

Comparison of the Risks associated with Natural Gas and Hydrogen Distribution Networks

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The H21 Network Innovation Competition (NIC) project aims to address the issues associated with the conversion of the Great Britain gas distribution networks from natural gas to pure hydrogen gas. The objective of the project is to provide safety-based evidence for a 100% hydrogen conversion. As part of this objective, a comparative Quantitative Risk Assessment (QRA) has been carried out to evaluate the difference in safety risk to the public associated with supplying 100% hydrogen versus natural gas. The aim of the project is to show how a hydrogen distribution system can be operated at a risk level no higher than the low level posed by the current natural gas system.

Development of the QRA package during Phase 1 of the H21 project was described in a paper presented at Hazards 31. The CONIFER risk assessment package was developed and used to quantify the risks associated with mains and services upstream of the Emergency Control Valve (ECV). The package is based on existing natural gas models developed by DNV and its predecessors, data from full scale tests carried out previously and as part of H21, and decades of historical data from the gas industry. The package was extended to represent pure hydrogen systems based on research carried out as part of H21 and other major hydrogen projects.

Releases downstream of the ECV have were incorporated into the package in Phase 2, including releases from the meter installation, downstream pipework and appliances in homes. In addition, risks from governor enclosures on the network have been incorporated into the assessment. This allows the total risk to which the public is exposed to be quantified for the whole of the Great Britain networks operating up to 7 barg, using a consistent methodology and set of models.

This paper describes updates to CONIFER that have been carried out as part of H21 Phase 2, and notes some differences between assessments of natural gas and hydrogen systems.

Key words: gas distribution, hydrogen, QRA

Introduction

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Development of the QRA package during Phase 1 of the H21 project was described in a paper presented at the Hazards 31 conference (Acton et al, 2021). The CONIFER risk assessment package was developed and used to quantify the risks associated with mains and services upstream of the Emergency Control Valve (ECV). The package is based on existing natural gas models developed by DNV and its predecessors, data from full scale tests carried out previously and as part of H21, and decades of historical data from the gas industry. The package was extended to represent pure hydrogen systems based on research carried out as part of H21 and other major hydrogen projects.

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Model Description

DNV and its predecessors have developed risk assessment models for distribution networks since the 1990s (Acton et al, 2021). The original model was developed to aid in the prioritisation of the replacement of cast iron mains, but subsequent work extended the model to polyethylene (PE) mains and various improvements have been included over time. Separate risk assessment models were developed for related scenarios such as failures of services and releases from meter installations in houses. There has been a lot of interest in these types of models in recent years as many gas distribution networks, within and outside Great Britain, are considering the implications of moving to supplying a natural gas and hydrogen blend, or pure hydrogen. In particular, as part of the H21 project, DNV's models have been developed significantly, resulting in the production of the CONIFER risk assessment package.

The current CONIFER model has the following features:

- Releases from mains, services, meters, pipework downstream of the ECV and appliances can be modelled. The package covers all three tiers of the distribution network (low pressure up to 75 mbar, medium pressure over 75 mbar and up to 2 bar, and intermediate pressure over 2 bar and up to 7 bar) as well as the pressure downstream of the end user's regulator (typically 21 mbar).
- Natural gas, pure hydrogen and blends can be represented. The composition can be specified, and its thermodynamic properties are automatically taken into account.
- The effects of outdoors fires on mains and services, and explosions from gas accumulation indoors are included. The possibility of overpressure generation from delayed ignition of vapour clouds in the open is also considered, as there is evidence that this hazard could be significant for hydrogen releases (H21, 2021).
- Different failure modes are considered. For example, interference damage from machinery impact is treated differently to corrosion failures on metallic pipes or joint failures on PE pipes. Each combination of pipe material and failure mode has an appropriate frequency and hole size distribution.
- A variety of building types and occupancy patterns can be included in risk calculations. The configuration of the meter and appliances can also be specified.

The structure of the model is shown in Figures 1 to 3 below. Each of the numbered steps in the figure represents a stage in the risk calculation, most of which involve the application of detailed sub-models. Figure 4 shows the steps in the risk calculation for releases directly into buildings.

