the risks.

To make an initial assessment of the risks of hydrogen in the Dutch distribution network, a quantitative risk analysis (QRA) was performed using a model developed specifically for this purpose. In it, the risk is compared between the current natural gas distribution system and the future hydrogen distribution system. In the analysis, the total risk consists of the risk arising from leaks in the distribution system and the risk arising from leaks in the home itself. The results of the analysis provide a quantitative basis of whether hydrogen distribution poses more risk to society and if so, what measures have large impact to reduce this risk. In [1], the QRA model for the Netherlands is described and the results for both the risk of leaks in the home and in the distribution network are given. One of the important sensitivities to the risk of hydrogen in the home is the ventilation rate in the home. Poorly ventilated homes can more quickly lead to hazardous concentrations for the same leak. To investigate this effect in practice, measurements were made within the work package on the influence of ventilation on the build-up of concentrations for relatively small leaks. These are described in [2].

In addition to these two main tasks in Hydelta's work package, a number of smaller topics related to the same main objective have been carried out. These knowledge gaps were identified during Hydelta's scoping phase and may lead to additional measures in the pilot projects. They are:

1. Are existing QRA tools applicable for hydrogen gas pressure regulating stations?
2. Is flame detection necessary for hydrogen fires?
3. To what extent is the effectiveness of barrier odorization affected by, for example, adsorption and/or absorption of the odorant?
4. What is the effect on safety and gas quality of the permeation of nitrogen, oxygen and water from outside the pipeline to the inside?

With a literature review, relevant information was gathered to answer the questions. Conducting experimental research or analysis was not part of the scope of this study. The results of the literature review are explained for each question in the respective chapters.

2 Applicability of existing QRA tools for a hydrogen district station

2.1 Introduction

As part of the further development of the QRA model, tailored to the situation in the Netherlands [1], a specific task was formulated to assess the suitability of the available QRA tools for determining the safety contours around gas pressure regulating and measuring stations operating with hydrogen.

This chapter provides an overview of possible models available for the assessment of risk contours around so-called gas pressure regulating stations (from 8 barg to approximately 100 mbarg) and the applicability of these tools for pure hydrogen specifically. For each tool, a description is given for the application(s) for which the tool has been developed and validated. Furthermore, a generic overview is given of the possibilities and whether the tool can be made applicable for calculating the risk contours around gas pressure regulating stations. Finally, it is determined per tool whether it is capable of calculating risk contours for hydrogen and/or whether it can be adapted to enable such calculations for hydrogen. If one or more suitable resources are identified, the calculated risk contours (safety distances) are presented for a hydrogen scenario around a gas pressure regulating station. It should be noted that the applicability of the various software packages for determining the risk contours around pipelines or other elements in a gas distribution network are outside the scope of this chapter.

2.2 Pipesafe / Carola

2.2.1 Introduction

The software packages PipeSafe and Carola [3] are based on the same methodology, with the difference that Carola uses the 'lookup table' principle. In other words, the Carola software interpolates between values present in the database, while PipeSafe uses direct (non-public) calculation methods for the various parameters. The difference in end result between both software tools is limited (< 2%) and is caused by the higher accuracy of the parameters as determined with PipeSafe. Because the same method is used, only PipeSafe is referenced in this document.

2.2.2 Application area of software tool

PipeSafe [4] has been developed as a quantitative risk assessment package (QRA) for underground (high pressure - 40, 66 and 80 bar) natural gas transport pipelines and associated components. The tool is centred around mathematical models for predicting the effects of gas leaks, such as a fire, on people and nearby buildings. The software tool is able to estimate the failure frequency of a pipeline and determine the individual and societal risk levels. The models have been validated over the years against experimental data, from small to large scale.

2.2.3 Generic description of the software tool

For the risk assessment of a high-pressure natural gas pipeline, PipeSafe takes into account the following four aspects [4], schematically shown in Figure 1:
1) Evaluation of the failure frequency
2) Probability of ignition
3) Assessment of the consequences
4) Calculation of the risk

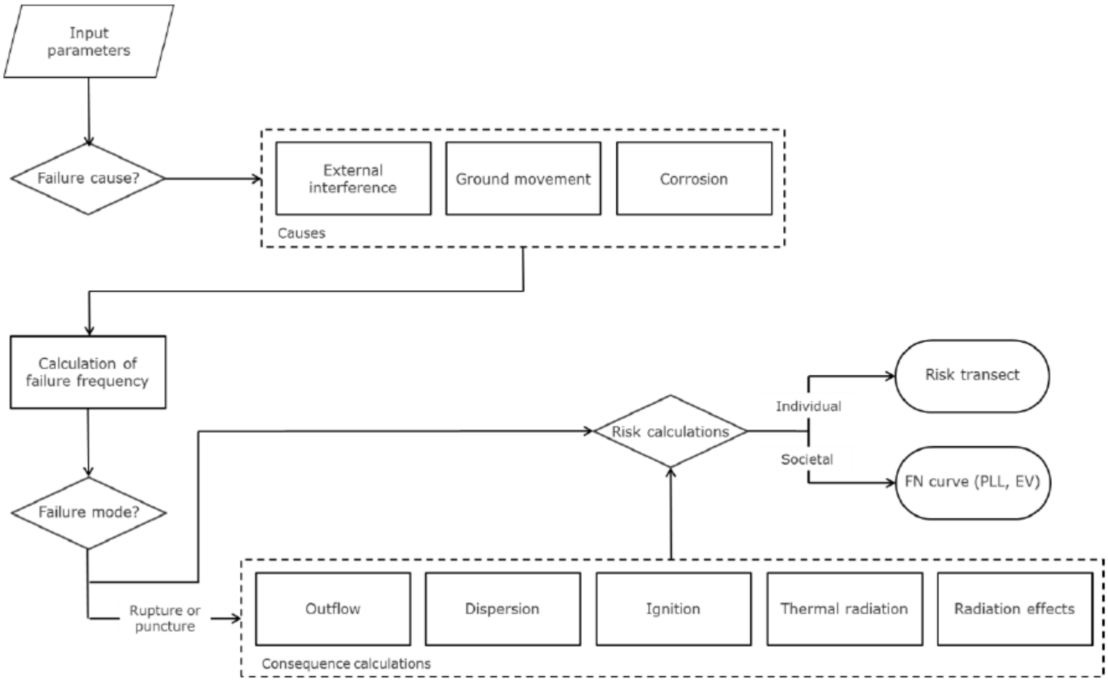


Figure 1 Risk assessment method of the PipeSafe software tool for high pressure underground natural gas transmission lines [4]

Three causes are considered for the failure of the pipeline, namely an external cause (such as construction work), ground movements and corrosion. If the pipeline fails, PipeSafe takes into account two types of failure: leakage (perforation) or rupture (breaking the pipe in two). The failure mode is determined by the length, depth and type of defect and is mainly dependent on the pipe diameter, wall thickness, material properties and operating pressure. The probability of each failure mode can be added up and is expressed as a failure frequency per year and per unit length of the pipeline. The ignition probability is based on historical data and further depends on whether there is an ignition probability. In case the ignition probability is non-zero an assessment is made whether it is an immediate ignition leading to a partial flare, or a delayed ignition leading to a fireball and pressure waves. The consequence modelling in case of ignition depends on the gas leak rate and the underlying radiation profiles (flare versus fireball). The latter profiles have an effect on the people and buildings in the area. To estimate the effects, the model takes into account the meteorological events that influence the consequences of the natural gas leak. Since PipeSafe is designed for underground pipelines, it also takes into account the size of the potential crater being formed, depending on the mode of failure (puncture versus rupture). The risk to the population can be expressed as individual risk, which is the frequency with which a person in a given location can become a victim, or as a societal risk, determined as the relationship between the frequency of an incident and the number of victims.

2.2.4 Applicability to hydrogen gas regulation station

PipeSafe (Carola) has been developed for underground high-pressure natural gas transport pipelines. The pressures most commonly used for Gasunie's high-pressure transport pipelines are 40, 66 and 80 barg, and the experimental validation programs have therefore largely been carried out at these pressures. For the natural gas situation, the package can be used reliably from 7 barg. Below 7 barg, the software package indicates that the results are outside the validation range and may therefore be less accurate. The lower limit of PipeSafe corresponds approximately to the highest pressure occurring in the gas distribution networks of the regional operators. The validation of PipeSafe is currently being extended to include hydrogen, for example through the HyWay27 project [5]. Technically, the current version of PipeSafe can be used to determine the risk contours of hydrogen with a pipe diameter of 18 inches or more at a pressure from 16 barg [6]. Given the current version of PipeSafe, it cannot be used to determine the risk contours around hydrogen gas pressure regulating stations. In the future, with further validation with hydrogen data and knowing that the tool is based on underground pipelines, the applicability for hydrogen gas pressure regulating stations is limited. There are specific models in the tool for risk assessment of components (such as joints, valves) used in pipelines, which can also be used for stations at high pressure (7 barg and above). In those specific cases, there may be some applicability with future versions of the tool.

2.3 Safeti-NL

2.3.1 Application area of software tool

Safeti-NL is the Dutch version of the Safeti software tool from DNV [7] and takes into account the risk regulations and methodology as described in the so-called Purple Book [8]. Safeti-NL is a generic quantitative risk assessment tool that can be applied to all installations involving toxic and/or flammable chemicals, such as those found in the chemical process industry and other industries that handle, transport and store such materials.

2.3.2 Generic description of the software tool

Safeti-NL calculates the individual risk and the group risk in the event of the accidental release of flammable and/or toxic substances into the atmosphere from a certain location, as shown in Figure 2 [7]. By uploading a map into the software and selecting the nearest weather station, the tool automatically imports the relevant weather data from that location. The user then defines, among other things, the failure frequency, the operating conditions (substance, pressure, temperature, volume), type of scenario (piercing, fracture, catastrophic rupture of the vessel/pipe) and whether the leakage occurs indoors or outdoors.

