

Quantification of the Risks Associated with a Hydrogen Gas Distribution Network

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The H21 Network Innovation Competition (NIC) project aims to address the issues associated with the conversion of the Great Britain (GB) gas distribution networks from natural gas (predominantly methane) to pure hydrogen gas. The overriding objective of the project is to provide the compelling safety-based evidence for a 100% hydrogen conversion in the GB gas distribution networks; specifically, that the pipes and equipment in 2032 will be as safe operating on 100% hydrogen as the current natural gas system. As part of this objective, a comparative Quantitative Risk Assessment (QRA) was required to evaluate the difference in safety risk to the public associated with supplying 100% hydrogen versus natural gas. The risks calculated cover releases upstream of the meter only, i.e. the network up to and including the Emergency Control Valve (ECV).

In order to consider the relative risks associated with the two gases, a QRA methodology has been developed for a 100% hydrogen network, which was closely based on the existing approach developed and refined over many years for application to the existing natural gas networks (used in applications including risk-based prioritisation of metallic distribution pipelines or "mains" for replacement with polyethylene, PE). The QRA methodology is embodied in the CONIFER software package, comprising a series of modules which combine operational experience of the frequency and nature of uncontrolled gas releases with a linked series of mathematical models to predict the potential consequences (fire and explosion) in different circumstances. This provides a quantified basis to demonstrate whether distribution of hydrogen through an existing gas network presents higher or lower risks to the public than a natural gas network and, if the risk is higher for hydrogen, how it can be lowered.

Phase 1 of the H21 project has been completed and included full scale experiments to investigate the extent and potential consequences of hydrogen leakage from a converted gas distribution network; both from background leakage and through network failures such as 3rd party damage. As part of Phase 1, the QRA package was initially adapted for hydrogen using existing knowledge identified through a literature review and judgement where appropriate. Gaps in the knowledge for hydrogen were identified and the results from the experimental work were compared with the predictions of the individual models to refine the predictions of the package.

In parallel with the development of the QRA methodology for hydrogen gas networks, data was gathered on details of the assets owned and operated by gas networks, including the operating parameters and locations relative to buildings and populations. This data was used in conjunction with the hydrogen QRA package to extrapolate the risk calculations to predict the risks following the conversion of the GB natural gas distribution networks to 100% hydrogen and to provide a baseline for quantification of possible risk reduction measures, such as targeted replacement of metallic pipes with new PE pipes.

This paper describes the QRA methodology developed for hydrogen gas networks during Phase 1 of the H21 NIC project and its application to predict the risks associated with a converted gas distribution network, including consideration of risk mitigation options. Phase 2 is in progress, incorporating the predicted risks associated with hydrogen leakage from downstream of the ECV, to provide a holistic overview of the potential risks associated with a possible conversion from natural gas to hydrogen and the effectiveness of practical risk reduction measures.

Keywords: Hydrogen, Distribution, QRA

Introduction

The H21 Network Innovation Competition (NIC) project led by Northern Gas Networks (NGN) aims to address the issues associated with the conversion of the GB gas distribution networks from natural gas, which is predominantly methane, to transporting pure hydrogen gas [1]. Phase 1 of the programme addressed two important aspects [2]:

- Phase 1A – Background testing - "The background leakage position of the network, i.e. does it leak more on 100% hydrogen and if so by how much and where?"
- Phase 1B – Consequence testing - "The consequences of hydrogen leakage both background and through network failures such as 3rd party damage, i.e. where does it go and can it be ignited?"

Phase 1A included a test programme carried out by HSE Science Division at their site in Buxton, and Phase 1B included a test programme carried out by DNV at the Spadeadam Testing & Research Facility in Cumbria.

In order to consider the relative risks associated with the different properties of hydrogen versus natural gas, a Quantitative Risk Assessment (QRA) has been undertaken as part of the evaluation of the safety of a hydrogen network in Phase 1B. This provides a quantified basis to demonstrate whether distribution of hydrogen through an existing gas network presents higher or lower risks to the public than a natural gas network and investigates the potential for lowering the risk through the application of risk mitigation measures. The QRA methodology for hydrogen, as established in the CONIFER risk assessment package, can be used to:

- Quantify the risks to the public
- Highlight the main contributors to the risk

- Identify potential restrictions on operations
- Suggest effective mitigation measures
- Compare risks with those of a natural gas network

The QRA addresses the safety risks to the public (100% hydrogen versus natural gas) from leakage resulting from both normal operation of the network and accidental interference. The QRA methodology is based on the existing natural gas distribution QRA model, which is being modified to enable the necessary calculations to be performed for hydrogen. This development has been undertaken in the stages that are summarised below:

- Part A: Information gathering. Includes a literature review and identification of hazards pertinent to hydrogen distribution.
- Part B: Preliminary QRA model for hydrogen and gap analysis. Identification of necessary changes to the model.
- Part C: Preliminary risk analysis and risk evaluation. Initial estimates of the risks in order to inform priorities for improvements and specification of the experimental programme.
- Part D: Refine QRA model and risk results for hydrogen and consider mitigation options. Update the models using the experimental results and identify risk mitigation options.
- Part E: Extrapolation of QRA results across the GDNs. Estimation of societal risk for the whole of the GB gas distribution networks for both natural gas and 100% hydrogen (without and with mitigation options applied) for direct comparison.