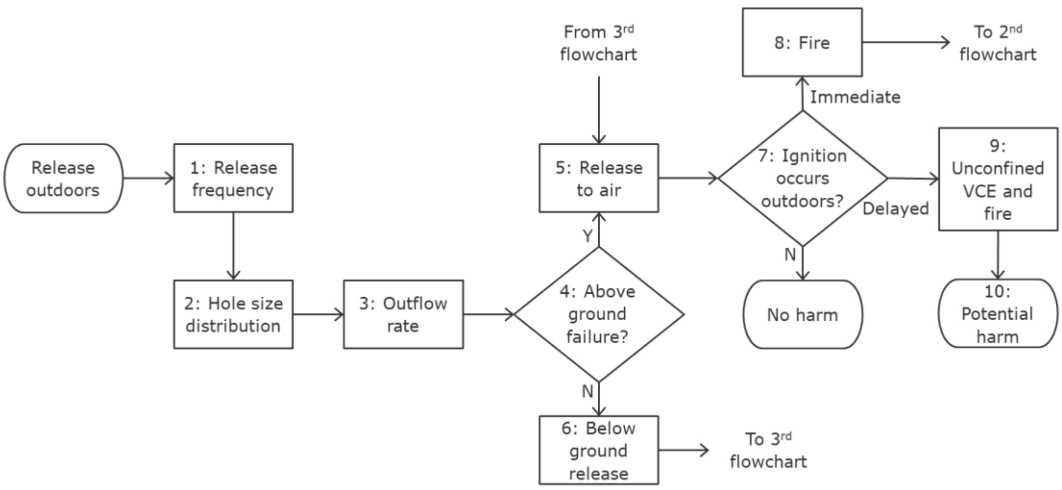

Figure 1: Outdoor releases within CONIFER, part 1: failure and release

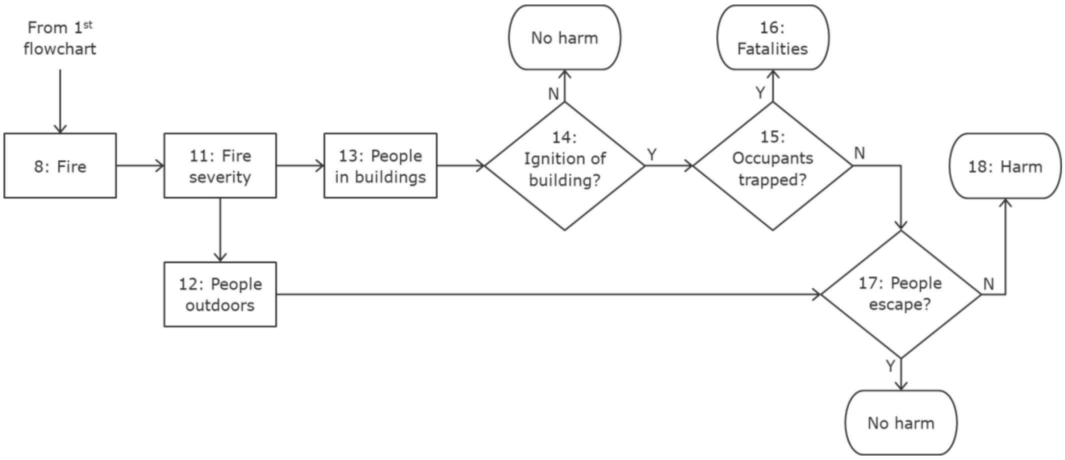

Figure 2: Outdoor releases within CONIFER, part 2: fires

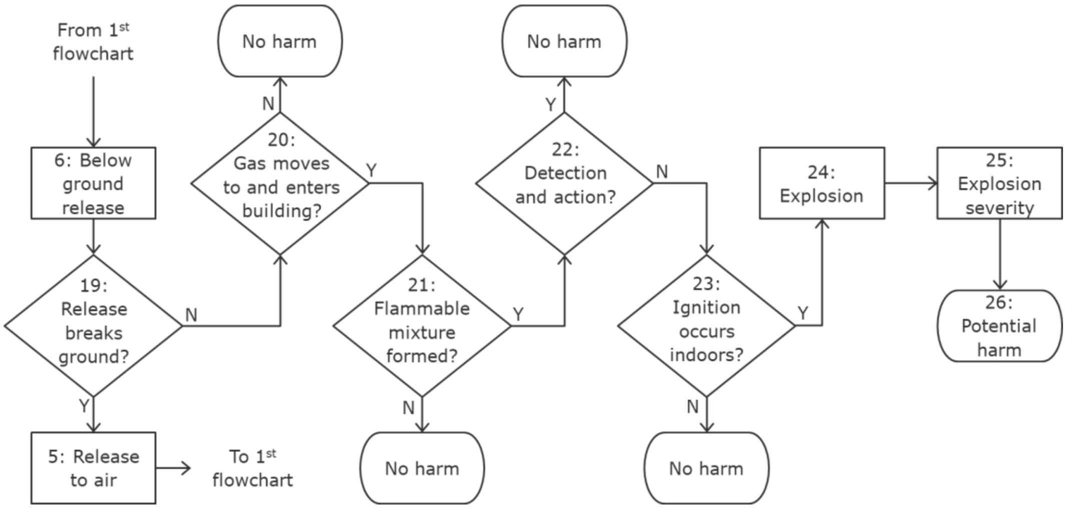

Figure 3: Outdoor releases within CONIFER, part 3: explosions

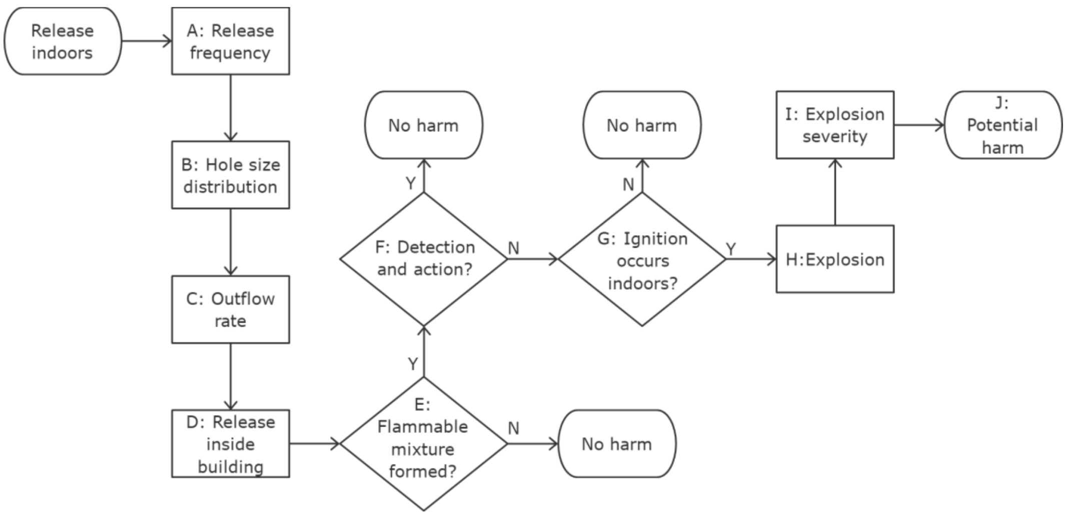

Figure 4: Indoors releases within CONIFER

Table 1 contains a summary of the steps shown in the figures above.

Table 1: Summary of steps in the CONIFER risk calculations

Step	Description
1: Release frequency	The frequency of any release occurring from a main or service is determined from the pipe characteristics (such as pressure, diameter and construction details) and failure mode (such as interference or joint failure). Each failure mode is considered in turn in the following steps. The release frequency is assumed to be independent of the gas under consideration, so hydrogen does not introduce any new failure modes or cause changes to failure rates.
2: Hole size distribution	A ‘hole’ means any leak path that allows gas to escape, in this context. A hole size distribution is defined, based on historical data appropriate to the pipe characteristics and failure mode. Each hole size is considered in turn in the following steps.
3: Outflow rate	The outflow rate from the failure is predicted for each hole size, taking into account the size of the hole, the operating pressure of the pipe and the properties of the gas.
4: Above ground failure?	The proportion of releases that occur on a pipe that is already uncovered (i.e. in a trench) is determined. Most interference damage occurs on an exposed pipe, but spontaneous failures occur on buried pipes.

Step	Description
5: Release to air	A release occurs that is open to the atmosphere. Releases to atmosphere pose a fire hazard if ignited. For hydrogen releases, there is a potential for overpressure to be generated if delayed ignition of a vapour cloud occurs, as modelled in Step 9.
6: Below ground release	A below ground release occurs, with covering soil still in place. Releases underground have the potential for gas to migrate through the ground, leading to the potential for gas ingress into a building, and ultimately to an explosion.
7: Ignition occurs outdoors?	The ignition probability is calculated for above ground releases. The ignition probability is affected by the gas properties, the hole size and the operating pressure of the pipe.
8: Fire	A fire occurs.
9: Unconfined VCE	Delayed ignition in the open occurs, leading to an unconfined Vapour Cloud Explosion (VCE) with the potential to generate overpressure. The fire effects are also modelled.
10: Potential harm	The effects of the unconfined VCE are evaluated for people outdoors and indoors, and they are combined with the thermal radiation effects from the residual fire.
