H21 Phase 1 Technical Summary Report

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Contents

The team

Core team

Tim Harwood

H21 Project Director

Tim has 39 years' experience in the UK gas industry, covering a wide range of operational and project roles across all pressure ranges and assets types within distribution and transmission. Tim's current role is Head of Programme Management at NGN with responsibility for the H21 project.

Mark Danter

Senior Project Manager

A highly experienced chartered engineer, Mark has a proven track record of delivering multi-disciplinary project programmes. Mark has worked on several innovation and pilot projects within the gas industry and Mark is now Senior Project Manager for NGN on the H21 project.

Russ Oxley

Senior Project Manager

Russ has spent his entire career working in the gas distribution industry delivering major mains replacement, diversion and CAPEX projects. As H21 Senior Project Manager, Russ is responsible for ensuring that critical safety evidence is gathered from a programme of strategic tests undertaken at a number of H21 test sites.

Stella Matthews

Assistant Project Manager

Stella has worked within the gas industry for over four years, undertaking various roles at Northern Gas Networks. She joined the H21 team in 2017 as a Project Officer and has recently taken up the role of Assistant Project Manager. Whilst on the project Stella has managed the Social Science research work, which looked at the public perception of hydrogen.

Catherine Spriggs

HSE Science Division – Phase 1a Buxton

Catherine is a Chartered Civil Engineer and Member of the Association of Project Managers with over 18 years' experience of working on complex projects in the business, science and construction sectors. As HSE Programme Manager, Catherine currently manages HSE's technical input to a number of high profile hydrogen projects including H21, HyDeploy, Hy4Heat IGEM Standards, HyNTS, H100 and BEIS Hydrogen Grid R&D Programme.

Dan Allason

DNV GL – Phase 1b Spadeadam

Dan is a Chartered Physicist with more than a decade of experience conducting major hazard research at DNV GL's world-leading Spadeadam Research and Testing Centre in Cumbria, UK. Dan has been involved in managing, conducting and analysing all manner of major hazard experimental programmes from large vapour cloud explosions, through liquified natural gas or hydrogen release studies, full scale pipeline fractures, dense phase CO2 releases and, more recently, hydrogen distribution and domestic use safety experiments for H21 and Hy4Heat.

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DNV GL – QRA

Senior Principal Consultant and Chartered Physicist with a strong academic background including a doctorate for research into brittle fracture behaviour from the University of Oxford, subsequently specialising in hazard and risk analysis for the natural gas industry. Currently working on several strategically important innovation projects responding to the challenge of climate change by decarbonisation of energy, addressing the safety aspects of conversion of the gas grid from natural gas to hydrogen.

Dr Fiona Fylan

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Fiona Fylan is a Health Psychologist who leads the Sustainable Behaviour team within the Leeds Sustainability Institute at Leeds Beckett University. Fiona and her team managed the implementation of the Social Sciences section of the H21 Phase 1 Project.

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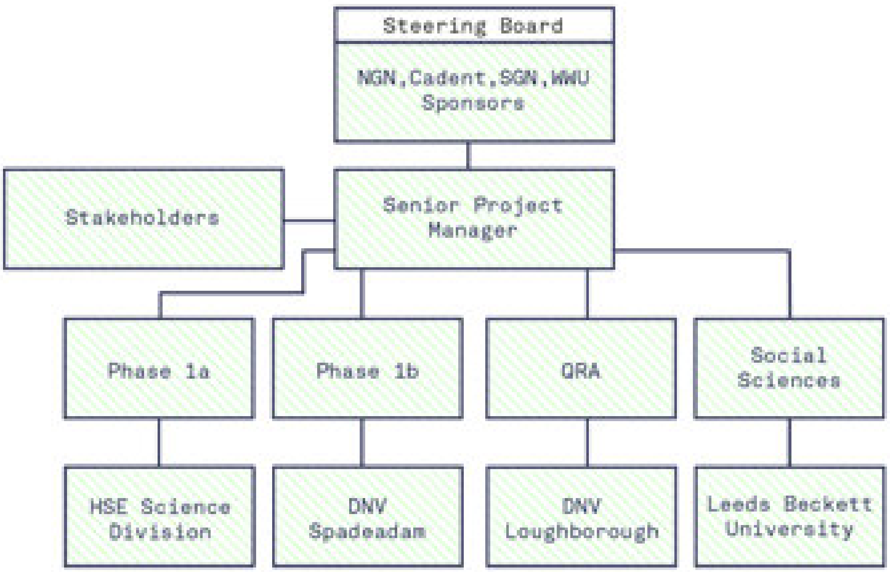
Northern Gas Networks | Cadent Your Gas Network | SGN | Wales & West Utilities

COLLABORATION AGREEMENTS

DNV | HSE

Project Organogram



1.0

EXECUTIVE SUMMARY

1.0 Executive Summary

The UK Government signed legislation on 27th June 2019, committing the UK to a legally binding target of Net Zero emissions by 2050. Climate change is one of the most significant technical, economic, social and business challenges facing the world today.

The H21 NIC Phase 1 project delivered an optimally designed experimentation and testing programme, supported by the HSE Science Division and DNV GL, with the aim to collect quantifiable evidence to support that the UK distribution network of 2032 will be comparably as safe operating on 100% hydrogen as it currently is on natural gas. This innovative project begins to fill critical safety evidence gaps surrounding the conversion of the UK gas network to 100% hydrogen. This will facilitate progression towards H21 Phase 2 Operational Safety Demonstrations and the H21 Phase 3 Live Trials, to promote customer acceptability and ultimately aid progress towards a government policy decision on heat.

DNV GL and HSE Science Division were engaged to undertake the experimentation, testing and QRA update programme of work. DNV GL and HSE Science Division also peer reviewed each other's programme of work at various stages throughout the project, undertaking a challenge and review of the experimental data and results to provide confidence in the conclusions.

A strategic set of tests was designed to cover the range of assets represented across the Great Britain gas distribution networks. The assets used in the testing were mostly recovered from the distribution network as part of the ongoing Iron Mains Risk Reduction Replacement Programme. Controlled testing against a well-defined master testing plan, with both natural gas and 100% hydrogen, was then undertaken to provide the quantitative evidence to forecast any change to background leakage levels in a 100% hydrogen network.

Key Findings from Phase 1a:

- Of the 215 assets tested, 41 of them were found to leak, 19 of them provided sufficient data to be able to compare hydrogen and methane leak rates.
- The tests showed that assets that were gas tight on methane were also gas tight on hydrogen. Assets that leaked on hydrogen also leaked on methane, including repaired assets.
- The ratio of the hydrogen to methane volumetric leak rates varied between 1.1 and 2.2, which is largely consistent with the bounding values expected for laminar and turbulent (or inertial) flow, which gave ratios of 1.2 and 2.8, respectively.
- None of the PE assets leaked; cast, ductile and spun iron leaked to a similar degree (around 26-29% of all iron assets leaked) and the proportion of leaking steel assets was slightly less (14%).
- Four types of joint were responsible for most of the leaks on joints: screwed, lead yarn, bolted gland, and hook bolts.
- All of the repairs that sealed methane leaks also were effective when tested with hydrogen.

A key part of the project objectives included updating the Quantitative Risk Assessment (QRA) model to allow the evaluation of the difference in safety risk to the public associated with supplying 100% hydrogen versus natural gas. 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. A review of the current natural gas model was undertaken and the gaps in the model relevant to the change to hydrogen from natural gas were assessed and a master test plan developed to provide the evidence required to update the QRA.

From the review of the QRA and the findings from Phase 1a, a set of experimental tests were designed to allow quantification of risk associated with background leakage, establishing what the consequence of leaking hydrogen will be for different scenarios with different leakage rates and potential sources of ignition when compared to natural gas. These experimental tests were undertaken in Phase 1b and further details of the results can be found in section 5.0 of this report.

The results from Phase 1b were evaluated and used to update and develop the QRA model to provide a hydrogen prediction model that can be utilised to assess the difference in safety risk.

After modifications were made to the QRA model with the benefit of access to the results of the Phase 1b experimental programme, and associated model development work, the analysis showed the following:

- → The risks from fires are lower for hydrogen than natural gas.
- → The risks from explosions are higher for hydrogen than natural gas.
- → Explosions are predicted to be a greater contributor to the societal risk than fires.

The overall risks from hydrogen could therefore be greater than those from natural gas, with greater explosion risks, partly offset by lower risks from fires and therefore further potential mitigation measures will need to be assessed.

The updated QRA model was used to assess the safety risk of the NGN current network in 2020 transporting natural gas, and the predicted network in 2032 transporting 100% hydrogen. The gas distribution network predicted to exist in 2032 was used in the risk calculations, as this is the year in which the Iron Mains Risk Replacement Programme is scheduled to be completed. It is expected that the Iron Mains Risk Replacement Programme will continue between 2020 and 2032, and that the composition of the network will change as a result, increasing the percentage of PE pipes within 30m of a property.

The model was then upscaled to provide a prediction for all of the GB distribution network. It is assumed that 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. Based upon the numbers of domestic services/meters for the NGN network vs the GB network, the Potential Loss of Life (PLL) values for the NGN network were scaled up by a factor of 11.05 to give the overall risk for the GB network.

The resulting societal risk, measured as Potential Loss of Life (PLL), estimates are shown in Figure 1.1, for the current network '2020 - Natural Gas', and the network in 2032 transporting 100% hydrogen '2032 - Hydrogen Planned Replacement'. The scope of this project also includes a review of potential mitigation measures that could be implemented to reduce the safety risk to an acceptable level. The graph in Figure 1.1 includes two possible mitigated hydrogen cases:

Option 1 - 2032 - Hydrogen, Additional Replacement – (refer to section 6.6.3.1) the completion of all currently planned replacement activities, plus the following:

- The LP metallic mains with diameters between 8 and 18 inches are reduced to 10% of their 2020 population.
- An additional 20% of the metallic mains in all other categories are replaced, not including IP mains.

Option 2 - 2032 - Hydrogen, All LP/MP Replaced – the completion of all planned replacement activities, plus replacement of all remaining metallic mains in the LP and MP pressure tiers (refer to section 6.6.3.1).

The PLL for the 2032 hydrogen case is 1.88 times greater than the PLL for the 2020 natural gas case, with around 83% of the hydrogen risk being associated with the metallic mains that are forecast to remain in the system based on current replacement plans. The risk mitigation measures considered demonstrate that it is possible to reduce the PLL associated with the whole distribution network further. This allows the hydrogen gas distribution network to be operated at the same or lower overall risk level as the current natural gas network, with credible and practical risk reduction measures.

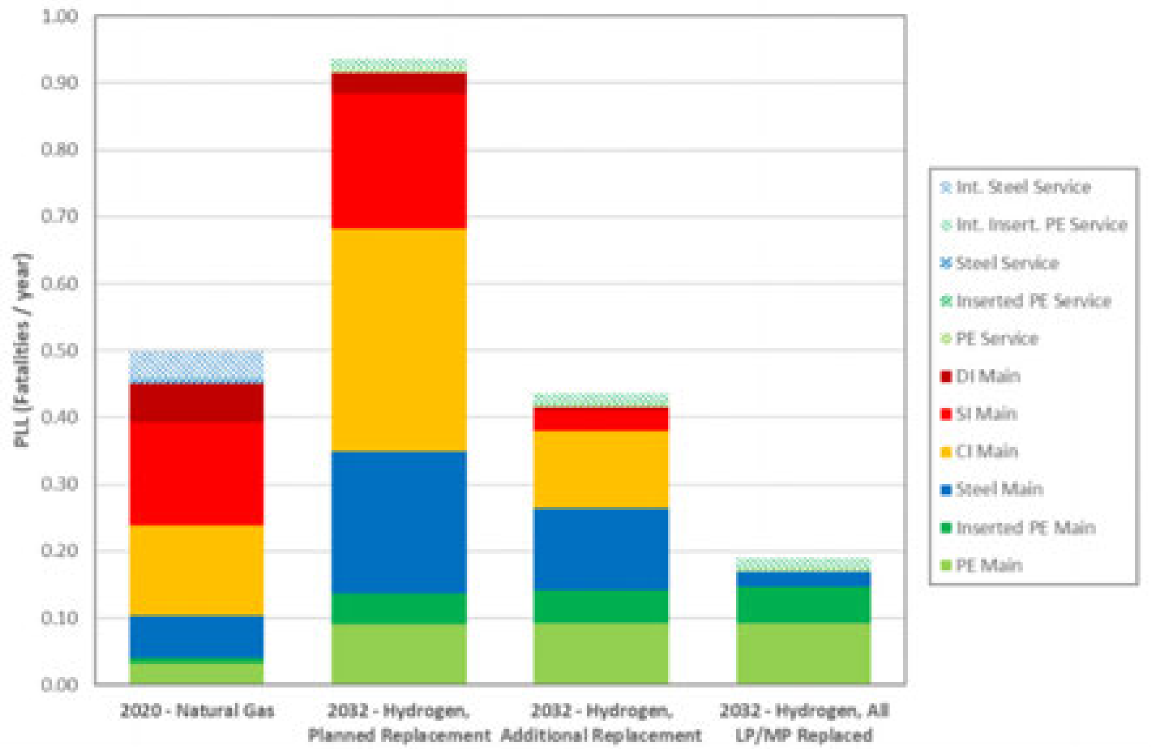


Figure. 1.1 Estimated PLL for the whole GB gas distribution network, showing detail of the two most relevant cases with two possible further mitigation options

Other potential mitigation measures were reviewed and are summarised below:

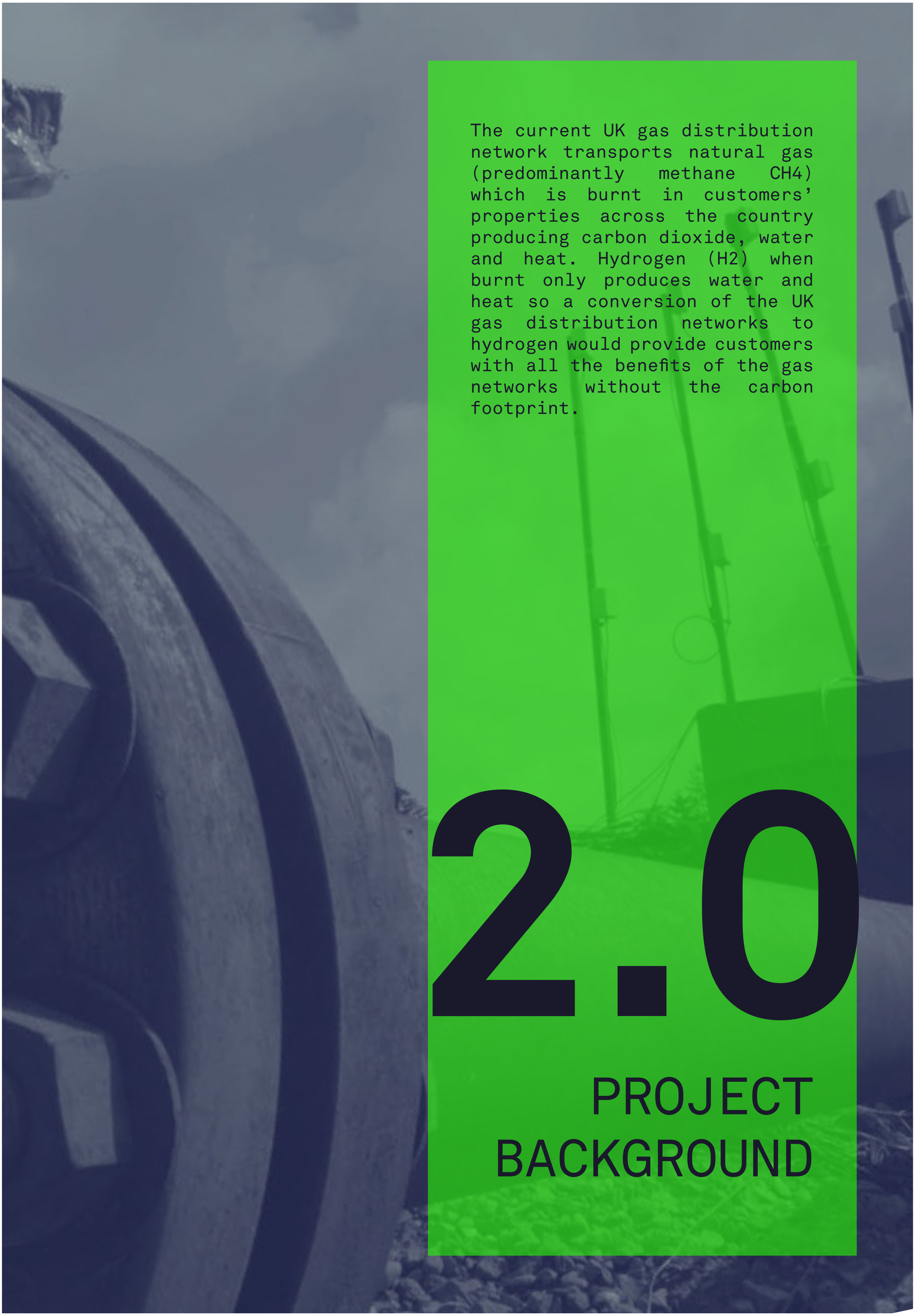
- Moving Internal Meters - Removing all internal services gives a PLL reduction of less than 0.01 fatality per year, or 1.6% of the base case total societal risk. However, this represents a 72.6% reduction in the risk associated with the services.
- Reducing the Pressure of Mains - Reducing the pressures at which some of the LP network operates gives a PLL reduction of less than 0.02 fatalities per year for the hydrogen network, or 3.9% of the base case value. Reducing the operating pressures of the MP network results in a PLL decrease of around 0.04 fatalities per year, or 10.3% of the base case value.
- Protective Measure - The reduction in PLL is 0.03 fatalities per year when all mains are protected, corresponding to a 7.2% reduction from the base case. However, the reduction in the PLL is less than 7×10^{-4} fatalities per year when only IP mains are protected, which is less than 0.6% of the base case. These reductions are small relative to other risk reduction measures.
- Fitting Excess Flow Valves - It is found that 97.8% of the 2032 hydrogen case PLL is due to releases from the mains, which are not affected by the excess flow valve. Hence, excess flow valves have a relatively small effect on the overall PLL, achieving a reduction of around 0.6%. Note that this analysis does not include any benefit from the mitigation of releases downstream of the ECV, where the risk reduction could be more significant.

Summary

These results show that the future hydrogen gas network can be delivered at no greater risk to the public than the natural gas network today. This depends on the completion of the ongoing Iron Mains Risk Reduction Programme, currently expected to conclude in 2032,alongside targeted additional mitigation measures for areas which are converting from natural gas to hydrogen.

Replacement of the remaining legacy LP and MP metallic mains and services pipes with PE pipes was the most effective measure to reduce the risk for hydrogen.This is consistent with the reduction in risk achieved by the ongoing replacement programmes and indicates that further replacement of some or all of the remaining population of metallic pipes would achieve the aim of ensuring that the risk to the public from a future hydrogen gas network is no greater than that for a natural gas network today. However, it should be noted that it is not necessary to replace every metallic main and service,and that targeted replacement could achieve this aim.

Other measures, although beneficial, had a smaller effect on the overall risks. However, these potential risk mitigation measures should still be considered as they could provide sufficient safety benefit to be implemented,independently of any metallic pipe replacement programme. The corresponding cost benefit analysis is outside the scope of this project.



The current UK gas distribution network transports natural gas (predominantly methane CH4) which is burnt in customers' properties across the country producing carbon dioxide, water and heat. Hydrogen (H2) when burnt only produces water and heat so a conversion of the UK gas distribution networks to hydrogen would provide customers with all the benefits of the gas networks without the carbon footprint.

2.0 PROJECT BACKGROUND

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The current UK gas distribution network transports natural gas (predominantly methane CH_4) which is burnt in customers' properties across the country producing carbon dioxide, water and heat. Hydrogen (H_2) when burnt only produces water and heat so a conversion of the UK gas distribution networks to hydrogen would provide customers with all the benefits of the gas networks without the carbon footprint. Converting the gas networks to 100% hydrogen has the potential to provide the biggest single contribution to decarbonisation in-line with the Net Zero 2050 target.

Almost half of the energy consumed in the UK is used to provide heat (760 TWh), of which around 57% of this heat (434 TWh) is used in meeting the space and water heating requirements of our homes. This means that decarbonising domestic buildings, many of which are connected to the gas grid, forms a key part of the challenge of reducing greenhouse gas emissions (Ofgem, 2016). In 2017, Great Britain's gas network heated over 85% of UK households, and provided 50% of the total energy demand for both industrial and services sectors. Excluding transport, natural gas provided more than 50% of total UK energy consumption in 2017 (Institute of Engineering and Technology, 2019).

The UK, as with most other countries around the world, recognises the challenge of climate change and has resolved, by 2050, to reduce carbon emissions by 100% of their level in 1990. In the UK, this is a legal obligation defined under the terms of the UK Climate Change Act 2008. The UK Government signed legislation on 27th June 2019, committing the UK to a legally binding target of Net Zero emissions by 2050. Climate change is one of the most significant technical, economic, social and business challenges facing the world today and, therefore, addressing this sector is pivotal to meeting the UK's 2050 Net Zero carbon emissions targets.

The safety-based evidence for a conversion to 100% hydrogen transported through the existing gas distribution networks needs to be addressed before the viability of the option can be confirmed. A credible government policy decision on decarbonisation of heat will not be possible without this critical information.

The H21 Leeds City Gate (H21 LCG) innovation project confirmed that a conversion of the UK gas distribution network to hydrogen is possible (NGN, 2016). Phase 1 of the H21 Project, funded by the Network Innovation Competition (NIC), was designed to build on the H21 LCG project by addressing some of the technical issues and is a collaborative bid involving NGN, SGN, Cadent and Wales & West Utilities.

The H21 LCG report (NGN, 2016) included a detailed roadmap of this outstanding evidence, further developed by Northern Gas Networks (NGN) 'Executing the H21 Roadmap' document. This document clearly sets out the steps required to de-risk a hydrogen for heat pathway including providing:

→ Quantifiable safety-based evidence in both the distribution networks and downstream of the meter (predominantly within buildings).

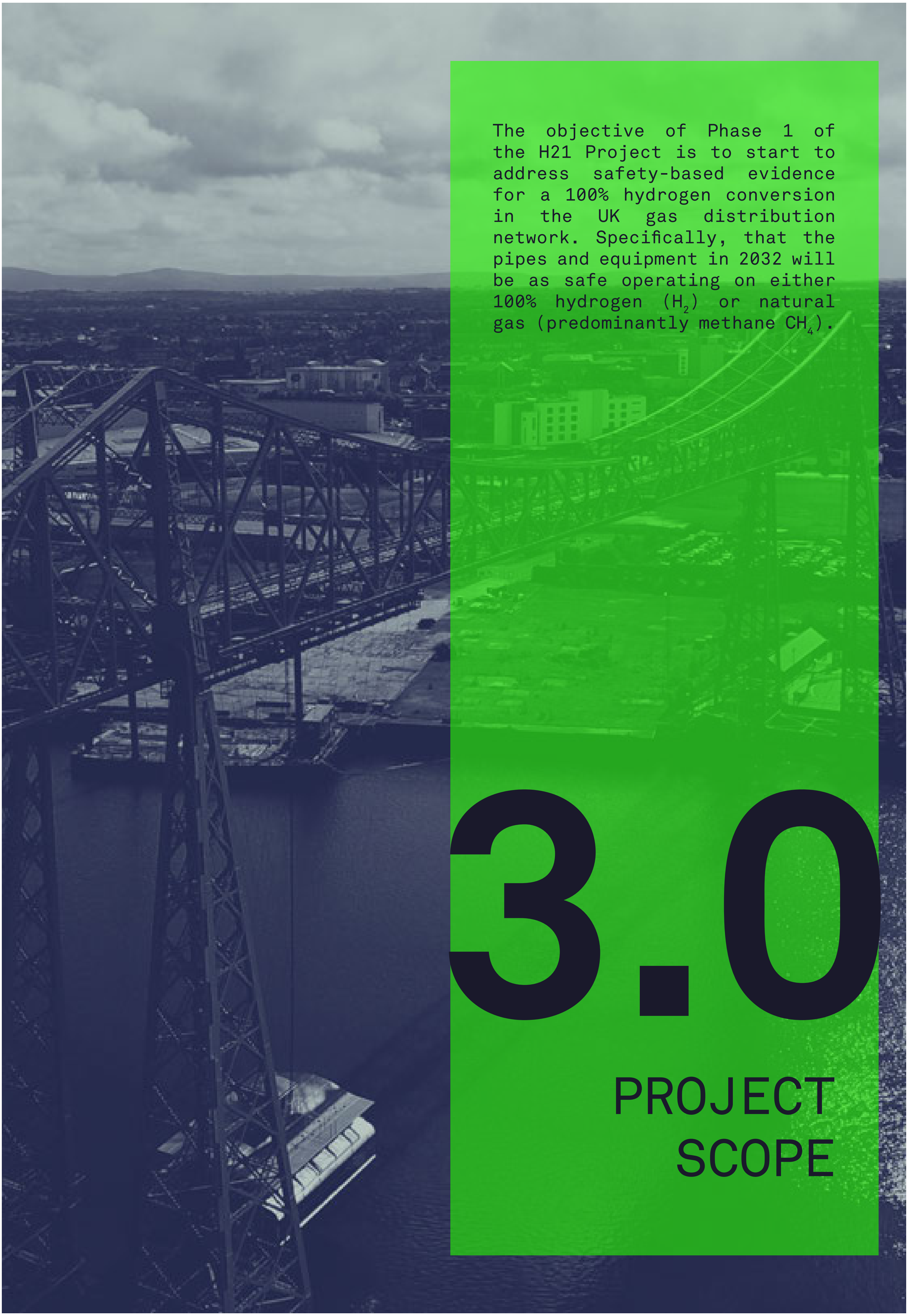
→ Live trials, to promote customer and GDN asset manager acceptability.

→ Front End Engineering Design to confirm the economics and strategic rollout for policy.

This is further reiterated by the recommendation by the Department of Business, Energy and Industrial Strategy (BEIS) as detailed in the Reducing UK Emissions: 2020 Progress Report to Parliament:

→ Develop a strategy for low-carbon hydrogen use (across power, industry, transport and buildings), production and infrastructure, aiming for large-scale hydrogen trials to begin in the early 2020s (Committee on Climate Change, 2020).

If the evidence for a gas grid conversion to 100% hydrogen can be provided, the benefits in terms of climate change obligations are enormous. However, timescales to provide this evidence are now critical to enable optimised policy decisions.



3.0 PROJECT SCOPE

The objective of Phase 1 of the H21 Project is to start to address safety-based evidence for a 100% hydrogen conversion in the UK gas distribution network. Specifically, that the pipes and equipment in 2032 will be as safe operating on either 100% hydrogen (H_2) or natural gas (predominantly methane CH_4).

3.1 PHASE 1a

Background testing

In 2032, at the end of the Iron Mains Risk Replacement Project (IMRP), the gas network will still be subject to leakage through its pipe and equipment. Understanding how this 'background' leakage level may alter when converting the gas network to 100% hydrogen is critical for three reasons:

- If changes cause a safety concern.
- If changes cause a commercial concern, i.e. there is no additional risk, but there is a commercial impact from increased lost gas.
- Any operational impact, e.g. a rapid increase in publicly reported gas escapes, which could be a safety and/or logistics problem which would also undermine public confidence.

A strategic set of tests was designed to cover the range of assets represented across the UK gas distribution networks. A cross-section of these assets were removed from the networks and transported to the Health & Safety Executive Science Division (HSE-SD) site at Buxton. Controlled testing against a well-defined master testing plan, with both natural gas and 100% hydrogen, was then undertaken. These tests provide the quantitative evidence to forecast any change to background leakage levels in a 100% hydrogen network.

The background testing involved removal of existing, in use network assets, building of a new testing facility at Buxton, testing the assets and quantification of results. These tests are essential to forecasting how the network may change (in terms of leakage) on day one following a 100% hydrogen conversion. In effect, does it leak more on 100% hydrogen and, if so, by how much and where? A change to this background position could have any combination of three consequences:

- A safety impact, determined and quantified through Phase 1b.
- A commercial impact, i.e. the cost of lost gas if leakage substantially increases.
- An operational impact, e.g. a rapid increase in publicly reported gas escapes which could be a safety and/or logistics problem, difficulty in making new connections and diverting mains.

The project team selected the assets to test based on a range of criteria including:

- Current pipe risk assessment criteria: Consideration of the metallic mains population in 2032 and the associated risk score based on the existing risk scoring methodology used for the IMRP. This methodology, certified by the HSE, enables an understanding of which of the remaining metallic mains populations represent the highest risk.
- Historical leakage data for different assets, particularly joints.
- Operational experience, drawing on engineering staff to identify assets to be tested and also cross-checked with similar input from Cadent.
- Potential to extrapolate the results, selecting an appropriate range of tests that will provide data which can be extrapolated across all assets whilst keeping tests to a minimum.

To ensure wide consensus on tests across all project partners, a three-phase approach was adopted. Firstly, the GDNs identified the range of assets they would recommend for testing based on the criteria above. Secondly DNV GL reviewed the recommendations, using their historical background data to confirm agreement. Finally, the HSE SD reviewed the recommendations and confirmed acceptability to meet the project objectives.

The tests included a baseline test on natural gas followed by a test on 100% hydrogen to quantify any difference. The results of these tests were used to confirm assumptions against the master test plan for Phase 1b to ensure that the range of consequence tests covers the background leakage position.

3.2 PHASE 1b
Consequence testing

A strategic set of tests was designed to allow quantification of risk associated with background leakage including the following areas of testing:

- → Small Release Testing
- → Large Release Testing
- → Ignition Potentials
- → Explosion Severity Testing
- → Operational Safety Testing

This required establishing what the consequence of leaking hydrogen will be for different scenarios with different leakage rates and potential sources of ignition when compared to natural gas.

