H21 PHASE 2 TECHNICAL SUMMARY REPORT

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THE TEAM

Project team

Tim Harwood

Hydrogen Programme Director

Tim is the Project Director for the H21 programme of work. He has over 40 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.

Previously working for eight years in National Grid Transmission, he held several senior roles as Pipeline Engineer, Project Delivery Engineer and Engineering Manager.

Tim's previous roles at Northern Gas Networks (NGN) include Head of Capital Projects, Head of Maintenance and Programme Manager for Major Projects.

Mark Danter

Senior Project Manager

A highly experienced chartered engineer, Mark has a proven track record of delivering multi-disciplinary project programmes including water, LPG, bio-diesel, ethanol and white fuels, as well as methane.

Prior to joining NGN has worked on several innovation and pilot projects within the gas industry and took on the role of Project Director for conversion from LPG to natural gas in Douglas, Isle of Man.

Mark prepared the NIC bid to Ofgem having developed the overall philosophy. On project award he kicked off the individual packages of work and oversaw the initial phases of the project.

Russ Oxley

Senior Project Manager

Russ has spent over 30 years working in the gas distribution industry predominantly within operations by ensuring major mains replacement, diversion and CAPEX programmes are delivered to the highest levels of safety performance, efficiency and customer satisfaction.

Russ is responsible for ensuring that critical safety evidence is delivered from a programme of strategic projects undertaken within NGN's Energy Futures team. The outcome of these projects will support government in making an informed future energy policy decision, allowing commercial, operational and customer impact to be assessed.

Ryan Mallinder

Project Manager

Ryan joined Northern Gas Networks over 12 years ago as a Gas Operative within the Emergency and Repair team before progressing to a role of Team Leader, with responsibility for safeguarding life and property whilst replacing mains and services and carrying out specialist repairs on the gas network.

Ryan then moved into the Capital Projects team as a Site Assurance Officer, overseeing high risk work including the demolition of redundant gas holders and later undertook the role of Project Manager within the Capital Projects team where he was required to oversee the design, tender and build of above ground installations on the high-pressure network.

Ryan joined the H21 team as Project Manager to oversee Network Operations of the H21 project.

Neil Travers

Project Manager

Neil has worked in the gas industry for over 21 years, predominantly in operations ensuring our escape, repair and replacement activities are delivered safely and efficiently. From an emergency background, Neil spent his early career safeguarding life and property as a First Call Engineer. His wealth of industry knowledge and experience enabled him to take up a new role in the H21 team in 2019.

Neil has worked on the H21 Phase 2 project supporting the procedures review and is responsible for the delivery of the Phase 2b Unoccupied Trial. This saw the world's first conversion of an existing distribution network, from natural gas to 100% odorised hydrogen.

Neil has supported the Hydrogen Village Trial submission, developing plans for training and assessment, and is now leading on the Hydrogen Town Pilot project.

Stella Matthews

Hydrogen Development Manager

Stella has worked in the gas industry for seven years, starting as a Document Controller before undertaking Project Coordinator and Assistant Project Manager roles. In 2019 Stella was successfully awarded the Ralph Halkett Travelling Fellowship, which saw her travel to New Zealand to undertake a work placement with Powerco and First Gas.

For the past three years, Stella has been working on the H21 project and has led the Social Science research which has formed part of the programme.

Most recently, Stella has been working in Business Development, developing relationships with stakeholders who are interested in joining us on our hydrogen journey.

Jarred Knott

Project Engineer

Jarred has spent two years in the Energy Futures team, leading the charge on changes for the business and customers. He has delivered a variety of projects from Gas Detection Dogs to ground-breaking robotic platforms during his nine years with the network.

Jarred has previously been an Assistant Manager, Auditor, Photographer and full time Artist. He graduated from the University of Huddersfield with a BA Hons in Contemporary Arts and Contextual Studies.

Jarred brings creativity to the H21 team along with portfolio and project management skills, plus the ethos of innovation needed to realise a hydrogen gas future.

Simon Gant

HSE Science & Research Centre

Purging and Venting

Simon is a Chartered Engineer and Technical Fellow in the Fluid Dynamics Team, where he is responsible for fluid dynamics analysis on a range of projects including incident investigations, support work on new guidance and standards, model reviews, government-funded research and consultancy for various companies.