11: Fire severity	The physical size of the fire and the associated thermal radiation field is predicted. Different fire models are used, depending on the situation.
12: People outdoors	At least some people in the vicinity of the fire are located outdoors.
13: People in buildings	At least some people in the vicinity of the fire are located inside buildings.
14: Ignition of building?	The possibility of the thermal radiation igniting the building is considered. The thermal dose received by the building is calculated, taking into account the decay of the outflow rate, and hence the fire severity, over time.
15: Occupants trapped?	A proportion of the building's occupants are assumed to be unable to leave the building. This is based on the size of the fire and the proportion of the building exposed to the fire. For example, most people are able to escape a burning building for a small fire that initially only affects the front face of the building, but people are less likely to escape if a building is engulfed.
16: Fatalities	People trapped in burning buildings are assumed to become fatalities.
17: People escape?	The manner in which the radiation field changes with distance and time are taken into account as each person outdoors moves away from the fire. The total thermal dose received while escaping determines the probability of fatality.
18: Harm	The number of fatalities and injuries is recorded for each fire event and occupied location and summed appropriately.
19: Release breaks ground?	The probability of the release breaking through the covering soil in determined. A release that is initially buried can be sufficiently energetic to break the ground and provide a route to atmosphere. Both above and below ground cases are analysed.
20: Gas moves to and enters building?	Three different models are used to predict gas movement below ground and through tracking routes. This determines the flow rate at the outside face of the building. The probability of any gas entering the building is determined. For cases with ingress, the proportion of gas entering is calculated.
21: Flammable mixture formed?	Gas accumulation calculations determine the gas concentration as a function of time. The gas ingress rate, the properties of the gas and the building characteristics are taken into account.
22: Detection and action?	Probability distributions are used to calculate the likelihood of gas detection and subsequent action (or lack of it), and First Call Operative (FCO) arrival times, all as a function of time after ingress begins. The calculation considers the probability of people being present, and the probability of being awake, both of which depend on the type of building and the time of day.
23: Ignition occurs indoors?	The ignition probability for gas accumulated inside buildings is calculated. This is closely related to the detection step as 75% of ignition sources are assumed to be related to the presence of people.
24: Explosion	An explosion occurs.