The H21 NIC project partners agreed to conduct the consequence testing at Spadeadam to make efficient use of resources whilst allowing the HSE SD to bring important oversight as an independent expert organisation intrinsically linked to the health and safety regulator. The master testing plan was developed based on decades of gas industry experience in destructive/consequence testing, drawing extensively on the unique expertise and extensive background experience that DNV GL supply.

The tests at Spadeadam involved development of new testing areas and utilisation of existing testing facilities. Tests were undertaken to confirm the ground and air concentration levels associated with a range of hydrogen leaks and to quantify the consequences of those leaks, e.g. ignition potential, explosion severity and operational safety.

The tests examined three critical areas to be subsequently used in the quantitative risk analysis:

Ground and air concentration testing: Confirming how hydrogen dissipates in the air and in the ground from network assets (both above and below ground) compared to natural gas. These tests were undertaken by installing gas mains in trenches and then undertaking various tests. This verified the associated concentrations of hydrogen in the ground (including ductwork) and air for different types of backfill and cover (concrete, open ground, tarmac etc.) and at different distribution pressure tiers.

Background consequence testing: Having understood how hydrogen is likely to migrate, the consequence of such migrations needed to be determined, i.e. how leaking hydrogen could ignite and/or explode when exposed to a range of background ignition sources; for example, engines, cigarettes, tools creating sparks under operational repair activities etc. The results of these tests were then contrasted against the known results for natural gas, to update the quantitative risk assessment.

Operational testing: A 100% hydrogen network will still have background leaks which will need to be repaired and operational activities undertaken e.g. purging. Initial understanding of whether the network can be managed/repaired using key working practices is critical to quantifying the risk and progressing to further network operation testing and field trials.

Phase 1b was therefore broken down into the following five work packages:

- → WBS1 Small release testing – to observe the dispersion of hydrogen through a variety of soil and building materials
- → WBS2 Large release testing – to measure consequences where the breaking of ground surface is likely
- → WBS3 Ignition potential – a converted ignition chamber for natural gas will measure consequences of hydrogen ignition
- → WBS4 Explosion severity testing – decommissioned kiosks will help compare the point at which hydrogen becomes more reactive than natural gas
- → WBS5 Operational safety testing – demonstrating key operational activities, e.g. purging and repair of leaks.

3.3 Quantitative Risk Assessment

The overriding objective of the project is to begin to fill critical safety evidence gaps surrounding the conversion of the UK gas network to 100% hydrogen. As part of this objective, a comparative Quantitative Risk Assessment (QRA) was required which can be used to evaluate the difference in safety risk to the public associated with supplying 100% hydrogen versus natural gas.

The QRA reflects both the layout of NGN's existing distribution network and the hazard assessment findings from this phase of testing and the full-scale field trials to be conducted in future phases of this project. The risks assessed cover the network upstream of the meter only, i.e. the network up to the Emergency Control Valve (ECV). Furthermore, an evaluation was made of the risk posed by a 100% hydrogen gas network against a range of other options, to put the overall risks into context as well as comparing risk levels with other external factors faced by the public day-to-day.

The QRA is the process of obtaining a numerical estimate of risk by quantitatively estimating the likelihood of occurrence of specific undesirable events (the realisation of identified hazards) and the severity of the harm or damage caused, together with a value judgement concerning the significance of the results. The process of carrying out a QRA study for the supply of 100% hydrogen through the distribution network results in an improved understanding of the level and significance of risks compared against those associated with the current supply of natural gas. This will inform decisions regarding the suitability of the network for hydrogen use and also provides important information relating to the implementation of appropriate risk control and reduction measures.

The QRA addresses the safety risks to the public (100% hydrogen versus natural gas) from leakage resulting from both normal operation of the network (e.g. component leakage) and third-party accidental interference (e.g. impact during construction work). The QRA required the existing natural gas distribution QRA model to be modified first, to enable the necessary calculations to be performed for hydrogen and was performed in stages to include:

Part A: Information gathering

→ Literature review to identify existing knowledge to modify natural gas QRA model for hydrogen.

→ Identification of hazards and scenarios pertinent to hydrogen transportation highlighting key differences from natural gas.

Part B: Developing a preliminary QRA model for hydrogen and gap analysis

Evaluation of modules and logic in natural gas QRA model to specify where changes may be required to reflect hydrogen service, including:

→ Failure mode and frequency for pipelines and components.

→ Gas release rate calculation (in-ground gas releases and releases direct to atmosphere).

For gas releases direct to atmosphere – extent of gas dispersion in the atmosphere, probability of ignition (immediate or delayed) and fire hazards.

For in-ground releases – extent of gas migration through the ground under different conditions, potential for gas ingress into buildings, build-up to flammable concentrations, detectability, ignition (immediate or delayed) and explosion hazards and their potential effects, potential for distributed fires due to gas migration to the surface.

→ The possibility of explosion hazards arising from unconfined hydrogen releases or releases into confined or congested regions of above-ground installations will also be considered for possible inclusion in the model.

→ Modify existing QRA models and logic for hydrogen using existing knowledge or judgement.

Part C: Preliminary risk analysis and risk evaluation

- Definition of network parameters for the QRA, including pressures, pipeline sizes, proximities, etc., based on NGN's network.
- Estimation of risk (combining likelihood and consequences), applying judgement and cautious assumptions to identify the key areas of sensitivity and uncertainty that impact on risk.
- Preliminary evaluation of significance of initial risk results (comparison of hydrogen versus natural gas, comparison against risk tolerability criteria, evaluation of risk reduction options, etc.).
- Specification of experiments and model development required to address key uncertainties.

Part D: Refine QRA model and risk results for hydrogen and consider mitigation options

- Evaluation of data from Phase 1a and 1b and validation/modification of hydrogen QRA models and methodology as appropriate in light of the results.
- Revised estimation of risk (combining likelihood and consequences), using the newly developed hydrogen QRA methodology and evaluate significance of risk results (comparison of hydrogen versus natural gas and risk tolerability criteria).
- Identify options and effectiveness of measures for risk reduction in light of the refined results.

Part E: Application of QRA results, risk reductions and mitigations

- Survey of GDNs to establish the appropriate network parameters to allow the risk results for NGN's network area to be extrapolated across the whole of the UK gas distribution networks.
- Estimation of societal risk for the whole of the UK gas distribution networks for both natural gas and 100% hydrogen (with mitigation options applied if required) for direct comparison.

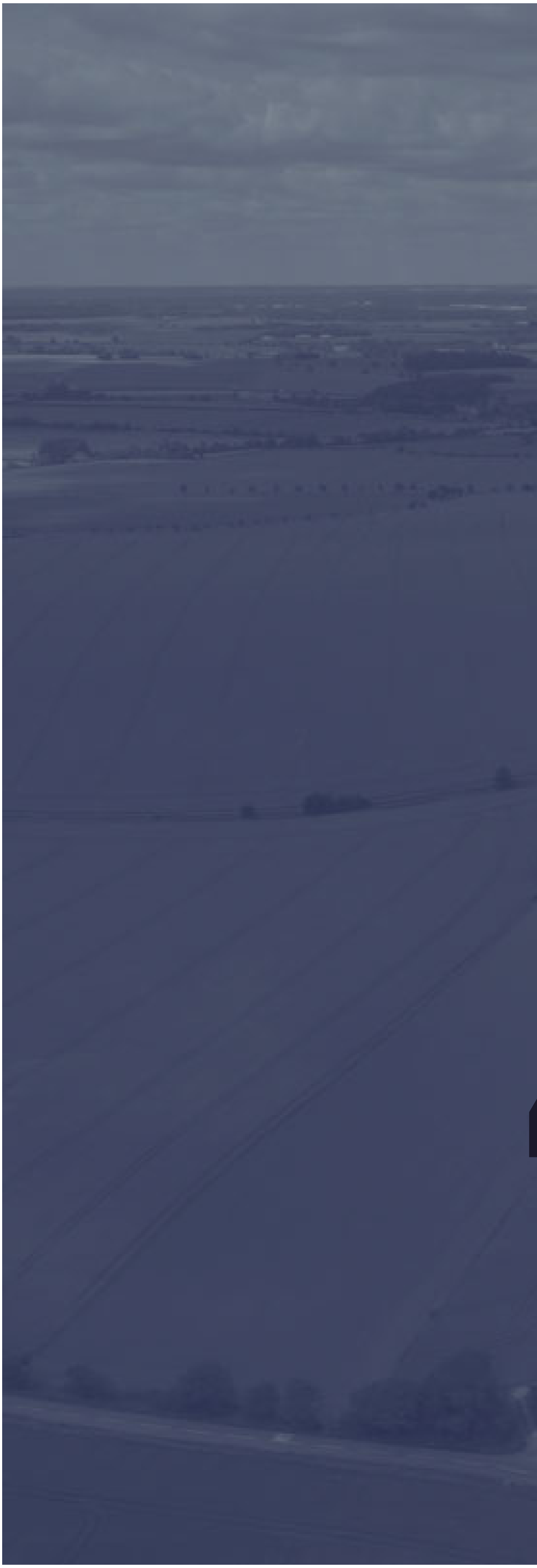
3.4
Social Science

Currently there is considerable uncertainty about how communities and individuals would respond to the prospect of using 100% hydrogen in the UK gas distribution network and potentially in their homes, businesses and vehicles, what barriers may exist and what perceptions of hydrogen may already be in place. Furthermore, a great deal hinges on how the core practices of cooking, heating and mobility would respond to the introduction of hydrogen as a replacement for current fuels.

Despite hydrogen holding great potential, public perceptions of hydrogen are currently only guessed at by the research and industry community. It is also well established in research and applied contexts that public engagement with new technologies can be a complex process in which outcomes are not always predictable. This is amplified yet further where there are perceived to be possible risks to safety and where long-held norms about the 'look and feel' of the materials of daily life are being challenged – both of which may be true of hydrogen. If hydrogen is to play a role in the UK future energy system, then the ways in which members of the public understand it and how these perceptions affect its integration into everyday activities need to be determined.

As part of the H21 NIC a programme of social science research was funded to ensure that some of these issues were confronted and new knowledge generated. This programme of work aimed to:

- Generate insight into baseline public perceptions of the safety of hydrogen and other energy technologies/vectors, including how they vary by a range of sociodemographic and geographic variables.
- Generate insight into how people respond to the possibility of using 100% hydrogen in the three key, gas-fuelled social practices (heating, cooking, travelling), including how they vary by a range of socio-demographic and geographic variables.
- Understand how public perception of the safety of hydrogen evolves across the range of socio-demographic and geographic variables when considering the H21 NIC evidence.
- Build a hydrogen research network of social scientists across the UK who may then become involved in the delivery of the proposed research activity or who may play advisory roles in the development of a body of research, data and expertise around the opportunities and challenges of hydrogen.



The following section contains information collated from the HSE SD report and DNV GL reports listed in section 10.0 References.

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4.0

PHASE 1A BACKGROUND TESTING

4.0 Introduction

Phase 1a included a strategic set of tests that cover the range of assets and pipe configurations representative across the UK. A cross-section of these assets was removed from the network and transported to the HSE Science and Research centre at Buxton. Controlled testing with 100% hydrogen was undertaken and then if the asset leaked, the test was repeated with methane, CH_4 (prominent compound found in natural gas).

The Phase 1a tests involved measuring the leakage rates of typical gas network assets at a range of pressures up to and including 7 barg with both methane and then hydrogen. These tests were to assess whether certain assets leak hydrogen more or less than methane, and to quantify the difference in leakage rates of the two gases. The tests were all conducted above ground, in the open air, and flow meters, soap tests and gas detection were utilised to identify leak sources. It should be noted that the majority of the assets tested were decommissioned assets previously used in the network and therefore it was not known whether they leaked until the testing was undertaken.

This project focused on assets that will be in service in 2032, when it is estimated that around 90% of the gas distribution network will be polyethylene. However, some retained iron and steel mains will still be in service at that time, and this project will examine these. Furthermore, there will be a range of transition fittings (between PE, iron, steel with different diameters etc.), services, service connections, buried valves, repairs, service governors and district governors, that require further investigation.

The scope of the Phase 1a testing encompassed Low Pressure (LP, 19–75 mbar), Medium Pressure (MP, 75 mbar–2 bar) and Intermediate Pressure (IP, 2–7 bar) assets from Tier 1 (≤ 8”), Tier 2 (8”–18”) and Tier 3 (≥18”) from the UK natural gas network. Assets used in the testing were mostly recovered from the network as part of the ongoing Iron Mains Risk Reduction Programme (IMRRP).

The majority of assets were retrieved through the Iron Mains Risk Reduction Programme (IMRRP) and so the assets were more likely to be older compared to an average asset in the network. Therefore, there is a possibility that the recovered assets would have a higher likelihood of leaking, but they are representative of the types of assets in the current network.

4.1 Objectives

The objective of the background testing was to measure leakage rates of methane and hydrogen from a range of assets and pipe configurations that are representative of the UK gas network from 2032 onwards, to help quantify the risks presented by a 100% hydrogen network in comparison to the natural gas network.

The rate at which gas leaks from assets in the network is controlled by four main factors:

- Gas properties (density, viscosity etc.)
- Pressure of the gas within the asset, relative to the atmospheric pressure
- Characteristics of the leak in the asset (hole size, shape, crack length etc.)
- Resistance to penetration of the gas through the ground surrounding buried assets

The Phase 1a background testing addressed the first three of these four factors, while factor four was covered in the Phase 1b consequence testing programme.

The primary interest of this project is the ratio of the hydrogen leak rate to the methane leak rate; not the absolute leak rate. The outcome of the phase was judged to either show a consistent ratio of the hydrogen to methane leakage rates across different types of assets, or that the ratio of hydrogen to methane leak rates is a complex function of several factors (e.g. the aspect ratio of the crack or defect, the leakage path length).

The Phase 1a project did not consider:

- Leakage rates of hydrogen and/or natural gas when the asset is buried
- Leakage rates from tools and fixtures that are used for repairing assets or attaching services, which do not remain in continuous service in the gas network (e.g. WASK drilling machine and syphons)
- The safety of gas network construction/repair procedures using either natural gas or hydrogen.

Item 1 is covered under Phase 1b, items 2 and 3 will be covered under the H21 NIC Phase 2 Network Operations project.

4.2 Predictions

Leaks of gas from pressurised pipelines and vessels can occur in several different flow regimes. The regimes analysed in this project are listed below in order of decreasing pressure:

- → **Choked flow velocity** of the gas at the orifice is sonic (i.e. at Mach 1). The upstream pressure must be above the critical pressure (0.85 barg for methane or 0.91 barg for hydrogen) to have choked flow. Downstream of the orifice, the gas expands as the pressure in the flow falls to atmospheric pressure, and the flow is turbulent.
- → **Subsonic flow (compressible)** – high flow through the orifice is subsonic and not choked. The upstream pressure is below the critical pressure, gas compressibility effects can be important, and the flow is turbulent.
- → **Turbulent flow (incompressible)** – at lower pressures, gas compressibility effects become insignificant, but the flow is still turbulent, with rapid chaotic fluctuations in pressure and velocity that enhance mixing within the flow.
- → **Laminar flow** – at low pressures through small holes (where the velocity is low and the Reynolds number is typically below 2,000), the flow becomes laminar, with smooth flow paths and little or no mixing within the flow.

By analysing equations for flow through a hole, ratios for the flow rate of hydrogen compared to methane can be obtained for each regime. The H21 rig measured volumetric leak rates of gas, and therefore the volumetric flows of the two gases are compared here, rather than mass flows.

The results of the predicted ratio analysis are summarised in Table 4.1, which shows that choked, subsonic and turbulent leaks behave similarly in terms of the change in behaviour of hydrogen relative to methane. In these three cases, the hydrogen mass flow rate is roughly a third of the methane flow rate for the same leak geometry and pressure. Methane is eight times denser than hydrogen, so in volumetric terms, the hydrogen flow rate is roughly three times greater than methane. The energy density per unit volume for hydrogen is just under a third of the energy density for methane; therefore, in terms of energy flow rates, the same leak geometry and pressure produces a hydrogen energy flow rate that is around 10% lower than the methane energy flow rate.

Laminar leaks behave differently, with less hydrogen being released (relative to methane) than for the turbulent, subsonic or choked releases. In the laminar case, the hydrogen mass flow is reduced by around a factor of six, the volumetric flow rate is just 20% higher for hydrogen than methane, and the energy flow rate is reduced by around 60% when switching from methane to hydrogen.

Table. 4.1

Ratio of volumetric flow rates	
Choked*	2.9
Subsonic†	2.9
Turbulent	2.8
Laminar	1.2

* Applies for leak pressures above the critical pressure, i.e. P > 0.9 barg

† Applies for leak pressures below the critical pressure, i.e. P < 0.9 barg

The calculations presented here all assume that the pressure is maintained at a constant value over time. If there is a large leak in a pipeline, the pressure at the leak point decays over time as the pipeline unpacks.

Therefore, it is predicted that the ratio of volumetric flow of hydrogen to methane will lie between 1.2 and 2.9.

4.3
Leak Definition

Different leak rates are defined to be “acceptable” depending on the situation and the industry code of practice. When assets are being installed or repaired, any recorded leaks must be less than the Maximum Permissible Leak Rate (MPLR), a value that varies depending on the location of the installation.

IGEM technical gas standard IGEM/TD/3 Section A3.3, states that a standard figure used in the UK for a pass criterion is 0.003 m3/h std (50 ccn/min), which, converted to a flow rate for hydrogen gives 0.009 m3/h std (150 ccn/min).

The lower limit of the flow meters was taken to be 100 ccn/min, since below this, the flow was unsteady. Therefore, the value of 100 ccn/min was chosen as the lower limit of a leak and all measured leak rates above 100 ccn/min are documented in this report.

N_2

H_2

CH_4

4.4
Method

The scope of the Phase 1a experiments encompassed Low, Medium and Intermediate Pressure (LP, MP and IP) assets from Tiers 1, 2 and 3 in the UK natural gas network from 2032 onwards. This included a wide range of asset types (joints, valves, governors etc.), composed of various different materials. The aim of these tests was to provide good coverage of the potential range of assets and conditions, and to maximise the benefit of a limited number of tests.

4.4.1 Buxton Test Facility

A purpose-built test facility was constructed at the HSE Science and Research Centre in Buxton. The facility had three gas banks (hydrogen, methane and nitrogen) which fed into four test bays. The majority of assets were installed using end sealed couplings connected to the bay hoses. The tests were then conducted and logged from a control room on a semi-automated system.

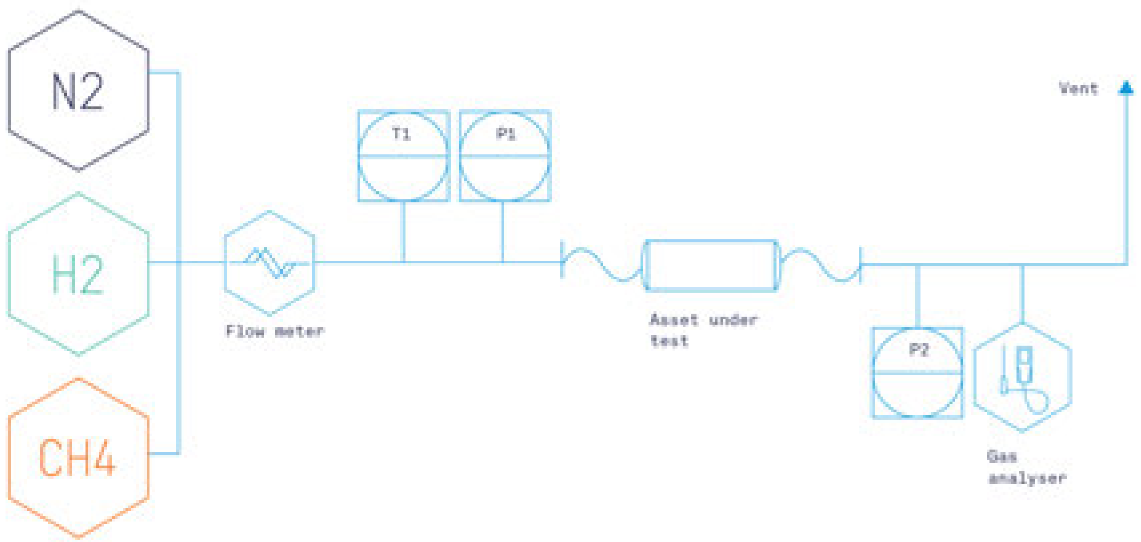


Figure. 4.1 Simple diagram of the experiment set up (T1, Temperature Sensor, P1 & P2 Pressure sensors)

A key principle of the Phase 1a tests was that assets should not be tested beyond the range of pressures that they would encounter in service. This limit was imposed to prevent over pressurisation of pipework in the test area to protect operators and test equipment.

During each test, the following data was collected for analysis; further discussion on the key recording methods is provided in the proceeding sub-sections:

- → Measured ambient temperature and atmospheric pressure
- → Measured pressure at the asset inlet and outlet
- → Measured leakage rate for range of pressures (hydrogen, methane)
- → Photo of leaks using leak detection fluid (soap tests)
- → Hydrogen concentration in air around the asset was checked using a portable hydrogen gas monitor to assess leaks
- → Details of any repair attempted on asset
- → Photograph of asset.

It was important to understand how leakage rate varies as a function of pressure with hydrogen. Prior to the testing it was unclear whether the relationship between leakage rate and pressure would be linear or non-linear. It was therefore proposed to test five separate pressures for each asset spanning the range of operating conditions. These were:

- **Low Pressure (LP):** 20, 30, 45, 60 and 75 mbar
- **Medium Pressure (MP):** 30 mbar, 75 mbar, 350 mbar, 1 bar, 2 bar
- **Intermediate Pressure (IP):** 30 mbar, 350 mbar, 2 bar, 5 bar, 7 bar

Tests were performed starting with the lowest pressure and working upwards in the five steps. This was important from a safety perspective in that, if the assets leaked significantly at low pressures, the tests were aborted and the asset was not tested at higher pressures. The second reason for this staged approach was that there was potential for high pressures to open up cracks or other defects in the assets. Starting from a low pressure and working upwards in steps was intended to prevent any further damage to defects.

4.4.2 Flow Meter Measurements

The method of measuring leakage on the H21 test rig was to measure the flow required to maintain the asset at a constant pressure. To measure the flow of gas, Bronkhorst F-111BX intrinsically safe mass flow meters were used, operated using a thermal mass flow measuring principle. Two flow ranges were utilised to allow for a greater range of leaks to be measured. On Bays 1 & 2, a lower flow range of 70 –3,500 ccn/min of hydrogen was employed and on Bays 3 & 4, a higher flow range of 400 –20,000 ccn/min of hydrogen was chosen.

The unit of ccn/min was used by the flow meter manufacturer and has therefore been used as the main unit in this report. The unit of ccn/min refers to cubic centimetres at a temperature of 0°C and at standard atmospheric pressure (1013.25 mbar).

4.4.3 Test Process

The test rig had two gas supply lines: a coarse fill and a fine fill. The coarse fill was used to quickly fill IP assets and reach a pressure set point, which was chosen to be 98% of the test pressure. The fine fill then filled the final 2% pressurisation to the set pressure. LP and MP assets were filled using the fine fill only.

The semi-automated test procedure incremented through the set point pressures (from 20 mbar through to 75 mbar for LP assets) and allowed the operator time to analyse the leak (e.g. conduct a soap test or inspect the asset) at each pressure increment, or when swapping over between hydrogen and methane.

It was assumed that if the asset is gas-tight for hydrogen, it will also be gas-tight for methane. The test procedure therefore stepped up the pressure increments with hydrogen. Only if a leak was detected with hydrogen (and the leakage rate measured for hydrogen) would the assets be switched over to methane tests.

When testing an LP asset, all the hydrogen pressure tests were completed before all methane tests, as the asset had already been pressurised to 50 mbar during the nitrogen purging process. For MP and IP assets, the test gas had to be switched over between each test pressure to prevent the leak being enlarged through the hydrogen tests at higher pressures, which would result in an increased leakage rate on methane tests. This approach saved time and effort by only testing assets with methane when a leak had been first detected with hydrogen. In most cases, assets did not leak and the test pressure was incremented from the lowest to the highest values (from 20 mbar to 75 mbar for LP assets) with only hydrogen, and without any methane tests.

4.4.4 Leak Locating – Soap Tests

Soap tests were conducted at the lowest set point pressures for each pressure regime (e.g. 20 mbar for LP assets 30 mbar for MP and IP assets) to detect any leaks. In some cases, the leaks on assets were so small that they went undetected by the flow meter at low pressures. It was useful to record the position of these small leaks at this pressure to understand the asset's behaviour at higher pressures, e.g. if new leaks presented themselves at higher pressures, or if the same leaks increased in leakage rate.

As the set point pressure was increased (e.g. from 20 to 30, 45, 60 and 75 mbar for LP assets), when the flow meter first detected a leak, the operator conducted another soap test to identify where the asset was leaking. The soap tests were also repeated with methane, where suitable, to examine any differences between the soap bubbles for hydrogen and methane. The bubbles showed no noticeable differences. At the final, highest, set point pressure, another soap test was undertaken to assess whether new leaks had opened up with the pressure increase, and to check for any other undetected small leaks.

In addition to the soap tests, a hydrogen gas detector was used to identify the location of any leaks, allowing leak detection fluid to be applied more accurately.

4.4.5 Temperature Recording

Temperature was recorded during the experiments using a suitable temperature sensor on the assets as it was believed that a change in temperature e.g. tests carried out during the day, would have an effect on the flow rate and any necessary adjustments may have to be made in the analysis.

4.4.6 Identifying Leaks

When a leak was identified, it was first analysed to determine its source. If the leak was from fittings that had been attached after the asset had been retrieved, then these fittings were made gas tight so that the test could be performed on the retrieved asset. Any leakage data from a test where the leak was deemed not to be associated with the retrieved asset itself was discarded from the subsequent analysis.

Where a leak was confirmed to be coming from the retrieved asset and the leak was in the measurable range of 100–20,000 ccn/min (flow meter range constraint), it was recorded and used in the subsequent hydrogen-to-methane ratio analysis.

Checks were made on leaking assets using a hydrogen detector and leak detection fluid to ensure that the asset was not leaking from fittings associated with the asset (i.e. end caps or emid plugs installed following asset extraction). Once a leak was confirmed as coming from the asset itself, i.e., is a representative leak which would be present on the existing network, then the leakage rate was recorded at various pressures on both hydrogen and methane. This then allowed for the leakage flow rates to be compared and a ratio obtained.

In all but one case, leakage rates were measured from actual leaks on assets, rather than using engineered orifices, to study the behaviour of realistic orifice geometry. The exception was IP asset AST12345. Since no leaking IP assets were retrieved for testing, an engineered leak was created by drilling a 0.7 mm diameter hole in this asset.

When an asset was found to be leaking, a decision was made if any of the repairs scheduled in the master test plan could be performed on the leak. Ideally, leaking assets suitable for repair would only have one leak source. More than one leak source could result in the repair failing to lower the leakage sufficiently to be counted as a successful repair.

Once the repair was complete, the asset was tested again to ensure that the repair was successful at stopping a hydrogen leak. If it leaked, it was then tested on methane to determine if the repair was unsuccessful on both gases, or just on hydrogen.

For a leaking asset, the flow rates were obtained for each pressure on both gases. Figure 4.2 provides an example of a typical 120 second test recording of a leak at a set pressure.

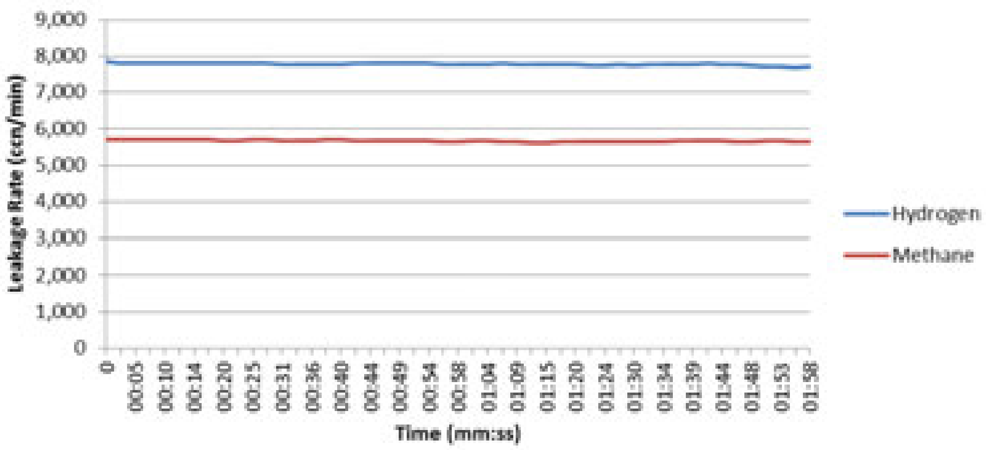


Figure. 4.2 Graph showing the measured leakage rates for AST00097, an example asset

This data was collated for each pressure, for example, in the LP range this would consist of graphs at 20, 30, 45, 60 and 75 mbar. For each set of data, a ratio could be obtained by averaging the flow for the two-minute test period and then dividing the leakage rate for hydrogen by the leakage for methane. These ratios are presented graphically in Figure 4.3 and Figure 4.4.