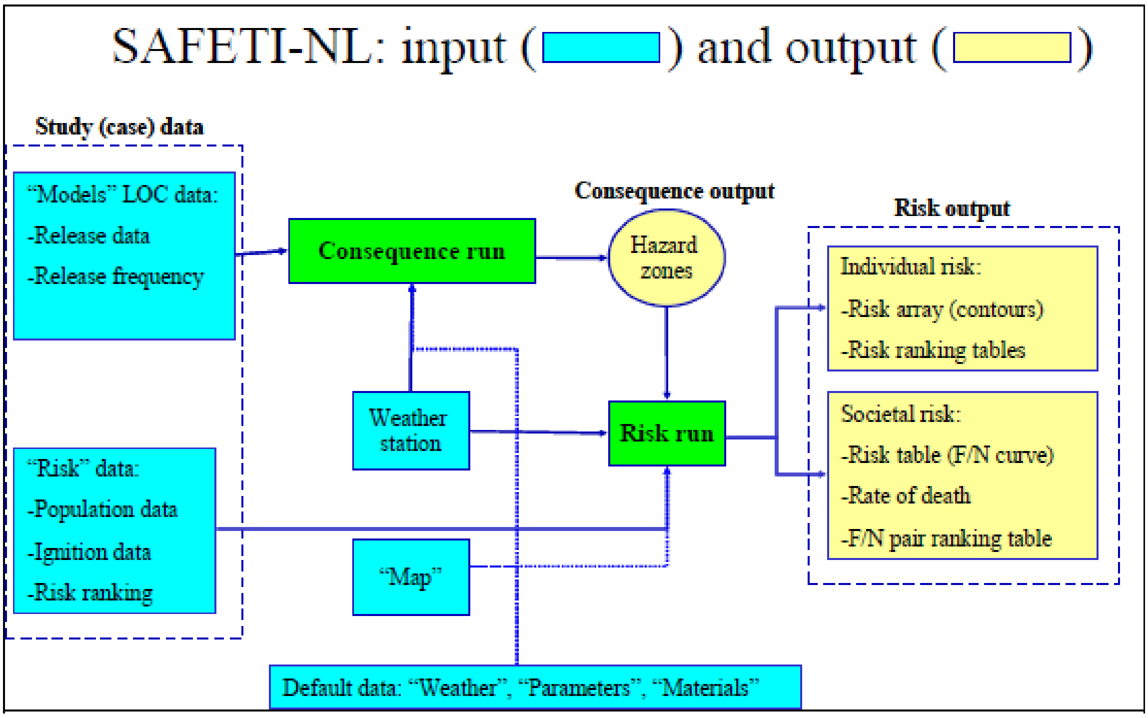


Figure 2 Risk assessment method of the software tool Safeti-NL [7]

With this input, Safeti-NL calculates thermal, overpressure and concentration profiles. When the user also defines input about the population in the immediate vicinity of the chosen location, and in the case of a combustible substance, the source of ignition and the mode of ignition (immediate versus delayed), Safeti-NL calculates the individual and group risk contours. It should be noted that Safeti-NL has no correlations for the probability of ignition. This must be user defined. Safeti-NL has specific models for the accidental release of hydrogen for leakage (expansion from the opening) and the spread of flammable substances, see also Figure 3.

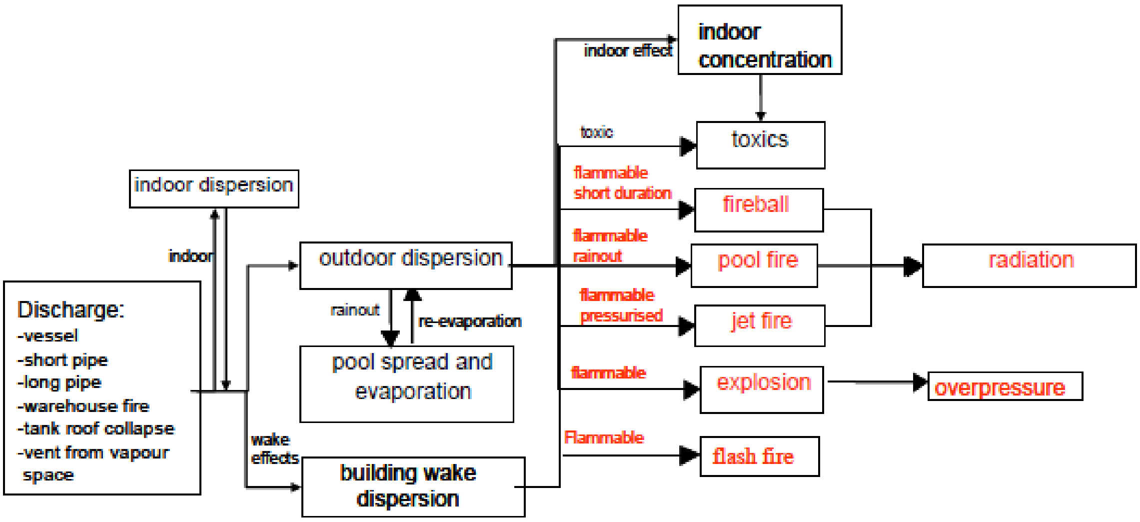


Figure 3 Models for thermal and overpressure profiles as used in the Safeti-NL software tool. [7]

The leakage and diffusion models and subsequent effects after ignition have been validated with published experimental data, including hydrogen. Safeti-NL does not define a pressure threshold below which the results are not valid and/or should be treated with care. However, the user should be aware that the possible margins of error can be considerable. At low pressures (up to 100 mbar) and in case of a perforation, the size of a possible flare and thus the associated risk contour (radiation) will be limited in range and the margins of error will be larger, without necessarily giving significant incorrect estimates. The same applies to low pressures (up to 100 mbar) and a rupture under conventional ventilation regimes; the chance of a combustible cloud forming is small and so the calculated risk contours will also be small. As the pressure increases, the accuracy of the results will improve. It should be noted that the Safeti models are more often validated against experimental data obtained at higher initial pressures, simply because more literature data are available for such conditions, but not exclusively (see also next section).

2.3.3 Applicability to hydrogen gas regulation station

Safeti-NL has all relevant data on hydrogen and can use this to calculate the risk contours for a gas pressure regulating station. Specifically for a hydrogen flare, the user can choose Miller's model [9], as implemented in Safeti-NL. This particular model has been validated against experimental data for both vertical and horizontal flares and for leak rates ranging from 0.02 to over 100 kg/s hydrogen. The Miller model [10] has been developed for low-intensity flames, which is reflected in the more realistic estimates of the (radiation) risk contours versus models that use highly luminescent (hydrocarbon) flames as a reference for determining the contours of hydrogen. The validation of Safeti-NL for hydrogen is steadily being expanded and attention is also being paid to implementing a realistic ignition probability.

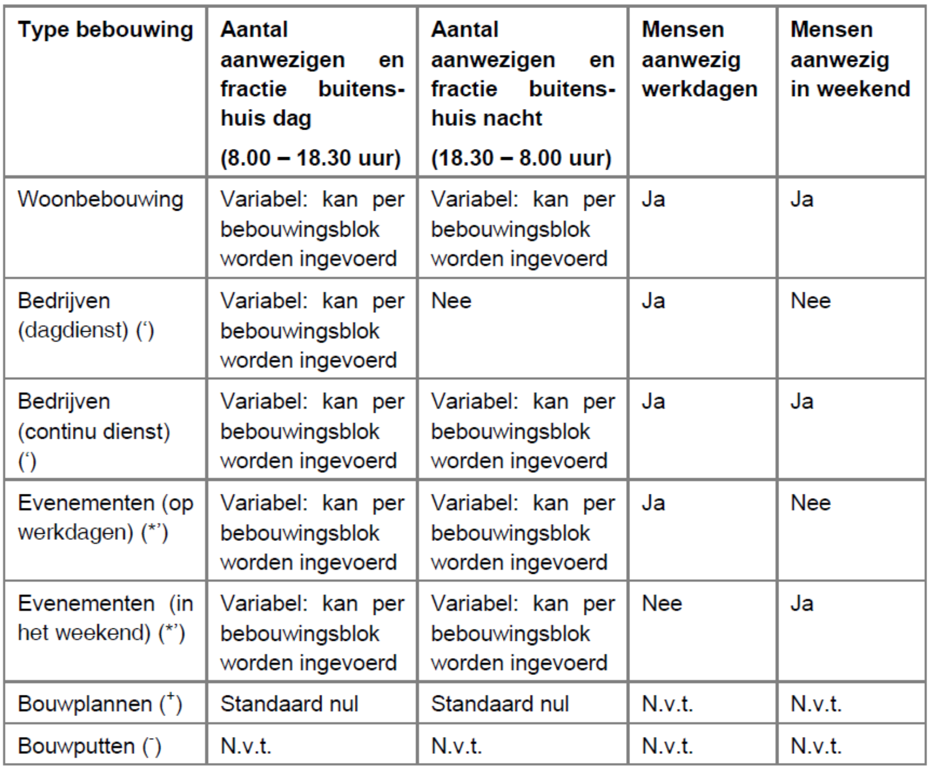
2.4 RBM II

2.4.1 Application area of software tool

RBM II (RisicoBerekeningsMethodiek Versie 2) calculates the risk of the transport of hazardous substances by road, rail and water [11] as prescribed in the Transport Risk Calculation Guide (HART) [12]. The effect models are based on those described in the so-called Yellow Book [13].

2.4.2 Generic description of the software tool

RBM II is a QRA tool based on a limited number of 'model' substances and associated accident scenarios. The substances are classified according to state (liquid, gas), flammability and toxicity [11]. The scenarios are based on continuous, public transport routes (rail, water or road) at ground level. Open transport routes here mean everything except completely or partially closed locations, such as tunnels, specific railway situations at stations (roofs) or waterway situations (bridges). With RBM a group risk and/or the risk for a (set of) building(s) can be calculated. The tool is not applicable for stationary situations and the user is referred to Safeti-NL. By importing a map, the user can indicate which path to follow and use can be made of the built-in application of the geographic information system (GIS). By selecting a weather station in the vicinity, the corresponding meteorological data can be retrieved and the distribution of the hazardous (gaseous) substances is modeled. The number of people on the specified route can be entered manually or the National Population Service [14] can be used. The buildings are residential areas, companies 'during the day', companies 'continuous' (such as hospitals, hotels), events during the working week and events during the weekend, see also Figure 4.



Type bebouwing	**Aantal aanwezigen en fractie buitenshuis dag** **(8.00 – 18.30 uur)**	**Aantal aanwezigen en fractie buitenshuis nacht** **(18.30 – 8.00 uur)**	**Mensen aanwezig werkdagen**	**Mensen aanwezig in weekend**
Woonbebouwing	Variabel: kan per bebouwingsblok worden ingevoerd	Variabel: kan per bebouwingsblok worden ingevoerd	Ja	Ja
Bedrijven (dagdienst) (‘)	Variabel: kan per bebouwingsblok worden ingevoerd	Nee	Ja	Nee
Bedrijven (continu dienst) (‘)	Variabel: kan per bebouwingsblok worden ingevoerd	Variabel: kan per bebouwingsblok worden ingevoerd	Ja	Ja
Evenementen (op werkdagen) (*’)	Variabel: kan per bebouwingsblok worden ingevoerd	Variabel: kan per bebouwingsblok worden ingevoerd	Ja	Nee
Evenementen (in het weekend) (*’)	Variabel: kan per bebouwingsblok worden ingevoerd	Variabel: kan per bebouwingsblok worden ingevoerd	Nee	Ja
Bouwplannen ($^+$)	Standaard nul	Standaard nul	N.v.t.	N.v.t.
Bouwputten ($^-$)	N.v.t.	N.v.t.	N.v.t.	N.v.t.

Figure 4 Definition of the different types of buildings [11]

By default, the length of the route is at least 1000 meters, although smaller routes can be defined. The maximum group risk per kilometre is calculated from the group risks of the individual contributions. The societal risk is superimposed over 1000 meters with a resolution of 25 meters. In Table 1 - Table 3 [12], the classification of the 'model' hazardous substances is given for the various logistical options. Depending on the combustible model substance, the probability of ignition is fixed for both instantaneous and delayed ignition, as well as the associated effects (BLEVE, flare, flash fire, explosion or pool fire). No specific information is given on the validation of the chosen ignition probability and associated effects. The pressures of the gaseous substances that can be used for calculations correspond to the pressures that apply to a gas pressure regulating station.