After joining HSE in 2005, Simon led the dispersion modelling work on two major incidents: the Buncefield Incident in 2005 and the foot-and-mouth disease outbreak in 2007. Over the period from 2007 to 2017, he was heavily involved in research on Carbon Capture and Storage (CCS) and led work on the vapour dispersion Model Evaluation Protocol (MEP) for the US regulator, PHMSA. In recent years, he has led modelling work on various UK hydrogen research projects (e.g. H21 and HyDeploy)

Richard Goff PhD CChem MRSC

HSE Science & Research Centre

Ignitions and Flow Stop

Richard Goff is a Senior Scientist in Explosive Atmospheres at The Health and Safety Executive and is a Chartered Member of the Royal Society of Chemistry. Richard gained his PhD in Chemistry and degree in Natural Sciences from Cambridge University.

Richard performs research, experimental tests and incident investigations related to explosive atmospheres. He also carries out work on hazardous area classification and DSEAR assessments.

Richard has also worked as Risk Assessment and Process Safety Specialist at The Health and Safety Executive, where he assessed fire, explosion and risk assessment in offshore safety cases and predictive aspects of COMAH safety reports.

Johnathan Hall

HSE Science & Research Centre

Jonathan graduated with an aerospace engineering degree and has been working at HSE's Science & Research Centre since 2010. He is the technical team lead of the Explosive Atmosphere Team, Major Hazards Capability Group, which specialises in commercial research and incident investigation involving explosible/flammable dusts, gases and mists.

Throughout this time Jonathan has worked predominantly on; hydrogen-based research, involving cryogenic liquid spills, high- and low-pressure gaseous releases and vapour cloud explosions and dust explosion testing involving ignition energy testing and vented and enclosed explosions.

Dan Allason
DNV – Phase 2a and 2b Operational Demonstrations

Dan is a Chartered Physicist with more than a decade of experience conducting major hazard research at DNV'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.

Andy Phillips
DNV – Phase 2c – QRA

Andy has a background in mathematics and physics and is a chartered engineer. He has worked in DNV's safety team since 2001 and has carried out many Quantitative Risk Assessments of onshore sites and pipelines. He has also developed methodology and models used in those studies, including parts of the CONIFER risk assessment package for distribution systems. He has taken part in several major safety studies for the distribution of hydrogen and blends of hydrogen and natural gas.

Ann Halford
DNV – Phase 2c – QRA

Ann has a background in mathematics. She has worked in DNV's safety team since 1991, developing models for outflow, dispersion, liquid spread and gas accumulation and developing risk assessment methodologies using these models. She has also carried out many Quantitative Risk Assessments of onshore sites and pipelines. Recently she has developed methodology and models used in the CONIFER risk assessment package for distribution systems, extending these models for use with hydrogen, and blends of hydrogen with natural gas.

Dr Fiona Fylan
Leeds Beckett University

Phase 2d – Social Sciences

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.

Dr Martin Fletcher
Leeds Beckett University

Martin specialises in building performance evaluation, and his research centres on the in-use monitoring of buildings to gain insight into energy use, thermal comfort and occupant behaviour.

Martin has led on a broad spectrum of low-carbon projects during his research career, working with both public and private sector partners to design and evaluate a range of new-build and retrofit projects.