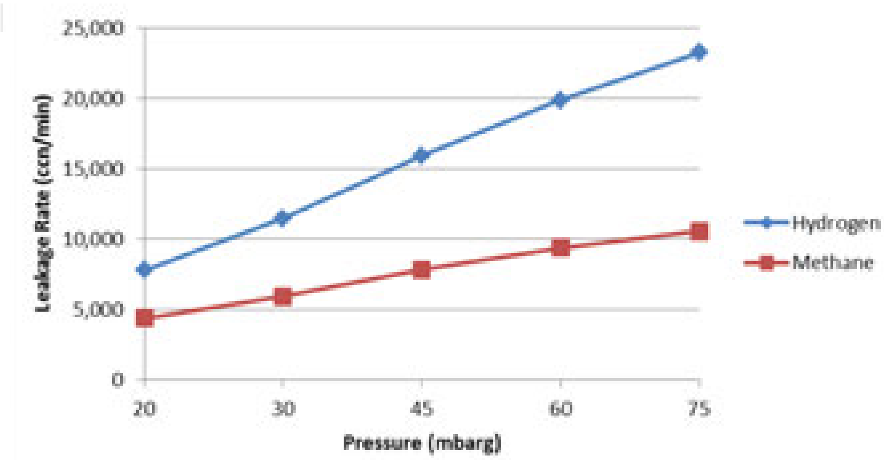


Figure. 4.3 Graph showing the average leakage rates over the pressure ranges for hydrogen (blue line) and methane (red line) for AST00097

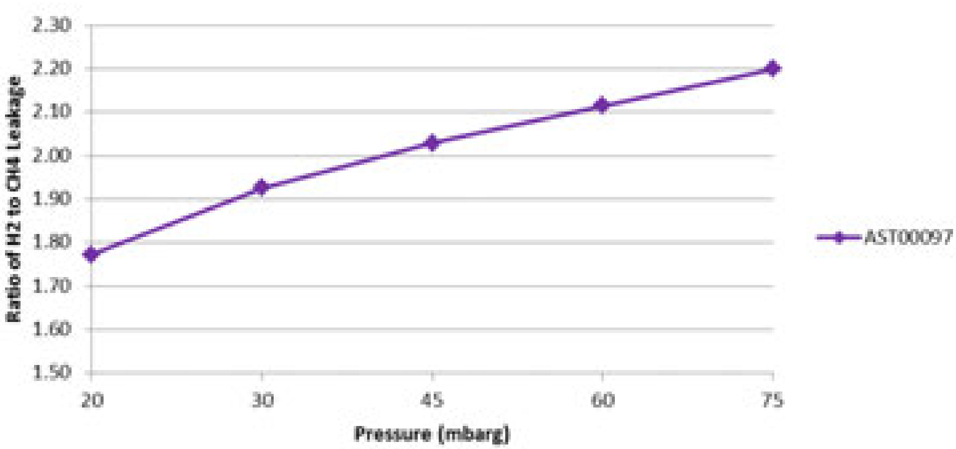


Figure. 4.4 Graph showing the ratios of leakage for the range of low pressures on AST00097

4.5 Results

215 assets were suitable for testing on the experimental rig, of which 41 leaked at a rate greater than 100 ccn/min.

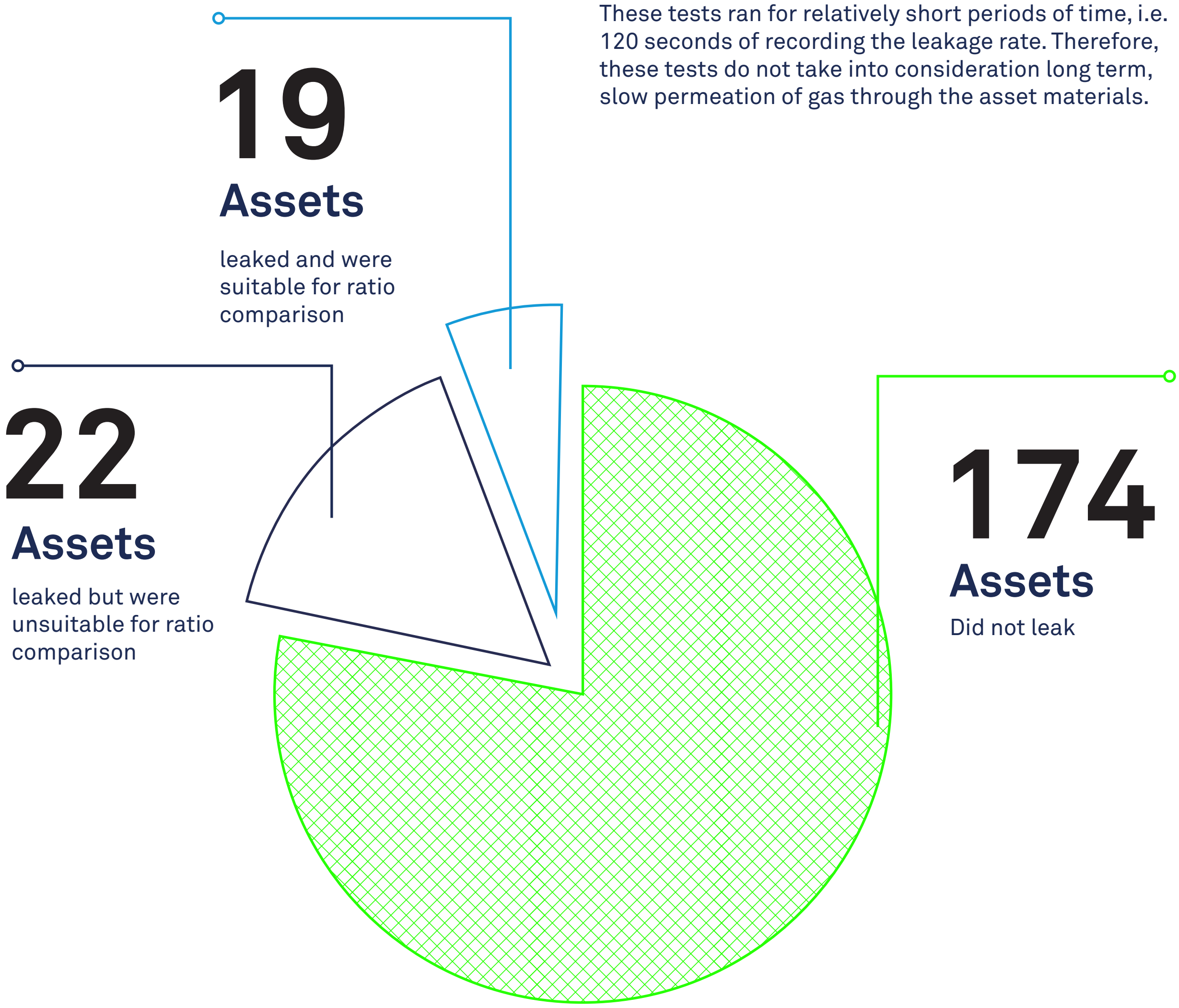
Of the 41 assets that leaked, all leaked on both hydrogen and methane, with 19 of these providing suitable data to allow a ratio comparison between hydrogen and methane. The 19 assets include asset AST 12345, a piece of PE pipe, with a leak induced by drilling a hole in the asset.

The other 22 assets which leaked were unsuitable for ratio comparison as their leaks were not within the measurable range of the rig (100-20,000 ccn/min), or the leaks were not stable.

The results show that the hydrogen flow rates are greater than methane flow rates (for the same pressure), and the ratio of the two flow rates falls within the expected upper and lower bounds of turbulent and laminar flow. Generally, the trend is for the ratio of hydrogen to methane flow rates to increase from the laminar value of 1.2 at low pressures, towards the turbulent (or inertial) value of 2.8 at higher pressures. This is consistent with the flow speed increasing with pressure and the tendency for inertial or turbulent effects to have a greater influence on the flow behaviour.

The 174 assets which did not leak provide evidence that supports the finding that if an asset is not leaking on methane, it will not leak on hydrogen.

These tests ran for relatively short periods of time, i.e. 120 seconds of recording the leakage rate. Therefore, these tests do not take into consideration long term, slow permeation of gas through the asset materials.



4.6
Leaking Asset Analysis

Table 4.2 below lists the 19 leaking assets which provided suitable flow data to be analysed in detail in this report including one asset, AST 12345, that was drilled to create a leak in a section of PE pipe.

Key: SI = Spun Iron, CI = Cast Iron, DI = Ductile Iron, ST= Steel

Asset No.	Test Type	Additional Fittings Present	Date Installed/ Laid	Diameter (inch)	Material (see key)	Pressure Regime	Joint Type
AST00009	Main	n/a	Unknown	12	SI	LP	Bolted
AST00011	Main		Unknown	10	CI	LP	Lead Yarn
AST00013	Main	n/a	1968	4	SI	LP	Bolted
AST00014	Fitting	2 Part UPT	Unknown	12	SI	LP	Bolted
AST00026	Main	2x2” Emid Plug	1947	12	DI	LP	Bolted
AST00035	Main	Valve	1973	6	DI	LP	Bolted
AST00061	Main	n/a	1990	2.4	CI	LP	Hook Bolt
AST00069	Main	2x Lead joints	Unknown	18	CI	LP	Flanged
AST00088	Main	1x Emid plug	1955	4	SI	LP	Screw Gland
AST00097	Main	Equal tee	1956	6	SI	LP	Hook Bolt
AST00099	Main	n/a	1950	10	SI	LP	Hook Bolt
AST00102	Main	n/a	1964	12	SI	LP	Holt Bolt
AST00113	Main	3x1” Emid Plug	1956	4	SI	LP	Hook Bolt
AST00125	Main	2x3” None tap plug	1920	18	CI	LP	Lead
AST00129	Main	n/a	1970	12	SI	MP	Hook Bolt
AST00160	Main	1x Muffed Endcap 3x Emid	1959	8	CI	LP	Lead Yarn
AST00180	District gov	Donkin 270 regulators, 3”donkin 555 Valve & 2” Orseal valve. includes filters slam shut and relief valves	Unknown	2 - inlet 3 - outlet	ST	IP	Bolted
AST00210	Repair	Hook Bolts	1950	10	SI	LP	Hooked Bolt
AST12345	Main	Leak created by drilling a hole in AST00106	2020	4.9	PE	IP	Electro-fusion

Table. 4.2 Summary of leaking assets

Figure 4.5 and Figure 4.6 below present the ratios measured for the LP, MP and IP assets. The two horizontal lines on the graph are the predicted ratios of laminar and turbulent flows. The majority of the results lie between these two predictions.

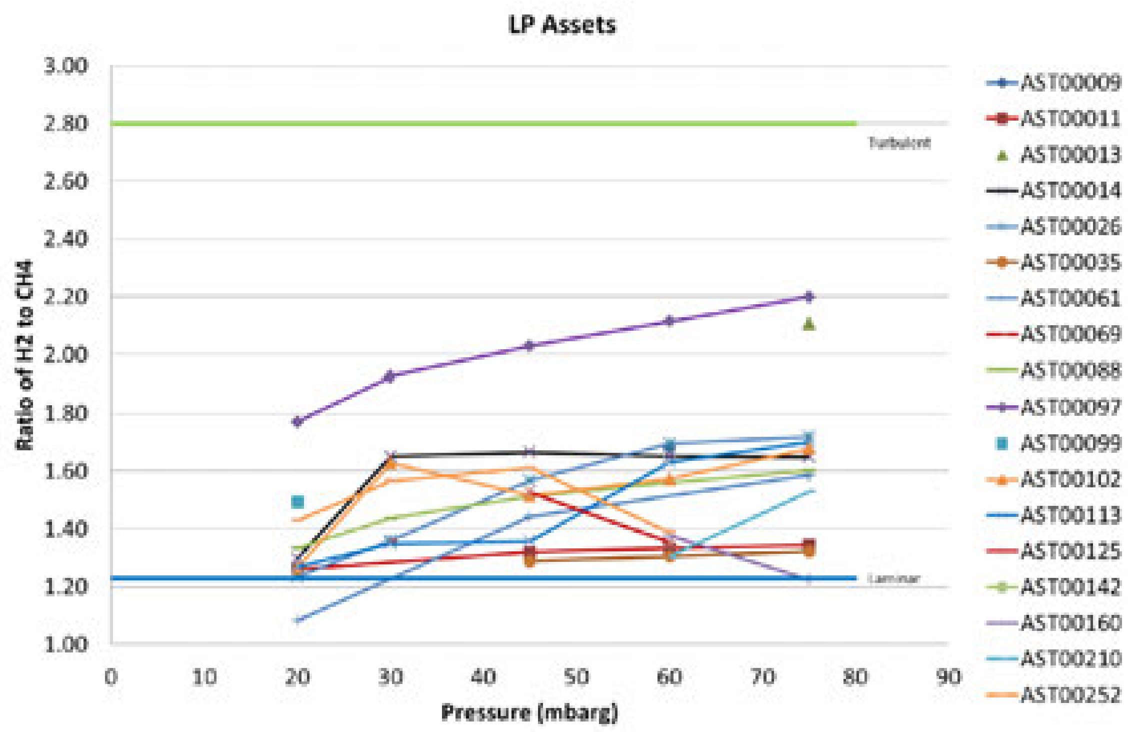


Figure. 4.5 Results of the measured ratio of volumetric flow rate of hydrogen and methane for LP assets

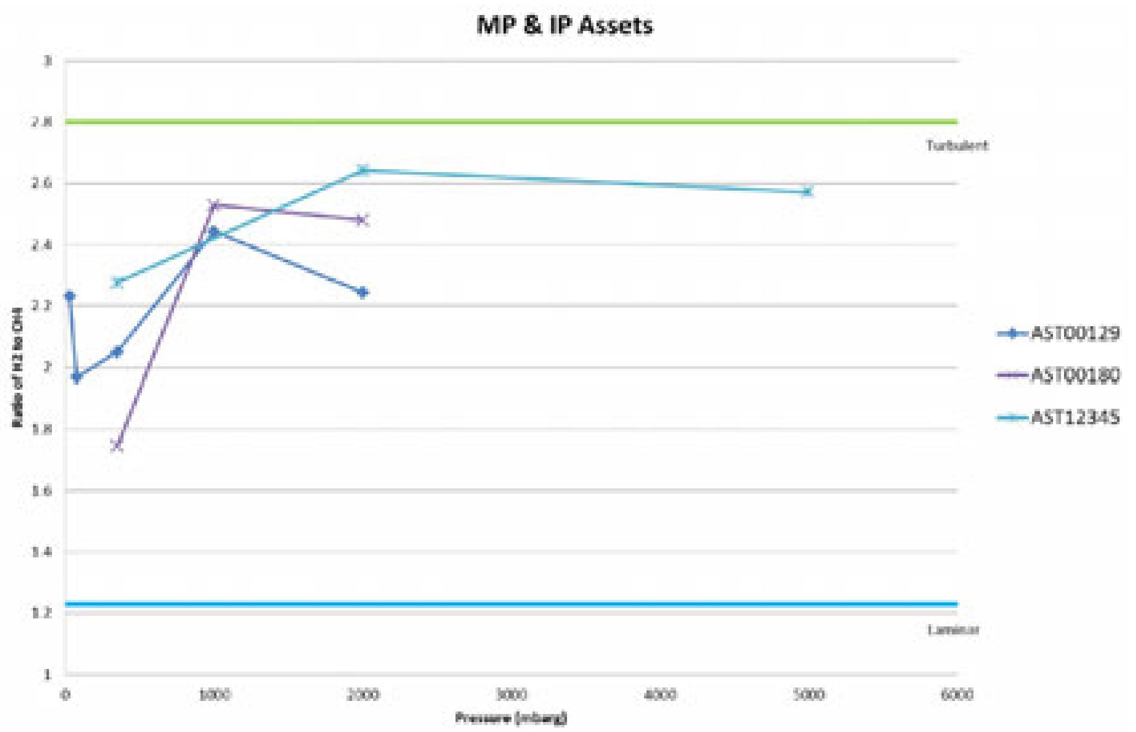


Figure. 4.6 Results of the measured ratio of volumetric flow rate of hydrogen and methane for MP and IP assets

The number of leaking assets recorded was relatively small (41 in total), which makes statistical analysis difficult, but the following sections attempt to identify any common trends in leakage behaviour according to:

- → Asset diameter,
- → Pipe material type
- → Date of installation
- → Joint type
- → Valve type
- → Fittings type
- → Services
- → Regulators
- → Repairs

4.6.1 Asset Diameter Analysis

To analyse trends based on diameter, the data from the leaking assets was filtered to compare leaks in the 60–75 mbar range. This pressure range covers all diameter tiers and therefore was chosen as it provided the largest data set for comparison. The data was also filtered to show just mains, services and governors and not valves, fittings and repairs (which were generally hosted on a main or service), to avoid data being double counted in the analysis.

The data has been collated (see Figure 4.7) and, **while the data does not show any trends, this was expected,** since through the testing programme it was apparent that other properties of the asset such as joint type and condition were contributing factors to leakage rate.

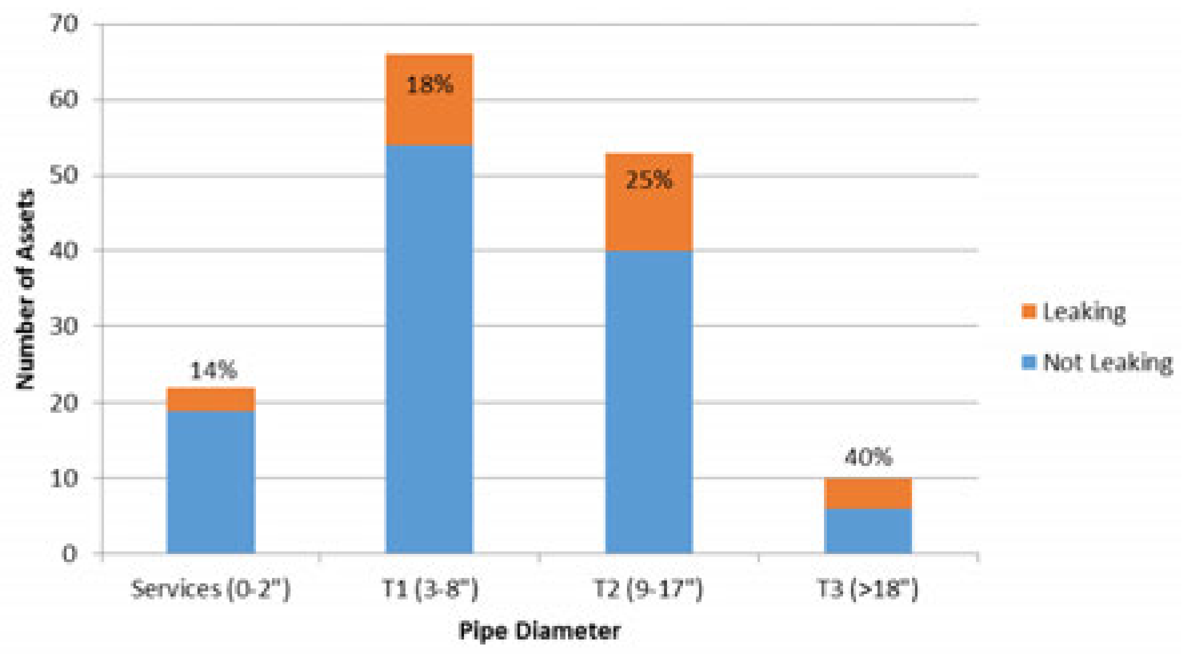


Figure. 4.7 Test results by pipe diameter tiers

4.6.2 Pipe Material Analysis

It is important to understand if the leakage rate of hydrogen differs from methane due to various pipe materials. In most cases, it was the joint that leaked rather than the pipe wall itself, and the joints are, in many cases, similarly constructed in the different types of iron pipes.

Figure 4.8 shows the spread of the tests conducted over the different asset materials. It shows that no leaks were identified on the 29 PE assets tested. This was a positive result, given that PE is due to make up the majority of the network by 2032. **There were broadly similar proportions of leaking assets across cast, ductile and spun iron (26% to 29%), and a slightly lower proportion of leaking steel assets (14%).**

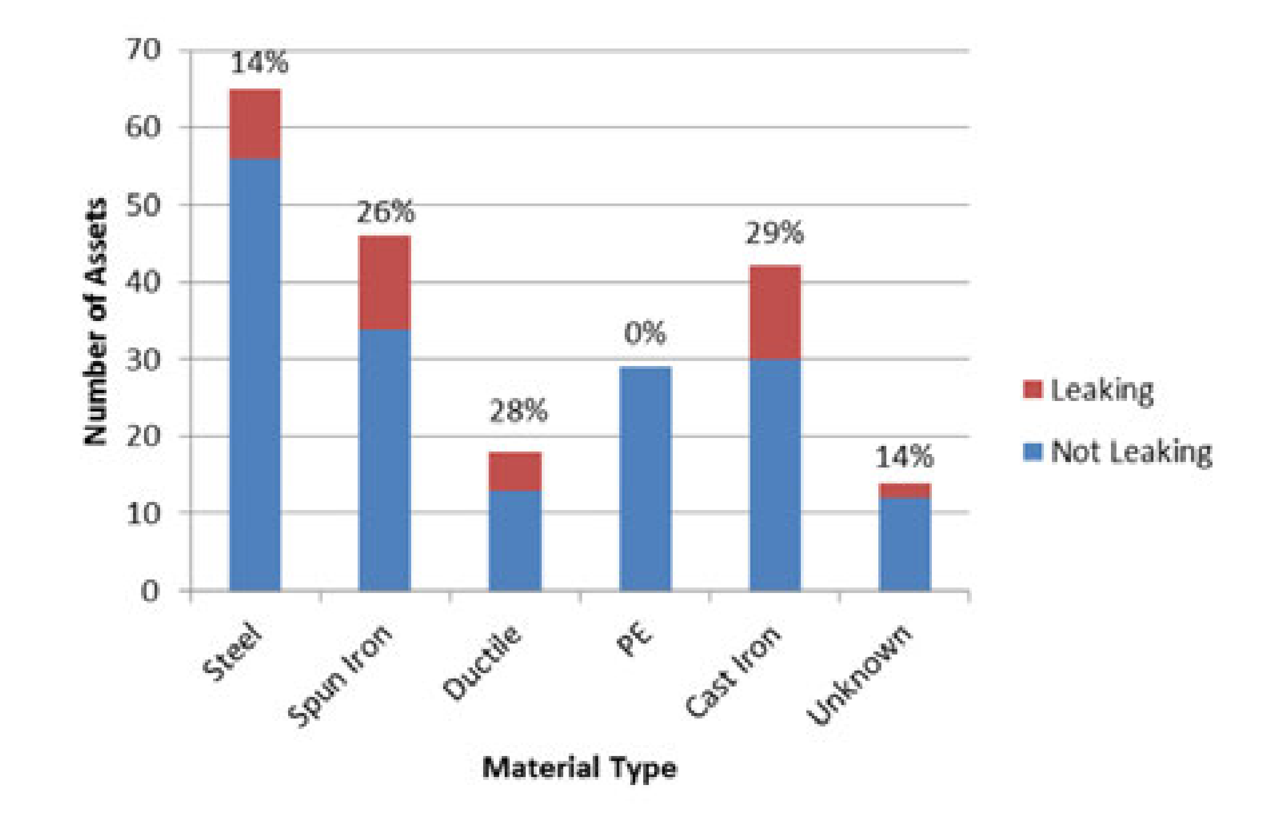


Figure. 4.8 Material Analysis of Assets

4.6.3 Date of Installation Analysis

The year in which an asset was installed for first use was obtained for a number of the assets. Figure 4.9 shows the spread of the data over the decades. 41 assets were obtained from new due to difficulties sourcing used assets of their type from the network. The year of installation was unknown for 68 of the assets, either because the asset had been retrieved from salvage or the recorded year was not available.

Overall, there are no significant trends for assets from a particular decade to show greater tendency to leak than those from another decade.

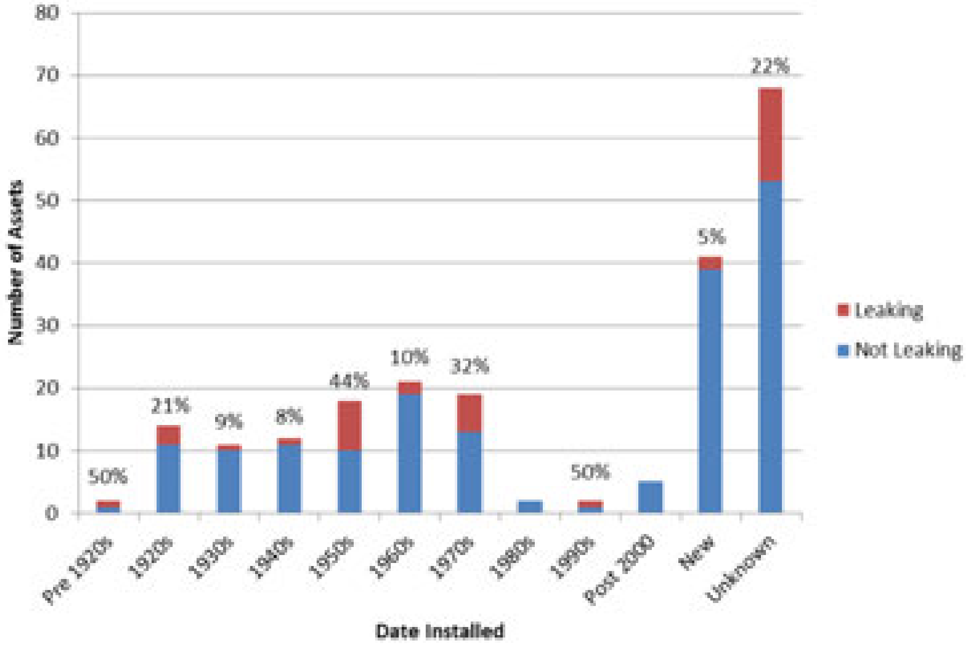


Figure. 4.9 Analysis of leaks according to date of installation

4.6.4 Joint Type Analysis

Figure 4.10 shows the spread of joints tested during this project and the number which leaked. Above each bar the number which leaked is provided as a percentage.

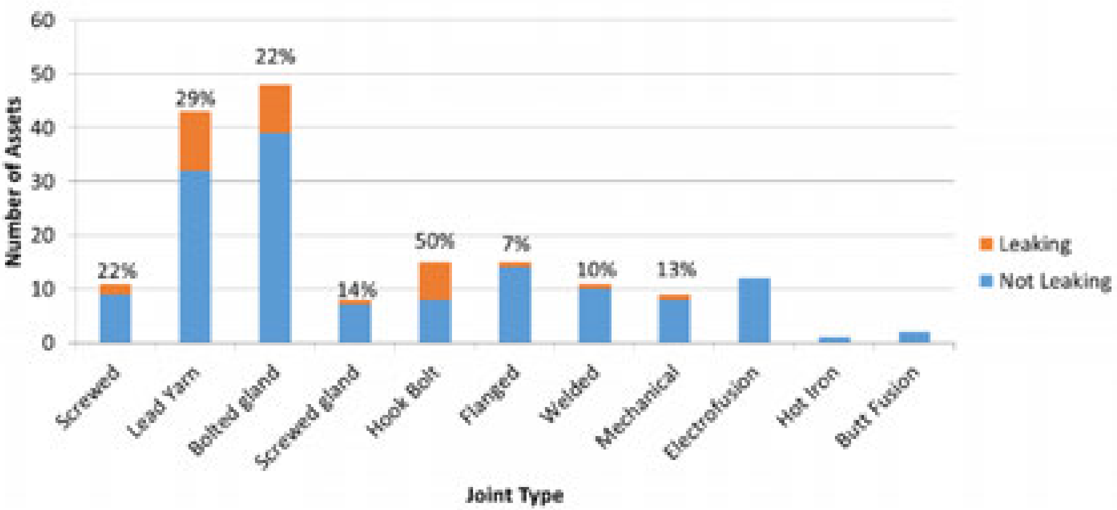


Figure. 4.10 Analysis of leaking joints according to joint type

The four main joint types which recorded numerous leaking joints were:

Hook Bolts

Lead Yarn

Screwed

Bolted gland

The rest of the joints showed relatively low levels of leakage. It is a common issue in the gas network that lead yarn joints can dry out and lead to increased leakage. As the lead yarn joints had been extracted from the ground and left for a number of months before being tested, it is possible that this was the cause for the high number of leaking lead yarn joints. It is current practice in industry to inject Mono Ethylene Glycol (MEG) as a swelling agent to counter the drying out of lead yarn joints, a practice which will need to be reviewed during a conversion to 100% hydrogen.

Figure 4.11 shows joint analysis by asset material. The majority of the leaking lead yarn joints were installed on cast iron assets and the hook bolt joints were mostly installed on spun iron.

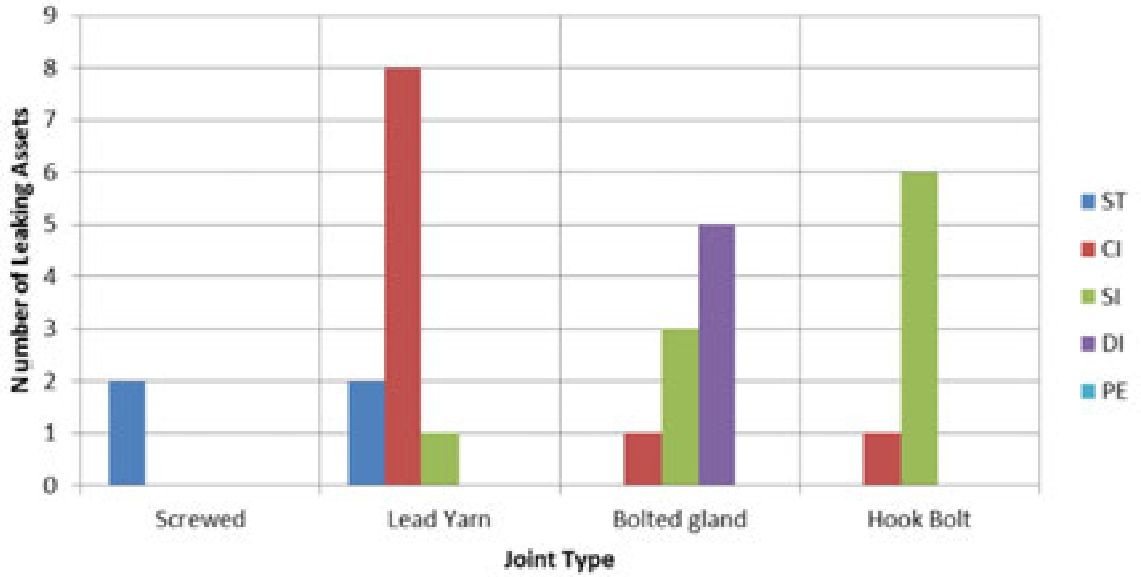


Figure. 4.11 Joint analysis by asset material

Due to the low number of leaking assets, the project was unable to provide a statistical analysis of whether the same types of joint in different materials behave similarly. However, the testing did indicate that a lead yarn joint installed in a steel asset was found to show larger bubbles in the soap tests when compared to those in the cast iron assets.