Step	Description
25: Explosion severity	The overpressure generated by the explosion inside the building is calculated. The calculation considers factors such as the size of the room, the type of gas and the gas concentration.
26: Potential harm	The number of fatalities and injuries is recorded for each explosion event and occupied location and summed appropriately. This includes effects in the building where the explosion occurs, in adjoining properties, outdoors as a result of debris throw and inside nearby buildings as a result of overpressure effects.
A: Release frequency	The frequency of any release occurring downstream of the ECV is determined for the meter installation, downstream pipework and appliances, for interference damage and/or spontaneous failures. Each combination of failure location and mode is considered in turn in the following steps. The release frequency is assumed to be independent of the gas under consideration, so hydrogen does not introduce any new failure modes or cause changes to failure rates.
B: Hole size distribution	A 'hole' means any leak path that allows gas to escape, in this context. A hole size distribution is defined for each leak source and location.
C: Outflow rate	The outflow rate from the failure is predicted for each hole size. This is typically into free air and considers different shapes of holes, which can result in laminar or turbulent flow.
D: Release inside building	A gas release occurs directly into the building. Different locations and room sizes can be considered.
E: Flammable mixture formed?	Gas accumulation calculations determine the gas concentration as a function of time. The outflow rate, gas properties and building characteristics are taken into account.
F: Detection and action?	Probability distributions are used to calculate the likelihood of gas detection and subsequent action (or lack of it), and FCO arrival times, all as a function of time after the release begins. Different assumptions are used for interference damage, which is likely to be noticed. The calculation considers the probability of people being present, and the probability of being awake, both of which depend on the type of building and the time of day.
G: Ignition occurs indoors?	The ignition probability for gas accumulated inside buildings is calculated. This is closely related to the detection step as 75% of ignition sources are assumed to be related to the presence of people.
H: Explosion	An explosion occurs.
I: Explosion severity	The overpressure generated by the explosion inside the building is calculated. The calculation considers factors such as the size of the room, the type of gas and the gas concentration.
J: Potential harm	The number of fatalities and injuries is recorded for each explosion event and occupied location and summed appropriately. This includes effects in the building where the explosion occurs, in adjoining properties, outdoors as a result of debris throw and inside nearby buildings as a result of overpressure effects.

The steps are the same whether evaluating the risk from natural gas or hydrogen. The differences between natural gas and hydrogen systems are discussed below.

The major changes to CONIFER that were made as part of H21 Phase 2 include:

- Releases downstream of the ECV were included in the assessment process.
- The hole size distributions applied to mains and services were reviewed and improved using historical failure data.
- The possibility of overpressure generation from hydrogen ignition in the open was included.
- The approach to the gas ingress probability and the proportion of gas entering a building was reviewed.
- The gas accumulation modelling has been further improved.
- The explosion severity model has been updated to remove some conservatism from the hydrogen explosion predictions, by improving the validation against additional experimental data that is available in the open literature.
- The potential for harm outside the building in which an explosion occurs has been modified to include the possibility of debris throw and blast effects outdoors and inside nearby buildings.

In addition, numerous small changes were made to improve the differentiation between natural gas and hydrogen releases, or to provide a more accurate prediction of the natural gas system performance. Further details of this benchmarking process are given below.

Differences between Natural Gas and Hydrogen

There are several differences between the risks posed by natural gas and hydrogen distribution systems. These factors are represented automatically within the CONIFER risk assessment package. Further details are given below for some features.

Gas Characteristics

The thermodynamic properties of the gas are directly taken into account in many steps of the calculation. As an example, the volumetric outflow rate of hydrogen is around 1.2 times that of natural gas for laminar flow, and around 2.9 times that of natural gas for fully turbulent flow (Garrison and Gant, 2021) for the same type of failure at the same operating pressure. In many cases, the ratio would be expected to lie between these values, with a tendency towards the lower end of the range for below ground releases, small holes and tortuous leak paths, and values approaching the upper end of the range for large releases into free air above ground. This suggests that the differences between natural gas and hydrogen could be more pronounced inside buildings than from below ground releases on pipes, if all other factors were equal. Note that the mass outflow rate behaves differently due to the densities of the two gases. For example, for the same failure type leading to turbulent flow, the hydrogen volumetric outflow rate is almost 3 times that of natural gas, but the mass outflow rate is around one third that of natural gas.

The properties of the gas are also important in the gas accumulation calculations within buildings. Buoyancy-driven ventilation dominates the behaviour, so the hydrogen concentration is lower than the natural gas concentration for a fixed volumetric flow rate into a room. However, it should be noted that the volumetric flow rate of hydrogen is higher for a particular failure mode, as discussed above.

Ignition Probability

The ignition probability is higher for a hydrogen release than a natural gas release, from the same size hole at the same operating pressure. This is the case for both releases outdoors and for gas accumulated within buildings.

Hydrogen has a lower minimum ignition energy than natural gas, although this might not have as significant an effect as some studies suggest. Many potential ignition sources found in a typical home have associated energies that are many times greater than the minimum value required for ignition, and yet ignition occurs in a relatively small proportion of cases where gas is detected in buildings, even when the gas concentration is within the flammable range. Nevertheless, there is some evidence from the H21 Phase 1 (H21, 2021) and Hy4Heat (Hy4Heat, 2021b) experimental programmes that ignition is more likely for hydrogen than natural gas. This is represented within CONIFER by applying factors to the likelihood of ‘human activity’ and ‘background’ ignition sources having sufficient energy to result in ignition for gas accumulated within a building.