This paper describes the QRA methodology developed for hydrogen gas networks in Phase 1 of the H21 NIC project and its application to predict the risks associated with a converted gas distribution network. At the time of writing, Phase 2 is in progress, which will incorporate releases downstream of the Emergency Control Valve (ECV) in order to provide a holistic comparison between the natural gas and hydrogen risks. This will make use of the information gathered and methodology established in the Hy4Heat project as far as possible [3].

Information Gathering

Literature Review

A literature survey of publicly available documents was carried out in order to gather information that is relevant to the development of the QRA model. This included experimental data that could be used to validate models and modelling approaches developed by others. This enables existing information to be used to bridge the knowledge gaps, particularly when extending the model from handling natural gas to representing hydrogen.

Over 150 relevant publications were identified in the review, highlighting the long history of research into hydrogen safety, particularly in industrial applications. The sources collected were grouped into topics and those documents that were most relevant to the development of the QRA model and the H21 Phase 1B testing programme were summarised. Important sources of information include the EC funded HySafe project [4], published work by the HSE Science Division (e.g. [5], [6]) and experiments undertaken by DNV (e.g. [7], [8]). The potential for hydrogen to be transported by either existing or new networks as a replacement for natural gas to be used for heating and cooking in homes and businesses is an active area of ongoing research. There are several ongoing projects in the UK alone (summarised in [9] and [10]) and close relationships are being maintained between the projects to avoid duplication and to benefit from shared learning and experience.

The physical and chemical properties of hydrogen are well understood and can be readily compared with those of methane, and a selection of relevant properties is given in Table 1. Hydrogen is highly buoyant and has wider flammability limits than methane when mixed with air, and a lower minimum ignition energy. At relatively high concentrations, hydrogen can produce higher explosion overpressures (with an increased potential for detonation) due to a higher maximum burning velocity. However, the products of combustion of hydrogen are benign, comprising only water, whereas the combustion of methane produces carbon dioxide (contributing to global warming) and, under certain circumstances, carbon monoxide (a toxic gas and the main cause of fatalities in the UK from using natural gas).

Table 1. Typical properties of methane and hydrogen [11]

Fuel	Molecular weight	Flammability limits (% v/v)		% Gas at stoichiometric ratio	Maximum laminar flame speed (m/s)	Minimum ignition energy (mJ)
		Lower	Upper			
Hydrogen H_2	2	4	75	30	28	0.02
Methane CH_4	16	5	15	9.5	3.5	0.29

The distribution of hydrogen in gas networks is not a new concept – prior to the introduction of North Sea natural gas in the late 1960s and early 1970s, the gas supplied by the networks was manufactured “Town Gas”, typically comprising 50%

hydrogen by volume. Cross-country high pressure pipelines transporting 100% hydrogen are already in operation and have been for many years. However, very few previous publications specifically address the risks associated with the differences between the properties of natural gas and hydrogen in the context of the distribution of 100% hydrogen at low pressures to domestic and commercial premises for general use by the public.

Note that the GB gas distribution system is limited to pressures up to 7 bar, in three tiers:

- Low Pressure (LP), up to 75 mbar
- Medium Pressure (MP), over 75 mbar and up to 2 bar
- Intermediate Pressure (IP), over 2 bar and up to 7 bar

The majority of mains and services operate in the LP range. Values are given as gauge pressures where 1 mbar is 100 Pa and 1 bar is 100,000 Pa.

In addition, the Safety Risk department of DNV (formerly part of British Gas R&D) has a long history of performing safety and risk studies to support natural gas networks and has built up a considerable library of relevant internal research reports, including those describing the technical basis of the existing natural gas distribution risk model. These reports were used to inform the model development work for hydrogen and experimental programme, where appropriate.

Information supplied by NGN

A large amount of statistical data has been supplied by NGN for their network, including:

- Lengths and details of mains, pressure governors and services supplying individual meter points.
- Data showing the physical locations of mains and nearby buildings.
- Summary information on historical failures and repairs, leakage and "gas in building" (GiB) events.