Category		Model substance
A	Flammable gas	Propane
B2	Toxic gas	Ammonia
B3	Very toxic gas	Chlorine
C3	Very flammable liquid	Pentane
D3	Toxic liquid	Acrylonitrile
D4	Very toxic liquid	Acrolein

Table 1 Dangerous model substances as used in the RBM II software tool for rail transport [12].

Category		Model substance
GF1	Flammable gas	Ethylene oxide
GF2	Flammable gas	Butane
GF3	Flammable gas	Propane
GT2	Toxic gas	Methyl mercaptan
GT3	Toxic gas	Ammonia
GT4/GT5	Toxic gas	Chlorine
LF1	Flammable liquid	Heptane (diesel)
LF2	Flammable liquid	Pentane (gasoline)
LT1	Toxic liquid	Acrylonitrile
LT2	Toxic liquid	Propylamine
LT3	Toxic liquid	Acrolein
LT4	Toxic liquid	Methyl isocyanate

Table 2 Dangerous model substances as used in the RBM II software tool for road transport [12].

Categorie		Modelstof
GF2	Brandbaar gas	Butaan
GF3	Brandbaar gas	Propaan
GT3	Toxisch gas	Ammoniak
LF1	Brandbare vloeistof	Heptaan (diesel)
LF2	Brandbare vloeistof	Pentaan (gasoline)
LT1	Toxische vloeistof	Acrylonitril
LT2	Toxische vloeistof	Propylamine

Table 3 Dangerous model substances as used in the RBM II software tool for transportation by water [12].

2.4.3 Applicability to hydrogen gas regulation station

The RBM II model cannot directly calculate safety contours for hydrogen. Because the tool uses so-called model substances, a chemical substance can be selected that best approximates the behavior of hydrogen. Given the model substances, there is no chemical in the database that comes close to the behavior (lighter-than-air) of hydrogen. If a model substance were present, the probability of ignition must be corrected for that of hydrogen and possibly also the associated effects. RBM II is intended for mobile applications, as the risk is expressed per unit of length travelled. Since the gas pressure regulating station is a stationary facility, the resulting calculated safety contours will therefore deviate from the actual ones.

2.5 Conifer

2.5.1 Application area of software tool

The QRA software package CONIFER [15] [16] has been specially developed for that part of the natural gas distribution network that extends from the gas pressure regulating stations (7 barg) to the gas meter (21 mbarg) in, for example, a house. With a view to the energy transition, the tool has been expanded to include hydrogen/natural gas mixtures and pure hydrogen. The tool is based on existing natural gas models and is now being expanded to include models based on pure hydrogen.

2.5.2 Generic description of the software tool

The methodology used by Conifer is shown schematically in Figure 5 to Figure 7 and consists of several modules to provide a safety contour of an object experiencing a natural gas or hydrogen leak. Conifer has been validated for natural gas and has recently been validated for hydrogen based on literature data and data obtained from the H21 project [17].

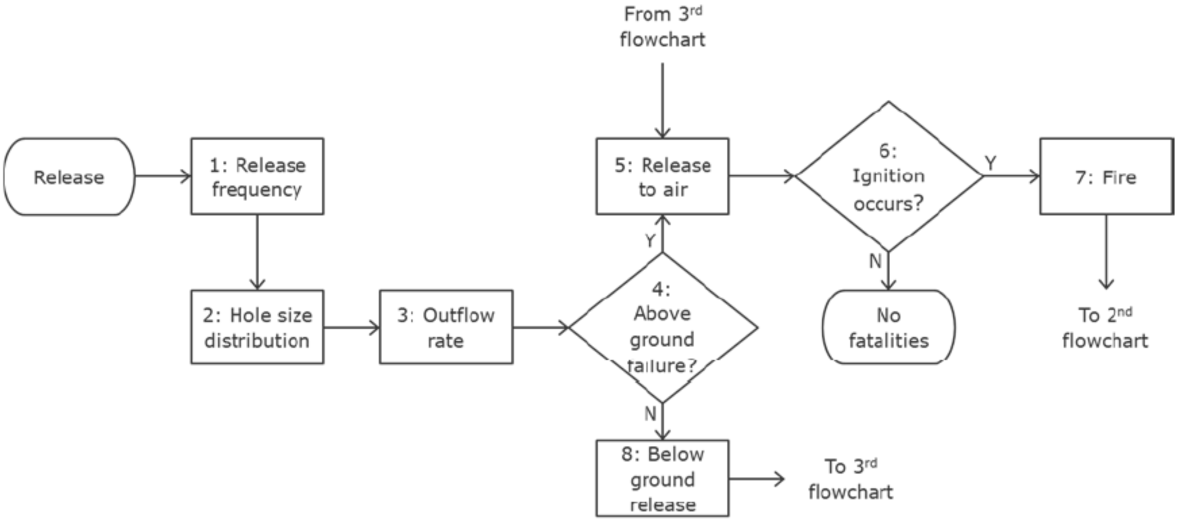


Figure 5 Scheme 1 of the methodology used by Conifer to determine the effects of the incidental release of natural gas/hydrogen gas

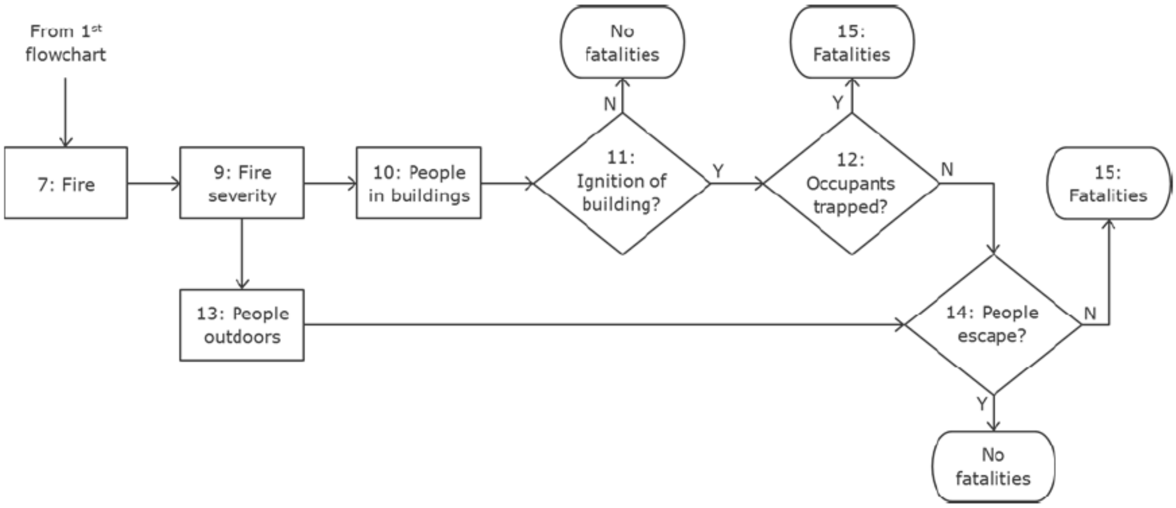


Figure 6 Scheme 2 of the methodology used by Conifer to determine the effects of the uncontrolled release of natural gas/hydrogen gas

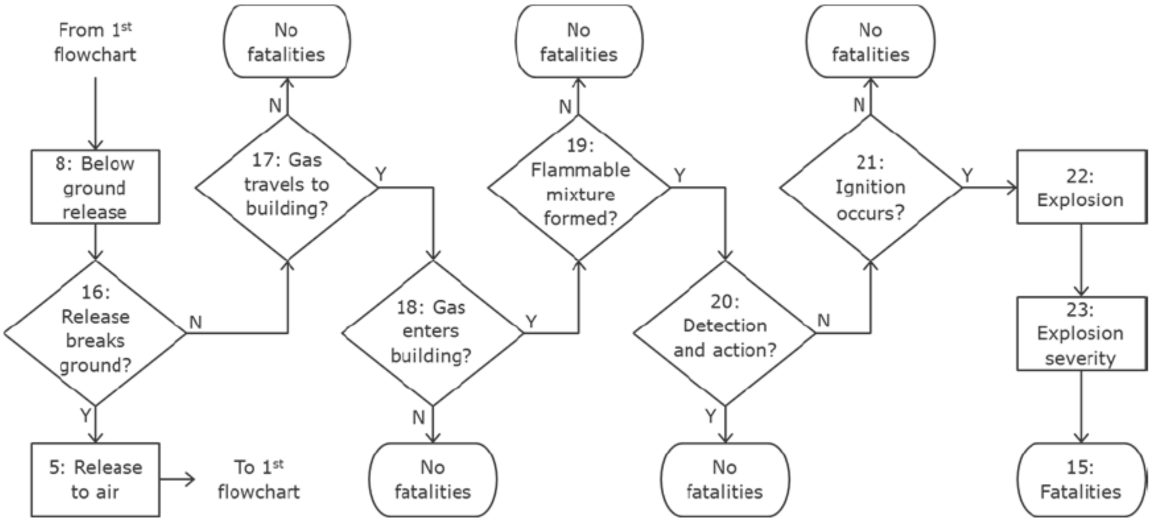


Figure 7 Scheme 3 of the methodology used by Conifer to determine the effects of the uncontrolled release of natural gas/hydrogen gas

The failure frequencies based on historical data have been implemented in the tool and the failure frequencies for hydrogen and natural gas are assumed to be the same for the time being. Since new data for hydrogen will be obtained in the future, the database will be adjusted accordingly. A fixed range of five perforation sizes is available with the associated probabilities of occurrence. Various failure modes are available, such as external damage due to, for example, excavation work, corrosion defects on metal pipes and connection defects. Each combination of pipe material and failure mode has a specific frequency and perforation size distribution. Depending on the scenario, the user can select an above-ground or underground release, where ignition probabilities are based on historical data for natural gas. For hydrogen, the dataset for the probability of ignition is under development. The user can choose instantaneous and delayed ignition. In case of an outdoor fire, the effect of wind is taken into account, but not the meteorological conditions for that location. The risk predictions given are presented in terms of potential loss of life, which represent the societal risk beyond individual risk values. Different building types and occupancy patterns can be included in the risk calculations.

2.5.3 Applicability to hydrogen gas regularion station

The Conifer QRA tool has been developed specifically for natural gas pressure regulating station and covers all operating conditions between such a station and a gas meter. The software package has been expanded with hydrogen gas and work is underway on further validation of the hydrogen models.

2.6 Discussion and comparison of the software tools

2.6.1 Introduction

Of the aforementioned QRA models that are frequently used for the Dutch situation (Pipesafe, RBM II and Safeti-NL), Safeti-NL can be used to determine the safety contours around a gas pressure regulating station for hydrogen. A fourth model, Conifer, is an existing model developed for the UK situation and fully validated for natural gas. This model is currently being expanded with models for hydrogen and is being tailored more to the situation in the Netherlands, such as the presence of so-called crawl spaces (not applicable in the UK). For a comparison of the packages, only Safeti-NL and Conifer are therefore relevant.