Many ignition probability models are based on the mass outflow rate of the fluid, which is a valid approach for typical risk assessments involving hydrocarbons. If this approach is applied to hydrogen, using the same correlation as applied to natural gas, then the ignition probability is predicted to be lower for hydrogen due to the differences in mass outflow rate, as discussed above. CONIFER uses the following approach for releases outdoors:

- The thermodynamic properties of hydrogen are taken into account when calculating the volumetric outflow rate from a given leak size at a given pressure. The mass outflow rate is not used directly.
- The volumetric flow rate of hydrogen is converted to the same volumetric outflow rate of natural gas.
- The equivalent mass outflow rate of natural gas is determined, based on its thermodynamic properties.
- This natural gas mass outflow rate is used with the natural gas ignition correlation to calculate the hydrogen release ignition probability. The natural gas ignition correlation was developed specifically for mains and services.

The volumetric outflow rate is more representative of the release size than the mass outflow rate because it is related to the size of the flammable cloud that is formed. The larger the flammable cloud, the more likely it is to reach an ignition source.

Fire Severity

The CONIFER model for fires outdoors, following a release from a main or service, predicts slightly less severe fires from hydrogen releases than the equivalent natural gas releases, for a given failure type and operating pressure. This is consistent with experimental evidence from the H21 test programme, and from the observation that the energy flow rate in a hydrogen leak is around 90% of that from the same natural gas leak (Garrison and Gant, 2021).

In addition, for larger leaks where the pipe depressurises, the outflow rate reduces more rapidly for a hydrogen release. This suggests that the severity and the duration of hydrogen fires are lower than that of natural gas, although the ignition probability might be higher, as discussed above.

Explosions in Open Air

Ignited vapour clouds in the open have the potential to produce overpressure as well as flash fire effects. For natural gas releases, there is very little potential for harm to people or damage to buildings, so the overpressure effects are usually ignored in risk assessments (IGEM, 2016). However, there is evidence that this is not necessarily the case for hydrogen releases (Thomas et al, 2015; Jallais et al, 2018; Mukhim et al, 2018; H21, 2021). CONIFER includes a model to predict the overpressures generated by hydrogen clouds in the open, without confinement and congestion, and their contribution to the total risk is not negligible.

Explosion Severity

Hydrogen explosions have a greater potential than natural gas for catastrophic damage to the building where an explosion occurs, for harm to people in adjoining buildings and to people outdoors or in nearby buildings. Figure 5 shows some example explosion severity predictions made using the model within CONIFER. This shows the following:

- For concentrations up to around 12.5% gas in air, by volume, natural gas is predicted to produce a higher overpressure than hydrogen.
- Hydrogen has a much wider flammable concentration range, not all of which is shown in this figure.
- Hydrogen has the potential to produce much higher overpressures if the gas is allowed to accumulate over time, and ignition occurs. Explosions have occurred in homes on the natural gas network where a leak began late in the evening, allowing gas to accumulate overnight while the occupants were asleep, so this type of event is possible without additional means of detection.

The predicted overpressures are dependent on a number of factors such as the room volume, ventilation rate, gas release size, ignition time and the pressures at which doors, windows, walls and the ceiling are predicted to fail. The example is intended only to illustrate the principle and it is not applicable in all situations. Generally, the higher the overpressure, the greater the potential for damage to the building and harm to people. Note that this figure does not show the probability of an explosion of a particular severity occurring.

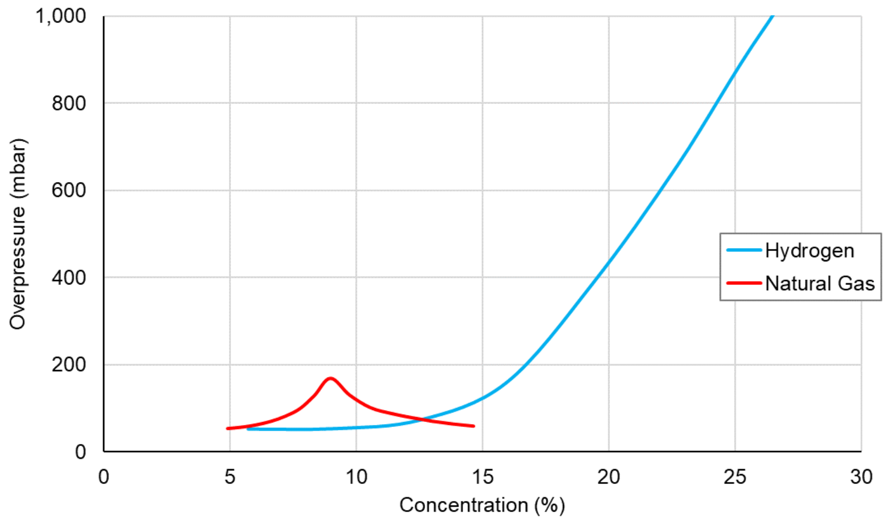

Figure 5: Example explosion severity predictions for a typical room

The potential for debris throw and blast wave damage beyond the building where the explosion occurs is greater in the cases where a higher source overpressure is generated. Experience of incidents on the natural gas distribution network shows that these aspects of an explosion are not typically major risk contributors, but people outside the explosion source building have occasionally been harmed in previous incidents. It is therefore important to take these factors into account when modelling hydrogen systems, as it could affect the number of people predicted to be harmed in a given event. These predictions could influence emergency procedures that govern the response to hydrogen leaks, including the number of buildings evacuated and the placement of safety cordons.