Gas Distribution QRA Model

Development History of the Gas Distribution QRA Model

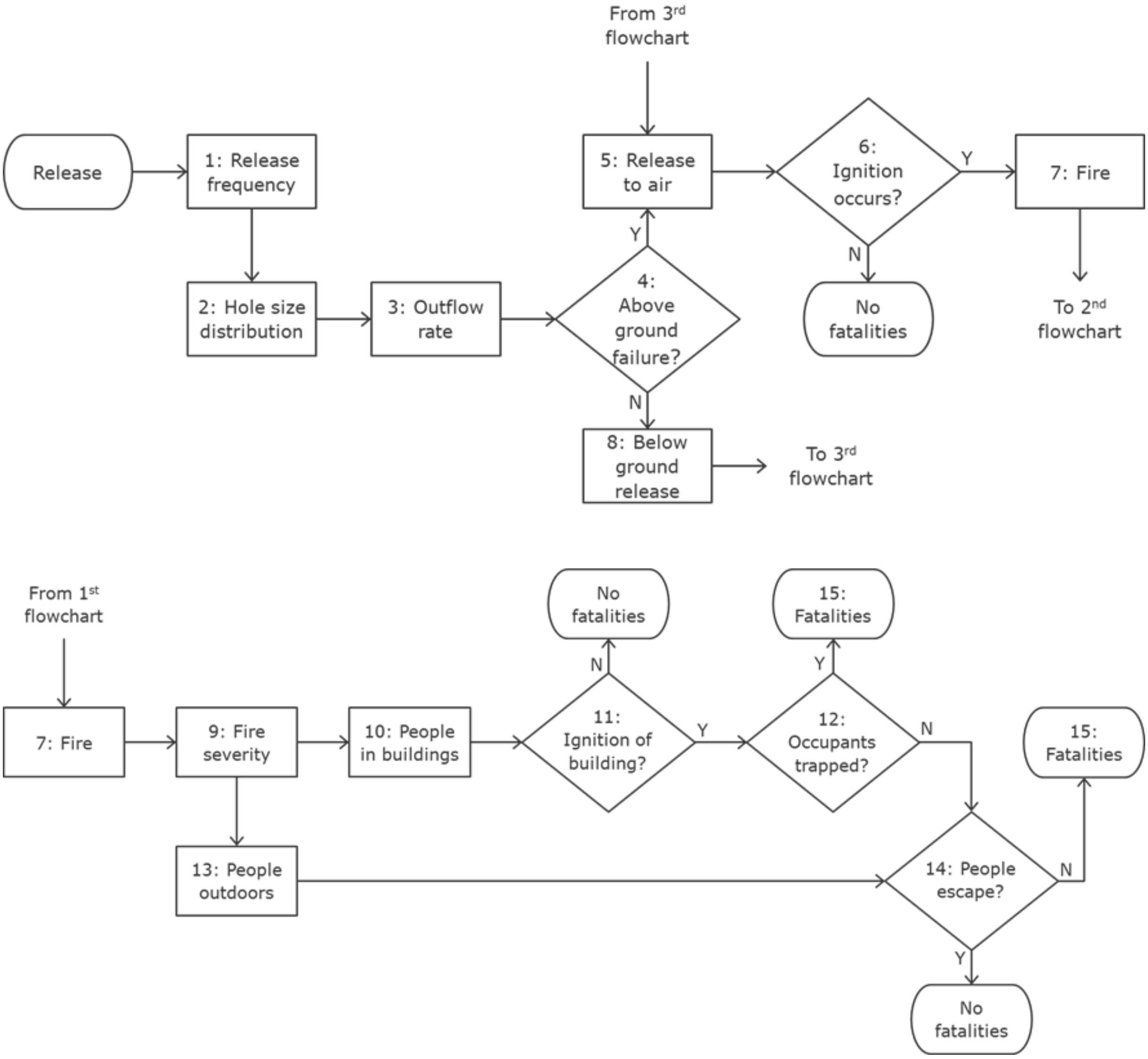
The following timeline summarises the history of the development of the distribution QRA model, and how the model has evolved over time. Prior to the H21 project, all versions of the model were developed for application to natural gas only.

- In 1974, the first national replacement programme for cast iron mains was introduced.
- The King Inquiry was carried out in 1977 to investigate the causes of a series of gas explosions that occurred in the winter of 1976/1977. This resulted in the introduction of a mains replacement programme that has continued in various forms ever since.
- In 1990, the "Points Scheme" was developed. This was a method of prioritising metallic mains for replacement using a ranking process, rather than a calculation of the risk.
- Between 1995 and 1999, the Gas Research and Technology Centre of BG Technology (now part of DNV) developed a quantitative risk-based approach for prioritising cast iron mains for replacement comprising two complementary methodologies:
    - A statistical model; applied to mains up to 12" diameter. This was possible as a large pipeline population existed and there was ample operational data for statistical analysis.
    - A predictive model; applied to mains over 12" diameter. There was insufficient data for statistical analysis in this category; hence, the need for a predictive model.
- The Mains Replacement Prioritisation Scheme (MRPS) was implemented in 2000, using these two models for cast iron mains. In addition, statistical models are included for ductile iron and steel mains.
- The predictive gas distribution QRA model was developed for application to both metallic and PE mains [12], following a similar structured approach and a linked series of mathematical models as other QRA methodologies being developed for gas industry applications at that time [13]. This was supported by full scale experiments to investigate aspects of natural gas releases from the distribution network.
- The distribution QRA model has continued to be developed subsequently for natural gas, particularly for application to the PE mains that form an increasingly significant proportion of the gas distribution networks. An important recent application of the model was the development of risk-based allowable building proximity distances for PE distribution mains, involving several updates to the methodology. The resulting proximity distances for natural gas are included in IGEM/TD/3 Edition 5 [14].

The existing predictive natural gas distribution QRA model was selected as providing the most appropriate basis for the development of a QRA model for hydrogen distribution networks, as the model already includes the key elements required, including failure frequencies and consequences (gas release rates; gas dispersion, ingress and accumulation; ignition likelihood; effects of fires and explosions). Many elements of the model are based on extensive operational experience which remains relevant for hydrogen. The model has proved to be robust in use over an extended period and the predictions are broadly consistent with the history of fires and explosion incidents associated with leakage from the GB gas distribution networks. Although the focus to date has been on calculating risk from gas distribution mains to prioritise them for replacement, versions of the model have been developed previously for other network assets including services and meter installations, which can be combined in a single QRA to calculate the overall network risks associated with all the assets. The construction of the model, with individual modules for each of the relevant steps in the calculations, lends itself to being adapted to accept different gas compositions including pure hydrogen, natural gas, or in principle any mixture of the two.