Support Team

QEM Solutions
Summary Report Writing

Design by Marlowe
Graphics

Third Party Support
Various Subcontractors

Project Governance

Ofgem
Governance and Compliance

H21
Project direction

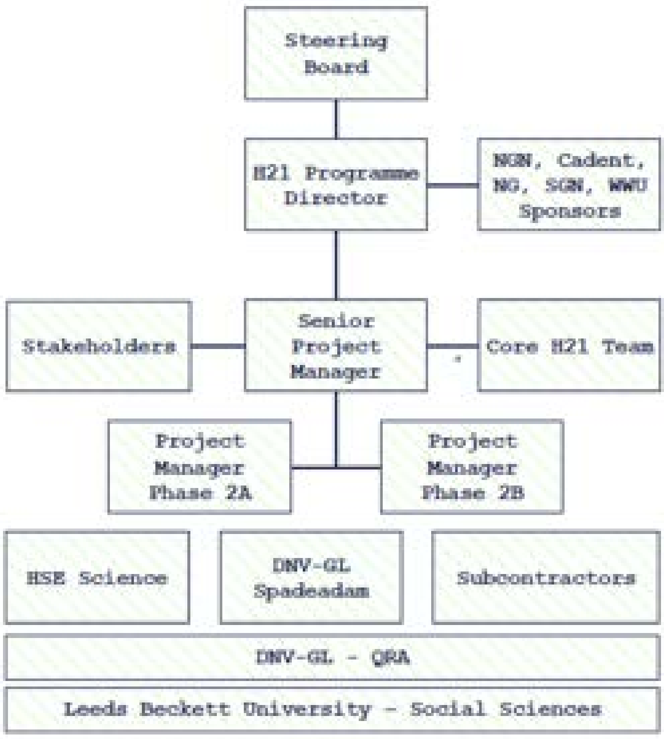
NETWORK PARTNERS

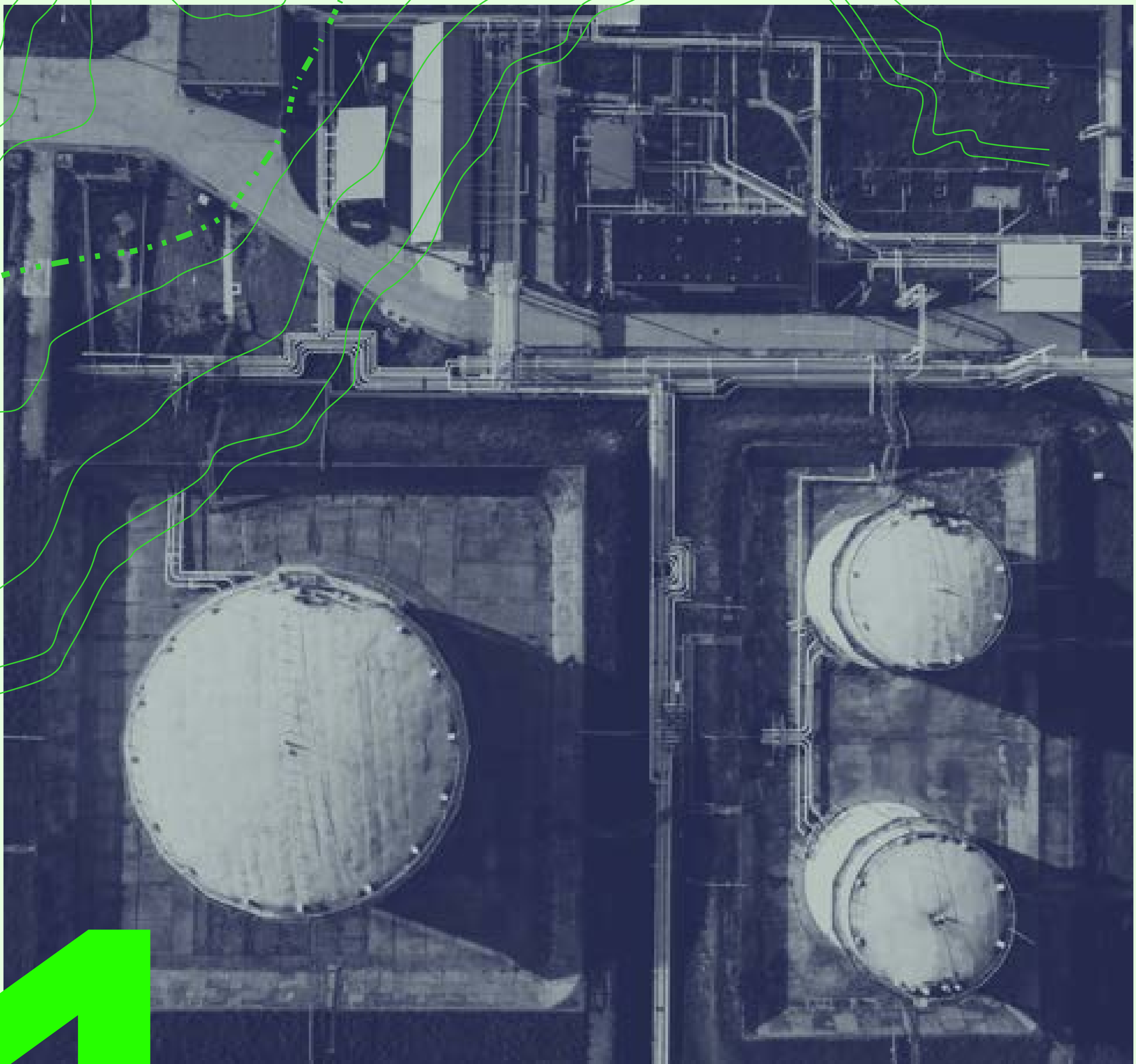
Northern Gas Networks · Cadent (Your Gas Network) · SGN · Wales&West Utilities · national gas