Figure 4.12 shows the main leaking types that provided sufficient data to group them into the different asset diameter tiers. As data was present for all three tiers of lead yarn joints, further analysis was performed.

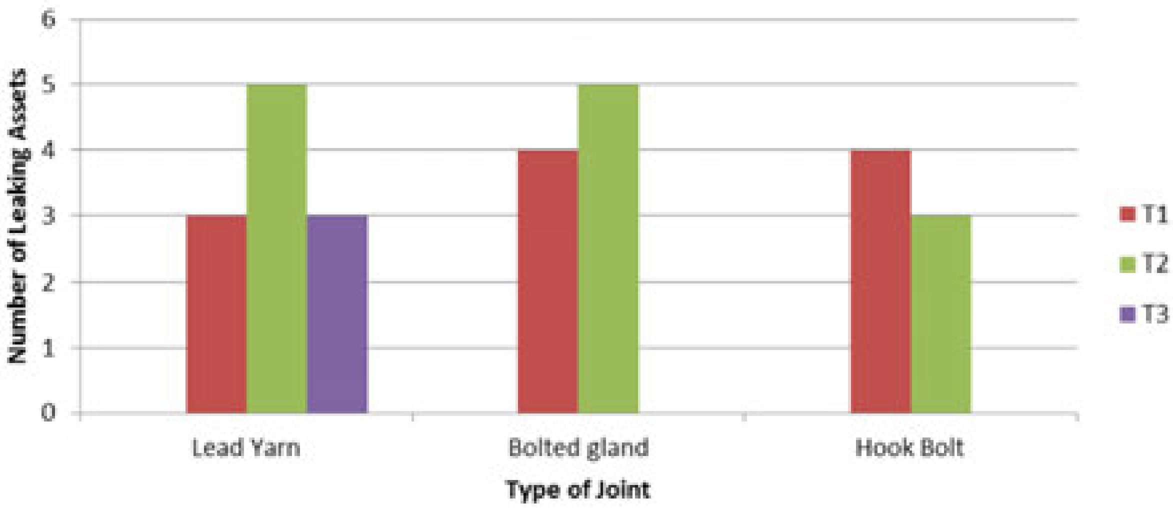


Figure. 4.12 Joint analysis by asset diameter

4.6.5 Valve Type Analysis

The procedure for testing valves was somewhat different from the other asset tests, because it was important to quantify the leakage from the valve stem and also the "let-by" leakage along the pipe when the valve was closed. The modified tests that were conducted on valves are listed here:

- → LP, MP or IP phased leakage tests on the valve in the open position
- → Final phase leakage tests on the valve in the closed position with both sides of the valve pressurised
- → Final phase let-by tests on the valve in the closed position and one side of the valve depressurised

This ensured that all leak mechanisms were covered by the tests and their characteristics studied.

Eleven tests were undertaken on thirteen valves (note test AST00072 includes three valves) that were suitable for testing and two of these registered a leak (AST00223 & AST00228) during the closed valve tests (see Table 4.3). Both leaks were identified as coming from the valve spindle when in the closed position. In both cases the leakage rate was not consistent when repeated and it was found that the force used to close the valve was the main variable that controlled the leakage rate. Therefore, as the exact position and force used to close the valve could not be determined, the tests were not repeatable. The valves were tested on methane and found to be leaking but a comparison on the leakage rate with hydrogen could not be made, due to the varying nature of the valve stem leaks.

Table. 4.3 Summary of Valve Tests

Barcode/ serial no	Valve Type	Diameter (inch)	Material	Pressure	Leaked Open Y/N	Leaked Closed Y/N	Let by Y/N
AST00072	100mm Audco 1/4 turn ball, Valve, 300mm Donkin gate Valve CL, 100mm Donkin gate Valve CL	12	ST	MP	N	n/a - valve would not operate	n/a - valve would not operate
AST00223	Donkin CL Valve	6	ST	MP	N	Y	N
AST00227	63mm 1/4 turn Banides P.E body service Valve	63	PE	LP	N	N	N
AST00228	12 Donkin CL Valve	12	ST	LP	N	Y	Y
AST00246	12" Donkin Fig555 Valve	12	CI	IP	N	N	N
AST00247	6" Donkin Fig555 Valve	6	CI	IP	N	N	N
AST00249	8" Donkin Fig555 Valve	6	CI	IP	N	N	N
AST00251	6" Donkin Slide Valve	6	CI	LP	N	n/a - valve would not operate	n/a - valve would not operate
AST00255	6" Donkin 555 Valve	6	CI	MP	N	N	N
AST00256	10" Donkin UP drilling valve	10	CI	MP	N	N	N
AST00257	4" Donkin CI Valve	4	CI	LP	N	N	N

4.6.6 Fitting Type Analysis

Table 4.4 lists the fitting types that were successfully tested and shown not to be leaking when pressurised with hydrogen up to the test pressures. This shows that (for short durations at least), **the fittings did not leak and that they could be suitable for use with hydrogen, once the long-term use and safety aspects have been established.**

Not all the fittings listed on the master testing plan were tested, as some could not be sourced, while some fittings were tested multiple times, as they were present on multiple assets. For some assets, the fitting type was sourced but the pipe used to test the fitting was only suitable to 75 mbarg which limited the test pressure.

Table. 4.4 Fitting Types tested during the project

Asset Number	Max Pressure (barg)	Fitting type	Diameter	Diameter Tier
AST00201	7	Insulation Joint	4-8"	T1
AST00206	2	Viking Johnson Flange Adapter	90mm	T1
AST00230	0.0075	Viking Johnson Coupler	4-8"	T1
AST00019	0.0075	Sydall Under Pressure Tee	4-8"	T1
AST00226	0.0075	Sydall Under Pressure Tee	10-16"	T2
AST00250	0.0075	2 part Under Pressure Tee	4-8"	T1
AST00105	0.0075	Flanged MDPE CAT Adapter	4-8"	T1
AST00211	0.0075	Flanged MDPE CAT Adapter	10-16"	T2
AST00212	7	Flanged HDPE CAT Adapter	4-8"	T1
AST00205	0.0075	Non-tap Plug	3-4"	T1
AST00238	2	Flange with Full Faced Fibre Gasket	4-8"	T1
AST00239	2	Flange with Full Faced Fibre Gasket	10-16"	T2
AST00241	2	Flange with Half Faced Fibre Gasket	4-8"	T1
AST00217	2	Flange with Half Faced Fibre Gasket	10-16"	T2
AST00243	7	Flange with Full Faced Rubber Gasket	4-8"	T1
AST00244	7	Flange with Full Faced Rubber Gasket	10-16"	T2

4.6.7 Services Analysis

To maximise the efficiency of the test programme, it was proposed to test typical service runs comprising a selection of fittings and representative pipe materials (e.g. steel, Serviflex, copper, DuPont, Pex 80 and 100, soft copper) in one test, as opposed to testing individual components one at a time. If the whole service run did not leak, then this avoided the need to test individual components.

Where possible, services were extracted from the network. However, due to the location of services near buildings (often within the boundary of a householder's property), this was not always possible. Certain assets could not be retrieved from the network, so some of the service runs were constructed from new fittings and pipework.

35 service assets, both new and retrieved, (0–2" diameter) were tested and in total three leaked on both hydrogen and methane.

The three leaking assets and the details of the leaks are listed here:

- → AST00083 was a 2" steel pipe with a screwed joint, the leak source was undetermined.
- → AST00119 was a 2" steel pipe with a screwed joint and the leak was identified as being from a large hole in the pipe wall.
- → AST00273 was a 2" steel pipe and the leak was identified as being from a 2" collar on the asset.

The service component types tested are listed in Table 4.5

Barcode/ serial no	Test Type	Additional fittings present	Actual diameter	Unit of diameter	Actual material	Leak Y/N
AST00083	Service	n/a	2	inch	ST	Yes
AST00089	Service	n/a	2	inch	ST	No
AST00118	Service	n/a	2	inch	ST	No
AST00119	Service	n/a	2	inch	ST	Yes
AST00123	Service	n/a	2	inch	ST	No
AST00124	Service	n/a	2	inch	ST	No
AST00201	Service	House entry Crimp/ or LPS	0.8	inch	ST	No
AST00202	Service	Serviflex, draw lock SHA. Repair clamp fitted at buxton.	0.8	inch	ST	No
AST00214	Service	Crimp Meter box adaptor	0.8	inch	PE	No
AST00215	Service	Above ground factory fitting	2.5	inch	PE	No
	Service	Crimp Top Tee, draw lock SHA	0.8	inch	PE	No
AST00218	Service	L.P Steel Screwed House Entry with steel Screwed bend for mains connection	1	inch	ST	No
AST00219	Service	Crimp Side Entry Tee with	1	inch	PE	No
AST00221	Service	1”/32mm Crimp Top Tee+ 32mm E/F Coupler and 32mm/1” draw lock SHA	1.3	inch	PE	No
AST00222	Repair	Heat Shrink Sleeve Raychem	1.5	inch	ST	No
AST00224	Service	Kontite Top tee and Screwed Wall Entry	1	inch	ST	No
AST00225	Service	Cellar Entry/Below Ground	2.5	inch	PE	No
AST00227	Valve	63mm 1/4 turn P.E Service Valve	2.5	inch	PE	No
AST00231	Service	2” Screwed bend for mains connection and 2” Screwed wall entry Tee	2	inch	ST	No
AST00232	Service	32mm Punch Top Tee off a 2” main. With 32mm Crimp off Punch Tee and 1”/32mm Draw lock Service Head Adaptor. The 1” by 3/4” threaded reducer and 3/4” meter control Valve.	2.5	inch	PE	No
AST00233	Service	1”/32mm Crimp Top tee and 32mm Crimp Service Head Adaptor	2.5	inch	PE	No
AST00234	Service	1” Kontite Top tee with 1” Steel to Copper brass compression fitting. 1” Soldered Copper	1	inch	PE	No
AST00236	Repair	1” Heat Shrink Sleeve, Raychem	1	inch	ST	No
AST00237	Service	2” Kontite Top tee, 2” Steel Service with 2” Screwed Wall Entry Tee	2	inch	-	No
AST00259	Fitting	1” Top Tee	1	inch	PE	No
AST00260	Fitting	2” Top Tee	2	inch	PE	No
AST00266	Fitting	2”/63mm Top tee, including, sockets, valve and cap end. Attached to 00265	2	inch	ST	No
AST00267		2” IGA Axial Flow single stream with full bore 2” by-pass Includes RV’s Filters	2	inch	ST	No
AST00268	Service Governor	3/4 inch service in and out. Twin stream	-	-	ST	No
AST00269	Fitting	2” Screwed socket	2	inch	ST	No
AST00271	Fitting	See AST 00232. & refer to AST: 00277. 1”/32mm Crimp Top Tee	1.3	inch	PE	No
AST00272	Fitting	See AST 00232. & refer to AST: 00277. 32mm Crimp Service Head Adaptor	2.5	inch	PE	No
AST00273	Service	2” service with 2” couplers	2	inch	ST	Yes
AST00274	Repair	2” repair clamp on AST 00119	-	-	ST	No
AST00277	Service	Host to 00271 & 00272. Previously tested to LP as AST00232. Retested to MP	2.5	inch	PE	No

Table. 4.5 Service tested during the project

4.6.8 Regulator Analysis

Rather than test governors in isolation, the experiments tested skids comprising governors, slam shut valves and wafer valves (non-return valves). The reason for this approach was the same as that applied for services, namely, that if there were no leaks from the skid then there was no need to test the individual assets. Skids were retrieved from the network and new skids were sourced by NGN.

The regulators on the skids were operated to regulate the pressure to below the maximum design pressure of the outlet. **From these short-duration tests, no issues were encountered when operating on hydrogen and the regulators were successful at regulating the pressure.**

Asset	Type	Max Inlet pressure	Set pressure of regulator	Comments
AST00172	Twin stream, slam, active, Donkin 280	2 barg	40 mbarg	Not leaking
AST00173	Donkin 280	75 mbarg	75 mbarg	Not leaking, regulators tested in the closed position as inoperable
AST00174	Vector module, Donkin 280 Orpheus 4	2 barg	100 mbarg	Not leaking. PRV set to 100 mbarg
AST00176	Orpheus “Type” module	2 barg	100 mbarg	Not leaking
AST00177	RMG Rig, Honeywell Regulator	2 barg	2 barg	Not leaking
AST00267	Single Stream, 2” (50 mm) monitor, active, Axial Flow with 1203 pilots and a 1” (25 mm) IGA 10L relief valve	2 barg	90 mbarg	Not leaking
AST00268	1” (25 mm), twin stream, IGA 1800 Service Governor	2 barg	36 mbarg	Not leaking

Table. 4.6 Regulator Types tested during the project

4.6.9 Repair Analysis

It was proposed to test a range of repairs in the H21 Phase 1a experiments. In some cases, assets retrieved from the network for testing already included repaired sections, and these were therefore tested during those experiments. It was also proposed to make new repairs on assets found to be leaking. The repairs tested on site were not made under hydrogen, but were instead made using the standard NGN operating procedures with methane where possible. This is because the aim of the Phase 1a tests were not to demonstrate the safety or effectiveness of repairing assets under hydrogen: this is to be addressed in Phase 2. Table 4.7 summarises the repairs: **all repairs were found to seal on hydrogen where the repair was successful with methane.**

Asset Number	Repair type	Max Pressure (barg
AST00222 (LP)	Heat Shrink Sleeve (Raychem)	0.075
AST00235 (LP)	2 Muffless Encapsulation LP/<14”	0.075
AST00178 (MP)	Muffed Encapsulation	2
AST00276 (LP)	Muffless Encapsulation MP/>14”	2
AST00220 (LP)	External Anaerobic Injection	2
AST00278 (LP)	External Two Part Joint Injection	2
AST00203 (LP)	Repair Clamp	7
AST00263 (LP)	Split collar	7
AST00209 (LP)	Bolt Replacement	7
AST00229 (LP)	Cut out and replace	7

Table. 4.7 Summary of Repair Tests

4.6.10 Temperature Analysis

During the experiments, it was evident that the temperature changed as the assets were tested throughout the day. To assess the potential impact of the changing temperature on the leak rates, the flow equations presented in BS EN 60079-10-1: 2015 were analysed. These equations predict the flow rate to be proportional to the square root of the inverse of the temperature. Therefore, a change in temperature of 5 Kelvins (K) (2%) would lead to a 1% change in the flow.

To confirm this relation between flow and temperature, the results of asset AST00011 were analysed to see if they showed this relationship. The regression of the plotted data for hydrogen and methane is calculated to be 0.98 for both gases, which supports the relation defined in BS EN 60079-10-1.

A change in temperature of 5 K was considered suitable for use in estimating the error in flow. As this change in temperature only relates to a 1% change in flow, it was not considered necessary to perform temperature corrections of the flow.

4.7 Conclusions

The assets provided a representative sample of those anticipated likely to be present in the UK natural gas network if it were to be converted to hydrogen from 2032 onwards. They included a selection of LP, MP and IP assets from Tiers 1, 2 and 3, including iron, polyethylene and steel pipes, joints, valves, fittings, services, valves, regulators and repairs.

Leakage was assessed on hydrogen at five, set-point pressures spanning the range of maximum operating pressures for the LP, MP or IP assets. Where assets were found to leak on hydrogen, they were tested on methane to allow a like-for-like comparison of leakage rates. Repairs where possible were then carried out under the methane.

Of the 215 assets tested, 41 of them were found to leak and 19 of them provided sufficient data to be able to compare hydrogen and methane leak rates.

Analysis of the data was focused on answering the following questions:

Did any assets leak hydrogen if they were gas-tight with methane?

The tests showed that assets that were gas-tight on methane were also gas-tight on hydrogen. Assets that leaked on hydrogen also leaked on methane, including repaired assets.

What was the leak rate ratio for hydrogen relative to methane?

The ratio of the hydrogen to methane volumetric leak rates varied between 1.1 and 2.2, which is largely consistent with the bounding values expected for laminar and turbulent (or inertial) flow, which gave ratios of 1.2 and 2.8, respectively.

What were the trends in the measurements?

Due to the limited number of assets that were found to leak, it was difficult to draw definitive trends, although asset diameter and asset age did not have a notable effect on leakage rate.

Did assets material types affect the leaks?

In terms of asset material: none of the PE assets leaked; cast, ductile and spun iron leaked to a similar degree (around 26-29% of all iron assets leaked); and the proportion of leaking steel assets was slightly less (14%).

Did joint type affect the leaks?

Within the limited sample set, four types of joint were responsible for most of the leaks on joints (screwed, lead yarn, bolted gland, hook bolts). Other types of joints were less likely to leak (flanged, welded, mechanical). None of the PE joints leaked (butt welded, hot iron, electrofusion).

Did valves affect the leaks?

Two of the valves leaked, both from the valve stem. It was not possible to quantify the ratio of hydrogen to methane leak rate for these valves, since it depended on the position of the spindle.

Did service assets leak?

Only 3 of the 27 service assets which were tested leaked, and these leaked on both hydrogen and methane.

Did regulators leak?

Eight regulators were tested, none of the repurposed regulators leaked.

Do bubbles in leak detection fluid appear different for hydrogen and methane in the soap tests?

No, there were no visible differences between bubbles produced by hydrogen leaks and those from methane leaks.

Do existing repairs methods leak on hydrogen?

All of the repairs that sealed methane leaks were also effective when tested with hydrogen.

The Phase 1a test programme is considered to have successfully achieved its objectives in answering these questions. Further work on asset leak tests is planned in the H21 Phase 2 experiments.

4.8 Impact of Hydrogen Conversion on Shrinkage

An assessment of the possible commercial implications of hydrogen conversion for the gas lost during transportation through the network ("shrinkage"), in the light of the experimental results obtained in the background testing in Phase 1a, has been undertaken by DNV GL.

Several different scenarios were considered, assuming that the commercial value of the lost gas is directly related to the energy content (calorific value). Note that the absolute quantities of gas lost through shrinkage are expected to continue to fall as a result of future replacement of metallic pipes with PE, but it is the relative differences between natural gas and hydrogen that is considered here.

With cautious best estimate assumptions, the energy leakage rate for hydrogen is lower than for natural gas. **Provided hydrogen adds no more than double to the cost of natural gas for the equivalent energy, the commercial consequences of shrinkage will be neutral or better.**

The analysis follows a cautious best estimate methodology based on the available information and assumes that the pressures in the network are the same for both gases.

4.9
Impact on Public Reported Gas Escapes

In the light of the experimental results obtained in the background testing in Phase 1A, the project considered the possible implications of hydrogen conversion on the numbers of Public Reported gas Escapes (PREs), where a smell of gas is detected by members of the public and reported to the gas emergency service number.

An overall estimate of the possible increase in the numbers of PREs following hydrogen conversion has been made and is predicted to increase by approximately 27% above current levels, without mitigation. It is acknowledged that there are significant uncertainties in the analysis and important factors (such as the level of odorant added to hydrogen) that are yet to be determined. Nevertheless, the predictions give a degree of confidence that the increase in the number of PREs should be manageable.

By the time of possible conversion, substantial additional replacement of metallic mains and service pipes are scheduled to have taken place, together with upgrades to the internal gas installations to accommodate hydrogen (including meter and appliance replacement or modification), which would be expected to reduce the numbers of PREs.

To illustrate the possible effects of mitigation on the expected numbers of PREs following hydrogen conversion, it was assumed that external leaks are dominated by metallic mains and service pipes and that the vast majority of the remaining external metallic pipes are replaced with PE prior to conversion to hydrogen. In addition, it was assumed that gas meters will need to be replaced and appliances replaced or modified for hydrogen and, as a result of which, the internal gas installation will be tightness tested and any leaks rectified, prior to conversion. The illustrative calculations suggest that, with mitigation taken into account, the numbers of PREs could be substantially lower (by 42%) following hydrogen conversion than the numbers of PREs for the natural gas network today.

The following section contains information collated from the DNV GL reports listed in section 10.0 References.

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5.0

CONSEQUENCE TESTING (WBS 1-5)

5.1 Objectives

The objective of Phase 1b was to carry out a programme of consequence testing to allow quantification of risk associated with background leakage of hydrogen vs methane.

The tests were to combat the following three critical areas which would subsequently be used in the quantitative risk analysis:

Ground and air concentration testing: Confirming how hydrogen dissipates in the air and in the ground from network assets (both above and below ground) compared to natural gas. These tests were undertaken by installing gas mains in trenches and then undertaking various tests. This verified the associated concentrations of hydrogen in the ground (including ductwork) and air for different types of backfill and cover (concrete, open ground, tarmac etc.) and at different distribution pressure tiers.

Background consequence testing: Having understood how hydrogen is likely to migrate, the consequence of such migrations needed to be determined, i.e. how leaking hydrogen could ignite and/or explode when exposed to a range of background ignition sources; for example, engines, cigarettes, tools creating sparks under operational repair activities etc. The results of these tests were then contrasted against the known results for natural gas, to update the quantitative risk assessment.

Operational testing: A 100% hydrogen network will still have background leaks that will need to be repaired and operational activities undertaken e.g. purging. An initial understanding of whether the network can be managed/repaired using key working practices is critical to quantifying the risk and progressing to further network operation testing and field trials.

Phase 1b was therefore broken down into the following five work packages:

- WBS 1 Small release testing – to measure consequences where the breaking of ground surface is unlikely in two scenarios;

  Part 1 – Below Ground

  Part 2 – Houses & Gardens
- WBS 2 Large release testing – to measure consequences where the breaking of ground surface is likely.
- WBS 3 Ignition potential – a converted ignition chamber for natural gas will measure consequences of hydrogen ignition.
- WBS 4 Explosion severity testing – decommissioned kiosks will help compare the point where hydrogen becomes more reactive than natural gas.
- WBS 5 Operational safety testing – demonstrating techniques, operations and equipment in live scenarios.

Following completion of each WBS element of the experimental programme, the various model predictions in the CONIFER (Calculation of Networks and Installations Fire and Explosions Risk) risk assessment package were assessed for suitability against the experimental data, and the relevant models were either modified or replaced.

5.2
WBS 1 Small Release Testing Part 1: Below Ground

Small releases of hydrogen were conducted at a specially constructed buried release pit facility to enable releases below ground to be examined in different types of backfill and with differing ground coverings. The in-ground behaviour of the hydrogen was assessed where the release rates were not high enough to create a direct route to the surface. The migration and tracking of hydrogen, coupled with its interaction with different ground surfaces, was investigated. Variations of hole size, release pressure, ground coverings and orientation of the leak were chosen to both provide comparisons with natural gas information from previous experimental work, and to cover potential operational conditions in a future hydrogen network. Measurements of both surface and accumulated gas concentrations (where tracking is considered), outflow conditions and atmospheric conditions provide data to assess the potential consequences of each leak. More than 100 experiments were performed.

5.2.1 Method

The small release experiments consisted of unignited releases from different hole sizes in a buried pipe, with different ground coverings (soil, sand and/or slabs or block paving). The objective of these experiments is to investigate the gas migration characteristics of a buried release and the subsequent levels of gas concentrations above ground in the vicinity of the release.

Details of the parameters of the releases are summarised in Table 5.1 below.

Scenario	Release Orientation	Release diameter (mm)	Release Pressures (mbar
Puncture	Horizontal, Vertical, Downwards	5, 20 and 45	30, 70 and 350

Table. 5.1 Unignited release experiments

The measurements from the experiments included gas concentrations at locations surrounding the release. The pressure, temperature and flowrate of gas, as well as weather conditions, were also measured. The majority of the experiments were carried out using hydrogen, but selected experiments were repeated with methane so that a direct comparison with the hydrogen data could be made.

The gas was released from leaks located on the top, side and bottom of a 14" diameter carrier pipeline, as shown in Figure 5.1. The pipe was buried before the experiments were carried out. The 14" carrier pipe contains several smaller pipes that feed each hole size of each orientation. These pipes can be seen on the left side of the image, entering the carrier pipe.

Figure. 5.1 Release locations in an allotment

Funnels connected to analysers were located close to the ground in an array centred over the release; however, for a few scenarios the funnels were placed in a single line centred over the release. An example of a funnel arrangement is shown in Figure 5.2.

Figure. 5.2 An example of a funnel arrangement

The buried release pits were covered by a tarpaulin to keep the moisture content of the soil stable and to offer some shelter from the wind. The wind speeds inside the tarpaulin were generally low, at around 1 m/s. The programme of experiments was performed over some months, so there was some variation in the weather conditions.

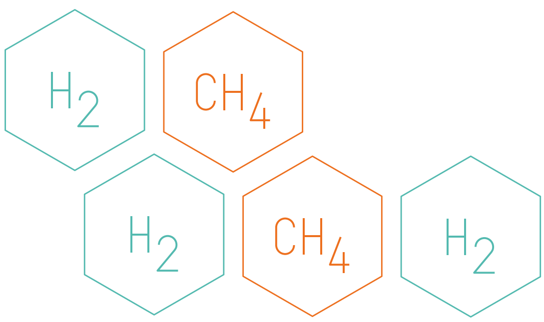
Due to the number and duration of the tests and the weather conditions, the soil was replaced during the testing and recompacted as required.

5.2.2 Evaluation of Results

A total of 108 experiments were performed into the soil and the sand buried pits. These experiments were designed to provide information on the idealised migration of hydrogen in soil and sand with some comparison information from a limited number of repeat experiments with methane.

The repeatability of the experiments was generally not good unless experiments were more-or-less performed back to back e.g. in quick succession; $H_2 > CH_4 > H_2 > CH_4 > H_2$ and when the funnel grid was in the 1-D line arrangement e.g. the sensor funnels were much closer together.

Despite the buried release pits being covered to provide protection from rain, there was clearly some variation over time which resulted in a large variation in the flow rates when experiments were repeated. It is therefore difficult to come to any definitive conclusions about the influence of leak orientation, ground covering or soil type. However, the following could be deduced;



5.2.2.1 Consistency in the Data

- Data from experiments involving releases from a single location gave consistent flowrates, i.e. higher flowrates at higher pressures, higher volumetric flowrates for hydrogen versus methane.
- The back to back and funnel line experiments were nominally identical to experiments carried out two months apart. The experiments early in the H21 programme gave flow rates between 11% and 30% of those measured in the back to back experiments. The earlier H21 experiments involving releases with different diameters and at different locations on the circumference of the pipeline gave flow rates typically around 20% of equivalent releases in the back to back experiments. These differences could be due to natural variations in the soil properties, such as moisture content or the packing of the soil. (The area was refilled during the experimental programme).
- The outflow rates varied according to leak position. Releases at the top of the pipe typically had outflow rates around half of that found for an equivalent release on the side. Releases at the bottom of the pipe typically had approximately five times the outflow rate of a release on the side.
- Data from experiments involving releases from a single location gave consistent distributions of high and low gas flow at the ground surface. However, there are significant differences between the measured outflow and the total outflow inferred from the funnel measurements, with inferred flows generally smaller than measured flows. In particular, this difference was significantly greater for the hydrogen experiments than for the methane experiments.

5.2.2.2 Hydrogen/Methane Comparison

- For a given leak diameter and pressure, the volumetric flowrate of hydrogen was 1.4 to 2.2 times greater than the flowrate for methane. The ratio of the hydrogen to methane flowrates tended to be larger than the ratio of the viscosities, particularly at pressures in the MP tier (greater than 75 mbar).
- The distribution of the flow through to the surface was very similar for hydrogen and methane. The flowrates for hydrogen were consistently higher at all locations than for methane, because the outflow from the pipe is greater, rather than because of any fundamental difference in the behaviour of the two gases as they migrate through the soil. Hydrogen does not migrate significantly further through soil than methane.

5.3
WBS 1 Small Release Testing Part 2: Houses & Gardens

Three purpose-built houses and gardens were constructed on Hy Street at the DNV site at Spadeadam. Each house was built with a different construction method:

The three houses have slightly different ground floor configurations, with the East house having a kitchen and adjacent utility room and the middle house having an enclosed cupboard under the stairs. Each house has a single room on the first floor. The staircases in the houses are not enclosed and they lead directly from the living room on the ground floor to the first-floor room. The cupboard doors were closed during the experiments. The internal doors were generally left open during the experiments, although the doors around the release location were closed. For example, for releases in the cellar, the door separating the cellar from the hall was closed, whereas for releases in the kitchen, the door between the kitchen and the hall was closed.

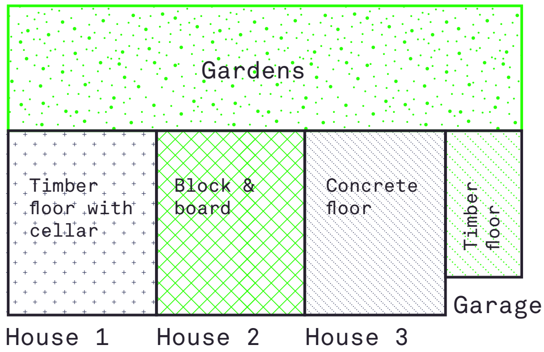


Figure. 5.3 Overview plan of the houses on Hy Street

The small release experiments in the houses and gardens were carried out for several significantly different experimental configurations, as listed below, and concentration measurements taken throughout the houses.

The data was used in the development of the model for gas accumulation inside buildings, which is based on an existing model for gas accumulation in enclosures. This section describes the WBS 1 experiments in the Hy Street houses and reviews of the data from the experiments. It also includes the comparison of the existing models with the experimental data and describes the modification of the models to account for trends in the experimental data.

5.3.1. Method

A total of 85 experiments involving realistic releases were conducted either directly into a property, out of a service pipe or out of a main. Twenty releases simulating leaks directly from distribution services into the basement or kitchen of one house and into an under stairs cupboard or into a floor void of another house were conducted. These releases were conducted to generate data on the gas accumulation of hydrogen and methane when released into these different geometries and ventilation regimes.