Description of the Gas Distribution QRA Model

The structure of the CONIFER model is shown in Figure 1. Each of the numbered steps in the figure contains a detailed sub model that cannot be reduced to a simple set of equations, and hence cannot be described fully here. A brief description of each step and the applicability of the natural gas model to hydrogen is given in Table 2 below the figure.



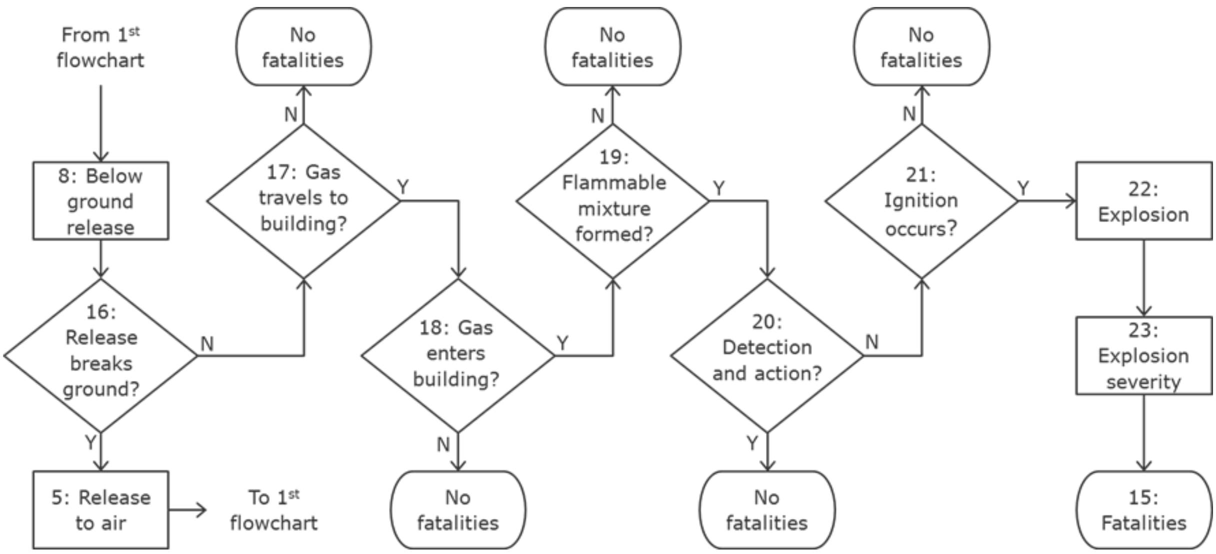


Figure 1. Structure of the CONIFER distribution risk assessment model

Table 2. Summary of the gas distribution QRA model and possible application to hydrogen

Step	Description	Basis	Modifications Required
1: Release frequency	The frequency of a gas release is determined from the pipe characteristics (such as pressure, diameter and construction details) and failure mode (interference and/or spontaneous). Each failure mode is considered in turn in the following steps.	5 years of data from mains in one distribution network.	The existing values are adequate for initial QRA predictions and comparisons between natural gas and hydrogen. It is assumed that the failure frequencies are the same for natural gas and hydrogen. Failure frequencies could be updated when new data becomes available.
2: Hole size distribution	A range of hole sizes and their probabilities is defined, based on the pipe characteristics and failure mode. Each hole size is considered in turn in the following steps.	Largely judgement.	The existing values are adequate for initial QRA predictions and comparisons between natural gas and hydrogen. Further data would help to refine or validate the current assumptions.
3: Outflow rate	The outflow rate from the failure is predicted for each hole size.	Detailed models and test data are available.	The model can be applied to hydrogen and validation data is provided by the H21 Phase 1B experiments.
4: Above ground failure?	The proportion of releases that occur on a pipe that is already uncovered (i.e. in a trench) is determined. Both above and below ground cases are analysed.	Historical data for natural gas.	The existing values are adequate for initial QRA predictions and comparisons between natural gas and hydrogen.
5: Release to air	A release occurs that is open to the atmosphere.	This is just a step in the flow chart, without an associated calculation.	
6: Ignition occurs?	The ignition probability is calculated for above ground releases.	Historical data for natural gas.	The approach for natural gas is based on historical data, so an equivalent approach is not possible for hydrogen. Information on ignition of hydrogen by a range of credible sources was provided by the H21 Phase 1B experiments to inform judgement in conjunction with information in the open literature.
7: Fire	A fire occurs.	This is just a step in the flow chart, without an associated calculation.	
8: Below ground release	A below ground release occurs, with covering soil still in place.	This is just a step in the flow chart, without an associated calculation.	