Figure 6 illustrates these effects beyond the ‘Event House’ where the explosion occurs. In this case the semi-detached Event House has one adjoining property and one neighbouring house that is nearby but not attached. The risk calculations account for harm to people in these three houses, the three across the road and the three houses with gardens that back onto the Event House and its immediate neighbours. The house and garden sizes and the width of the road are representative of a residential area within Great Britain.

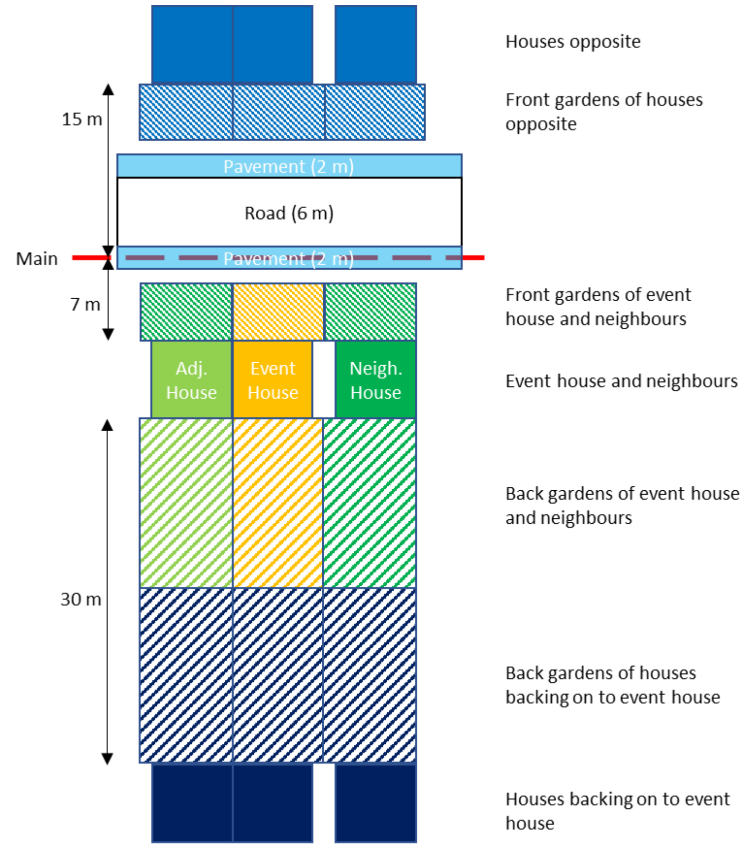

Figure 6: Illustration of locations affected by an explosion in a house

Table 2 shows the proportion of people who are predicted to receive fatal injuries for the example of an explosion involving a stoichiometric hydrogen/air mixture in a typical room within the Event House. The rows and columns in Table 2 appear in the same relative positions as the locations in Figure 6. This is a case with severe consequences that is not typical, but is included to illustrate the approach. The proportion of people who become fatalities in the Event House and adjoining house are calculated using the predicted source overpressure and a correlation derived from historical incident data. For people inside other houses, the overpressure decay with distance outside the Event House is taken into account. For people outdoors, the CONIFER model accounts for direct exposure to overpressure, translational effect and impact from ejected glass and bricks.

Table 2: Predicted vulnerabilities for the example severe hydrogen explosion

Location		**Vulnerability**		
		Left	**Centre**	**Right**
Houses Opposite	Indoors	0.019	0.026	0.019
	Front Garden	0.040	0.049	0.040
Event House (centre), Adjoined House (left), Neighbouring House (right)	Front Garden	0.056	0.492	0.056
	Indoors	0.454	0.500	0.226
	Back Garden	0.098	0.216	0.098
Houses Behind	Back Garden	0.051	0.062	0.051
	Indoors	0.002	0.002	0.002

The CONIFER model accounts for population variations within houses in eight 3-hour intervals throughout the day. Each occupant is assigned an occupancy pattern, where the probability of being at home is greater at night than in the day. People who are present are assumed to spend 10% of their time outside during the day and 1% at night. People are assumed to spend 90% of their time outdoors in the back garden and 10% in the front garden. The time spent in the front garden includes time spent arriving at and leaving the property. These occupancy patterns affect the risk predictions within each building as they affect the probability of gas detection, but also influence the probability of ignition sources being present.

The predictions in Table 2 for a stoichiometric hydrogen/air explosion represent the worst case. Predictions have also been made for a credible release through a leak with an area of 9.3 mm^2. The leak is assumed to be through a gap that is 0.3 mm wide and extends around the full circumference of a 22 mm diameter copper pipe inside a house. This could represent a failed soldered joint for example. Using an outflow model that accounts for the frictional losses in the narrow crack, the predicted flow rate is 0.90 m^3/hour for natural gas and 1.45 m^3/hour for hydrogen, and the ratio of the volumetric flow rates is 1.62. This is close to the laminar flow limit of 1.2 that is discussed above. Gas accumulation predictions are carried out for a range of open areas and wind speeds, assuming a gas pressure of 21 mbar inside the house. For mid-range ventilation parameters, the predicted steady gas concentration is 9.02% for natural gas and 7.22% for hydrogen.

Table 3 summarises the predicted number of fatalities from the two example explosions, based on a population of three people per house and accounting for time spent away from home and outdoors while at home. The 'Average' column represents the total number of predicted fatalities when averaged across explosions occurring at all times of the day. The 'Range' column indicates the variation in the total number of predicted fatalities, depending on the time at which the explosion occurs.