5.3.1.1. Services Pipes and Gas Mains

During the build and landscaping of HyStreet, gas mains and service pipes were installed in the gardens and road and routed into the houses. An intact service pipe was provided into each house to allow a supply of gas for releases into the house. Outside the houses and in the rear gardens, service pipes were installed with predetermined release points at set distances (1.5m, 2.5m and 3.5m) from the houses. At each predetermined release point, three service pipes were installed with varying holes diameters of 5mm, 25mm and 45mm.

Figure. 5.4 Services installation through gardens and under the road

At the edge of the garden a buried gas main with 5mm, 20mm, and 45mm diameter holes was installed with the hole side facing the houses; see Figure 5.5 below. The buried pipe was located 5m from the house wall.

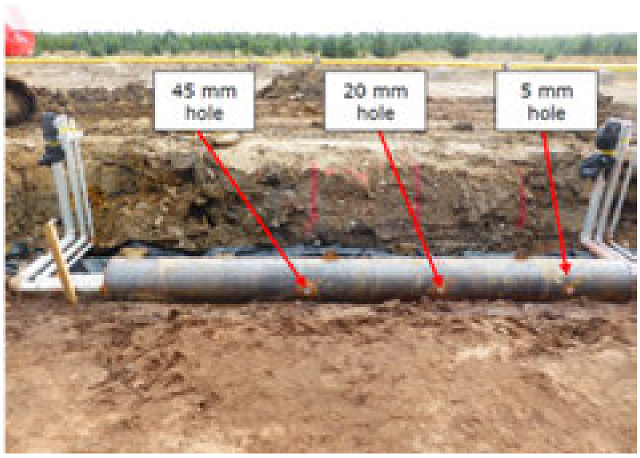


Figure. 5.5 Gas Main installation at edge of garden

5.3.1.2. High Momentum Release in an Under Stairs Cupboard

The experiment consisted of free flow (high momentum) releases, representative of leaks from meters installed in under stairs cupboards, or from the upstream service pipe supplying the meter. Releases were conducted from two release diameters (5.1mm & 20mm) at various pressures (20, 30, 75 mbar), with measurements at multiple points throughout the house. The experiments were undertaken both with hydrogen and methane.
The measurements from the experiments include the release pressure, flowrate and concentrations at 23 locations, including inside the cupboard and throughout the three houses, as well as wind speed and direction.

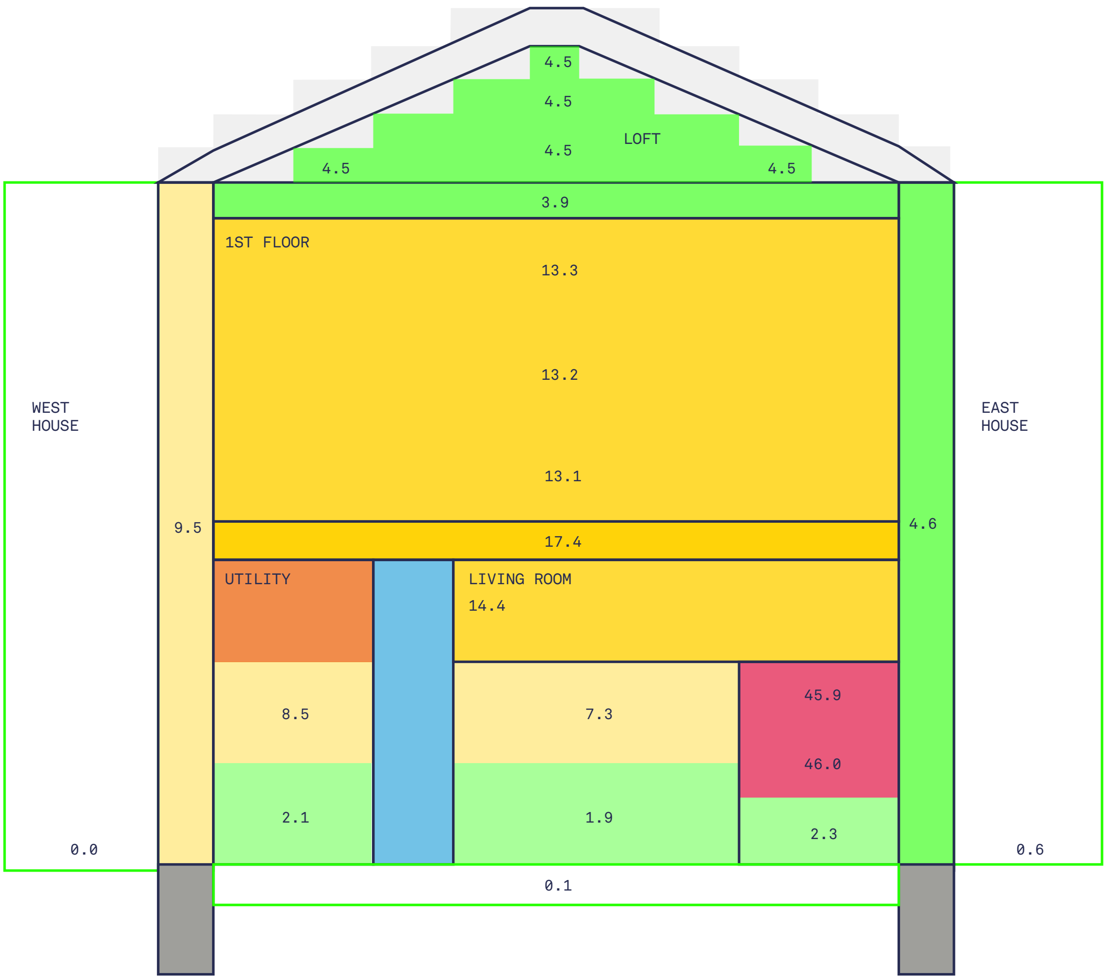


Figure. 5.6 Example concentration distributions for releases into the under stairs cupboard

5.3.1.3. High and Low Momentum Releases into the Cellar

Two series of experiments were carried out releasing gas into the cellar of the East house. The first series consisted of free flow (high momentum) releases representative of leaks from pipework, undertaken with hydrogen only. Releases from two release diameters (5.1mm & 20mm) at various pressures (20, 30, 75 mbar) were undertaken, with measurements at multiple points throughout the house.

The second series of experiments consisted of low momentum releases in the cellar, representative of releases from leaks on mains or services where the gas percolates through the soil into a house. The release was located inside a small box, with the release directed at the side of the box to reduce its momentum with the box being located at the top of the cellar. Holes were drilled in the other sides of the box, to allow the gas to flow out of the box into the cellar with low momentum. Releases from two release diameters (5.1mm & 20mm) at various pressures (5, 20, 30, 75 mbar) were undertaken, with both hydrogen and methane, with measurements at multiple points throughout the house.

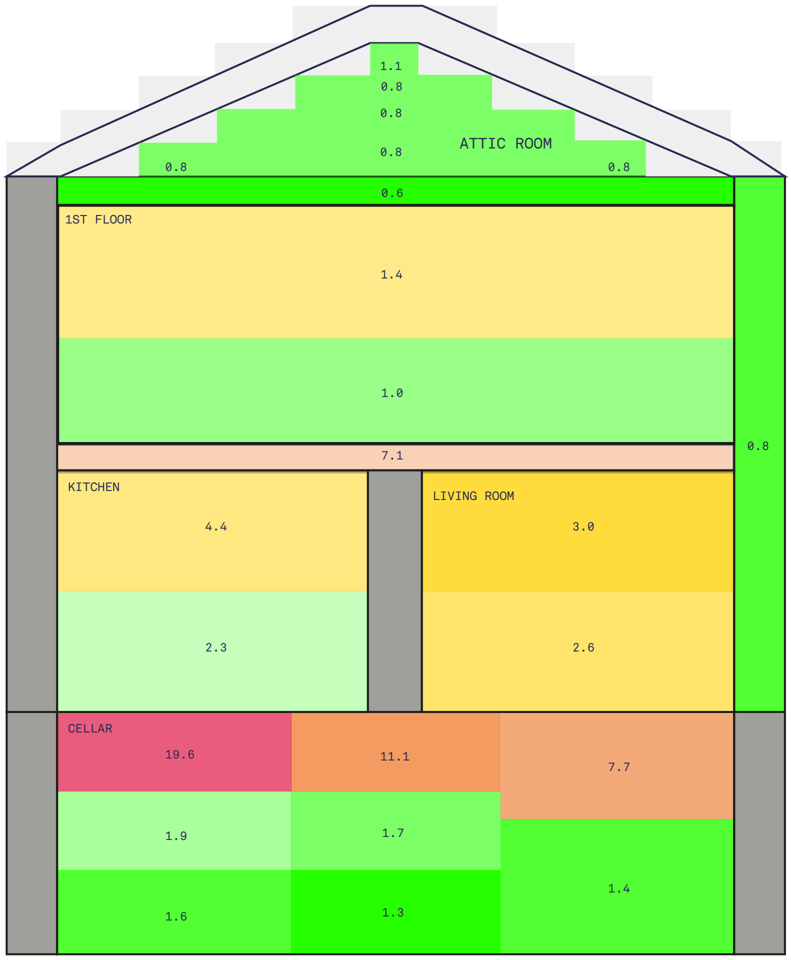


Figure. 5.7 Example concentration distributions for low momentum releases into the cellar

5.3.1.4. Low Momentum Releases into the Kitchen

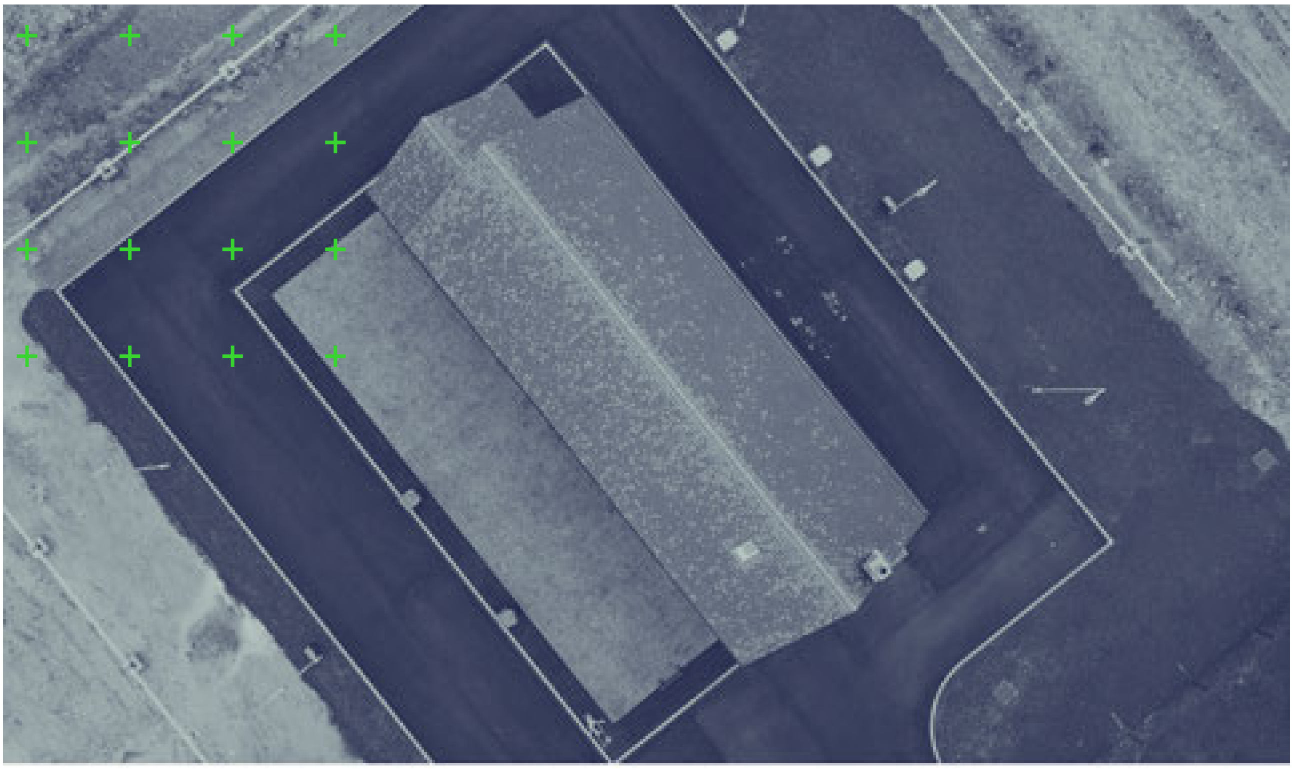
The experiments were similar to the low momentum releases into the cellar, with the release located inside a box designed to reduce the momentum of the gas release. The experiments were designed to represent gas percolating through the soil and flowing into the room close to ground level. To get detailed information about the stratification of the release, the concentration was measured at seven locations within the kitchen. Releases from two pipe diameters (5.1mm & 20mm) at various pressures (5, 12, 20, 75 mbar) were undertaken with both hydrogen and methane.

5.3.2. Evaluation of Results

5.3.2.1. Services and Gas Mains

Realistic releases into the garden or tarmac road were subject to significant experimental variation due to the number of variables involved in each release. For example, it was not possible to control moisture levels in the gardens, nor the presence of, or lack of, snow on the ground. This meant that it was difficult to reproduce results. These experiments were not consistent with each other and point to potentially subtle changes in release, ground, tracking and ventilation regimes, driving potentially significant differences in the final result (gas concentrations within the house).

Releases from mains and services under tarmac in clay backfill produced no significant or dangerous gas concentrations within the properties, despite significant flows being generated. However, the lack of gas tracking here in clay under tarmac cannot be interpreted in any way as being indicative of a lack of gas tracking in real-world scenarios. These types of leaks and tracking mechanisms have been known to cause significant natural gas accumulation and explosion in the past.



5.3.2.2. Concentrations & Stratification of Hydrogen in the Houses

The experimental data was analysed and a summary of the stratification observed in the three groups of experiments is shown in Table 5.2, below.

Accumulation Location	Releases in Cupboard (Jet)	Releases in Cellar (Jet and Low Momentum)	Releases in Kitchen (Low Momentum)
Cupboard	Sometimes stratified, well mixed for higher momentum	-	-
Cellar	-	Always stratified	-
Kitchen	-	-	Well mixed in top 80-90%, low concentrations at floor level
Living Room	Strongly stratified, high:mid:low 1:0.5:0.1	Some stratification, high:mid 1:0.7-0.9	Some stratification, high:mid 1:0.4-0.7
First Floor	Well mixed	Little stratification, high:mid 1:0.9-0.95	Little stratification, high:mid 1:0.95-1
Attic Room	Well mixed	Little stratification, high:mid 1:0.95-1	Well mixed

Table. 5.2 Summary of stratification observed in the experiments

5.3.2.3. Concentration / Flowrate Consistency

The concentration measurements are generally consistent. Higher volumetric flowrates give higher concentrations.

5.3.2.4. Flowrates

For free flow releases, the volumetric flowrates for hydrogen are between 2.73 and 3.00 times greater than for the equivalent methane experiments.
For subsonic leaks the flowrate is expected to be approximately proportional to the inverse of the square root of the molecular weight, so this ratio is expected to be approximately 2.82. The experimental measurements are consistent with this expected value.

5.3.2.5. Comparison of Hydrogen and Methane Experiments

For high momentum releases (free flow releases), hydrogen releases are more likely to stratify than methane for the same release diameter and pressure.

For low momentum releases, similar stratification is observed for both gases, with the stratification being affected by the location of the release:

- Releases at high level tend to stratify
- Releases at low level tend to be well mixed
- Releases at mid-level, such as exchange flows through the gaps around doors, tend to stratify above the mid-height of the door

For the same volumetric flowrate and the same release location, the hydrogen concentrations are consistently lower than the methane concentrations.

5.4
WBS 2 Large Release Testing Part 2: Houses & Gardens

WBS 2 focused on large releases in which the gas is expected to find a way to the surface. Such large releases are typically (although not always) caused by interference, meaning that personnel are generally present at the time the release occurs. The subsequent outflow then has the potential to form first a flammable mixture with the potential for asphyxiation, followed secondly by an ignition giving rise to a fire of some description at the surface or within the excavation.

In order to compare the quantitative risk with natural gas, it is necessary to understand the outflow, crater/fissure formation in the case of buried releases, dispersion and thermal radiation behaviour of such releases with hydrogen. This formed the aim of WBS 2, and an experimental programme was developed and modified throughout to provide data suitable for model validation in these knowledge areas.

The data gathered has been used in the development of the model for hydrogen fires from distribution pipelines, which is based on the existing model for natural gas fires.

5.4.1. Method

A total of 85 experiments were performed, involving releases of hydrogen both ignited and unignited. The programme can be broken down into the following groups:

- → Set of 24 unignited experiments involving releases through circular holes in a pipe sidewall into an open excavation representative of a third-party interference. This included variations in release diameter, supply pressure and orientation to investigate the dispersing behaviour of the release.
- → Repeat set of 24 experiments in open excavations, but ignited to allow measurements of the thermal radiation field from similar releases.
- → Set of 32 unignited releases through side-wall holes and circumferential slots buried in clay that was either uncovered or covered with tarmac or paving slabs.
- → Full bore ignited releases into open excavation scenarios to simulate the worst-case catastrophic failure of a pipe.

The large release experiments were conducted with variants of the following criteria:

- → Source pressure (30 mbar to 7 barg)
- → Hole size (20 mm to 200 mm)
- → Source type (main side wall, double ended or circumferential failure)
- → Orientation (for main side wall releases)
- → Cover (open excavation, soil, soil + slabs, soil + tarmac)
- → Deliberate ignition (yes/no)

Experiments in this programme were conducted into either an open excavation or buried under a backfill material. The experiments involving releases from the release spools were performed into both open, pre-formed trenches and with backfill of varying types. The open-ended releases were all conducted into a pre-formed trench.

5.4.1.1. Measurements

The following were measured for each test:

- Fluid Pressure in Pipework – pressure of the gas in the reservoir and pipework monitored up to 10 locations
- Fluid Temperature in Pipework – measured at up to 10 locations
- Pipework Wall Temperatures – measured at up to 10 locations
- Gas Mass Flow Rate – determined using measurement of static wall fluid pressure, temperature and differential pressure across an 85 mm diameter orifice plate
- Gas Concentration – using sensors which measure the oxygen displacement by hydrogen
- Field Temperatures – atmosphere temperature above and around the release, measured at up to 25 locations
- Thermal Radiation – measured at up to 15 locations
- Overpressure Measurement – using 6 pressure transducers to measure any pressure variation above ambient pressure
- High Speed & Normal Video – to determine flame visibility and length between methane and hydrogen
- Ambient Weather Conditions – pressure, temperature and relative humidity.

5.4.1.2. Release Spools

The different spools provided one of the following release arrangements:

- 20 mm and 70 mm diameter holes in the side wall of a 200 mm pipe, see Figure 5.8 below.

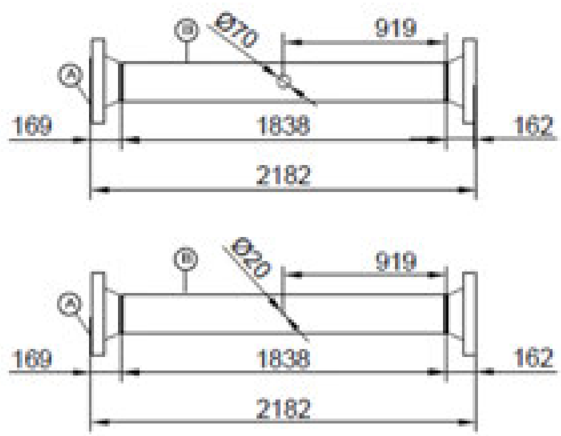


Figure. 5.8 Circular side-wall hole release spool

- 3 mm circumferential separation in a 100 mm pipe and a 200 mm pipe, see Figure 5.9 below.

Figure. 5.9 Example 3 mm circumferential separation

5.4.1.3. Open Excavations

The open excavation releases were completed in a steel trench to ensure consistency between the tests and to prevent the sides from collapsing. The steel trench was approximately 1 m deep and 4 m in length, with a horizontal edge furthest from the release and a 30-degree tapered end behind the release pipework to simulate the sort of situation which might be faced in an interference damage scenario involving an excavator. See Figure 5.10.

Figure. 5.10 Open excavation steel trench

The release pipe flanges were housed in steel boxes either side of the trench (see Figure 5.11) with access lids which enabled the pipework to be changed or turned to accommodate the different release scenarios.

Figure. 5.11 Open excavation, side-wall hole release point

5.4.1.4. Buried

The experiments involving a release from a buried pipe were completed to understand how the ground above the release would behave and what effect this might have on the outflow and dispersion of hydrogen. The release spool was buried underneath the backfill and, where required, a top sealing layer.

The reservoir was pressurised to approximately 0.5 barg above the required release pressure for each test. To initiate a release, the 6" NB actuated isolation valve was opened, and the full reservoir pressure delivered to the release point. The valve took between 12–16 seconds to open fully.

The instruments above the release point were fixed to a metal frame with a 3 m leg span to prevent the instrument supports from inhibiting ground movement. See Figure 5.12.

Figure. 5.12 Unsealed, slabs, and tarmac buried arrangements

5.4.1.5. Double Ended (Ruptures)

The 200 mm tee branch feeding the spool releases was removed for the double ended releases and replaced with open ended outlet pipe sections of either 100 mm or 200 mm, depending on the requirements of the experiment. The outlet pipes were installed leaving a 450 mm gap between the two open ends. The same pre-formed open excavation trench described earlier was installed with its major axis running normal to the outlet pipes.

10 mm thick restricting orifice plates were installed 1.4 m upstream of both ends of the pipework. Limiting the size of the restricting orifice to 20 mm diameter and using initial starting pressures up to 70 barg within the reservoirs allowed extended run time with decaying flow in these experiments, whilst providing exit conditions similar to that which might be expected in a sudden failure of a distribution pipe.

For these releases, the two 150 mm actuated valves were opened at the same time to start the release from each open end together, and to be representative of a catastrophic interference damage scenario.

5.4.1.6. Ignition

Where an experiment was to be ignited, this was achieved by the installation of an incendiary firework 'gerb' installed near to the edge of the excavation. The firework was oriented to project sparks across the top of the pre-formed trench to ensure ignition.

5.4.2. Evaluation of Results

5.4.2.1. Thermal Radiation

The thermal radiation has been well characterised by the programme of fire experiments, and some information also obtained about the visibility characteristics of these fires. The scenarios modelled an unburied pipeline simulating a trenching machine which has damaged a distribution main. A variety of damage types were included in the studies. Some of these experiments were similar to previous natural gas tests and comparisons made. The model for natural gas distribution main fires has been modified for hydrogen fires and compared satisfactorily with the experimental data.

Unignited releases in the open trench used for the fire experiments were performed to investigate the flammable hazards in the vicinity of the trench. Gas concentration measurements just above the trench were used in the development of the source model for the fires. For the scenarios where the release impacted inside the trench, resulting in loss of momentum of the release, gas concentrations measured at low levels close to the trench were significant.

5.4.2.2. Overpressures

The experiments show that although the fire hazards from unconfined releases of hydrogen generally dominate (as with natural gas), overpressures following the delayed ignition of unconfined hydrogen releases outdoors are higher for hydrogen than for natural gas. This gives the possibility of overpressure causing damage to nearby properties and hence could harm people indoors. People outdoors could also be harmed if they are close to the release at the time of ignition. The likelihood of this scenario causing a fatality is remote because it would require a very large hydrogen release combined with delayed ignition (hydrogen ignites more readily than natural gas).

Overpressures were only measured for the ignited releases from completely open pipes in the trench, and the values are a function of the outflow and wind conditions. However, these tests resulted in overpressures that could give a similar level of hazard as thermal radiation for people nearby, but only in a small subset of failures. For smaller releases such as punctures, the overpressures are likely to be much lower and have no significant effects. It is therefore considered that overpressure generation is a secondary effect that applies to a small proportion of main failures and it is not recommended that it is included in the QRA at this stage due to its minor influence over the risk posed by the gas distribution network as a whole.

Unignited buried releases were performed to investigate the ground-breaking characteristics of the release and the subsequent levels of gas concentrations above ground in the vicinity of the release. The experiments suggest that multiple routes to atmosphere may be formed for some scenarios, and that the crater may not be formed directly above the point of failure.

5.5 WBS 3 Ignition Potential

WBS 3 carried out a programme of tests to consider the ignition potential of a range of typical household items such as phones, thermostats and light switches in explosive hydrogen/air atmospheres. The purpose of this work was to begin to determine if the risks of ignition of hydrogen are greater than natural gas, and where further work may be required.

The test items, where possible, were installed as they would be in a typical domestic or operational setup, with the item under test being placed inside a 2.4m^3 test chamber or connected to an idealized spark system within the chamber, allowing the worst-case circuitry to be investigated. Hydrogen was then added to the chamber and circulated to achieve the required homogeneous mixture at an ER (equivalence ratio) of hydrogen in air. Specific operations of the device were then performed, and several cycles of the operation carried out.

5.5.1. Devices Tested

Table 5.3 details the specific equipment item or device used for each test. The arrangement of items inside and outside of the chamber was determined and the item being assessed placed inside the chamber. For example, where the light circuit is being considered, it is the ignition potential of the switch which is being assessed; therefore, the switch (and not the lamp) is within the chamber. Where no definitive single item is subject of the test, the arrangement was such that it is representative of what would be inside or outside a domestic property, with the chamber being considered as the boundary. For example, in the case of the doorbell, the push button is outside of the chamber, with the transformer and sounder inside.

Test item	Model
Mobile phone	Apple iPhone 8 Smart Ex black label smartphone replacement battery for iPhone 8
Cordless phone	BT3580 Quad Digital cordless telephone and answer machine, Item code: 086920
Thermostat	Honeywell T6360B Room Thermostat 10A connected to a Grundfos UPS 3 15-50/65 130 circulator for heating systems model A, 4 – 60 W.
Light switch	White 20 A Flush Mount Push Button Light Switch RS Stock no: 222-8266, Manufacturer part no: K4878P WHI. This was connected to a lighting circuit with a 7W LED bulb or a 230W halogen bulb.
Door entry system	Aperta audio door entry system. Power supply: EVBPSBB Electromagnetic lock: EV-ML-250 Strike lock: ENTERD
Static discharge	Van der Graaff generator: used to replicate static discharge from a person
Mechanical spark	Metal disc attached to an air-driven motor was contacted with flint stone or a steel plate to generate mechanical sparks. This is to replicate sparks caused during mechanical excavation scenarios.
Vehicle starter motor	Starter motors both new and used were for a Ford Transit Connect Model no: PIC018E2
Telecoms equipment	Baystack 450-24T network switch. Model: AL2010A14 Part No: 300798-A Rev. 1B
Cable TV equipment	DVD player with mechanical drawer. Manufacturer: Tesco Model No: TDVD213
Cigarettes	Traditional and electronic cigarettes

Table. 5.3 Equipment item tested

5.5.2. Test Setup

The rig assembly consisted of a chamber of approximately 2.4m3 with a recirculation loop and a pneumatically controlled roof frame. When in the closed position, the roof frame held a Polythene sheet in place to seal the rig. The Polythene sheet also served as a vent to relieve any pressure generated inside the chamber in the event of an ignition. A recirculating loop including a fan was installed to circulate the hydrogen/air until a uniform concentration was achieved across the chamber. A section of this loop was also made up of polythene tubing to prevent an explosion from propagating through the pipework, leading to a possible detonation. A polycarbonate window on one side allowed the tests to be remotely viewed and filmed with a CCTV camera.

Filling and venting of the chamber were controlled using five remotely actuated valves, which were manually operated using a SCADA system. The concentration in the chamber was monitored from three sample points: one at the top and bottom of the chamber, and one which could be moved to be close to the test item.

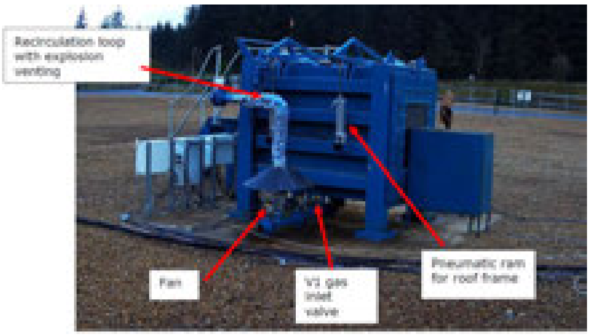


Figure. 5.13 Test Equipment Arrangement

To run a test, the required equipment item was installed in the chamber and electrically or pneumatically connected so that it could be remotely activated. Hydrogen concentration levels were raised incrementally, adding a small amount of hydrogen and allowing it to circulate before adding more to reach the required concentration. The concentration at the three sample points was monitored until the required concentration was achieved and the concentration across the chamber was uniform. The stoichiometric concentration (ideal fuel:air ratio giving complete combustion) for hydrogen in air is 29.6%. The equivalence ratio (ER) is used to allow easier comparisons between different fuels and is the ratio of fuel to air, normalised to the stoichiometric ratio (i.e. E.R = 1 is 29.6% Hydrogen in Air, ER = 0.5 is 14.8%).

Tests were carried out on each piece of equipment at a range of concentrations, detailed in Table 5.4.

Equivalence ratio (ER)	Concentration (%vol)
0.2	5.9
0.3	8.9
0.6	17.8
0.9	26.6
1.0 (stoichiometric)	29.6

Table. 5.4 Concentrations for ignition potential testing

The polyethene sheet used to seal the roof of the chamber was used as an indicator for ignition. For a vent of this size, the plastic sheeting fails at an overpressure in excess of 70 mbar. In the tests described in this report, all successful ignitions by this definition could be identified by failure of the plastic sheet.

5.5.3. Testing Results

The outline results for each item are detailed in Table 5.5.