Step	Description	Basis	Modifications Required
9: 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.	Established models.	Previous fire experiments provided this information for high (transmission) pressure hydrogen releases. The H21 Phase 1B experiments provide validation data for an appropriate range of fire sizes more relevant to lower pressure gas distribution releases.
10: People in buildings	At least some people in the vicinity of the fire are located inside buildings.	This is just a step in the flow chart, without an associated calculation.	
11: Ignition of building?	The possibility of the thermal radiation igniting the building is considered.	Established models.	The current methodology is adequate.
12: Occupants Trapped?	A proportion of the building's occupants are assumed to be unable to leave the building.	Based on historical data of house fires.	The current methodology is adequate.
13: People outdoors	At least some people in the vicinity of the fire are located outdoors.	This is just a step in the flow chart, without an associated calculation.	
14: People escape?	The way in which the thermal radiation field changes with distance and time are taken into account as each person outdoors moves away from the fire.	Established models.	The current methodology is adequate.
15: Number of fatalities	The number of fatalities is recorded for each event and occupied location and summed appropriately.	Established models.	The current methodology is adequate.
16: Release breaks ground?	The probability of the release breaking through the covering soil is determined. Both above and below ground cases are analysed.	Test data for natural gas.	The H21 Phase 1B experiments supply some information on when below ground releases break through the surface.
17: Gas travels to 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.	Detailed models and test data available.	The H21 Phase 1B experiments supply information for a range of relevant scenarios. The underlying approach for natural gas and hydrogen is the same, but the gas properties are taken into account.
18: Gas enters building?	The probability of any gas entering the building is determined. For cases with ingress, the proportion of gas entering is calculated.	Historical data for natural gas, but some judgement.	The approach for natural gas is based on historical data and is not possible for hydrogen without operational experience. The ingress probability is assumed to be the same for natural gas and hydrogen.
19: Flammable mixture formed?	Gas accumulation calculations determine the gas concentration as a function of time. The ingress rate and building properties (such as ventilation rate and ingress into cellars) are taken into account.	Established models and data.	The differences between natural gas and hydrogen are understood and are taken into account. The H21 Phase 1B experiments collected information about gas concentrations within buildings for known ingress rates to validate the modelling. Additional relevant data is available from the Hy4Heat project [3].
20: Detection and action?	Probability distributions are used to calculate the likelihood of gas detection and subsequent action (or lack of it), and engineer arrival times, all as a function of time after ingress begins.	Detailed model available.	The existing values are adequate for initial QRA predictions and comparisons between natural gas and hydrogen. This assumes that the detectability (odour) is equivalent for natural gas and hydrogen.
21: Ignition occurs?	The ignition probability for gas accumulated inside buildings is calculated. This is closely related to the detection step. A proportion of ignition sources are assumed to be related to the presence of people.	Historical data for natural gas.	The approach for natural gas is based on historical data, so an equivalent approach is not possible for hydrogen. Information on ignition of hydrogen by a range of credible sources is provided by the H21 Phase 1B experiments to inform judgement in conjunction with information in the open literature.

Step	Description	Basis	Modifications Required
22: Explosion	An explosion occurs.	This is just a step in the flow chart, without an associated calculation.	
23: Explosion severity	The overpressure generated by the explosion is calculated. This is used to determine the probability of an individual becoming a fatality.	Established models and data.	Modifications were required but some hydrogen data was already available and the concepts are understood. The H21 Phase 1B experiments provided relevant data for a range of network assets.

Phase 1B Experimental Programme – Consequence Testing

The large scale experimental programme of consequence testing undertaken in Phase 1B was developed to satisfy two important requirements before the operation of a gas network on pure hydrogen can be considered. The first was to address gaps in the knowledge to enable a comparative risk assessment to be made between natural gas and hydrogen, using the gas distribution QRA model. The second was to develop a detailed understanding of the behaviour of hydrogen in operational scenarios, to support the development of safe working practices and procedures for network personnel, including, for example, when responding to gas emergencies. Details of the experimental programme have been published separately [1], [15].

The Phase 1B experimental programme is a major project and addresses five main themes as follows:

- "Small" releases underground to investigate outflow from the pipe and the migration of gas through soil, including different ground surface materials.
- "Large" releases underground to investigate the potential for breaking the ground for releases underground, and in the open to confirm the properties of hydrogen fires at relevant scales.
- Ignition potential focussed on domestic appliances and potential sources that might be encountered while responding to emergencies.
- Explosion tests in a variety of enclosures used on distribution networks, to investigate severity and behaviour of hydrogen explosions.
- Operational safety tests and demonstrations that did not directly affect the development of the QRA.