Given the development trajectory of Conifer, the fact that this package is not yet widely used in the Netherlands and setting up a QRA is time-consuming, especially if exactly the same situation has to be introduced in the respective packages, an indirect comparison has been chosen. This comparison considers the effect of the use of natural gas versus hydrogen on the risk within 1 software package – for the same situation. This means that the packages cannot be compared directly with each other, but it can be determined whether switching from natural gas to hydrogen brings about a change in risk. With regard to Conifer (see below), this package has been specifically developed for determining the risk contours around gas pressure regulating stations up to and including the connection in a house.

2.6.2 Conifer – natural gas versus hydrogen

To illustrate the difference between hydrogen and natural gas, the overpressures that both gases can produce were assessed [16]. It is known that hydrogen has a greater risk of catastrophic damage to a building or to people than natural gas. When natural gas and hydrogen are released into the open air, there is little risk of damage to people or buildings.

The situation sketch as shown in Figure 8 is used for the comparison. The house in which the explosion takes place is referred to as the 'Event house'. This particular house is a semi-detached house with one nearby but not adjoining house. The risk calculations take into account damage to persons in these three houses, the three houses across the street and the three houses with gardens that border the 'Event House' and the immediate neighbours. The dimensions of the house and garden and the width of the road are representative of a residential area in Great Britain.

Table 4 gives an overview of the predicted number of fatalities for a hydrogen and natural gas explosion, based on a population of three people per house and taking into account time away from the house (during the day – at work) and time away from home while people are not at work (like evenings, weekend). The 'Average' column shows the total number of predicted fatalities, averaged over explosions that occur at any time of the day. The 'Range' column shows the variation in the total number of predicted fatalities, depending on the time of the explosion.

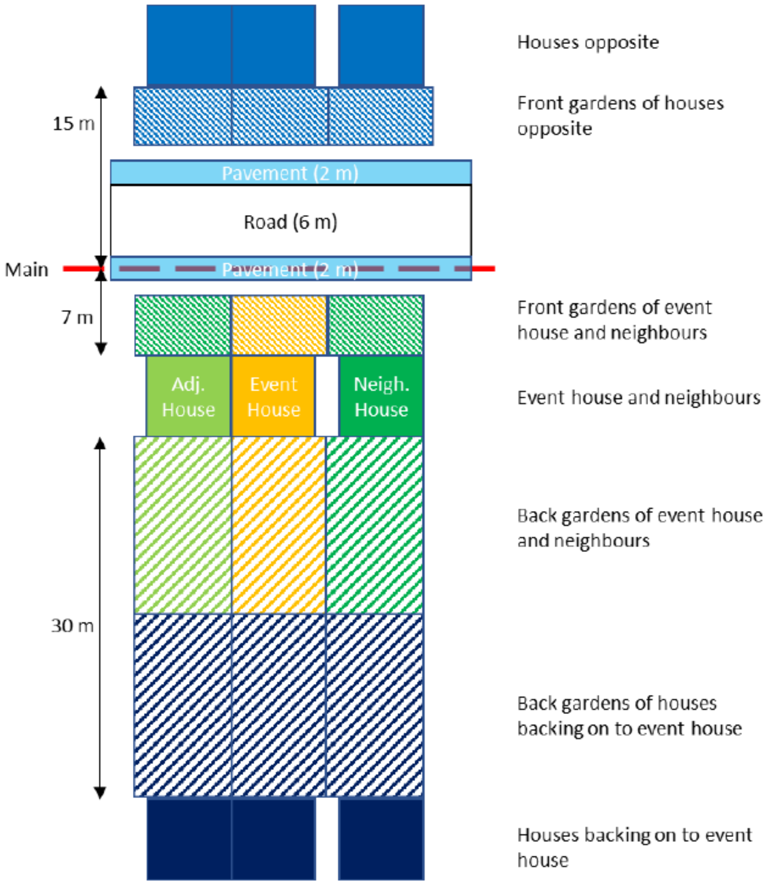


Figure 8 Consequences of an explosion in a house on the adjoining houses in case of either a natural gas or a hydrogen gas explosion [16]

Explosion	Number of casualties as predicted by Conifer					
	'Event house'		Other houses		Total	
	Indoors	In garden	Indoors	In garden	Indoors	In garden
Stoichiometric CH_4	0,27	< 0,01	0,10	< 0,01	0,37	0,19 – 0,56
Stoichiometric H_2	0,96	0,02	1,43	0,03	2,44	1,30 – 3,67
Representative CH_4 leak	0,10	< 0,01	0	<0,01	0,10	0,05 – 0,15
Representative H_2 leak	0,06	0	0	0	0,05	0,03 – 0,08

Table 4 Predicted number of casualties for a natural gas or hydrogen gas explosion for the situation as depicted in Figure 6 and as calculated by the software tool Conifer [16]

In the case of a stoichiometric natural gas explosion, the effects are particularly greatest for the house in which the explosion occurs. This is in contrast to a stoichiometric hydrogen explosion, in which the effects are particularly greatest for the surrounding houses.

2.6.3 Safeti-NL – natural gas versus hydrogen gas – high pressure pipelines

The Antea group [18] carried out a risk analysis regarding the location-related risk and heat radiation effects for high-pressure pipelines (> 40 bar) using Safeti-NL version 8.5 for hydrogen. This was compared with data for the same natural gas pipelines using the Carola method. Ideally, the comparison was to be carried out with Safeti-NL. The Center for Safety of the RIVM established [19] that there are no significant differences for gas transport pipelines between Carola on the one hand and Safeti-NL on the other in terms of robustness, validity and verifiability. As such, Carola's results are included in this comparison as being representative, knowing that explicit differences were included for a number of parameters during modeling with Safeti-NL, see further below.

In the first instance, a direct comparison of a number of pipelines was assumed and no account was taken of any mitigating measures that are actually in force, see Table 5. This included looking at the maximum risk at the level of the hydrogen pipelines ("on pipeline").

Tube diameter [mm]	Pressure [barg]	Wall thickness [mm]	Risk H_2 'on pipeline' [10^{-6}/year]	Risk CH_4 'on pipeline' [10^{-6}/year]	Ratio	10 kW/m^2 H_2 [m]	10 kW/m^2 CH_4 [m]	Ratio
323,9	40	7,1	1,65	0,22	7,4	132	138	0,96
406,4	80	6,6	8,46	1,82	4,7	203	231	0,88
610	66,2	9,3	0,62	0,17	3,6	263	315	0,83

Table 5 Risk and heat radiation effects of selected high-pressure pipelines for hydrogen and natural gas [18]

It follows from these calculations that the 10^{-6}/year site-specific risk contours for hydrogen pipelines are greater than those for natural gas pipelines. Given the difference in the appearance of the flames of hydrogen and natural gas, the heat radiation contours of hydrogen are smaller than those of natural gas. This also follows from the calculations, see Table 5. It should be noted that there is a difference in the outflow rate between hydrogen and natural gas. Subsequently, calculations were performed on existing pipelines, taking into account the mitigating measures in force on site, see Figures below.

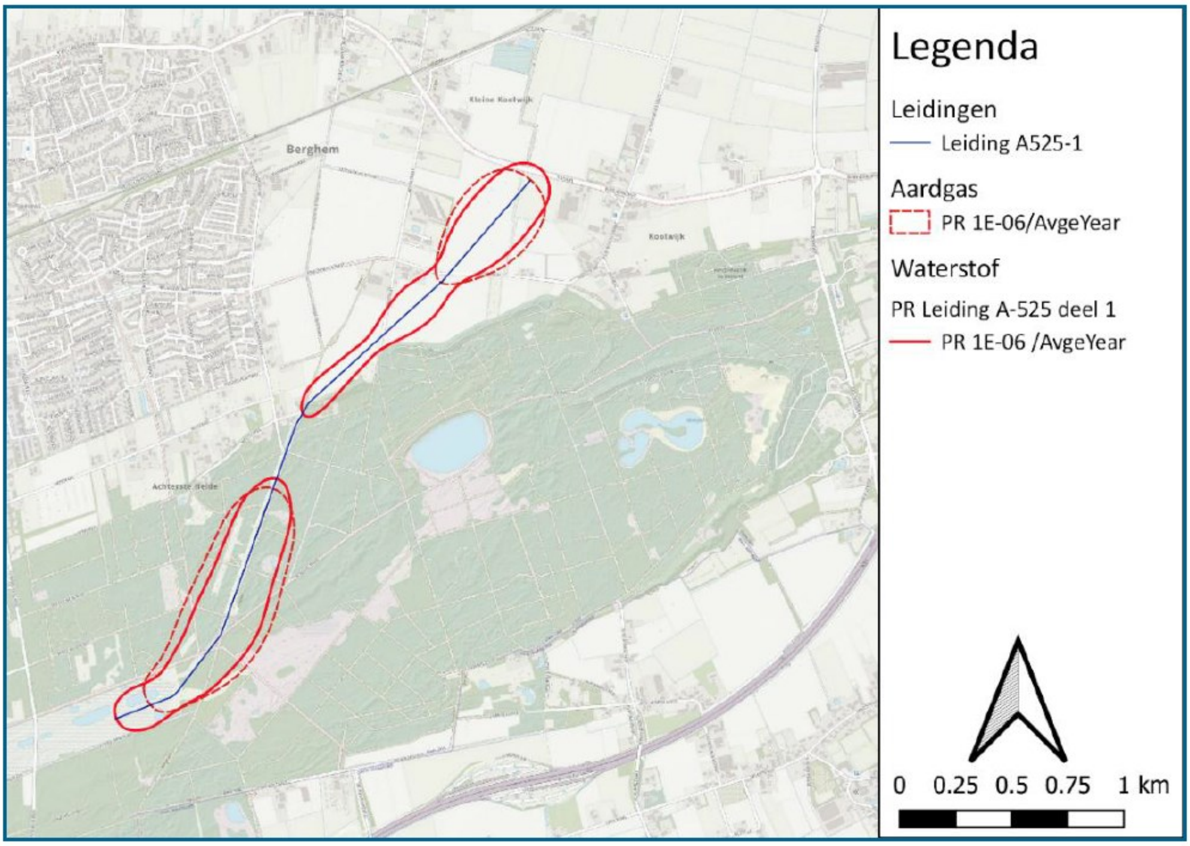


Figure 9. Size-specific risk contours of pipeline A525-1 (diameter 914 mm, pressure 66,2 barg) [18]