Test Item	Result
Mobile phone	→ No ignition with actual device or battery (3.82 V) → Ignition was only achieved with a conservative inductance / capacitance circuit, using a 10 V supply after 560 cycles at ER1.0 (low ignition energy)
Cordless phone	→ No ignition with device, battery (3.3 V) or cradle
Thermostat	→ No ignition
Light switch	→ No ignition with LED bulb (7 W) → Immediate ignition with halogen bulb (230 W) at ER0.2 (high ignition energy)
Door entry system	→ Ignition after 4 cycles with whole system, including push button inside the cloud (8V – doorbell) at ER0.2 (high ignition energy) → No ignition with intercom system and mag lock only inside the flammable volume (12V)
Static discharge	→ Immediate ignition (0.3 mJ) at ER0.2 (high ignition energy)
Mechanical spark	→ Immediate ignition at ER0.2 (high ignition energy)
Vehicle starter motor	→ Ignition with new starter motor at ER0.2 (high ignition energy) but unable to repeat the result at any other concentration. → Used starter motor resulted in no ignition at ER0.2 (high ignition energy) but immediate ignition at ER0.3.
Telecoms equipment	→ No ignition
Cable TV equipment	→ No ignition (10W)

Table. 5.5 WBS 3 results summary

5.5.4. Evaluation of Results

The following key findings were obtained including a review of the results from WBS 3 testing and previous work by others:

- Electrical sources using a mains supply which are low power and mostly resistive did not give rise to ignition of hydrogen.
- Electrical sources using a mains supply with higher power and mostly resistive load achieved immediate ignition of hydrogen at the lowest Er of 0.2.
- Electrical sources with largely reactive loads, e.g. inductive (motors), gave a propensity to achieve ignition, albeit generally at a far higher level than the theoretical minimum ignition energy hydrogen requires at approximately one tenth of the minimum energy of methane mixtures (at optimum concentration).
- Hydrogen proved hard to ignite with extra-low voltage items. No ignition occurred, for example, with a cordless telephone base-station, the associated equivalent battery short-circuit, an e-cigarette or mobile phone batteries.
- In the absence of physical experiments, electrostatic sparking from a clothed person was simulated using a human body model in accordance with an IEC standard. This gave immediate ignition of hydrogen at an Er of 0.2.
- Mechanical sparking experiments, involving shovel on stone and steel, were both simulated with a rotating shovel sample striking the subject at speed. Both mechanical spark experiments gave immediate ignition of hydrogen at an Er of 0.2.
- Hot surface experiments comprised the exposure of hydrogen/air mixtures to a lit and drawn cigarette, which produced no ignitions. No ignition of hydrogen occurred in any of the H21 tests when air was being drawn through the cigarette in the normal way, which is the same result obtained in similar testing with natural gas. Only when the cigarette had burnt right down to the filter with air continuing to be drawn in after the tobacco did ignition occur.

5.6
WBS 4 Explosion Severity Testing

WBS 4 aimed to produce information on the potential for the formation of a flammable cloud and severity of the consequences should a flammable mixture ignite within typical network enclosures and street furniture. Hydrogen leakage at various representative inlet pressures were admitted into a set of enclosed spaces which may be encountered on the gas network: including wall-mounted meter boxes, GRP kiosks of varying sizes, ducts, buried enclosures and telecommunication boxes.

Measurements of explosion overpressure (inside and outside the enclosures) and flame arrival times inside the enclosure provided data on the pressure rise times, the operation of any venting devices and the failure of the enclosure if venting fails in saving the enclosure. Post-test inspection revealed the extent of any debris throw and high-speed videography allowed the speed of fragments to be assessed.

5.6.1 Method

The programme of work included a total of 37 experiments using 7 types of enclosures typically found within the gas network. The selected enclosures were:

- → Brick wall-mounted meter box
- → Telecommunication box
- → Small governor kiosk
- → Medium governor kiosk
- → Large governor kiosk
- → Buried kiosk
- → Duct

To perform the experiments, DNV GL modified and re-commissioned an existing test facility designed and built for the conduct of large vapour cloud explosions. The test facility consists of:

- → Concrete pad with central instrumentation channel.
- → Fixed instrument lines for gas analysis, ionisation probes and pressure sensors.
- → Forward recording suite to house the data acquisition and control systems a suitable distance from the test enclosure.
- → Remote control room for safe control of the test rig and data acquisition equipment.
- → Gas analysis cabin in which a thermal conductivity analyser is located to analyse gas samples on-line from the test enclosure.
- → Remote viewing area for personnel and manned video recordings.
- → Timing system capable of triggering a spark at a known time relative to other equipment (e.g. data acquisition system, high speed video).

Realistic release rates were introduced into each of these enclosures. This was achieved by providing a leak source of a known size (fixed hole size) at a known pressure into the enclosure. Monitoring of the gas concentrations within the enclosure allowed determination of the hydrogen concentration distribution within the enclosure and when a flammable mixture was observed, ignition was attempted using a low energy spark. Typically, hydrogen was supplied into the enclosures at a set pressure of either 30 mbarg, 75 mbarg, 350 mbarg, 1 barg or 2 barg from a 3 mm hole. In experiments where ignition was thought unlikely with the low energy spark, a small chemical fuse was installed and fired in the event of non-ignition from the spark to give a better chance of ignition.

5.6.2. Measurements

The following measurements were undertaken:

- → Gas supply pressure
- → Gas concentration prior to ignition
- → Temperature and relative humidity inside the test enclosure
- → Overpressure (internal and external)
- → High speed and normal speed video
- → Ambient weather conditions

5.6.3. Evaluation of Results

The following conclusions can be drawn from the experimental data:

- → The internal overpressures are consistent for the different types of enclosure and show the expected trends with hydrogen concentration. The external overpressures are consistent with the internal overpressures and show the expected variation with distance from the enclosures.
- → The hydrogen experiments give much higher overpressures compared with natural gas in similar enclosures. The general trend to produce much higher overpressures with hydrogen as opposed to natural gas is due to the much more rapid combustion of hydrogen and, for the types of enclosures in the current study, the inability of the weakest part of the boundary to fail quickly enough to relieve the overpressure.

Example still images from high-speed video showing explosion events:

5.7 WBS 5 Operational Safety Testing

Work package WBS 5 from Phase 1b demonstrated a limited set of network operations involving hydrogen. These demonstrations were specified to provide preliminary insight into the practicalities and safety of operations required for commissioning, conversion, repair and decommissioning of gas network assets. The demonstrations were categorised into the following types:

- → Purging (air to hydrogen, hydrogen to air, methane to hydrogen)
- → Isolation (e.g. bag stop, squeeze off)
- → Excavations to find and access leaks (e.g. barholing, road breaking, excavating, air lance) and repairs (e.g. live service cut off, ECV changeover)

The results of the Operational safety testing (WBS 5) are not included in this report and shall be included in the H21 Phase 2 project report, but an overview of the demonstrations is included in the following sections.

5.7.1. Flow loop facility

To perform the demonstrations, a purpose-built flow loop facility was commissioned, consisting of a 24" diameter steel loop with two parallel sections of 12" pipe, one above ground and one below ground, in a reinforced pre-formed trench. The above ground pipework was constructed from steel and the buried pipe constructed from 315 mm PE pipe. The 24" steel section could also be used as a reservoir when performing purging trials in the smaller legs.

A set of bespoke demonstration procedures were designed to show the effectiveness of existing procedures for natural gas. For example, when performing purging operations, a selection of supply pipework, vent arrangements and source pressures was made to typically represent those that would be used today for a natural gas purging operation.

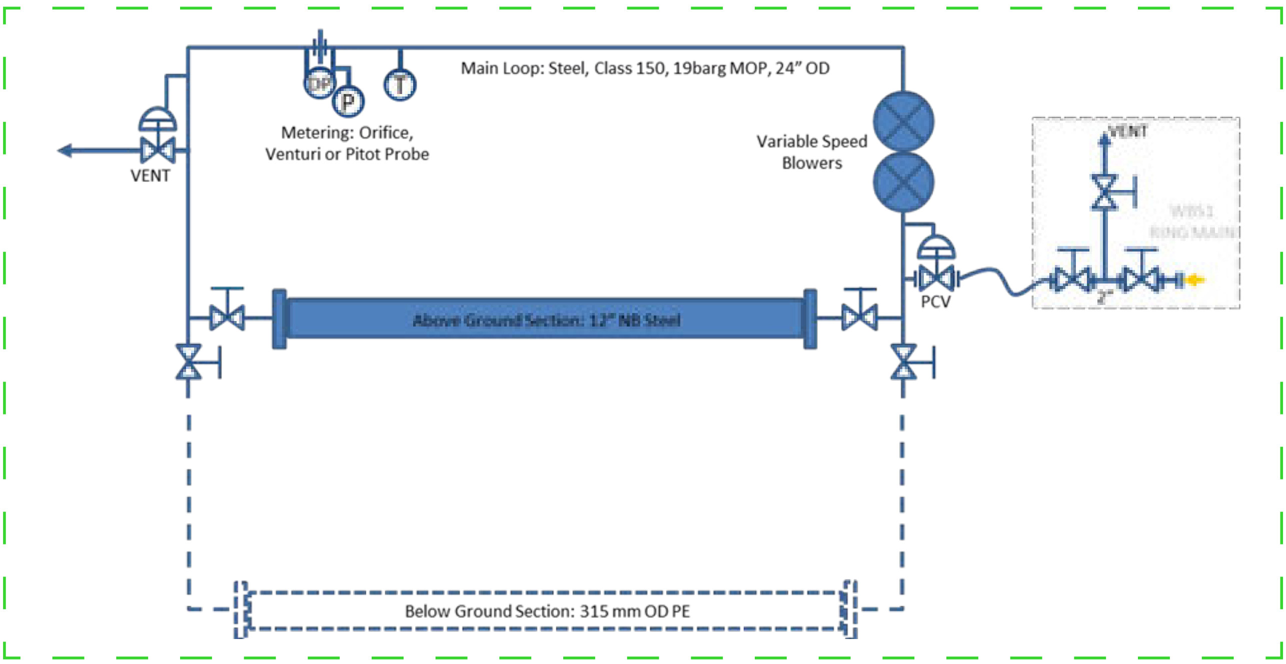


Figure. 5.14 Flow loop facility

5.7.2. Purging

The purge operations were conducted on the nominally 50 m long section of 315 mm PE pipe whilst still above ground, prior to it being lifted into the preformed trench. The effectiveness of the purge was then assessed by monitoring gas concentration instrumentation.

Figure. 5.15
Purging inlet and outlet arrangement

The following test programme was determined and considers the purging operations expected to be carried out during conversion activities. This included a range of pressures that the network operates at, as well as the use of purge ejectors.

Test	Pressure
Air to hydrogen	30 mbar 350 mbar 2 bar
Methane to hydrogen	30 mbar 350 mbar 2 bar
Hydrogen to air using a Steve Vick purge ejector	Atmospheric

Table. 5.6 Purging Test Programme

5.7.3. Isolations

Isolation of the hydrogen gas stream was performed with both 'Squeeze Off' and 'Bag Stop' techniques, with the rate of any gas passing the isolation at the various pressures being measured to assess the suitability of each technique.

The following test programme was implemented and considered the flow stopping operations which are typically carried out on PE pipe. This included the use of both squeeze off and bag off equipment.

Test	Pressure
Effectiveness of seal of secondary bags	30 mbar
Effectiveness of seal of primary bags	30 mbar
Effectiveness of seal of secondary squeeze offs	2 bar
Effectiveness of seal of primary squeeze offs	2 bar
Squeeze off (single)	34 mbar

Table. 5.7 Isolation Test Programme

Examples of the bag stop and squeeze off operations are given below:

Figure. 5.16

'Squeeze Off' and 'Bag Off' isolation arrangements

5.7.4. Excavations to find Leaks and Repairs

5.7.4.1. Excavations

The 315 mm OD PE pipe was fitted with a number of remotely operated leak sources, and then the pre-formed trench was backfilled with clay. The trench was covered in sections with a hot rolled asphalt road covering, a tarmacadam footpath covering and concrete slabs, typical of pavement. Using the now backfilled and covered pre-formed trench, finding and accessing leak demonstrations could be conducted where the remotely operated leaks were activated and leak finding activities conducted.

The following test programme of excavations, Table 5.8, was undertaken including excavations of varying sizes under different surface coverings.

Test	Pressure	Release size	Backfill	Surface covering
Excavation	30 mbar	10 mm	Sand padding and local clay	Type A road
Excavation	30 mbar	10 mm	Sand padding and local clay	Tarmac footpath
Excavation	30 mbar	10 mm	Sand padding and local clay	Paved footpath
Excavation	30 mbar	10 mm	Sand padding and local clay	Type A road
Excavation	30 mbar	10 mm	Sand padding and local clay	Tarmac footpath
Excavation	30 mbar	10 mm	Sand padding and local clay	Paved footpath

Table. 5.8 Excavation test programme

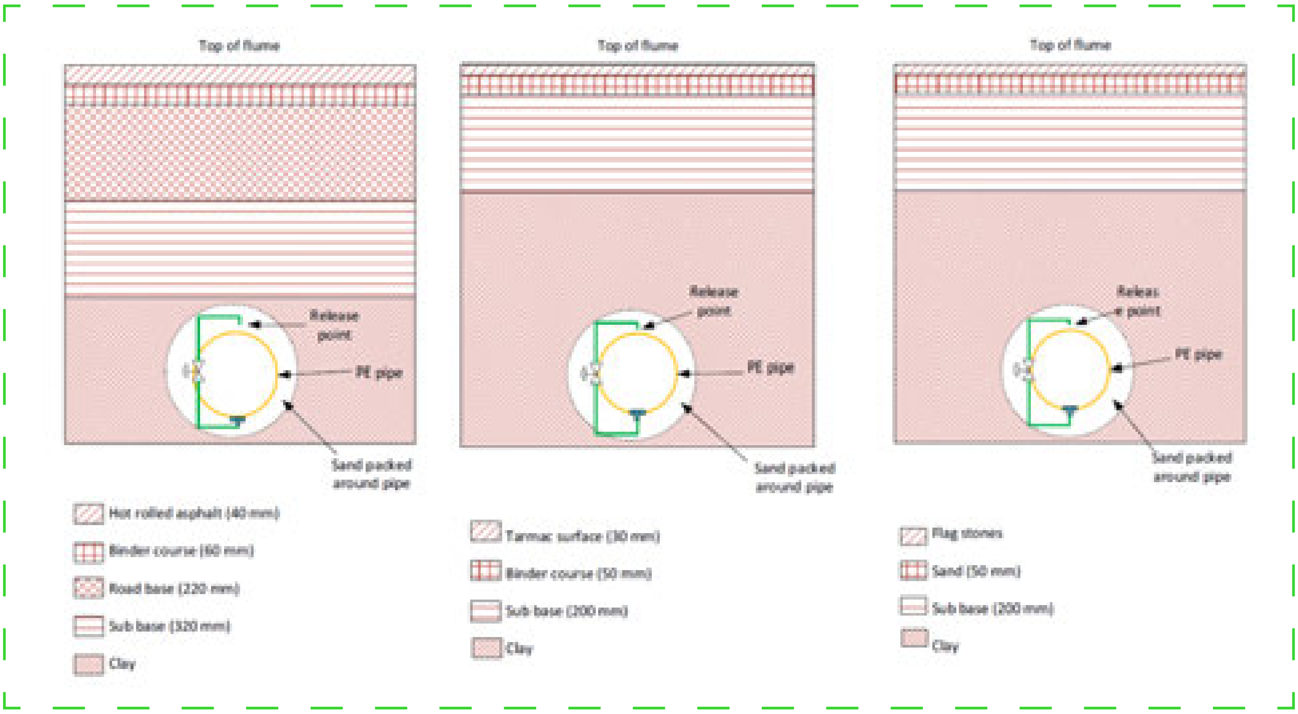


Figure. 5.17
Backfill configuration for surface coverings

Figure. 5.18
Actuated valve arrangement for remotely operated buried releases

Figure. 5.19
Tarmac road and paved flagstones

Surface cover	Gas sampling locations created by:	Surface covering removal tool	Excavation tool
Road surface	Rock drill (depth 380 mm)	Hydraulic Breaker	Toothless bucket
Tarmac footpath	Pin bar (depth 230 mm)	Hydraulic and Pneumatic Road Breakers	Toothless bucket
Flagged footpath	Pin bar (between flag stones) (depth 230 mm)	Toothless bucket	Air lance / Toothless bucket

Table. 5.9 Excavation tools

In line with NGN operating procedures, a range of tools were used as part of the excavation activities. The tools to be used for each excavation are identified in Table 5.9.

Figure. 5.20 Remotely operated excavator

A remotely operated excavator was then used, using the various tools, to break out surface coverings and excavate on the live leaks. The excavator had a proprietary remote-control system fitted which allowed operation at a range of up to 50 m. Three CCTV cameras were fitted allowing a full view to the operator as they would have had from the cab.

5.7.4.2. Repairs

The following three repairs activities were undertaken:

Test	Pressure	Release size
PECAT flange bolt replacement	30 mbar	12” flange joint
ECV replacement using ECV exchange kit	30 mbar	25 mm PE pipe
Flow stop operation –PE Service Pipe Squeeze off	30 mbar	25 mm PE pipe

Table. 5.10 Repairs test programme

PECAT Flange Bolt Replacement

PECAT flanges were welded to each end of the PE pipe test section and used to secure the test section into the flow loop, as in Figure 5.21. NGN procedures allow replacement of the bolts in the flanges where they have been damaged or corroded whilst the pipeline is at low pressure, typically 30 mbar. Every second bolt was removed whilst the pressure in the loop and oxygen cells were monitored. With 10 out of 12 bolts removed, approximately 5% hydrogen gas was detected on one of the oxygen cells at either side of the flange.

Figure. 5.21 PECAT flange on end of PE pipe section

ECV replacement using ECV exchange kit

NGN carry out ECV replacements on live systems as part of their routine operations with natural gas. The purpose of this demonstration was to determine if similar operations can be carried out with hydrogen.

The ECV was attached to approximately 5 m of 20 mm PE pipe which was in turn fed with hydrogen via a series of valves from the 4” reservoir. The ECV was closed and the section of PE pipe pressurised to 30 mbar with hydrogen and then isolated. The plunger was then fitted to the ECV, the valve opened, and the plunger deployed to seal the pipe, after which the ECV could be removed and replaced.

Figure. 5.22 ECV with plunger in place

Flow stop operation – PE service pipe squeeze off

Upon completion of the ECV replacement, the PE pipe was squeezed off, the ECV opened and gas measurements taken to assess if the squeeze off had been successful.

The following section contains information collated from the DNV GL reports listed in section 10.0 References

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6.0

QRA

6.1 Objectives

In order to consider the relative risks associated with the different properties of hydrogen versus natural gas, a Quantitative Risk Assessment (QRA) was undertaken as part of the evaluation of the safety of a hydrogen distribution network. 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. Once established, the QRA methodology for hydrogen 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 component and joint leakage and third-party interference. The QRA required the existing natural gas distribution QRA model to be modified first, to enable the necessary calculations to be performed for hydrogen. This was performed in stages, as summarised below.

- → Part A: Information gathering
- → Part B: Preliminary QRA model for hydrogen and gap analysis
- → Part C: Preliminary risk analysis and risk evaluation
- → Part D: Refine QRA model and risk results for hydrogen
- → Part E: Application of QRA results, risk remediation and mitigation

6.2 PART A

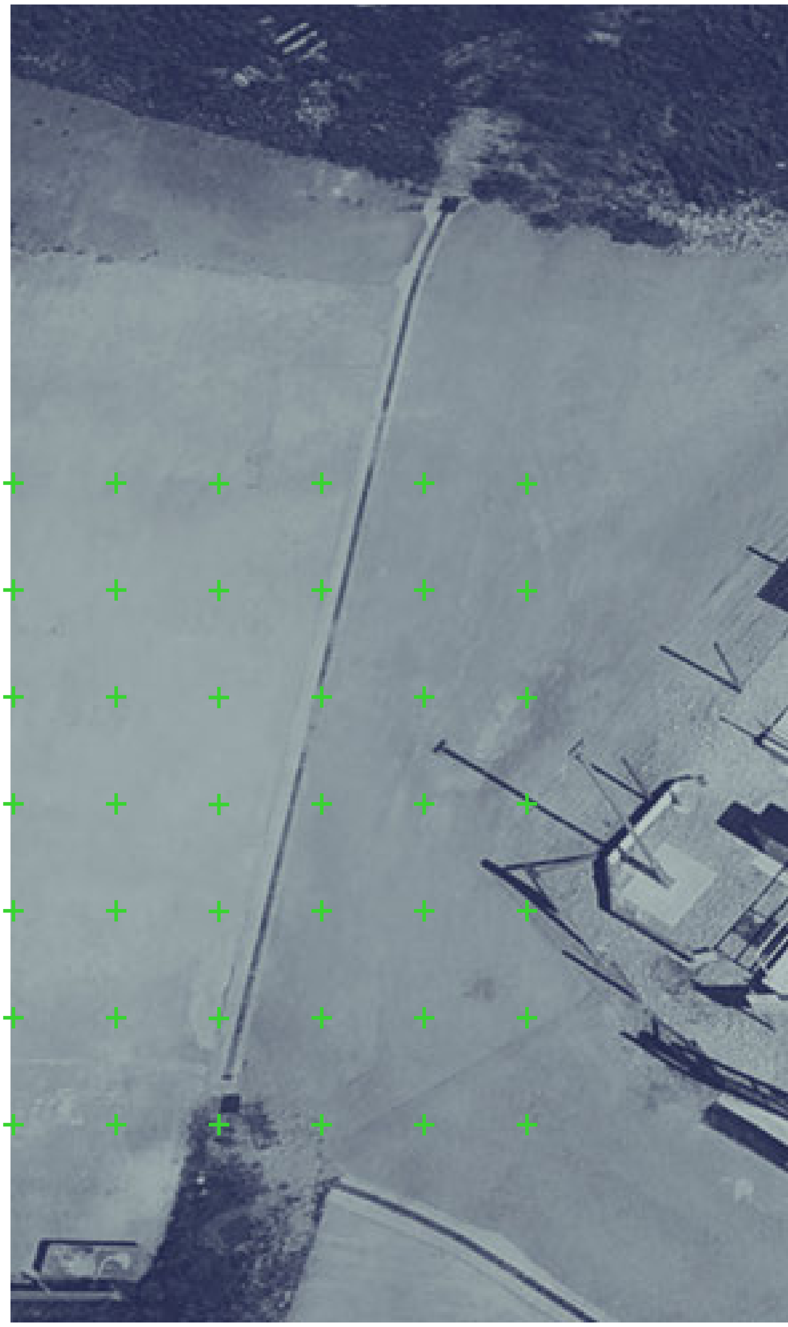
Information Gathering

A literature survey of publicly available documents has been carried out in order to gather information that is relevant to the development of the QRA model. This included previous experimental or test data that could be used to validate models, and modelling approaches developed by others. The research focused on:

- General Background Information
- Pipelines
- Below Ground Releases
- Ignition
- Explosions
- Releases in Enclosures
- Releases in Built-Up Areas
- Risk Assessment
- Projects
- Statistical Data

Information was obtained from various sources including:

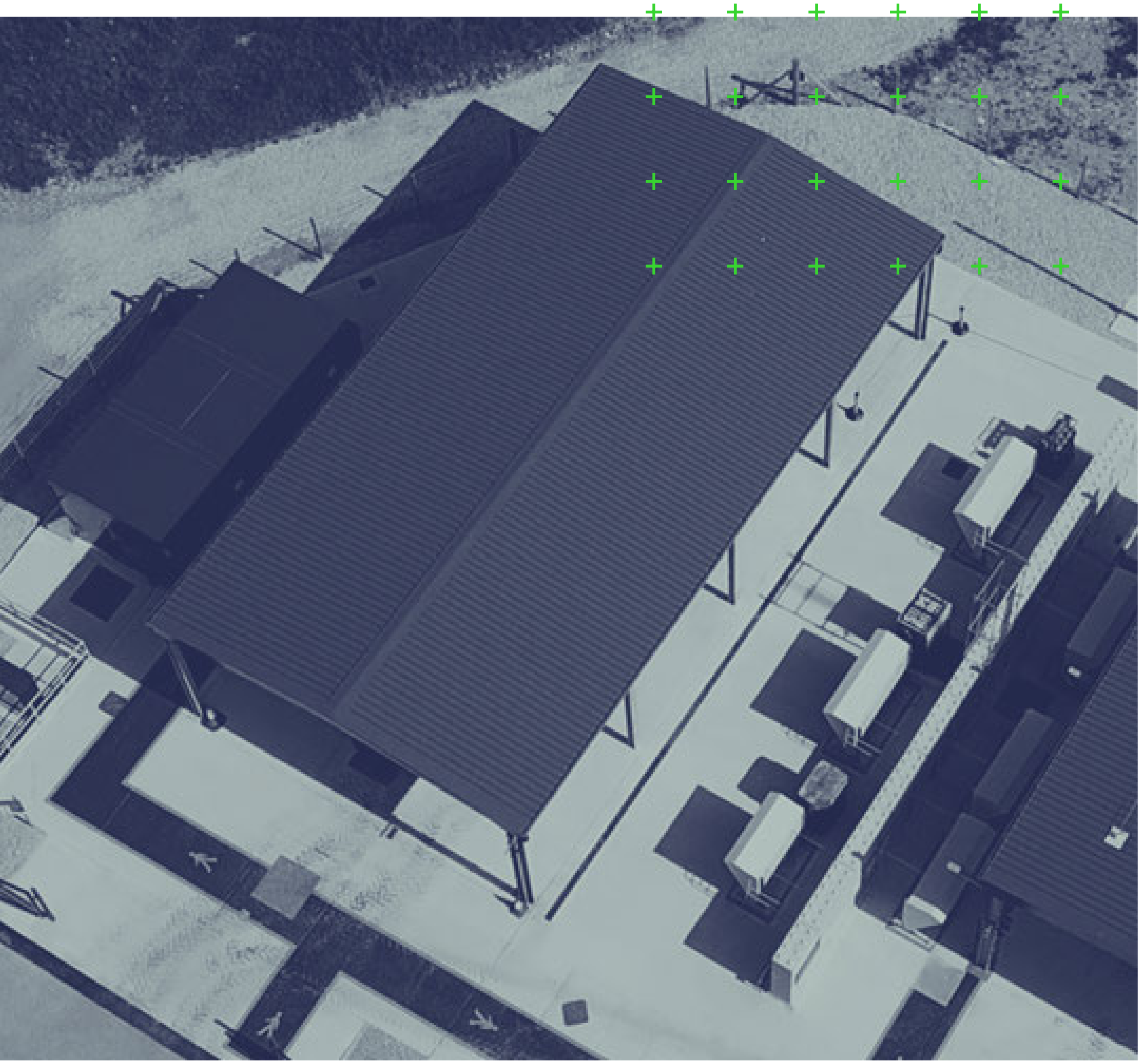
- Statistical Data from NGN
- Various Reports from DNV GL
- Various Reports from the HSE Science Division
- Documents from Universities, Laboratories and associations from around the world.



6.3 PART B
Preliminary QRA model for hydrogen and gap analysis

The risk assessment model for hydrogen distribution mains is based on an existing software package that was developed to assess the risk associated with natural gas PE mains.

The structure of the model is shown in Figure 6.1. Each of the numbered steps in the figure contains a detailed sub-model that cannot be reduced to a simple set of equations, as most of the sub-models perform complex calculations in their own right.



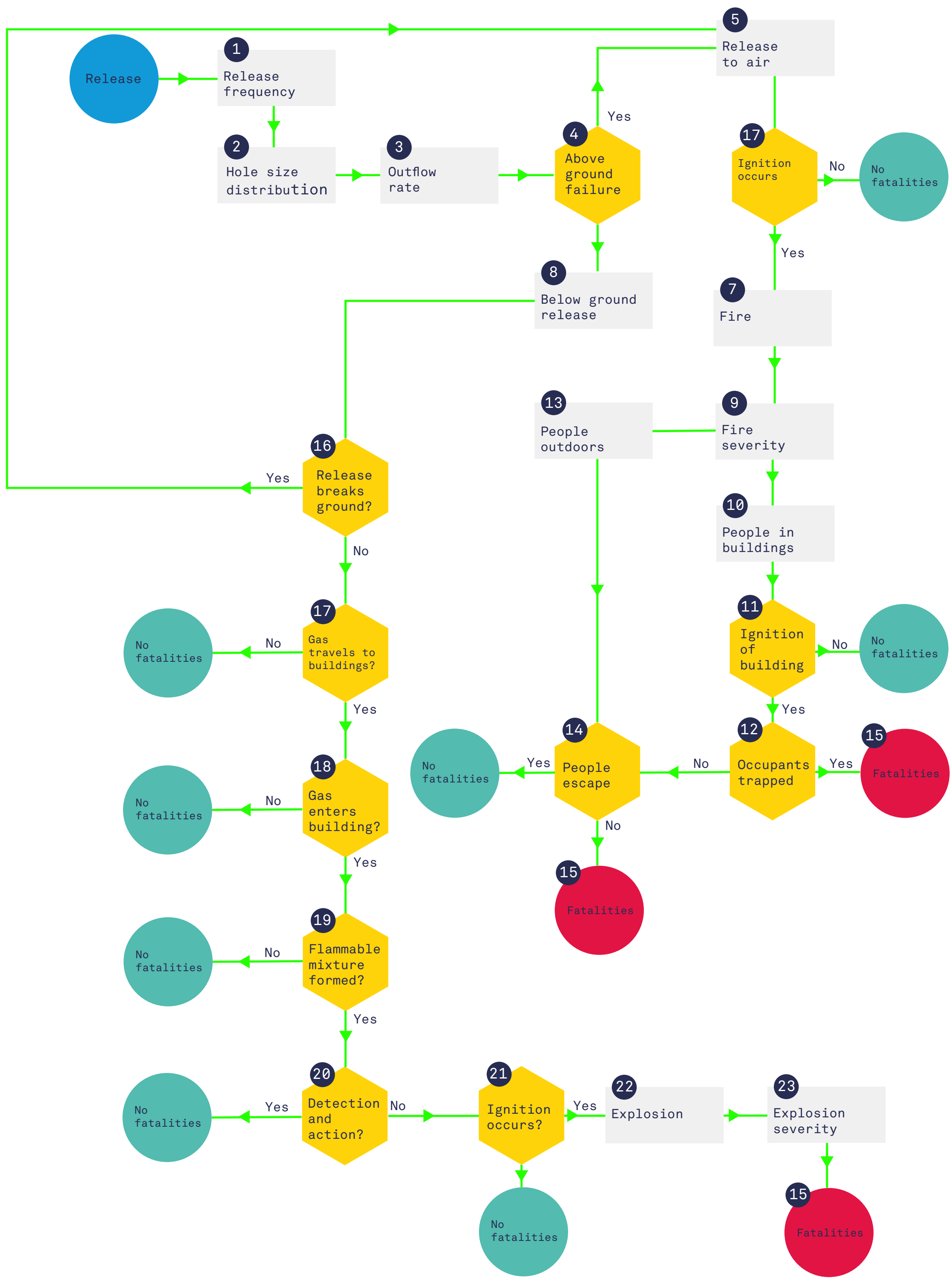


Figure. 6.1 The risk assessment model for hydrogen distribution mains

A brief description of each step and the applicability of the natural gas model to hydrogen is given in Table 6.1 below.