Distribution QRA Model Developments for Hydrogen Application

Updates Completed

The following changes were made to the risk assessment model as part of Phase 1 of the project:

- The ability to model hydrogen, in addition to natural gas, has been included. The composition can be specified, and typical UK natural gas was modelled.
- Thermodynamic parameters such as the density and viscosity that were previously fixed and applicable only for natural gas have been replaced by calculated values that depend on the specified fluid composition. In some cases, other inputs such as the operating pressure and temperature also influence the calculated parameter values. GasVLe [16] is used to determine the necessary thermodynamic properties of the fluid.
- The criteria for a release from a buried pipe breaking the ground were reviewed in the light of the experimental results. Releases which break the ground tend to have higher fire risks and lower explosion risks, with the latter effect expected to dominate for low pressure pipelines.
- The models that predict gas outflow from a hole in a pipe, and the subsequent migration of gas through the soil, were updated to reflect the finding of the experimental programme and capture the differences between natural gas and hydrogen.
- The model used to predict the radiation from above ground hydrogen fires has been recalibrated based on existing data for high pressure hydrogen pipeline fires.
- The effects of buoyancy and the gas accumulation calculations were improved within the explosion risk module. Due to the low density of hydrogen, the enhanced ventilation due to buoyancy effects is greater for hydrogen than for natural gas.
- The ignition probability model within the explosion risk calculation was adapted to include hydrogen. This is still an area of some uncertainty.
- The concentration of the flammable mixture at the time of ignition is considered in the explosion severity calculations. The bands of concentration are based on the flammable limits of the selected fuel. The dependence of the explosion overpressure on the concentration is significantly different for hydrogen and natural gas, so the

model was updated to ensure that this feature is captured. Although hydrogen explosions are potentially much more severe than natural gas explosions, this may not be the case at low concentrations.

- The method of calculating the vulnerability of building occupants to explosions was updated. This provides greater resolution to differentiate between natural gas and hydrogen explosions, but also considers harm to people in adjoining properties.

Further Updates under Consideration

The following modifications to the model are being considered as part of Phase 2:

- Releases downstream of the ECV, inside buildings, are being incorporated into the QRA.
- The assumed hole size distributions that result from a pipe failure will be reviewed. This is currently an area of uncertainty as very little data is currently collected concerning the severity of failures and the leak paths that result, although the overall frequencies of pipe failure are generally based on robust data.
- The gas ingress probability may be replaced with another approach, or modified, and the proportion of gas that enters a building upon reaching it will be reviewed within the explosion risk.
- Overpressure effects will be considered outside the building where an explosion originates. It is currently assumed that only people inside the building can be affected, but this may not be the case for the more severe events that could occur if hydrogen is present.

Risk Predictions

Approach

This section gives risk predictions for realistic examples of gas distribution systems transporting natural gas and hydrogen. It considers the risks to members of the public inside domestic properties only (i.e. not including people at industrial and commercial locations, people in the gardens of domestic properties, people on roads and pathways, and employees of the gas distribution companies carrying out work on the distribution system). It is stressed that the results will likely be updated during Phase 2 of the H21 project, as the models are developed further.

The risk predictions given in this paper are presented in terms of the Potential Loss of Life (PLL), representing the societal risk. Where appropriate, other measures of risk such as individual risk values, F-N curves and the frequencies of incidents can also be produced. The predicted individual risk levels are low, for natural gas and hydrogen, so they are not discussed further here.

Task E of the H21 QRA project involves extrapolating the results of the QRA methodology to the whole of the GB gas distribution networks. The PLL results given here apply to the whole of Great Britain, assuming that the NGN network is a representative subset.

Test Cases

Risk predictions were made for main configurations of mains, services and nearby buildings. NGN supplied information about their network as it was in 2020, and detailed data concerning the distances between each main and all buildings within 150 metres. All relevant permutations of the following were considered for mains:

- 6 main materials (open cut PE, PE inserted into a metallic pipe, steel, cast iron, spun iron and ductile iron)
- 8 representative main diameters (63, 90, 125, 180, 250, 315, 450 and 630 mm)
- 8 operating pressures (LP at 30, 40, 60 mbar; MP at 350, 1000, 2000 mbar; IP at 4500 and 7000 mbar)
- 23 building proximity distances (3, 5, 7, 9, 11, 13, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 120, 130, 140 and 150 metres)

The following cases were assumed for services:

- 3 service materials external to the property (steel, open cut PE and PE inserted into a metallic pipe)
- 2 service materials internal to the property (steel, PE inserted into a metallic pipe)
- 4 service diameters (15, 20, 25 and 32 mm internally)

The following building configurations were represented:

- 4 building types with different room sizes (detached, semi-detached, terraced, bungalow)
- 2 cellar configurations (with and without a cellar)
- 2 ground surface types between the main and building (sealed or open)
- 4 different household groups (1, 2, 3 and 4 people with different occupancy patterns)

The likelihood of each configuration of main, service and building occurring was taken into account, based on a detailed analysis of NGN's network and publicly available data concerning the UK housing stock.

The operating pressures across the network were assumed to be the same for natural gas and hydrogen.

The mains and services were assigned failure frequencies and leak size distributions that depend on factors such as the pipe material, pipe diameter and the failure cause (such as interference damage, corrosion or joint failures). The failure frequencies and modes were assumed to be the same for natural gas and hydrogen.

Based on detailed data from NGN, it was assumed that 50% of meters are located inside the property and 50% are on an external wall. The internal part of the service was included only for properties with internal meters.

Using these combinations of main, service and building type, the total predicted PLL for distribution mains across Great Britain is shown in Figure 2. The 2032 distribution network takes into account the planned changes from the 2020 network related to the Iron Mains Replacement Programme, with different replacement rates assumed for cast iron, ductile iron and spun iron in the different diameter tiers and pressure bands.