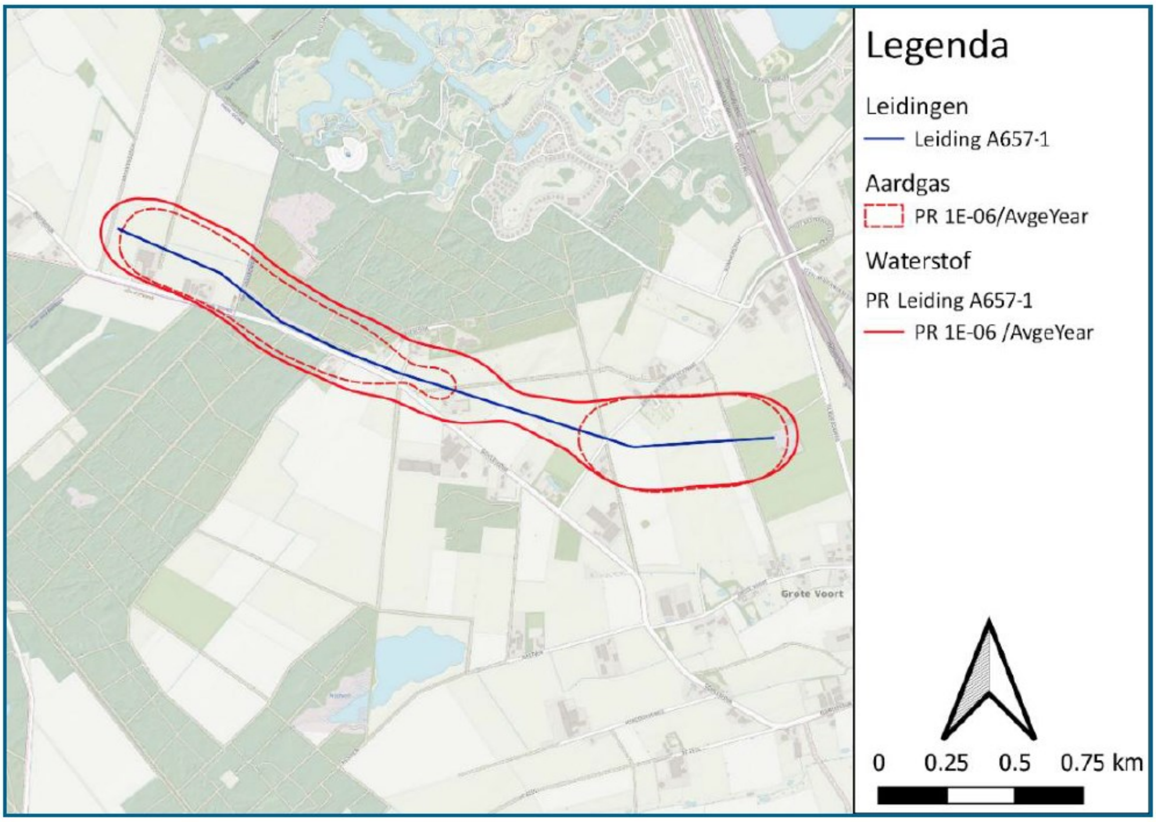


Figure 10 Site-specific risk contours of pipeline A657-1 (diameter 610 mm, pressure 66,2 barg) [18]

It can be concluded from the calculations that there is an increase in risk if hydrogen is used in the same natural gas transport pipelines. It should be noted that for the calculations it was assumed that the probability of ignition of hydrogen was 100%, while that of natural gas – depending on the diameter of the pipeline – was smaller. Furthermore, the failure frequency for the hydrogen pipelines was also assumed to be higher than that for natural gas. Both parameters have an effect on the risk contours found. These points do not correspond with the knowledge gained so far with regard to hydrogen in distribution networks.

2.6.4 Safeti-NL – natural gas versus hydrogen gas – gas regulation station

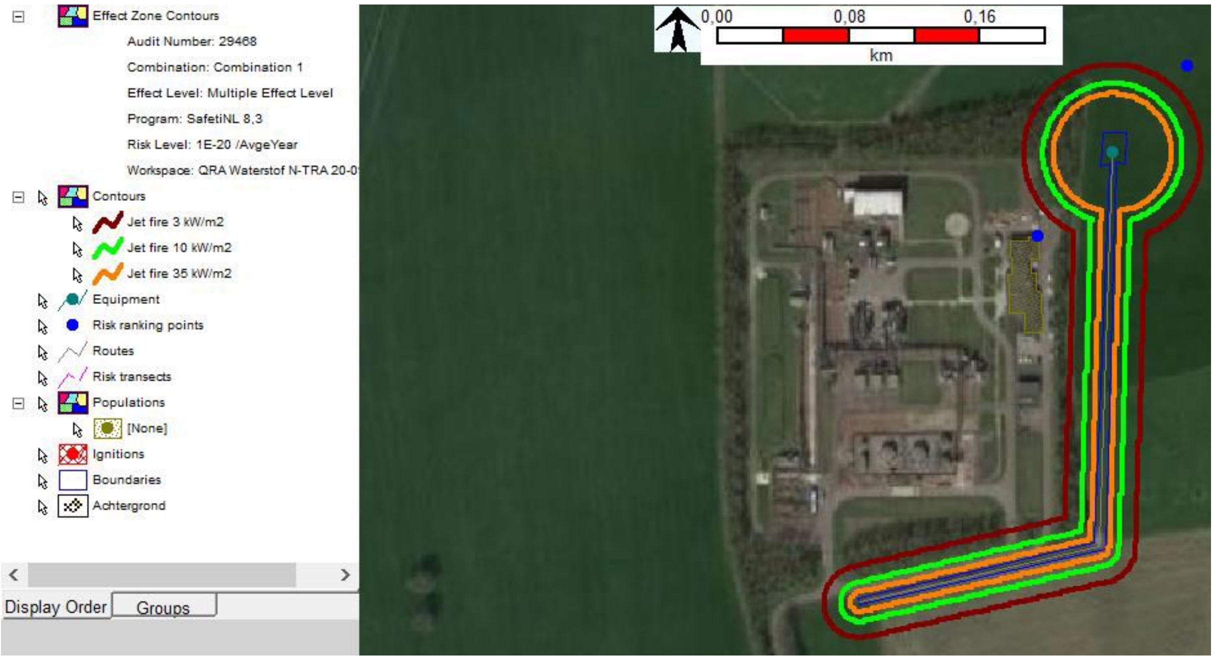
Arcadis [20] performed risk calculations for a hydrogen-based district in Hoogeveen with Safeti-NL, version 8.3. Part of this district is a gas pressure regulating station, where the hydrogen pressure is reduced from 4 barg to 100 mbar, see Figure 11. Parallel to the gas pressure regulating station is the NAM Ten Arlo location. The A28 is 115 meters south of the station and the existing Erflanden residential area is 200 meters east. The hydrogen district is located 80 meters north of the station. A receiving station is also shown in Figure 11, but it is not part of the present QRA. A concept of the gas pressure regulating station is shown in Figure 12.

The calculation of the risk of the gas pressure regulation station is based on the situation that 900 kg of hydrogen can be released. This is in accordance with the emptying of a truck trailer with hydrogen, which is parked upstream of the receiving station. Meteorological data were based on the weather station in Twente. The risk calculations were based on a horizontally directed outflow (standard in Safeti-NL), with an outflow duration of 30 minutes, and the risks of a flare fire were uniformly spread over all directions. Direct ignition was assumed and since there are no potential sources of ignition outside the boundary, and hence delayed ignition was declared not applicable.

Figure 11 Sketch of the reducing station in Hoogeveen [20]

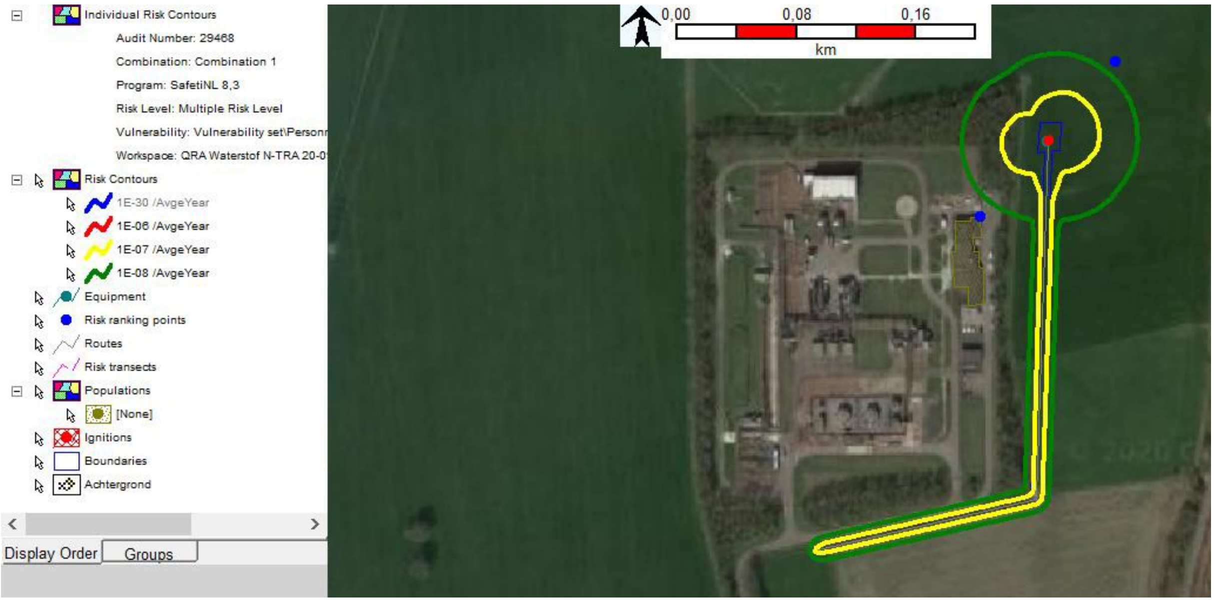
Figure 12 Concept of the gas pressure regulation station for the hydrogen-based district in Hoogeveen [20]

Based on the position of the pressure regulation station, there is only an area with fire risk, see Figure 13. The resulting risk contours are shown in Figure 14.



Effect Zone Contours
Audit Number: 29468
Combination: Combination 1
Effect Level: Multiple Effect Level
Program: SafetiNL 8,3
Risk Level: 1E-20 /AvgeYear
Workspace: QRA Waterstof N-TRA 20-0

Figure 13 Calculated fire area of the pressure regulation station and associated low-pressure pipelines (4 bar) for the hydrogen-based district in Hoogeveen [20]



Individual Risk Contours
Audit Number: 29468
Combination: Combination 1
Program: SafetiNL 8,3
Risk Level: Multiple Risk Level
Vulnerability: Vulnerability set\Person
Workspace: QRA Waterstof N-TRA 20-0

Figure 14 Risk contours of the pressure reducing station and the associated low-pressure pipelines (4 bar) for the hydrogen-based residential district in Hoogeveen [20]

As mentioned, the location of this pressure regulation station is such that no external safety risk can be expected from this station.

As stated, this analysis was performed for a hydrogen-based regulation station. As mentioned in chapter 2.6.3, calculations performed with Safeti-NL show an increase in the risk if hydrogen is used in the same application for natural gas. This also has to do with the fact that for the calculations in Safeti-NL it was assumed that the probability of ignition of hydrogen is 100%, while that of natural gas is smaller, which has an effect on the risk contours found. Given the fact that this station is at a remote location, this will not cause any change for external safety.

2.7 Conclusions

An inventory of the various Quantitative Risk Assessment (QRA) tools for determining the risk contours around a so-called gas pressure regulating station (pressure < 8 barg) was carried out. Of these tools, PipeSafe, Carola and RisicoBerekeningsMethodiek Version 2 (RBM II) are not suitable. Pipesafe and Carola have been developed for determining the risk contours of underground pipelines at pressures from 7 bar. Gas pressure regulation stations are above ground and operate at lower pressures. The RBM II tool uses a limited number of model substances, none of which simulate the behaviour of hydrogen. This tool is also intended for mobile applications and not for stationary applications such as a district station.