Table 3: Predicted number of fatalities from example explosions

Explosion Example	Predicted Fatalities					
	Event House		All Other Houses		Total	
	Indoors	In Gardens	Indoors	In Gardens	Average	Range
Stoichiometric natural gas	0.27	< 0.01	0.10	< 0.01	0.37	0.19 to 0.56
Stoichiometric hydrogen	0.96	0.02	1.43	0.03	2.44	1.30 to 3.67
Credible natural gas leak	0.10	< 0.01	0	< 0.01	0.10	0.05 to 0.15
Credible hydrogen leak	0.06	0	0	0	0.05	0.03 to 0.08

The natural gas explosion effects are mainly experienced in the Event House, and in the adjoining house if the overpressure generated is high. The worst case hydrogen explosion has the potential to cause fatalities in multiple surrounding locations, but mostly within the neighbouring houses either side of the Event House. In the case of the joint failure, the higher concentration for the natural gas release results in higher overpressures and hence a greater number of fatalities. This is consistent with Figure 5 above. This illustrates the differences between natural gas and hydrogen explosions and the need to account for surrounding occupied areas and variations in occupancy patterns.

Carbon Monoxide

Carbon monoxide (CO) poisoning from incomplete combustion is a significant contributor to the risks downstream of the ECV when operating a natural gas distribution system. CO poisoning is not possible when using hydrogen appliances.

RIDGAS data is publicly available as part of the statistics published by the HSE (HSE, 2007 to 2021). The data set is intended to represent only incidents related to natural gas, and hence should not include events related to carbon monoxide from appliances using other fuels. However, it can include events in commercial and industrial properties, as well as in homes. Data from 2006/2007 to 2020/2021 indicates that an average of over 6 gas-related CO poisoning fatalities occurred per year, although there is a trend for a decreasing rate of fatalities, as shown in Figure 7.

The number of fatalities per year is small, and comparable to the number that arise from fires and explosions. Further details are given in the benchmarking section below. The exact number of fatalities that occur per year from CO poisoning is subject to some interpretation of the data presented in Figure 7, but it is clear that the prevention of CO poisoning is a significant benefit of the conversion to hydrogen. Recent guidance (HSE, 2022) allows the reduction in CO poisoning to be taken into account in risk assessments.

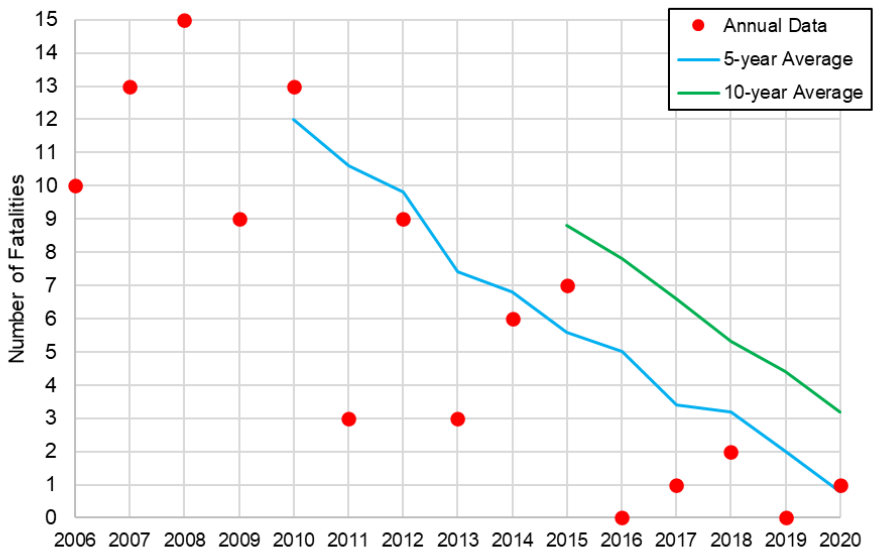

Figure 7: Number of carbon monoxide poisoning fatalities, as given in RIDGAS data

For reference, the same data source suggests that there are around 200 non-fatal carbon monoxide poisoning cases per year on the current natural gas distribution system.

Representation of Great Britain

As part of the H21 project, CONIFER was used to predict the risks to the general public across Great Britain associated with the operation of a natural gas or hydrogen distribution system. The 'distribution system' includes the upstream mains, services and governor kiosks as well as meters, pipework and appliances downstream of the ECV (so this is a wider definition than is typically used for the 'distribution network' upstream of the ECV). Two cases are considered:

- The 2020 distribution system carrying natural gas. This represents the current risk level for the general public.
- The 2032 distribution system carrying hydrogen. This represents the time at which hydrogen is expected to be introduced into the system. Planned changes in the distribution system between 2020 and 2032, particularly relating to the replacement of metallic mains and services with PE pipes, are taken into account.

These two cases are used to demonstrate that a hydrogen network can be operated at a risk level that is no greater than the current natural gas network.

The details of the network upstream of the ECV are based on information supplied by Northern Gas Networks (NGN). It is assumed that the condition and operation of the NGN network is representative of the whole of Great Britain, as all the networks have a common heritage and were constructed, operated and maintained according to the same British Gas standards. The network operators have continued to follow similar approaches to one another, and there are no significant differences between conditions of pipes in different parts of Great Britain. It is assumed that the housing distribution around the NGN network is typical of that across the whole of Great Britain, with approximately the same proportion of mains in urban and suburban areas when averaged across the whole of Great Britain.