- "Natural Gas" represents the 2020 network, as operated with natural gas. This is the target risk level that should not be exceeded for a hydrogen network.
- "Hydrogen, Planned Replacement" represents the risk posed by a hydrogen network, including the benefits of the planned replacement programme up to 2032, but with no additional mitigation measures.
- "Hydrogen, Additional Replacement" shows that it is possible to implement some additional risk mitigation measures and bring the 2032 hydrogen network risk below the 2020 natural gas network risk. It includes the following additional replacement:
    - The LP metallic mains with diameters greater than 8 inches (around 203 mm) and less than 18 inches (around 457 mm) are reduced to 10% of their 2020 population.
    - For other metallic LP and MP mains, 20% more is replaced than in the currently planned programme.
- "Hydrogen, All LP/MP Replaced" shows that replacing all the metallic LP and MP mains, without replacing the remaining IP metallic mains, brings the 2032 hydrogen network risk well below the 2020 natural gas network risk.

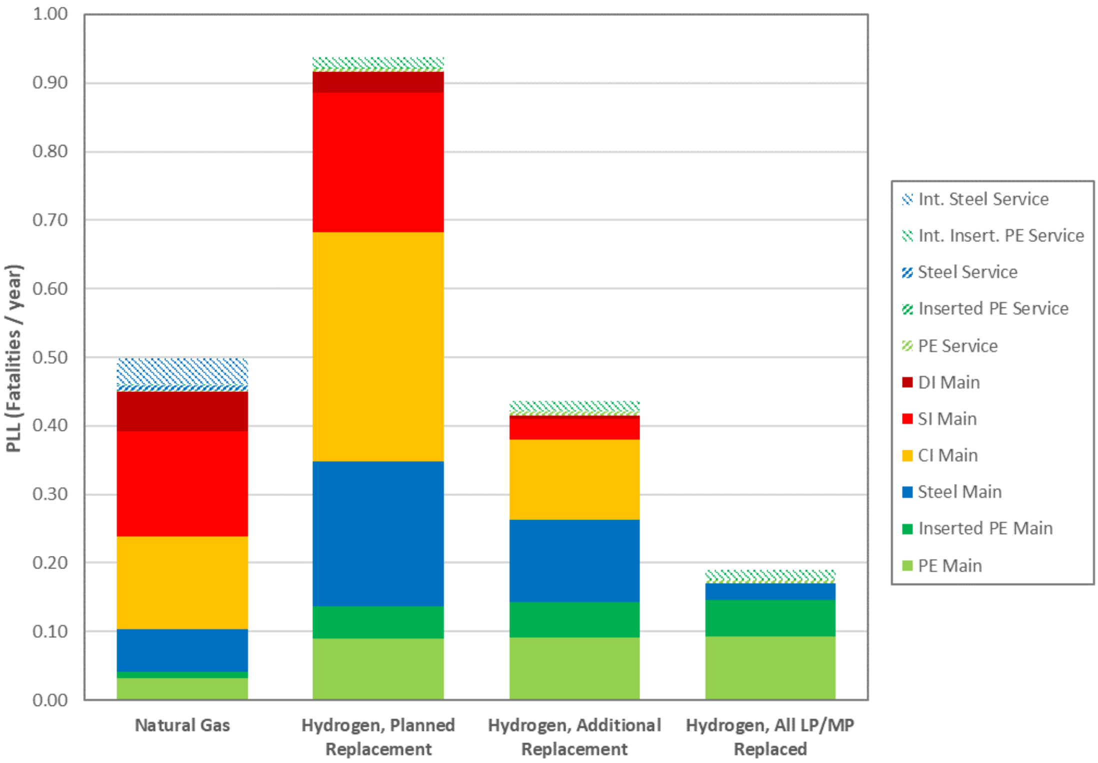


Figure 2. Total PLL for distribution networks across Great Britain

The major contributors to the PLL are explosions due to spontaneous failures of metallic mains and services. It should be noted that even without addition risk mitigation, less than 1 fatality per year is predicted from fires and explosions on a hydrogen network. This is much lower than the current fatality rate from carbon monoxide poisoning on the natural gas network, which is not taken into account in this comparison.

Other risk mitigation measures were also considered for releases upstream of the ECV:

- Moving all internal meters to external locations would reduce the PLL associated with services by 72.6%, but the overall PLL by only 1.6%.
- Reducing the operating pressures within the distribution network could result in small decreases to the overall societal risk, but this is not likely to be a practical solution.
- In principle, the network could be protected from interference damage. However, this would only result in a 7.2% reduction in the societal risk if the whole network were protected, and installing protective measures such as slabbing would be impractical. Targeted protection of the IP parts of the network operating above 2 bar would only result in a 0.6% reduction in the overall PLL.
- Excess flow valves at the upstream end of the services, set to a limit of 20 m^3/hour, give a very small reduction to the risks posed by releases upstream of the ECV. Therefore, if excess flow valves are fitted to mitigate releases downstream of the ECV, their location can be near the meter.

These results show that various risk mitigation measures are possible, but that replacement of metallic mains and services with PE pipework has the greatest benefit. Phase 2 of the project will give a more complete view of the risk profile of the networks once releases downstream of the ECV are included in the QRA. This will allow more focussed use of resources to lower the overall societal risk associated with a hydrogen network.