The QRA tools Safeti-NL and Conifer are suitable for determining the risk contours around a gas pressure regulation station. Conifer has been specifically developed for determining the risks for that part of the gas network from a pressure regulation station to a gas meter. Originally developed for natural gas and currently being expanded for hydrogen. Conifer is used in the Hydelta QRA model. Safeti-NL is the most common QRA software package that is recognized by the competent authorities in the Netherlands as a tool for determining the risk contours for installations involving toxic and/or flammable substances.

A direct comparison between the two tools Safeti-NL and Conifer specifically for a pressure regulation station was not made. When both tools are applied to an (arbitrary) situation where the risk contours of hydrogen are compared to those of natural gas, both tools show larger risk contours for hydrogen compared to natural gas. Both tools are further expanding their databases for hydrogen, which means that the validation process is in full swing. With the current situation of incomplete validation, both software tools use worst case scenarios in the case of hydrogen, such as an ignition probability of 100%. This means that the contours for hydrogen are larger than those for natural gas. With further expansion of the databases, especially for an open-air situation, it is expected that the contours will be similar.

It should be noted that Safeti-NL is accepted by the Dutch competent authorities and that a license for this tool can be obtained. Conifer is less known in the Netherlands and no license can be obtained from it.

3 Detection of hydrogen fires

3.1 Introduction

From a safety point of view, it is important that a hydrogen flame or fire can be visually detected. The properties of hydrogen and its combustion gases make the visibility of the flame with the naked eye extremely situation-dependent. Exactly how this works, what practical situations from the literature show, and what detection methods are available for making the hydrogen flame visible are discussed below.

3.2 Properties of a hydrogen flame

We can perceive objects with the naked eye because the eye captures radiation emitted by objects. There are different forms of radiation, from gamma rays to radio waves, but only radiation with wavelengths between roughly 400-750 nm can be perceived as colors by the naked eye. That wavelength range is also called the visible spectrum (see Figure 3-1).

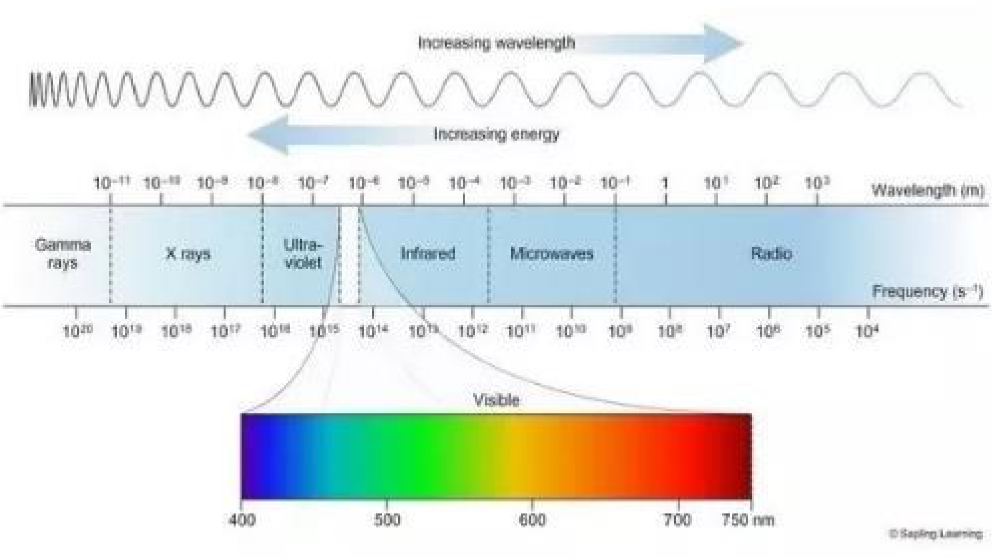


Figure 3-1 The different types of radiation of the electromagnetic spectrum. The visible light spectrum and the colors associated with specific wavelengths are magnified

The visibility of a flame depends on the components (molecules/radicals/atoms) contained in the gas-air mixture. The energy released during combustion excites electrons from components in the flame. When those components return to their original ground state, radiation is released. Therefore, a flame consisting of molecules/radicals/atoms that emit more radiation in the visible spectrum will be more observable by the naked eye. The emission of radiation from a flame can be measured and represented in the form of an emission spectrum. The emission spectrum of a typical hydrogen flame is shown in Figure 3-2. The peak in the wavelength range from 600 to about 900 nm is attributed to highly excited and vibrating water molecules (H_2O) and produces the red glow in a hydrogen flame. The elongated, relatively weak, blue emission continuum to the right of the OH peak is attributed to the reaction between OH and H radicals forming H_2O. This reaction is responsible for the blue color in the flame [21]. The latter reaction also takes place in the combustion of natural gas and creates the same blue hue there as well. The yellow-orange colors in a natural gas flame are attributed to reactions involving molecules/radicals with carbon. Molecules/radicals with carbon are absent in hydrogen combustion.

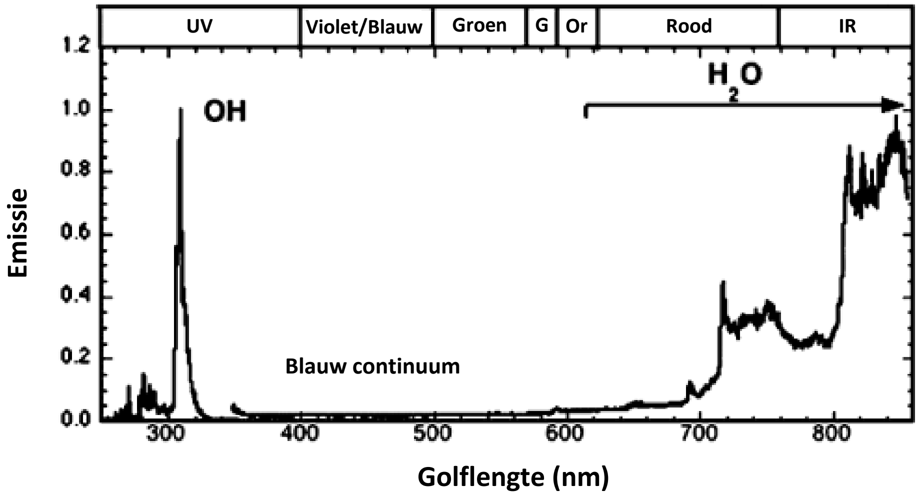


Figure 3-2 Typical emission spectrum of a hydrogen flame from ultraviolet to infrared (adapted from [21])

3.3 Factors affecting visibility hydrogen flame

Gas-to-air ratio

In addition to radicals/atoms present, the intensity of the flame and flame color also depend on the gas-to-air ratio of the combustible mixture. Normally, the hydrogen flame has a gray-blue color. However, as the gas-to-air ratio increases, shades of red also become visible and the intensity of the flame is slightly increased. We see a similar effect with natural gas, where shifting to yellow-orange tones occurs as the ratio of gas to air and thus incomplete combustion increases. This is explained by increasing incomplete combustion [21]. Figure 3-3 shows the pictures from the study that illustrate this.

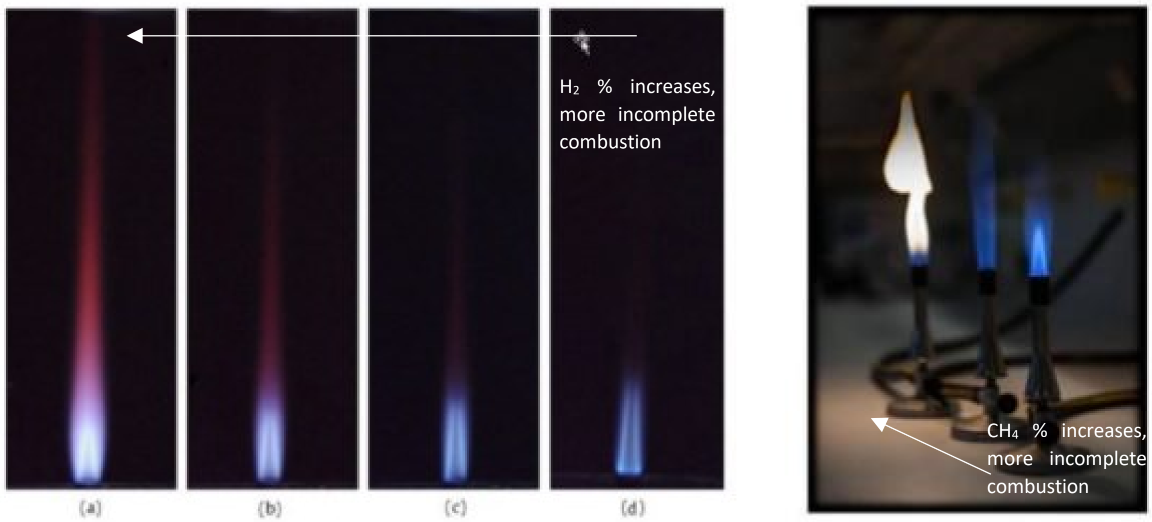


Figure 3-3 Hydrogen flame (left) and natural gas flame (right) [21]

Environmental factors (background and contaminating elements).

Ambient conditions can make a hydrogen flame stand out better or worse against the background and thus be more or less visible. A dark background, such as a nighttime situation or a dark material increases the visibility of the hydrogen flame. This can be clearly seen in images from an AlChE Academy experiment (Figure 3-4) [22] and as mentioned in the Hydrogen Colourant report van DNV [23] (Figure 3-5).

Figure 3-4 A propane flame and hydrogen flame at night (left) and during the day (right) [22]

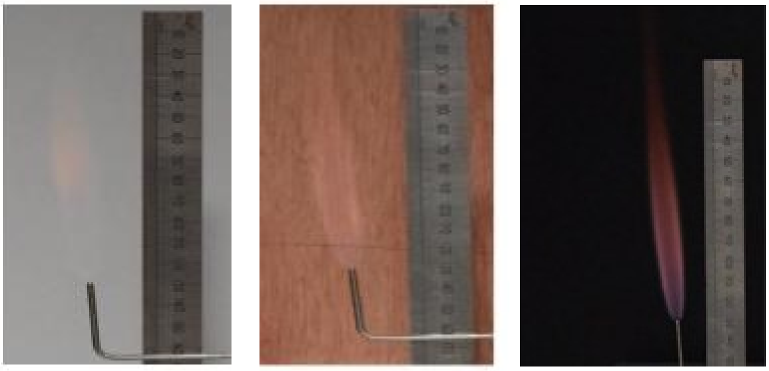


Figure 3-5 Hydrogen flame (80 mbar) against white background, wooden background and black background [23]

In addition to a dark background, observability can also be enhanced by the presence of pollutant elements. Their combustion products can also emit radiation in the visible spectrum upon excitation.