Steps	Description	Modifications/ Improvements
1: Release frequency	The frequency of any release occurring 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.	The existing values are adequate for the preliminary QRA and the initial comparison between natural gas and hydrogen.
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.	The existing values are adequate for the preliminary QRA and the initial comparison between natural gas and hydrogen. Incident 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.	The model works well for natural gas and hydrogen, as validated by the Phase 1b test data.
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.	The existing values are adequate for the Phase 1 QRA and the initial comparison between natural gas and hydrogen networks.
5: Release to air	A release occurs that is open to the atmosphere.	None required.
6: Ignition occurs outdoors?	The ignition probability is calculated for above ground releases.	The approach for natural gas is based on historical data and used a correlation based on mass flow rate. A similar approach is used for hydrogen, but the ignition probability is higher.
7: Fire	A fire occurs.	None required.
8: Below ground release	A below ground release occurs, with covering soil still in place.	None 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.	The models perform well for hydrogen, as validated using Phase 1b test data.
10: People in buildings	At least some people in the vicinity of the fire are located inside buildings.	None required.
11: Ignition of building?	The possibility of the thermal radiation igniting the building is considered.	The current methodology is adequate for natural gas and hydrogen.
12: Occupants Trapped?	A proportion of the building's occupants are assumed to be unable to leave the building.	The current methodology is adequate for natural gas and hydrogen.
13: People outdoors	At least some people in the vicinity of the fire are located outdoors.	None required.
14: 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 current methodology is adequate for natural gas and hydrogen.
15: Number of fatalities	The number of fatalities is recorded for each event and occupied location and summed appropriately.	The current methodology is adequate for natural gas and hydrogen.
16: Release breaks ground?	The probability of the release breaking through the covering soil in determined. Both above and below ground cases are analysed.	The approach in the model is assumed to be the same for natural gas and hydrogen.
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.	The Phase 1b experimental programme provides a large quantity of data. A new outflow and gas migration model has been developed.
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.	The approach in the model is the same for natural gas and hydrogen. This is adequate for a relative comparison of risk for natural gas and hydrogen networks, but will be reviewed in Phase 2.
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.	A more detailed gas accumulation model has been incorporated into the package, including more detailed representations of buoyancy and ventilation effects.
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.	Existing values are adequate for a relative comparison between natural gas and hydrogen networks. 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 and 75% of ignition sources are assumed to be related to the presence of people.	The ignition model has been updated to provide more transparency and to allow further development during Phase 2, when releases inside buildings will be included in the analysis.

22: Explosion	An explosion occurs.	None required.
23: Explosion severity	The overpressure generated by the explosion is calculated. This is used to determine the probability of an individual becoming a fatality.	The explosion model has been updated to include hydrogen predictions.
24: Number of fatalities for explosions	The number of fatalities is recorded for each explosion event and occupied location and summed appropriately.	The explosion severity calculations are adequate for natural gas and hydrogen . The methodology has been updated to include damage to buildings adjoining the structure in which the explosion originates.

Table. 6.1 Summary of the risk assessment model

6.3.1. Initial Risk Assessment Model Changes

The following changes were made to the risk assessment model as part of the initial review to allow hydrogen mains to be represented:

→ The ability to model hydrogen, in addition to natural gas, has been included.

→ Thermodynamic parameters such as the density and viscosity that were previously fixed and applicable only to natural gas have been replaced by calculated values that depend on the specified fluid composition.

→ The model used to predict the radiation from above ground hydrogen fires, has been recalibrated based on existing data for high pressure hydrogen pipelines.

→ 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.

These changes have been made to improve the methodology for natural gas and hydrogen:

→ The manner in which multiple individual points are linked to represent single buildings has been improved. The fundamental methodology has not changed, but the potential for error in specifying parameters that describe the building has been reduced.

→ Within the explosion calculations, rooms and cellars are assumed to be rectangular rather than square. The length of the longer side is assumed to be 1.5 times the length of the shorter side.

→ This manner in which output is written to the results database has been streamlined.

→ The explosion predictions for flammable gas in buildings are carried out with the current version of the confined explosion model.

6.4 PART C

Preliminary risk analysis and risk evaluation

Predictions were made for a range of mains with operating pressures of between 30 mbarg and 7 barg, and with diameters of between 63 mm and 630 mm. The example mains were selected to be consistent with the experiments being carried out at the Spadeadam test site. The preliminary analysis included only the mains and did not include the risks from services and installations such as governors. It considered 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).

This preliminary assessment suggested that the overall risks from hydrogen could be greater than those from natural gas, with greater explosions risks partly offset by lower risks from fires. This therefore became the focus of future development of the QRA model.

6.5 PART D
Refine QRA model and risk results for hydrogen

Modifications to the existing natural gas QRA methodology to accommodate hydrogen were made in the light of information obtained from a number of sources, in particular the results of a series of large-scale experiments carried out for the H21 project in Phase 1b. Specific details of the modifications to the natural gas QRA methodology are included in the DNV GL Phase 1b Evaluation reports listed in Section 10 – References.

6.5.1. Results

After modifications were made to the CONIFER risk assessment model with the benefit of access to the results of the Phase 1b experimental programme, and associated model development work, the analysis shows the following:

- → The risks from fires are lower for hydrogen than natural gas.
- → The risks from explosions are higher for hydrogen than natural gas.
- → Explosions are predicted to be a greater contributor to the societal risk than fires.

Overall risks from hydrogen could be greater than those from natural gas, with greater explosion risks, partly offset by lower risks from fires and therefore further potential mitigation measures will need to be assessed.

6.6 PART E
Application of QRA results, risk remediation and mitigation

Following completion of the QRA model development in Part D, the final model developed through this process has been used to evaluate the risk posed by a more realistic hydrogen network. This evaluation is based on data supplied by NGN, comparing natural gas and hydrogen and including consideration of the effectiveness of selected mitigation measures.

The calculations were based on real network asset data supplied by NGN for the NGN network, providing detailed information on the locations and properties of the range of distribution mains and service pipes, together with data on buildings and their positions relative to the pipeline network. Population data acquired by NGN has also been used to inform assumptions on the occupancy of buildings. The detailed predictions were then extrapolated to give an estimate of the overall risk for the GB gas distribution networks.

The methodology is cautious and, in comparison with recent historical experience, the predicted risks for gas escapes from the natural gas networks are higher than observed. Nevertheless, the QRA package is suitable for assessing the relative risks from a natural gas and hydrogen networks on an equivalent basis.

The QRA results presented here relate only to the risks to the public from a gas distribution network, defined as the gas supply system upstream of the consumer ECV, which may be located inside or outside the property. The results do not, at this stage, include the risk to the public from gas escapes downstream of the ECV. This will be addressed in Phase 2 of the H21 project, in order to provide a holistic assessment of the overall risks.

The QRA results presented here predict 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). The study considers only those parts of the distribution system operating at up to 7 bar and does not include the Local Transmission System (LTS) that operates at higher pressures, or installations (such as offtakes, pressure reduction sites etc) on the gas network. The base case analysis includes detached, semi-detached and terraced houses and bungalows, but not multi-occupancy buildings.

6.6.1 Societal Risk Summary

The predicted Potential Loss of Life (PLL) is a measure of the societal risk that can be expressed as a single numerical value and represents the average number of fatalities that would be expected to occur on the network, per year. The PLL for the network can be calculated by summing over all the possible fire and explosion events, for all main and building configurations that are considered.

This section contains an estimation of the societal risk posed by the gas distribution network across the whole of Great Britain, based on the results for NGN's network. It is assumed that there is one meter per service on the network, such that the following information can be used to estimate the risk associated with the whole GB network:

→ The NGN network has 2,273,503 domestic services

→ The entire GB network has 25,115,000 meters

It is assumed that 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. This analysis assumes that the population 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 GB.

Based on the numbers of services and meters given above, the PLL values for the NGN network can be scaled up by a factor of 11.05 to give the overall risk for the GB network but it is acknowledged that the model predictions are conservative.

DNV GL provides an incident investigation service that covers all the major UK gas networks, and an analysis of DNV GL's records shows that:

- Between 2010 and 2019, the average fatality rate due to releases of gas from upstream of the ECV was approximately 0.40 fatalities per year.
- Between 2000 and 2019, the average fatality rate for these types of releases was approximately 0.65 fatalities per year.
- There were more than 4 serious injuries, typically involving hospitalisation and potentially life-altering injuries, for every fatality.

Therefore, the predictions of fatality risk in the QRA model are too high by around a factor of 5, although it compares well with frequency of fatalities and serious injuries combined. Using a factor of 5, Figure 6.2 shows the '2020 - Natural Gas', and the '2032 - Hydrogen Planned Replacement' PLL for the whole GB network.

In addition, the graph includes two possible mitigated hydrogen cases, discussed later in this document:

Option 1 — 2032 - Hydrogen, Additional Replacement – (refer to section 6.6.3.1) the completion of all currently planned replacement activities, plus the following:

- The LP metallic mains with diameters between 8 and 18 inches are reduced to 10% of their 2020 population.
- An additional 20% of the metallic mains in all other categories are replaced, not including IP mains.

Option 2 — 2032 - Hydrogen, All LP/MP Replaced – the completion of all planned replacement activities, plus replacement of all remaining metallic mains in the LP and MP pressure tiers (refer to section 6.6.3.1).

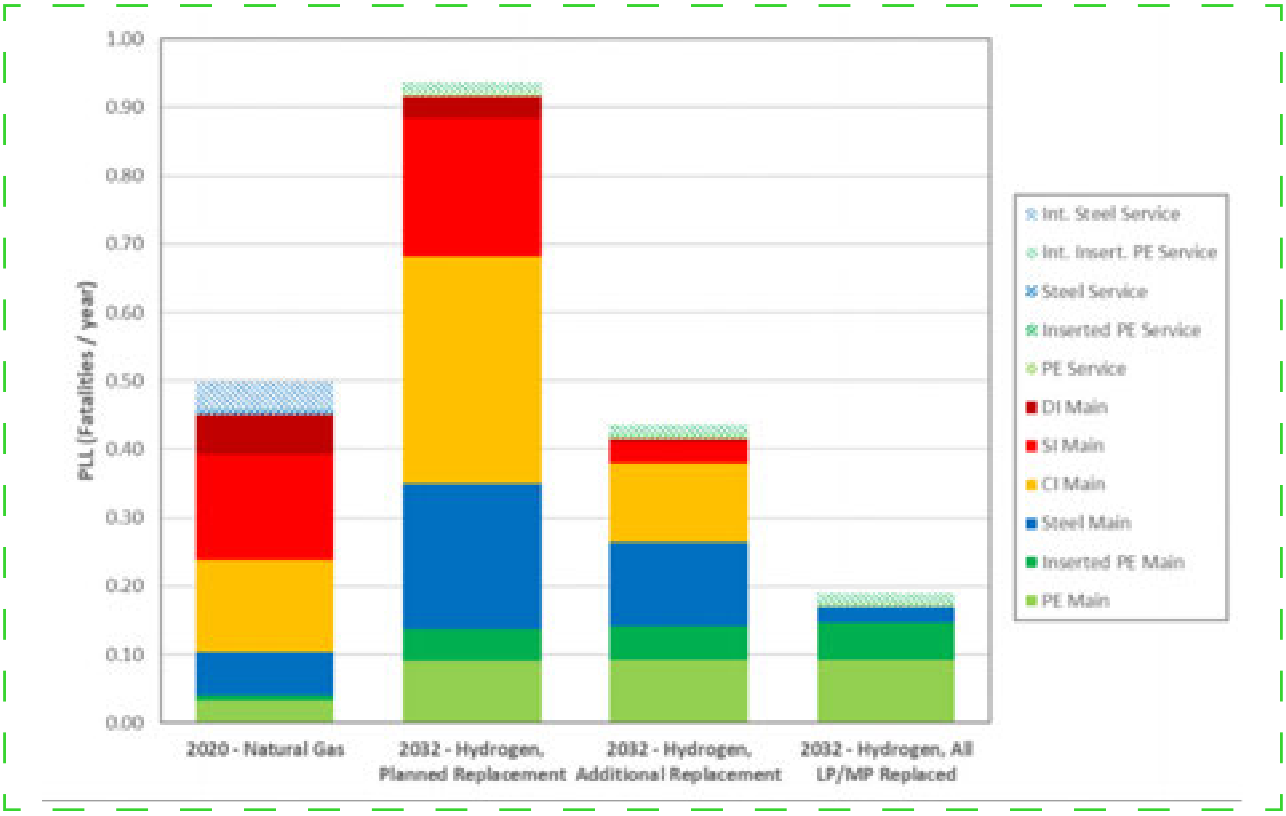


Figure. 6.2 Estimated PLL for the whole GB gas distribution network, showing detail of the two most relevant cases with two possible further mitigation options.

The results show that, without further mitigation, the risks to the public would be expected to be higher for hydrogen than for natural gas, for a particular distribution network, although the risk remains very low. The addition of further mitigations measures demonstrates that it is possible to achieve the aim of ensuring that the risk to the public from a future hydrogen gas network can be no greater than that for a natural gas network today.

The analysis of risk reduction and potential mitigation measures are discussed in the following sections of this report.

6.6.2. Risk Reduction Analysis

The contributors to the societal risks from the 2032 hydrogen network have been further examined, as shown in Figure 6.3 to Figure 6.6 utilising the data from the NGN network. The PLL values include contributions from mains and services, as indicated.

The results presented show that the main contributors to the PLL are explosions due to spontaneous failures of metallic mains and services. Releases from mains and services in the LP, MP and IP pressure tiers contribute 60.4%, 37.1% and 2.5% of the PLL respectively, as in Figure 6.3. Pipes with diameters up to 8 inches, between 8 inches and 18 inches, and of at least 18 inches, contribute 24.2%, 52.8% and 23.0% of the total PLL respectively, as in Figure 6.6.

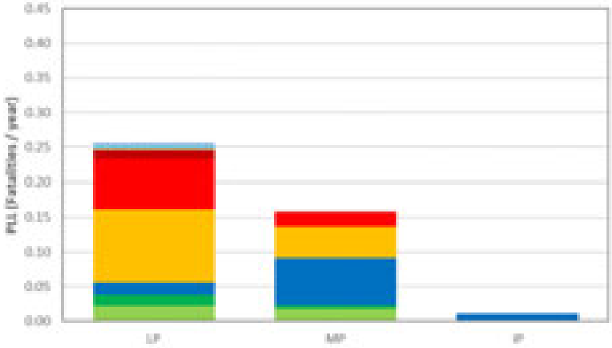


Figure. 6.3 Pressure tiers

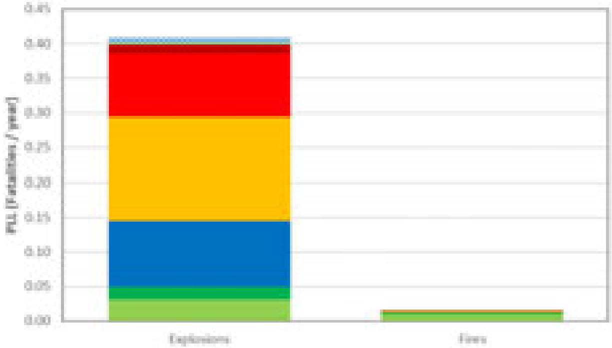


Figure. 6.4 Hazards

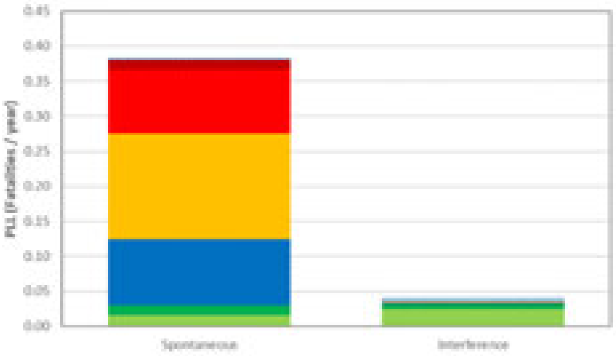


Figure. 6.5 Failure modes

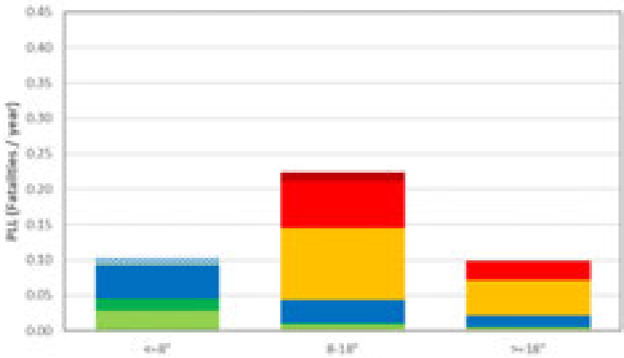


Figure. 6.6 Pipe diameter

In addition, Figure 6.7 below shows the contributors to the PLL for the 2032 hydrogen case, split by pressure and diameter tiers. This shows that LP iron mains with diameters greater than 8 inches and less than 18 inches are the greatest contributor to societal risk, with 0.16 fatalities per year, or 38.4% of the total.

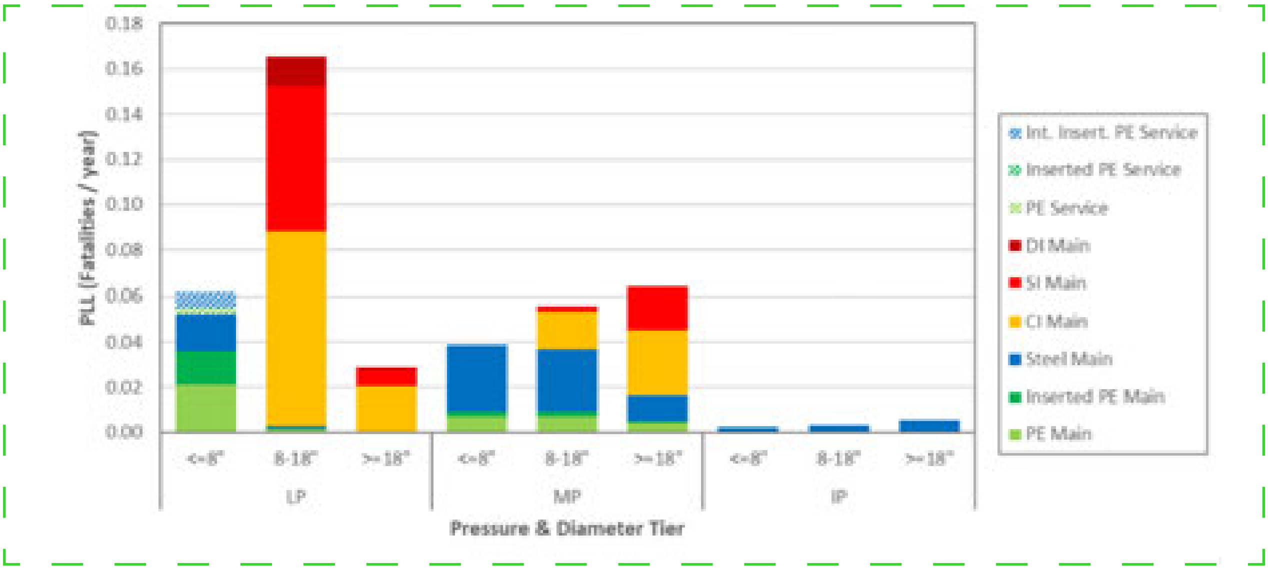


Figure. 6.7 Contributors to the NGN network PLL, for the 2032 hydrogen case, by pressure and diameter combined.

6.6.3. Potential Mitigation

The base case results include an indication of the benefits provided by the replacement of metallic mains and services with PE that is already planned for completion in 2032. In order to achieve a comparable risk level similar to 2020 natural gas, further mitigation measures must be considered.

6.6.3.1. Replacing Additional Metallic Pipes

The replacement of metallic mains and services between 2020 and 2032 is important because it reduces the frequency of gas releases. This is in line with the hierarchy that is often applied to risk reduction measures, where preventing a release entirely is preferable to mitigating the consequences.

As an example, the following options are considered:

Option 1 – '2032 – Hydrogen – Additional Replacement' represents the completion of all planned replacement activities, plus the following:

- → The LP metallic mains with diameters between 8 and 18 inches are reduced to 10% of their 2020 population
- → An additional 20% of the metallic mains in all other categories are replaced, not including IP mains.

Option 2 – '2032 – Hydrogen – All LP/MP Replaced' represents the completion of all planned replacement activities, plus the replacement of all remaining metallic mains in the LP and MP pressure tiers. This results in a predominantly PE network with some IP steel mains.

In the above cases, any replacement of metallic mains is applied uniformly across the relevant group of mains. This corresponds to random replacement of mains within that category, rather than a targeted risk-based approach, which would achieve a greater risk reduction. Within the scope of this calculation, it is not practical to specify exactly which mains would be replaced for these various options.

6.6.3.1.1. Results

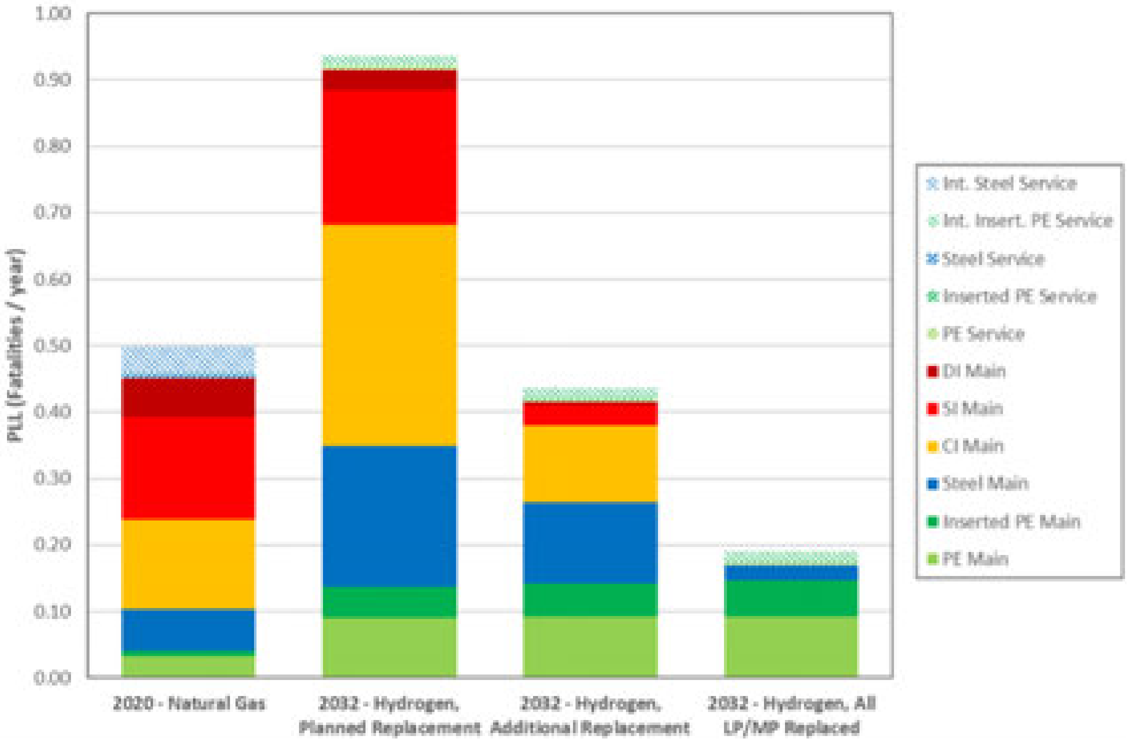


Figure. 6.8 Estimated PLL for the whole GB gas distribution network, showing detail of the two most relevant cases with two possible further mitigation options

The PLL for the 2032 hydrogen case is 1.88 times greater than the PLL for the 2020 natural gas case, with around 83% of the hydrogen risk being associated with the metallic mains that are forecast to remain in the system based on current replacement plans. The risk mitigation measures considered demonstrate that it is possible to reduce the PLL associated with the whole distribution network further. This allows the hydrogen gas distribution network to be operated at the same or lower overall risk level as the current natural gas network, with credible and practical risk reduction measures.

6.6.3.2. Moving Internal Meters

50% of houses are assumed to have an internal meter in the base case assessment. Internal meters are assumed to have an average of 2 metres of pipework inside the house, upstream of the ECV. This allows for some houses that have a greater length and some houses having a shorter length of pipework upstream of the ECV. The assessment reviewed the benefit of moving all meters to an external location, or immediately inside the building, to effectively remove all internal pipework upstream of the ECV.

6.6.3.2.1. Results

Removing all internal services gives a PLL reduction of less than 0.01 fatality per year, or 1.6% of the base case total societal risk. However, this nevertheless represents a 72.6% reduction in the risk associated with the services. Note that this analysis does not include any corresponding increase in the frequency of releases downstream of the ECV, as the total length of pipework inside a house is likely to remain approximately the same if the meter is moved to an external location.

6.6.3.3. Reducing the Pressure of Mains

The base case assessment has been carried out under the assumption that the operating pressures of all mains and services are the same when carrying natural gas or hydrogen. It is acknowledged that converting to hydrogen could involve some pressure increases in the distribution network in order to supply the same energy as the current natural gas system, due to differences in thermodynamic properties such as density and calorific value. However, there are parts of the current natural gas system that are currently operated above the minimum pressure required to supply customers, so the potential benefit of reducing the pressure in the mains has been examined. Note that this also gives an indication of the potential increase in risk if any increases to the operating pressures are required.

Two cases have been considered, separately reducing the pressures of the LP and MP parts of the network. The IP network is not included as it provides only a very small percentage of the overall risk.

→ In the base case analysis, it is assumed that 10% of the LP network operates at 30 mbar, 80% at 40 mbar and 10% at 60 mbar. The effect of reducing the pressure of the LP distribution system so that half operates at 40 mbar, and half operates at 30 mbar, has been examined.

→ In the base case analysis, it is assumed that 10% of the MP network operates at 350 mbar, 10% at 1 bar and 80% at 2 bar. The effect of reducing the pressure of the MP distribution system so that 10% operates at 350 mbar, 80% at 1 bar and 10% at 2 bar has been examined.

6.6.3.3.1. Results

Reducing the pressures at which some of the LP network operates gives a PLL reduction of less than 0.02 fatalities per year for the hydrogen network, or 3.9% of the base case value. Reducing the operating pressures of the MP network results in a PLL decrease of around 0.04 fatalities per year, or 10.3% of the base case value. The risk reduction would be lower if applied to an entirely PE network, but could still be considered if the pressure reduction can be achieved without significant cost or operational issues.

6.6.3.4. Protective Measures

Protective measures such as slabbing over pipelines and the installation of markers can reduce the frequency of third-party damage to pipelines. The predicted results show that releases due to third-party damage contribute approximately 9.7% of the overall PLL for the 2032 hydrogen network.

6.6.3.4.1. Results

The reduction in PLL is 0.03 fatalities per year when all mains are protected, corresponding to a 7.2% reduction from the base case. However, the reduction in the PLL is less than 7 × 10-4 fatalities per year when only IP mains are protected, which is less than 0.6% of the base case. These reductions are small relative to other risk reduction measures and would likely incur high installation costs for measures such as concrete slabbing.

6.6.3.5. Fitting Excess Flow Valves

The effect of installing excess flow valves where the services join the LP mains has been examined. This reduces the risks from large releases from the service but does not affect the risk associated with the main. Two cases have been considered, where it has been assumed that the valve will close if the flow rate of hydrogen exceeds 40 m3/hour and 20 m3/hour.

The value of 20 m3/hour is approximately the possible lower limit for excess flow valve activation, based on the capacity of boilers and other common household appliances. The value of 40 m3/hour is included as a second case to show the sensitivity of the results, as a shut-off point higher than 20 m3/hour would likely be required in order to avoid inconvenient 'false alarms' when multiple appliances are in use and there is no hazardous release.

6.6.3.5.1. Results

It is found that 97.8% of the 2032 hydrogen case PLL is due to releases from the mains, which are not affected by the excess flow valve. Hence, excess flow valves have a relatively small effect on the overall PLL, achieving a reduction of around 0.6%.

Note that this analysis does not include any benefit from the mitigation of releases downstream of the ECV, where the risk reduction could be more significant. The analysis shows that there would be little extra benefit for fitting an excess flow valve at the connection of the service to the main, compared to an excess flow valve fitted in the vicinity of the meter.

6.7 QRA Summary

The QRA methodology developed for hydrogen, as implemented in the CONIFER QRA package, has been used to predict the risks for a gas distribution network following conversion to 100% hydrogen for comparison with the equivalent risks for the existing natural gas network. Potential risk mitigation measures applied to a hydrogen gas distribution network have also been considered. The calculations are based on real network asset data supplied by NGN for the NGN network, providing detailed information on the locations and properties of the range of distribution mains and service pipes, together with data on buildings and their positions relative to the pipeline network. Population data purchased by H21 has also been used to inform assumptions on the occupancy of buildings.

The methodology is cautious and, in comparison with recent historical experience, the predicted risks for gas escapes from the natural gas networks are higher than observed. Nevertheless, the QRA package is suitable for assessing the relative risks from a natural gas and hydrogen networks on an equivalent basis.