Discussion

The calculations above show, at a high level, risk predictions for fires and explosions resulting from releases from Great Britain's gas distribution mains networks affecting members of the public within domestic properties. The predicted risks to the public are very low for both natural gas (consistent with operational experience following the implementation of the mains replacement programme) and hydrogen.

It is stressed that the results are likely to be updated in Phase 2 of the project. However, the following observations can be made when comparing the 2020 natural gas and 2032 hydrogen networks:

- The risks from fires are lower for hydrogen than for natural gas.
- The risks from explosions are higher for hydrogen than for natural gas.
- The explosion risk from a network is predicted to be significantly larger than the fire risk, particularly for hydrogen.
- It is possible to use risk mitigation measures to operate a hydrogen network at a societal risk level lower than posed by the 2020 natural gas network. Replacement of metallic mains and services with PE pipework is an effective option.

Note that the leakage testing undertaken in the H21 Phase 1A test programme [2] did not directly influence the development of the hydrogen distribution QRA model because the flow rates that were obtained were too low to pose a significant risk to people. However, the tests confirmed that the behaviour of small leaks is as expected and that assets that are gas-tight for natural gas would not be expected to leak when in hydrogen service.

Conclusions

The H21 Network Innovation Competition project aims to address the issues associated with the conversion of the GB gas distribution networks from natural gas (predominantly methane) to pure hydrogen gas. The overriding objective of the project is to provide the compelling safety-based evidence for a 100% hydrogen conversion in the GB gas distribution networks; specifically, that the pipes and equipment in 2032 will be as safe operating on 100% hydrogen as the current natural gas system. As part of this objective, a comparative Quantitative Risk Assessment was required to evaluate the difference in safety risk to the public associated with supplying 100% hydrogen versus natural gas. The risks calculated cover releases upstream of the meter only, i.e. the network up to and including the Emergency Control Valve.

In order to consider the relative risks associated with the two gases, a QRA methodology has been developed for a 100% hydrogen network, which was closely based on the existing approach developed and refined over many years for application to the existing natural gas networks (used in applications including risk-based prioritisation of metallic distribution pipelines or "mains" for replacement with polyethylene, PE). The QRA methodology is embodied in the CONIFER software package comprising a series of modules, which combine operational experience of the frequency and nature of uncontrolled gas releases with a linked series of mathematical models to predict the potential consequences (fire and explosion) in different circumstances.

The results show that a hydrogen network can be operated while posing risks no higher than currently experienced for the existing natural gas network (which are, in themselves, very low). This requires risk mitigation measures to be implemented and it was found that the replacement of metallic mains and services with PE pipework is effective. The contributions to releases downstream of the ECV to the overall societal risk are being evaluated in Phase 2 of the H21 project, which will provide a holistic view of where risk reduction should be focussed.

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References

[1] H21 project, www.h21.green

[2] H21 project, "H21 Phase 1, Technical Summary Report", May 2021

[3] Hy4Heat project, www.hy4heat.info

[4] HySafe project, The EC Network of Excellence for Hydrogen Safety, www.hysafe.org

[5] Royle, M. and Willoughby, D., "The safety of the future hydrogen economy", Process Safety and Environmental Protection 89 (2011), IChemE

[6] Hooker, P., Hoyes, J.R. and Hall, J., "Accumulation of Hydrogen Released into an Enclosure Fitted with Passive Vents – Experimental Results and Simple Models", Hazards 24 (Edinburgh), Symposium Series No. 159, IChemE, May 2014

[7] Acton, M.R., Allason, D., Creitz, L.W. and Lowesmith, B.J., "Large Scale Experiments to Study Hydrogen Pipeline Fires", Proceedings of the 8th International Pipeline Conference 2010 (Calgary), ASME International

[8] Tanaka, T., Azuma, T., Evans, J.A., Cronin, P.M., Johnson, D.M. and Cleaver, P. "Experimental study of hydrogen explosions in a full-scale hydrogen filling station", ICHS 2005, International Conference on Hydrogen Safety, Pisa, September 2005

[9] "Transitioning to hydrogen – Assessing the engineering risks and uncertainties", The Institution of Engineering and Technology (IET), www.theiet.org

[10] Future Gas Series: Part 1 "Next Steps for the Gas Grid", Carbon Connect, www.policyconnect.org.uk

[11] Harris, R.J., "The Investigation of Gas Explosions in Buildings and Heating Plant" E & FY Spon, ISBN 0 419 13220 1 (reprinted 1989)

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

[13] Acton, M.R., Baldwin, T.R., and Cleaver, R.P., "Development and Implementation of Risk Assessment Methods for Onshore Natural Gas Terminals, Storage Sites and Pipelines", Proceedings of the 22nd World Gas Conference Tokyo 2003, International Gas Union

[14] IGEM/TD/3 Edition 5, "Steel and PE pipelines for gas distribution", Institution of Gas Engineers and Managers, Communication 1780, 2015

[15] Allason, D., Jenney, L. and Acton M.R., "Thermal Radiation Properties of Large Hydrogen Leaks from Gas Distribution Networks", ICHS 2019, International Conference on Hydrogen Safety, Adelaide, September 2019

[16] GasVLe thermodynamic property calculator, www.dnv.com