The observability of a hydrogen flame or fire in practical situations in high and low pressure distribution pipelines has been described in several studies [23], [24], [25], [26], [27], [28], [29]. The available literature does not show a unified picture and does not conclusively establish whether a hydrogen flame is sufficiently visible in a situation. As part of the H21 project, large-scale hydrogen fires in 8-inch steel pipes under pressures of 350 mbar, 2 bar and 7 bar were investigated [28], [17]. The results show that the observability of flames in pipes without ground cover is interpreted differently. A study by DNV GL for the H21 project states that "very little visible radiation" can be seen, see Figure 3-6 [27]. At the same time, a DNV GL report for the H100 Fife project qualifies the flame observability of the exact same photographs in Figure 3-6 as 'clearly visible, although visibility of the flames may be enhanced by the background (dark tree line)' [26]. Data on hydrogen fires in pipeline ruptures with ground cover is scarce. A simulated pipeline rupture and fire in a 60 bar transport pipeline conducted at night [29] is very clearly observable. In the H21 project (H21 Phase1B), more tests are envisioned with ground-covered distribution pipelines. During hydrogen blowdown and flaring, colors are barely visible, if at all, during the day against blue skies or green foliage [24], [25].

Figure 3-6 Visibility of hydrogen fires in 8-inch steel pipes under pressures of (from left to right) 350 mbar, 2 bar and 7 bar and without ground cover [26] [27]

The visibility of a hydrogen flame in practical situations for gas distribution pipelines varies by application and is highly dependent on environmental factors, such as day/night, background and material present for "flame contamination," as well as human interpretation.

Presence of odorant

In the literature on hydrogen flame visibility, no information was found on the influence of odorant on the visibility of a hydrogen flame.

3.4 Detection techniques

For industrial applications, sensors have been used for hydrogen flame detection for many years. These are primarily stationary sensors that are often connected to the hydrogen supply and plant and provide safe automatic shutdown and isolation of hydrogen sources, as well as audible and visual alarms. These sensors do not focus on visually detecting flames. Engineers working on the gas (hydrogen) grid and emergency responders, such as firefighters, usually work in areas where continuous flame monitoring is not available. To see a hydrogen fire, they will need portable, easy-to-handle tools that provide a quick and reliable indication of the existence, location and size of a hydrogen flame.

Considering the electromagnetic spectrum of hydrogen flames, sensors that provide the link between invisible ultraviolet and infrared radiation and the human eye may be suitable detection techniques. A portable thermal imaging camera that measures infrared radiation by thermography and converts it in "real time" into a thermal image that can be perceived by the human eye is an example. Sensors that convert ultraviolet radiation into an observable image are not yet available on the market but the technique has been proven [30]. In addition, infrared-ultraviolet combination sensors are available for industrial applications (fixed setup). Combination sensors provide faster detection and higher reliability by filtering out false alarms such as sparks, lightning and other UV-rich non-flash sources. These combination sensors for portable application are also not yet on the market.

3.5 Flame visibility and detection in hydrogen appliances

Various ways to ensure hydrogen flame visibility are described in the Hy4heat Hydrogen Colourant report [23]. Here, particular emphasis is placed on hydrogen appliances. A thermochromic coating that discolors when heated [31], metal rods that glow in the flame and ways of "hot surface indication" with thermocouples coupled to LED displays, as also used in electric stoves, are mentioned as options. Detection devices based on infrared and ultraviolet radiation (IR sensors and UV sensors) are also seen as potential candidates. However, these will have to be developed for low levels of radiation [23]. However, the responsibility and development of these lies with the manufacturers and will not be discussed further here. Adding a colourant is ruled out as an option, as this could potentially result in the generation of harmful byproducts and lead to corrosion of materials [23].

3.6 Is flame detection equipment necessary for grid operators?

To answer the question of whether flame detection equipment is necessary for grid operators, the situations in which there may be a hydrogen outflow and possibly a hydrogen flame were considered. A hydrogen outflow may be planned, such as in the case of flaring or blowdown. A hydrogen outflow may also be unplanned, for example, as a result of leakage or as a result of damage from operations.

3.7 Planned gas outflow

A planned hydrogen outflow occurs during gas flaring and venting. Kiwa report GT-200096 [25] describes the investigation of the safe and effective commissioning and decommissioning of hydrogen pipelines by flaring or blowing off. The research carried out did not give reason to include the availability of means for flame detection as a recommendation.

More experience has since been gained with hydrogen flaring. Because the visibility of the hydrogen flame during flaring can be poor, depending on the environment, it is important that persons present during flaring be aware of the presence of a flame. As a result of this experience, it is a recommendation that safety work instructions for hydrogen flaring specify the danger of not being aware of the presence of a hydrogen flame specifically.

3.8 Unplanned gas outflow

Kiwa conducted an analysis of incident reports according to the State Supervision of Mines (SodM) reporting criteria in the period 2017 to 2019 for the benefit of the 'Kenniscetrum Gasnetbeheer's Sounding Board in 2021. During this period, there were 572 incidents reported involving gas outflow. In 505 incidents there was no ignition of the released gas, in 5 incidents there was delayed ignition of the gas and in 62 incidents there was direct ignition of the gas and thus a gas fire.

The 62 incidents involving direct ignition of the released gas are distinguished as follows:

- 31 incidents involving direct ignition involved fires in the meter box, where the gas fire was the result of another fire.
- In 16 incidents, the gas fire was the result of excavation work in which the gas and power lines were damaged simultaneously.
- In 15 incidents, the gas fire was the result of work on or near gas pipelines. The cause of the fire was damage to the gas pipelines combined with the use of power tools or burners. These incidents occurred both inside and outside the facade.

If these incidents were to occur with hydrogen, it is plausible that the hydrogen flame would be visible due to material from the surrounding area also burning. Currently, however, experience is lacking to support this assumption.

In addition, there is a lack of understanding of whether the leaks that currently occur in natural gas distribution as a result of asset failure (for example, due to corrosion or subsiding soil) and that do not lead to a gas fire will lead to a gas fire in hydrogen distribution.

Due to the lack of practical experience with hydrogen fires, it is assumed that situations where a hydrogen flame will be non- or poorly visible are not excluded.

3.9 Recommendation

Because experience is lacking, a recommendation is made that tools for detecting a hydrogen flame be made available to service technicians in pilot projects and that they are made aware of the possible presence of a hydrogen flame. The experience gained during the pilot projects and possible additional research can be used to determine whether flame detection equipment should continue to be available in the future for work on hydrogen grids.

Because information on the visibility of burning odorized hydrogen is lacking, the recommendation is to determine through research whether THT odorization has an effect on the visibility of a hydrogen flame.

To obtain knowledge about hydrogen flame visibility, the recommendation is to inquire about hydrogen flame visibility in the event of incidents and record this information in the incident report.

4 Effectiveness of THT odorization

4.1 Introduction

Because hydrogen gas, like natural gas, has no characteristic odor. In a future distribution of hydrogen, the gas will be odorized.

The question posed by the Hydelta 2.0 program is the following:

To what extent is the effectiveness of barrier odorization affected by, for example, adsorption and/or absorption of the odorant?

In the current distribution of natural gas, an odorant is added to the gas. This odorant should ensure that a gas leak can be detected by smell. The odorant aims to alert persons in the event of a gas leak. Odorization should allow the odor to be detected well below the lower flammability limit of the gas. Alerting should lead to taking action (closing gas supply yourself, calling emergency services, calling national emergency number). The combination of sensing and taking action thus forms a barrier (measure) to prevent a gas leak from escalating into, for example, a fire or explosion.

4.2 Scope

Not taking action or taking action too late after smelling the odorant also affects the effectiveness of the barrier (measure). This analysis did not consider the influence of "taking action”.

Odorant is added to the gas by means of an odorization unit. The situation where insufficient odorant is added to the gas due to the failure of the odorization unit is not considered in this analysis.

4.3 What determines the effectiveness of barrier odorization?

Barrier (measure) odorization consists of the activities of perceiving and taking action. The odorization of gas must make perceiving that gas possible. When perceiving is not possible, or when perceiving occurs only at a higher gas concentration, the effectiveness of the barrier (measure) decreases.

4.4 Welke fenomenen kunnen de effectiviteit van de barrière odorisatie beïnvloeden?

With input from the members of HyDelta work package 6a and using literature, an inventory of phenomena that could potentially affect the effectiveness of barrier (measure) odorization was made.

- **Fading of smellability when using new gas pipelines**

Gas network operators have experience with natural gas that when new gas pipelines are commissioned, there is a period when the gas released is not smellable. Several publications confirm the phenomenon, including; odor fading in natural gas distribution systems [32] and odor fade - possible causes and remedies [33]. The publications distinguish between odor fading due to oxidation on the one hand and adsorption and/or absorption on the other.

Odorant oxidation occurs due to the presence of iron oxide and air in a pipe. This presence causes the odorant to oxidize into components that are barely smellable. Sulfide-based odorants, such as THT, are not susceptible to this oxidation. The absorption and/or adsorption of odorant occurs in new pipes, both plastic and steel. No research results have been found that provide insight into the degree of absorption and/or adsorption of THT in new steel and/or plastic pipes.

To prevent odorant fading due to absorption/adsorption, it is advised to temporarily increase the amount of odorant when a new pipe is put into service. The effects described above will occur in both natural gas and hydrogen distribution.

- **Adsorption behavior of odorant in soil.**

During an underground gas leak, the gas will diffuse into the soil and eventually reach the ground surface. Research on the adsorption behavior of THT in soil was conducted as part of the Kenniscentrum Gasnetbeheer [33].

The main conclusion from this research is:

The research shows that there is a time lag between the moment hydrogen (or natural gas) is released from the soil and the moment the gas becomes smellable because the THT is also sufficiently detectable (smellable) above the ground. A statement as to whether this leads to an acceptable risk cannot be obtained from this study. For that, a risk assessment is required. This could include factors such as the probability of detection by bystanders based on smell as well as the probability that this will lead to a class 1 or 2 leak. It is recommended that such risk assessment be conducted at the sector level.

The study describes that it the delay in detecting the THT for a natural gas leak is about 40 hours and for equal leak size for hydrogen is about 100 hours. Due to the faster diffusion of hydrogen compared to natural gas, there is no reason to assume a greater risk in the event of an underground hydrogen leak.

- **Separation between the hydrogen and odorant upon leakage**

The Marcogaz report "odorization of natural gas and hydrogen mixtures" [34] mentions as a point of interest the stratification that occurs in a hydrogen-natural gas mixture upon leakage and thus the separation between the hydrogen and natural gas with odorant. A reference to the origin of this concern is missing in the report.

In Hydelta 1.0, in Work Package 2 "odorization of hydrogen", a literature review was conducted on the behavior of an odorant in a gas cloud of hydrogen [35]. The conclusion in this report is the following:

Studies conducted within the framework of the Hyhouse and H100 projects, as well as research by the British HSE and by Pulles from the Kenniscentrum Gasnetbeheer show that the diffusion in air of a gas mixture and of the individual components in the gas mixture, is determined by the density of the entire gas mixture. No spontaneous unmixing of lighter or heavier components will occur. There may be large differences between the gaseous components, in terms of laminar diffusion coefficients in air, but convection determines for diffusion in air and laminar diffusion is so slow that it plays no role. Experiments conducted as part of the Hy100 project have shown that the same is true for a mixture of an odorant in hydrogen. In the event of a gas leak, the odorant remains in the hydrogen cloud and no spontaneous separation occurs.