For releases on mains, the risks associated with NGN's network are scaled up to represent the whole of Great Britain using the lengths of mains of each material that are in operation. This information was obtained from previous studies carried out by DNV. The risks associated with services and downstream of the ECV are scaled from the number of domestic gas customers in NGN's network to the number across the whole of Great Britain.

The analysis includes approximately 274,000 combinations of main, building and separation distance between the main and building. Approximately 62,000 combinations of building, service and separation are considered in the risks from services and approximately 980 combinations of building and equipment are considered for the risks from leaks downstream of the ECV. Each of these many combinations is assigned a probability distribution such that the number of people exposed to each combination of risks can be estimated. Summing over all the permutations allows the total risk across Great Britain to be evaluated.

Benchmarking

The risk predictions made using CONIFER have been compared with historical data from the natural gas distribution system, collected from confidential and published sources (King et al, 1977; HSE, 2011; HSE 2015; H100, 2019; H100, 2020; Hy4Heat, 2021a; Hy4Heat, 2021b; Mouli-Castillo et al, 2021; HyDeploy 2020). A range of values was obtained for each parameter because the sources do not always agree, and because performance varies from year to year.

Table 4 shows the historical and predicted fire risks. The model gives a non-zero probability of ignition even for very small leaks. In practice these very small leaks would be unlikely to encounter an ignition source, and would not have any significant consequences if they were to occur. For this reason, fires with an energy flow over 10 kW are given separately as these fires have the potential to harm people or ignite buildings in some circumstances. These results show that the predicted number of natural gas fires and their effects are reasonable, based on historical performance of the existing system.

Table 4: Comparison of historical and predicted natural gas fire incidents

Release Source	**Category**	**Frequency (per year)**	
		Historical	**Predicted**
Upstream of the ECV	Number of Fires	15 to 40	90.1 total, 33.9 over 10 kW
	Number of Fatalities	0 to 0.1	0.13
	Number of Injuries	0 to 3	1.5 serious, 1.6 minor, 3.1 total

Table 5 gives similar results for explosion incidents. Events that generate over 70 mbar overpressure are given separately because many of the ignited events with lower overpressures would behave more like localised flash fires within the room where ignition occurs, and might not be reported as explosions. The predicted numbers of incidents and people harmed are broadly consistent with historical experience.

Table 5: Comparison of historical and predicted natural gas explosion incidents

Release Source	**Category**	**Frequency (per year)**	
		Historical	**Predicted**
Main	Number of Explosions	1.00 to 3.10	4.83 total, 2.15 over 70 mbar
	Number of Fatalities	0.30 to 0.50	0.53
	Number of Injuries	2.50 to 3.00	0.86 serious, 0.95 minor, 1.81 total
Service	Number of Explosions	0.50 to 1.50	2.59 total, 1.07 over 70 mbar
	Number of Fatalities	0.10 to 0.30	0.21
	Number of Injuries	1.00 to 2.00	0.45 serious, 0.50 minor, 0.95 total
Downstream of the ECV	Number of Explosions	4.00 to 6.50	22.10 total, 9.40 over 70 mbar
	Number of Fatalities	0.50 to 1.80	1.74
	Number of Injuries	4.00 to 11.00	3.80 serious, 4.28 minor, 8.08 total

Risk Predictions

The risk predictions for the hydrogen distribution system are under review within the H21 project at the time of writing. It is expected that the results will be made available through official communications and reports produced by the H21 project. This includes updates of the risk predictions from Phase 1 of the H21 project for releases upstream of the ECV (Acton et al, 2021; H21, 2021) and releases downstream of the ECV similar to those produced as part of the Hy4Heat project (Hy4Heat, 2021b).

It should be noted that conversion of the natural gas distribution system to hydrogen use would introduce the opportunity to operate the networks differently. For example, it is possible that new technology incorporated into hydrogen smart meters could be used to detect leaks or unusual gas use activity downstream of the meter, even if those leaks are not immediately hazardous. This could be linked to local alarms, automatic escape reporting or automatic ECV closure, depending on the size of the leak that is detected. It has been demonstrated that this is possible in principle (Phillips et al, 2021) and could have safety, environmental and operational benefits. Similarly, the use of hydrogen-ready appliances will ensure that safety features such as flame failure devices are included as standard, reducing the risk relative to the current natural gas appliance population.

Conclusions

The CONIFER risk assessment package was developed as part of the H21 project. It has been used to quantify the risks associated with mains and services upstream of the ECV, and from meters, pipework and appliances downstream of the ECV. In addition, risks from governor enclosures on the network have been incorporated into the assessment. This allows the calculation of the total risk to which the public is exposed for the whole of the Great Britain networks operating up to 7 barg, using a consistent methodology and set of models.

It has been demonstrated that the CONIFER model gives realistic predictions of the risks associated with the current natural gas distribution system. Some aspects of the model that are particularly relevant to hydrogen use have been discussed, and some of the differences between assessments of natural gas and hydrogen distribution systems have been highlighted.

It is noted that the transition to hydrogen is an opportunity to further lower the risk posed by the distribution system. For example, it could be possible to introduce new technology that could enable a step change in the prevention of gas explosions, or prevent gas loss for environmental, operational and financial reasons.

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