The results show that, without additional mitigation, the risks to the public would be expected to be higher for hydrogen than for natural gas, for a particular distribution network. The interactions between the different aspects of the calculations are complex, but important factors resulting in the increased risk include the higher ignition probability for hydrogen than natural gas and the possibility of more severe explosion overpressures. The legacy population of metallic mains and service pipes dominates the predicted risks.

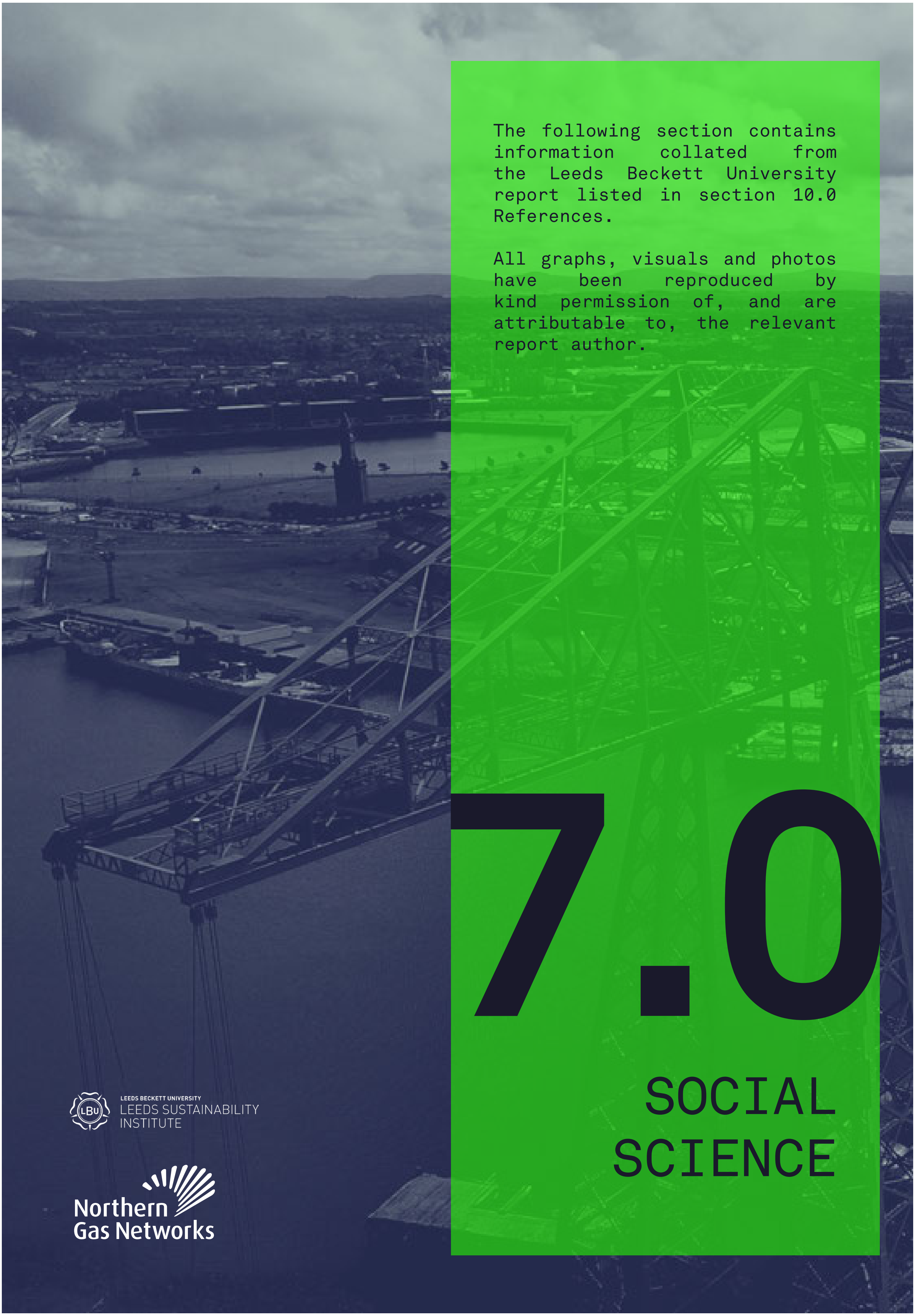
The potential risk reductions for selected risk mitigation measures have been evaluated. The measures selected were focused on those whose main effect is to reduce the risk associated with releases from the network itself. Measures that mainly affect the risk from releases downstream of the ECV, including the meter installation, will be considered in Phase 2. The measures considered here included:

- → Replacement of legacy metallic service pipes and mains
- → Relocating internal meters and ECVs from an internal position to an external wall
- → Limiting the pressures in the LP and MP networks
- → Protective measures against interference damage
- → Fitting excess flow valves at the point of interconnection between mains and services

Replacement of the remaining legacy LP and MP metallic mains and services pipes with PE pipes was the most effective measure to reduce the risk for hydrogen. Replacement of all the remaining LP and MP legacy metallic mains and services is predicted to reduce the level of societal risk for hydrogen to just 38% of the level associated with the existing natural gas network. This is consistent with the reduction in risk achieved by the ongoing replacement programmes and indicates that replacement of the remaining population of metallic pipes would achieve the aim of ensuring that the risk to the public from a future hydrogen gas network is no greater than that for a natural gas network today. However, it should be noted that it is not necessary to replace every metallic main and service, and that targeted replacement could achieve this aim.

Other measures, although beneficial, had a smaller effect on the overall risks. However, these potential risk mitigation measures should still be considered, as they could provide sufficient safety benefit to be implemented, independently of any metallic pipe replacement programme. The corresponding cost benefit analysis is outside the scope of this project.

The risk assessment model CONIFER developed during H21 Phase 1 enables the effectiveness of different risk mitigation measures to be quantified. The results do not, at this stage, include the risk to the public from gas escapes downstream of the Emergency Control Valve (ECV). This will be addressed in Phase 2 of the H21 project, where the results from the Hy4Heat project will be included in order to provide a holistic assessment of the overall risks.



The following section contains information collated from the Leeds Beckett University report listed in section 10.0 References.

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7.0

SOCIAL SCIENCE

LEEDS BECKETT UNIVERSITY
LEEDS SUSTAINABILITY INSTITUTE

Northern Gas Networks

7.1 Objectives

Currently there is limited understanding of public perceptions of hydrogen, or what information people need in order to make an informed choice about using hydrogen in their homes. There are also concerns that misunderstandings could present barriers to the uptake of hydrogen technology.

Gaining greater understanding of public perceptions is crucial to ensuring the success of future policy and investment.

7.2 Method

A multi-stage process was developed to identify the attitudes that the public have towards a potential conversion of their domestic gas supply to hydrogen:

01 Discovery Interviews

02 Online Survey
Larger Population sample

03 Groups
Examining Similarities and Differences between Groups

04 Conclusions
Explaining a Hydrogen Conversion

7.3 Discovery Interviews

7.3.1 Scope

The first stage comprised a series of discovery interviews, which explored how to talk to people about hydrogen and the H21 project and the things that were likely to interest and concern them.

This stage forms the foundation of the research and ensures that later stages explore areas that are relevant to the public and likely to differentiate their responses, rather than focusing only on those areas of interest to the researchers. The interviews covered:

- current and previous use of gas in the home
- how and why energy is valued
- thoughts on where gas and electricity come from
- imagined responses to a scenario of the current gas supply ceasing, and being replaced with an unspecified “new gas”
- and at the end of the interview, their response to this “new gas” being hydrogen

12 participants were interviewed, selected to ensure we included people with a range of experiences and domestic settings, for example, people who live in urban and rural areas, those who live alone, those who live with children or a partner, those who live in their own home, and those who rent. We analysed the interviews and the results were used to inform the second stage of the project.

7.3.2 Results

Our results from the discovery interviews showed that most participants had given very little thought to where their gas and electricity comes from, and had very little interest in it, although a few were concerned about fracking. They had not previously considered their domestic heating as a source of carbon emissions and were surprised that there may be a need to change their gas supply in the future. They had very little concern about safety of either their current supply or a future hydrogen supply. They were more concerned about getting enough notice of a future change so that they don't buy new appliances that would soon become obsolete. Following the discovery interviews, we identified several points of difference in our participants' responses which were taken forward into the next stage of the study.

Beliefs about the environment

People's beliefs about the environment, and the actions they currently take to be more environmentally friendly, are likely to influence their response to a hydrogen conversion.

Beliefs about inconvenience and cost

People's beliefs about the inconvenience and cost of changing the gas network, and of changing their appliances, are also likely to influence their response.

Beliefs about safety

There was consensus amongst the discovery interview participants that, if hydrogen is piped into their home, it will be safe to use. This suggests that concerns about safety are less likely to differentiate how people respond to a hydrogen conversion.

Beliefs about the economic impact

Beyond concerns around personal cost and inconvenience, participants displayed wider beliefs around the economic impact of a change in gas supply and how it may affect national priorities such as health and welfare.

7.4
Engaging a Larger Population Sample

7.4.1 Scope

This stage aimed to engage with a larger population sample to gain more detailed insights. An online survey was developed to identify attitudes to a hydrogen conversion, and how these align with energy-related attitudes and behaviours. The survey questions were informed by the findings of the discovery interviews.

Data was analysed to identify a meaningful classification system that groups people based on their support for an environmentally driven change to their gas supply, and their level of support for using hydrogen in their homes. Adopting a segmentation approach such as this is useful for defining groups that have a higher propensity for behaviour change and enables persuasive communication to be developed, tailored towards group attitudes.

Over 1,000 respondents (n=1027), representative of the UK population in terms of age, gender and geographic location completed the survey. Respondents were recruited by a fieldwork panel agency. Demographic details of the sample are shown in Figure 7.1.

The survey explored:

- → General views and attitudes towards the environment - environmental behaviours, views on climate change and awareness of domestic fuel sources
- → Current gas usage and thoughts on gas supply - current gas usage at home, beliefs about greener energy and preferences for gas versus electricity
- → Reactions to a potential change to the gas supply - reactions to the type of gas change, switching to hydrogen, key concerns and most appealing messages

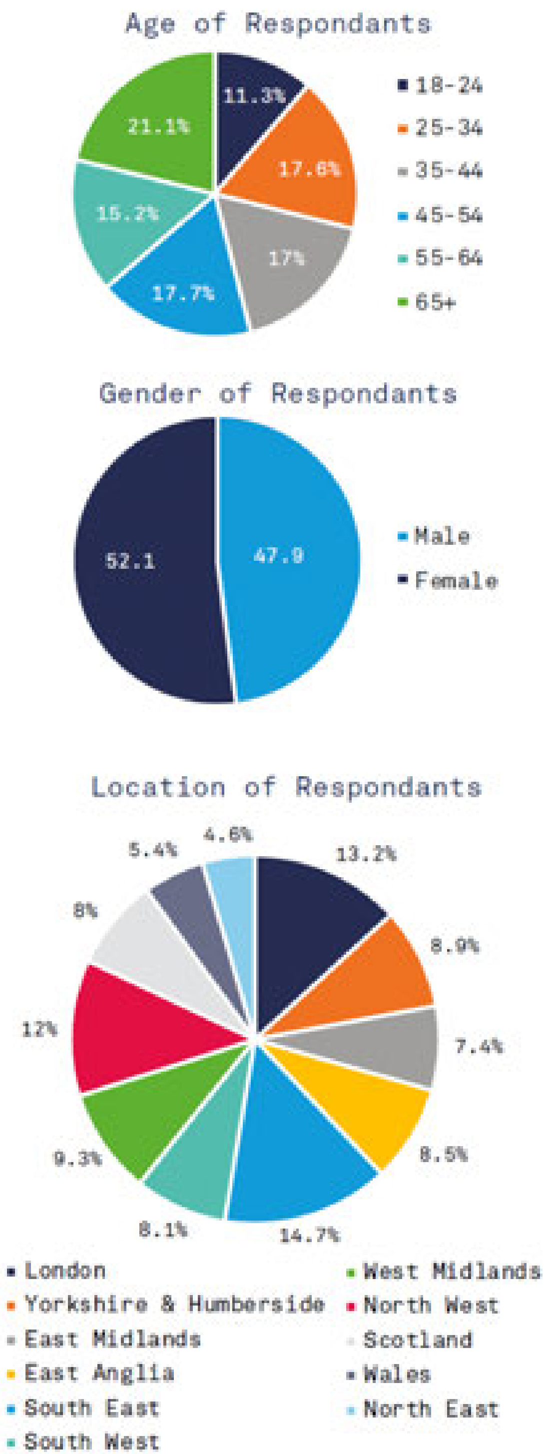


Figure. 7.1 Source – H21: Public perceptions of converting the gas network to hydrogen, Social Sciences Study, Page 11, Leeds Beckett University, June 2020.

7.4.2 Results

Subgroups were formed by examining responses to two questions (see below), which gave 49 possible combinations of responses. We defined our population subgroups by identifying combinations with similar responses to the survey questions, as opposed to a priori clustering based on theoretical assumptions. This produced five different groups, shown in Figure 7.2.

What are your feelings towards the potential change to the type of gas supplied to your home?

Very | Concerned | Slightly concerned | Not sure | Quite positive | Positive | Very positive

How do you feel about using hydrogen to run your heating/cooking?

Strongly against | Against | Slightly against | Not sure how I feel | Slightly in favour | In favour | Strongly in favour

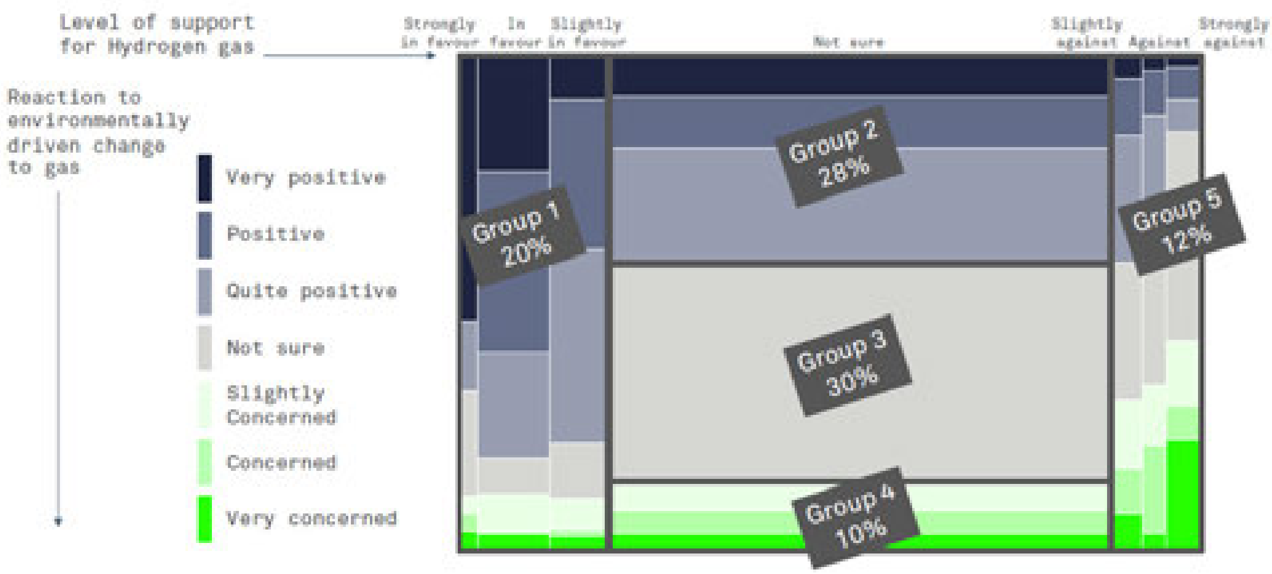
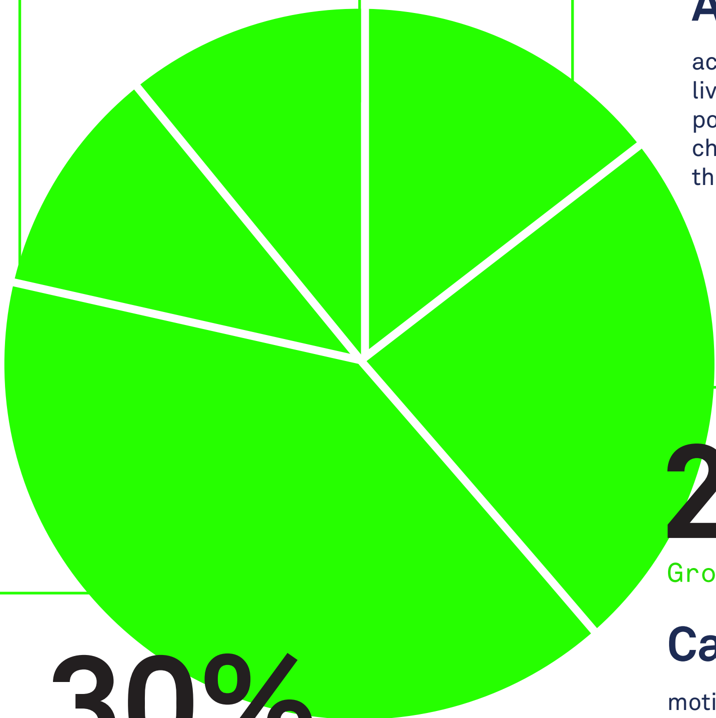


Figure. 7.2
Source – H21: Public perceptions of converting the gas network to hydrogen, Social Sciences Study, Page 13, Leeds Beckett University, June 2020.

There was broad agreement that investing in technology to support environmental wellbeing was a priority: **Messages that highlight the environmental benefits of hydrogen are well received.**

There was, however, scepticism amongst all groups around the motivations behind environmental action and the transition to hydrogen: **It is important to be clear on motivations and benefits.**

7.4.2 Results continued...



12%

Group 5

Rejecters

sceptical of the role of humans in climate change and of the motivations for a hydrogen transition and reluctant to make life changes to improve the environmental impact.

10%

Group 4

Unconvinced

unconvinced that a transition to hydrogen is the most appropriate response because they do not have sufficient knowledge of the issues.

20%

Group 1

Accepters

accept changes to their lives that have the potential to reduce climate change and improve the environment.

28%

Group 2

Cautious

motivated by climate change, but less confident in their knowledge and understanding of climate change issues.

30%

Group 3

Disinterested

disinterested in the hydrogen transition.

7.5
Group Perspective

7.5.1 Scope

Having established the profiles of the individual groups, the next stage of the research was to examine similarities and differences between the groups. This aims to **identify messages** that have the potential to be effective in influencing multiple groups. Identifying differences also provides an indication of which messages may be ineffective for certain groups.

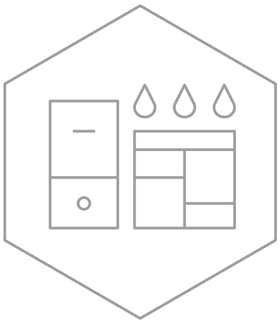
7.5.2 Results

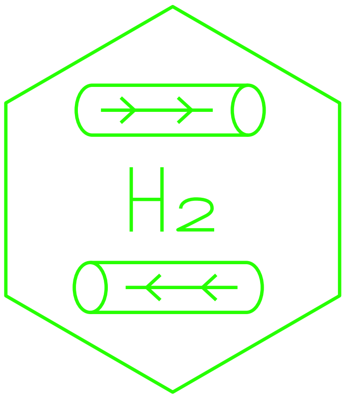
Most respondents in all five groups agreed that investing in low carbon energy technologies is a key part of investing in the environmental wellbeing of the earth and, further, that investing in the environmental wellbeing of the earth should be a top governmental priority.

Groups 1 and 2 are more supportive, with Group 3 less likely to have an opinion. This suggests that messages around hydrogen that highlight the potential for environmental benefits may resonate with all groups, regardless of scepticism on specific aspects. This does, however, present a challenge in framing the message to differentiate hydrogen from other renewable technologies that share the same environmental benefits.

Another area in which the groups show similar responses is beliefs about the motivations behind the transition to hydrogen and believing that other national concerns should take priority over a hydrogen transition. As would be expected, Group 3 (disinterested) shows a higher proportion of people who do not have an opinion on these topics. When framing messages around hydrogen, it is therefore important to ensure there is not an 'either/or' narrative that implies that other national priories will be overlooked if the hydrogen conversion goes ahead. Messages should also be clear around the motivation for change, why specific actions have been taken, and the benefits these bring.

Differences between groups emerge more clearly on beliefs about the current gas causing environmental damage and whether other countries are prepared to take action to tackle climate change. The results show that Groups 1 and 2 have a different pattern of responses to Groups 3, 4 and 5. The latter – in particular Group 5 (rejecters) – are less likely to believe that their current type of gas is causing climate change. Groups 4 and 5 are more likely to believe that there is no point in the UK taking action to tackle climate change because other countries will not do so.





7.6
Explaining a Hydrogen Conversion

7.6.1 Scope

It is particularly important to communicate effectively with Groups 2, 3 and 4 because they form a large proportion of the population (68%) that is undecided about their response to a potential hydrogen conversion. They will be unable to make an informed choice about using hydrogen in their home if they receive information that they misunderstand, or that generates unnecessary fears. In this stage of the research, we worked with people in these groups to explore their response to hydrogen as a domestic fuel and, together with hydrogen experts, co-designed explanations of the hydrogen conversion.

To find out how to explain a hydrogen conversion to people, we held deliberative workshops with members of the public and hydrogen experts. The experts were members of the H21 project team, the Health and Safety Executive team and the DNV GL team conducting safety tests. Deliberative workshops are facilitated group discussions that encourage participants to explore an issue in depth, challenge each other's views, and to consider evidence on the issue so that they can reflect on it and reach an informed view. Our participants all attended two workshops. In the first, we introduced the concept of a hydrogen conversion and facilitated discussion between the public and the experts. In between the two workshops, participants were given the task to interview a friend or family member about the conversion and send us the audio recording of the interview. The same participants returned for the second workshop two weeks later. They discussed their experiences of conducting the interviews and the responses of their interviewees. Together with the experts, they co-designed explanations of the conversion.

7.6.2 Results

We identified six themes that describe the questions and concerns that people had about a potential conversion. The insight gained at this stage of the research was used to develop a set of explanations of the hydrogen conversion that people find relevant and easy to understand.

Justifying a hydrogen conversion

Sceptical about the impact of a UK hydrogen conversion on global carbon emissions, believed that there is little point in the UK converting to hydrogen if other countries are not going to do so.

Where does hydrogen comes from?

Few were aware of different methods of producing hydrogen and most accepted that, in the short term, the process of producing hydrogen would involve carbon being captured and stored, although several had concerns about whether carbon dioxide can be stored securely.

Cost

Unconcerned about the estimated 7% gas bill increase should a conversion go ahead, although concerned more vulnerable people might struggle. Concerned about the need to purchase new appliances and wanted reassurance that there would be an incentive scheme to help with the cost.

Safety

Safety was not a major concern, assumed that if supply is converted to hydrogen then it will have been robustly tested and found to be safe.

Practicalities

What they would need to do to prepare for a conversion, most assumed the impact would be minimal. Will there be disruption from roads being dug up to replace pipes, how long the process would take, whether they would notice any difference in how their appliances work, and how they would find out about the conversion. Nobody asked how long their gas might be disconnected for, instead assuming that it would be hours rather than days.

Timing and certainty

Concerned about whether a decision will be made about the conversion quickly enough to prevent irreversible environmental damage arising from climate change, and also that people would be given sufficient notice so that they can avoid purchasing expensive appliances that soon become obsolete.

7.7 Outputs

This final set of explanations address what people want to know should a conversion go ahead, so they assume the decision to convert has already been made.

Why are we converting to hydrogen?

The gas that we currently use to heat our homes – methane – releases carbon dioxide when we use it, and carbon emissions are causing climate change. Hydrogen doesn't contain any carbon: it only produces water and heat when we use it. By converting to hydrogen, we will protect the environment.

Do we have to convert to hydrogen?

You will be unable to keep using methane when your area is converted, as it will no longer be available. It doesn't matter which company currently supplies your gas, as they will all change from supplying methane to supplying hydrogen. But you can choose to use electric appliances instead, if you prefer.

When will the conversion happen?

It will start in the late 2020s, and gradually the whole country will be converted by 2050.

Will it cost more?

It will cost a little more, and we expect that people's bills will rise by less than 10%.

What do we need to do to be prepared?

Over the next few years, hydrogen-ready appliances will be available. If you have one of those, then when your area is converted, a gas engineer will visit your home and simply make some adjustments to your appliances. If you don't have hydrogen-ready appliances, you will need to replace them. There may be incentive schemes to help with the cost.

Will I get more information?

You will receive lots of information and lots of notice of when your home will be converted. Information officers and gas engineers will be visiting every property to make sure everybody knows what is happening and to check that the conversion will go smoothly and safely.

Will hydrogen use the existing gas network?

Yes, so there will be no need to dig all the roads up to replace all the pipes. Disruption will be minimised.

How is hydrogen produced?

Hydrogen is the most abundant gas in the universe, but pure hydrogen doesn't exist in nature; it's always in other chemicals. For example, hydrogen is in water: it is the H in H20. At the moment, there are two main ways of producing hydrogen. We can break up water into hydrogen and oxygen, and this will be the main method in the future as technology improves. At the moment, most hydrogen is made from methane gas. Methane is four hydrogen atoms and one carbon atom, so we can remove and store the carbon, leaving hydrogen.

Where is the carbon dioxide stored?

It's stored securely in underground rocks and caverns where the methane originally came from. Once a cavern is full of carbon dioxide it is sealed and regularly inspected to make sure it remains safe.

Is hydrogen safe?

There are extensive safety tests being carried out to make sure that it is at least as safe as the current gas. These tests include tests of the pipes to make sure that there are no risks from leaks, as well as tests on homes. One of the major risks from the current gas is carbon monoxide poisoning, and hydrogen does not have this risk, as it does not contain any carbon.

Are any other countries converting?

There is a lot of interest from other countries, and many are also planning to convert. The UK is trying to lead the world in developing hydrogen technologies and therefore protecting the environment.

8.0

FURTHER RECOMMENDATIONS

8.0 Further recommendations

Upon completion of the project the following further recommendations have been made:

8.1 Phase 1a

- It is current practice in industry to inject Mono Ethylene Glycol (MEG) as a swelling agent to counter the drying out of lead yarn joints, which contributes to network shrinkage, this practice will need to be reviewed during a conversion to 100% hydrogen based on the mains population present at the time of conversion.
- The Phase 1a project did not examine the long-term impact of hydrogen on the materials in the gas network after 2032, which should be studied further.
- Demonstrate the safety or effectiveness of operations such as live repairs on assets under hydrogen pressure.
- Analysis of leak data in terms of pressure steps and leaks rates.

8.2 Phase 1b

- It is recommended that the outflow model is run for a wider range of cases within the QRA package. For example, the model might include releases from the top, side and bottom of the pipeline, combined with varying another parameter such as the permeability of the soil or the presence and size of the void.
- It is recommended that mechanical sparking of shovel on steel and shovel on stone experiments using natural gas/air mixtures should be undertaken for direct comparison with the range of hydrogen mixtures used in the H21 work programme.
- Wetting or use of damp cloths has been reported as being a mitigation in natural gas PE pipes, by reducing the charge on the outer wall of the pipe. This does not affect the charge on the inside wall. Insufficient data is available on the effectiveness of this method in reducing the potential for ignition of hydrogen mixtures so further investigation is recommended and will be covered in the H21 Phase 2 project.
- Static discharge experiments representing a clothed person produced immediate ignition at the lowest concentration of 5.9% hydrogen in air. Further investigation is recommended with similar experiments using natural gas/air mixtures for closer comparison.

8.3 QRA

- Possible further developments of the QRA methodology are recommended to refine the calculations, including obtaining further data on the frequency of gas leaks and the effective hole sizes that can result particularly relating to PE leak hole sizes as little data exists for leaks of this type.
- The results do not at this stage include the risk to the public from gas escapes downstream of the ECV, which will be addressed in Phase 2 of the H21 project, through liaison with the Hy4Heat project, in order to provide a holistic assessment of the overall risks.
- Further consideration to risk mitigation options and the statistical benefits that various opportunities/options could provide.
- The QRA addresses the risk for domestic properties and should consider extending for commercial and industrial on the below 7 bar consumers.

8.4 Social Science

The results highlight the need to develop a suite of communication resources for the general public. We recommend that this includes:

- A glossary of terms that explain the key concepts underpinning a hydrogen conversion and the safety testing that has been completed. This could be used in communication resources such as leaflets for the general public.
- An animation that explains the reasons for a hydrogen conversion and what it involves, including how hydrogen is produced and how any captured carbon is safely stored.
- An interactive display to demonstrate how hydrogen is stored and transported, and how the practicalities of the conversion are achieved.

9.0

ACRONYMS

9.0 Acronyms

Abreviation	Definition
ACPH	Air Changes Per Hour
BEIS	Department for Business, Energy & Industrial Strategy
CI	Cast Iron
CO	Carbon Monoxide
CONIFER	Calculation of Networks and Installations Fire and Explosion Risk
CPM	Chances per Million
DI	Ductile Iron
ECV	Emergency Control Valve
ER	Equivalence Ratio
GDN	Gas Distribution Network
GRP	Glass Reinforced Plastic
H21 LCG	H21 Leeds City Gate Project
HSE SD	Health & Safety Executive Science Division
IMRRP	Iron Mains Risk Replacement Programme
IP	Intermediate Pressure
K	Kelvin
LP	Low Pressure
LPS	Low Pressure Serviflex
LTS	Local Transmission System
MEG	Mono Ethylene Glycol
MP	Medium Pressure
MPLP	Maximum Permissible Leak Rate
MTP	Master Test Plan
NB	Nominal Bore
NGN	Northern Gas Networks
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
OD	Outside Diameter
OFGEM	Office of Gas and Electricity Markets
PE	Polyethylene
PLL	Potential Loss of Life
PRE	Public Reported Escape
QRA	Quantitative Risk Assessment
REPEX	Replacement Expenditure Programme
SCADA	Supervisory Control and Data Acquisition
SI	Spun Iron
ST	Steel
TWh	Terawatt Hour
UK	United Kingdom of Great Britain and Northern Ireland
WBS	Work Breakdown Structure

10.0

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