For the de-mixing of hydrogen and odorant in the event of an (above-ground) gas leak, there seems to be no indication as yet. The only source warning of this phenomenon is a Marcogaz report, but this seems to be based on an expectation rather than experiments or calculations.

4.5 Conclusion

The effectiveness of barrier odorization (with THT) for hydrogen is similar to that of natural gas.

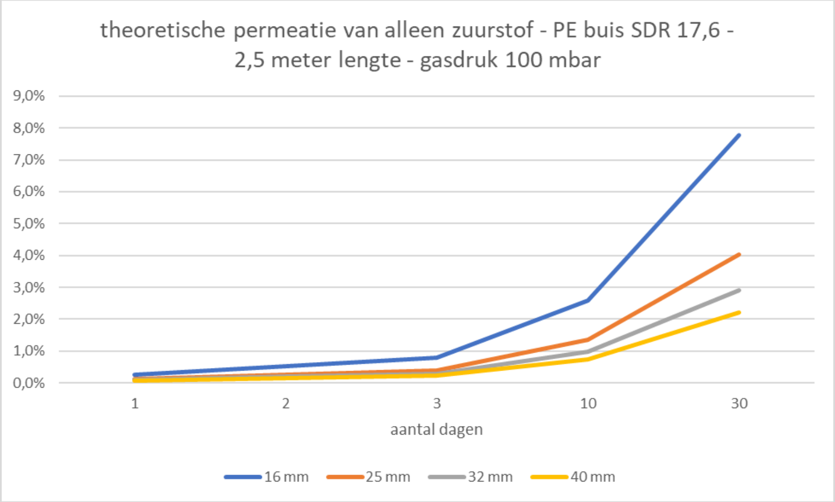
5 The effect on safety and gas quality of permeation of nitrogen, oxygen and water from outside the gas line to inside.

5.1 Introduction

The following question was asked as part of the HyDelta 2.0 program; what is the effect on safety and gas quality of the permeation of nitrogen, oxygen and water from outside the pipeline into the pipeline?

Permeation is a natural process in which a liquid, gas or vapor moves through a solid. This process is driven by a difference in concentration. In gas pipelines, the concentration of nitrogen, oxygen and water outside the pipe is higher than inside the pipe. As a result, nitrogen, oxygen and water will permeate in from outside the pipe. Conversely, the gas in the pipe will permeate outward.

In HyDelta 1 work package 1C 'Pipes and Indoor Installations', research was conducted on the permeation of nitrogen, oxygen and water from outside the pipe wall to the inside. The permeation coefficient of the materials PVC and PE was determined. The results were recorded in report D1C3 question number 135 - the influence of existing natural gas distribution networks on hydrogen quality [36]. In the report, using the determined permeation coefficient, several scenarios (different pipes, pipe materials, lengths and pressures) were run through which determined the amount of oxygen, nitrogen and water entering the pipe per unit time. To gain more insight into the degree of permeation, a number of additional calculations were made in accordance with these scenario calculations. The calculations show that in the case of stagnant gas in a pipe (for example, in the case of sealed pipe sections or in a situation of no gas consumption), the amount of oxygen increases to several percent of the gas volume in the pipe. Especially with small-diameter PE pipes (smaller DN40), this effect occurs more quickly than with pipes with diameters above DN40 or with PVC pipes.



3

Figure 5-1 Indicative the percentage of oxygen after x days relative to the total gas volume in a 2.5-m tube with a gas pressure of 100 mbar.(after 30 days, 8% of the total gas volume consists of oxygen).

The above gives the impression that permeation will have an effect on safety and gas quality. The figure above shows that, theoretically, in the case of a 16mm pipe, after about 15 days there may be 5 vol% oxygen in the pipe. With the hydrogen present in the pipe, this creates a flammable mixture. However, the findings are not without reservations. The scenario assumes a situation where there is no gas flow for days. The question is whether this is a realistic situation. In the report "An exploration into hydrogen specifications” [37], a worst-case situation of 6 hours of downtime is considered. Here it is determined that after 6 hours, 6.5 ppm oxygen and 10.4 ppm nitrogen have permeated into the pipeline. In the report, this degree of permeation does not lead to an unacceptable effect regarding safety and gas quality.

In addition, the aforementioned reports consider the permeation from outside to inside of nitrogen, water and oxygen individually. The real situation is that there are components going from outside to inside and from inside to outside. This total process affects the gas composition and thus quality and safety. To our knowledge, there has been no research on the change in composition of a gas during a period of shutdown. Research into the change in gas composition is being conducted on behalf of Netbeheer Nederland at the time of writing this report.

5.2 Summary

The answer to the question; what is the exact effect on safety and gas quality of the permeation of nitrogen, oxygen and water from outside the pipeline to the inside, cannot be given at this time. Permeation is a natural process and will have an effect on the gas composition in a pipeline especially in situations of prolonged stagnant gas. What effect this change in gas composition will have on safety and gas quality is not (yet) known based on available information.

5.3 Recommendation

Because the effect of permeation on safety and gas quality is unknown, it is recommended that pilot projects monitor gas composition especially in situations where there is prolonged shutdown of hydrogen in pipelines.

6 References

[1] A. Van den Noort, „D6a_2_3: Toepassen QRA model Nederland en Uitkomsten QRA model case studies," HyDelta, 2023.

[2] H. Salomons, „D6a_1: Uitkomsten uitstroomexperimenten - Concentratieopbouw bij lekkages tussen (50–1000 dm3/h)," HyDelta, 2023.

[3] RIVM, „Carola - Computerapplicatie voor risicoberekeningen aan ondergrondse leidingen met aardgas," Version 1.2, June 2013.

[4] PipeSafe Group, „An overview of the Pipesafe risk assessment package for natural gas transmission pipelines. PipeSafe version 2.19.0, Document number PG/15/01," March 2015.

[5] „HyWay 27," [Online]. Available: https://www.hyway27.nl.

[6] *Personal communication John Zevenbergen (TNO) and Marc Dröge (GasUnie).* [Interview].

[7] DNV, „Handleiding Safeti-NL versie 8.5," 2022.

[8] Committee for the Prevention of Disasters, Guideline for Quantitative Risk Assessment ("Purple Book") CPR 18E, The Hague : SDU, 1999, renumbered to PGS 3 in 2005.

[9] D. Miller, „New model for predicting thermal radiation from flares and high pressure jet fires for hydrogen and syngas," *Process Safety Progress,* vol. 36, nr. 3, pp. 237-251, 2017.

[10] D. Worthington, „Application of Phast and Safeti to hydrogen consequences and risks," June 2022.

[11] Adviesgroep AVIV BV, Handleiding RBM II Version 2.0, 2011.

[12] RIVM, Handleiding Risicoanalyse Transport (HART) Version 1.2, January 2017.

[13] Committee for the prevention of Disasters, Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases) ("Yellow Book"), CPR 14E, The Hague: SDU, 2005, renumbered to PGS 2 in 2005.

[14] Projectteam informatieproducten externe veiligheid (IPO), „Landelijke Populatieservice, Version 2.0," April 2022.

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

[16] A. Philips, A. Halford en O. R., „Comparison of the risks associated with natural gas and hydrogen distribution networks," in *HAZARDS 32, Symposium Series 168*, 2022.

[17] „H21 website," [Online]. Available: www.h21.green.

[18] AnteaGroup, „Consequentieonderzoek externe veiligheid – waterstofbuisleidingen. Projectnummer 0473733.100," 2023.

[19] Centrum Veiligheid, RIVM, „Rekenmethodiek transport waterstof in (aardgas)transportleidingen, 2021-0074/VLH/HdW/ibm," 2021.

[20] Arcadis, „Kwantitatieve risicoanalyse (QRA) N-TRA - Waterstofwijk Hoogeveen," oktober 2021.

[21] R. Schefer, W. Kulatilaka, B. Patterson en T. Setterst, „Visible emission of hydrogen flames," *Elsevier,* vol. June 2009, nr. Volume 156, Issue 6, pp. 1234-1241, 2009.

[22] A. adademy. [Online]. Available: https://www.youtube.com/watch?v=r-8H5u4YzuY. [Geopend 2022].

[23] DNV, „Hydrogen Colourant – Final Report," Hy4Heat - Department for Business, Energy & Industrial Strategy, 2019.

[24] S. Lueb, A. Kooiman en C. Lock, „Spoelen van aardgasleidingen met waterstof," HyDelta 1 - WP 1C Leidingen en binneninstallaties (componenten) - D1C.1 vraagnummer 187, 2021.

[25] C. Lock, C. Pulles en J. de Laat, „Affakkelen en afblazen van waterstof," rapport GT-200096, Kiwa Technology in opdracht van Netbeheer Nederland, april 2021.

[26] M. Caulfield, S. Kimpton en A. Phillips, „Flame Visibility Risk Assessment," DNV GL in opdracht van SGN - H100 Fife, 2021.

[27] D. Allason, L. Jenney en M. Acton, „Thermal radiation properties of large hydrogen leaks from gas distribution network," DNV GL voor H21 (ICHS conference 2019), 2019.

[28] „HySafe conference papers and presentations (2019)," [Online]. Available: https://hysafe.info/ichs2019/conference-papers-and-presentations/. [Geopend 2022].

[29] M. Acton, D. Allason, L. Creitz en B. Lowesmith, „Large Scale Experiments to Study Hydrogen Pipeline Fires," 2011.

[30] O. Toru, „A Real-Time Ultraviolet Radiation Imaging System Using an Organic Photoconductive Image Sensor," MDPI open access journals, 2018.

[31] Y. Shibarashi, „Thermochromic materials". US patent Patent 4,425,161, 1984.

[32] S. Mehrrad, F. Hooman, D. Tingsong, M. Trinayan, B. Tsilla en F. Ramin, „Odor fading in natural gas distribution systems," Process safety and Environmental protection - Elsevier, 2015.

[33] R. Hermkens en D. Reekers, „Adsorptiegedrag van THT in de bodem," Kiwa Technology in opdracht van Netbeheer Nederland, 2022.

[34] Marcogaz, „odorisation of natural gas and hydrogen mixtures," Marcogaz, 2021.

[35] E. Polman, „Hydelta WP2- D2.3 Stability of odorants in hydrogen," 2022.

[36] S. Jansma en D. Rekers, „Hydelta WP1C-D1C.3 vraagnummer 135 - invloed van aardgasdistributienet op kwaliteit waterstof," Hydelta 1.0, 2022.

[37] E. Polman, H. Vlap, P. Visser en A. v. d. Noort, „Een verkenning naar waterstofspecificaties,” Netbeheer Nederland, 2021.

[38] T. Bailey, „Slideplayer,” [Online]. Available: https://slideplayer.com/slide/14808479/. [Geopend 2022].

[39] European Commission, „Gas Appliances Regulation,” 9 March 2016. [Online]. Available: https://ec.europa.eu/growth/sectors/pressure-equipment-and-gas-appliances/gas-appliances-sector/gas-appliances-regulation_en. [Geopend 2022].

[40] M. J. Usher, „Odor Fade - Possible Causes and Remedies,” 1999.