COLLABORATION AGREEMENTS

DNV · HSE

Project Organogram





1

EXECUTIVE SUMMARY

The H21 Phase 2 project builds upon the successful outputs of Phase 1 to provide the next stage of quantified safety-based evidence to determine whether the gas distribution networks (GDNs) of Great Britain (GB), operating below 7 barg, are suitable to transport 100% hydrogen.

1.0

EXECUTIVE SUMMARY

The H21 Phase 2 research will provide vital evidence both towards the hydrogen village trial and potential town scale pilots, and to the Government, which is aiming to make a decision about the use of hydrogen for home heating by 2026.

The key objectives of the H21 Phase 2 NIC project were to further develop the evidence base supporting conversion of the natural gas distribution network to 100% hydrogen. The key principles of H21 NIC Phase 2 were to:

- Confirm how we can manage and operate the network safely through an appraisal of existing network equipment, procedures, and network modelling tools.
- Validate network operations on a purpose-built below 7 barg network, as well as an existing, unoccupied, buried network and provide a platform to publicise and demonstrate a hydrogen network in action.
- Develop a combined distribution network and downstream Quantitative Risk Assessment (QRA) for 100% hydrogen by further developing the work undertaken on the H21 Phase 1 QRA and the Hy4Heat ‘downstream of ECV’ QRA.
- Continue to understand how consumers could be engaged with ahead of a conversion.

This programme was split into four phases detailed below:

- **Phase 2a – Appraisal of Network 0-7 bar Operations**
- **Phase 2b – Unoccupied Network Trials**
- **Phase 2c – Combined QRA**
- **Phase 2d – Social Sciences**

The project, with the support of the HSE’s Science & Research Centre (HSE S&RC) and DNV, successfully undertook a programme of work to review the NGN below 7 barg network operating procedures. The project implemented testing and demonstrations on the Phase 2a Microgrid at DNV Spadeadam and Phase 2b Unoccupied Trial site in South Bank on a repurposed NGN network, to provide and demonstrate the supporting evidence for the required changes to procedures. Details of the outputs of the HSE S&RC procedure review and the evidence collected by DNV from the testing and demonstration projects is provided in detail in this technical summary report.

Due to the differences in gas characteristics between hydrogen and natural gas, changes will be required to some of the operational and maintenance procedures, the evidence of which is provided in this report. The Gas Distribution Networks (GDNs) will need to review the findings from this project when implementing the required changes to their operational and maintenance procedures.

The key objectives of the H21 Phase 2 NIC project were to further develop the evidence base supporting conversion of the natural gas distribution network to 100% hydrogen.

The project undertook the successful development of an end-to-end Quantitative Risk Assessment (QRA) for 100% hydrogen utilising the QRAs and data gathered from the H21 Phase 1 and Hy4Heat projects to get a more holistic view on risk. The project further modified and extended the Calculation of Networks and Installations Fire and Explosion Risk (CONIFER) model to additionally include releases downstream of the Emergency Control Valve (ECV).

The updated CONIFER model was used to evaluate a sample of potential risk mitigation control measures, demonstrating that it is possible to operate a hydrogen distribution network with a predicted societal risk no higher than that posed by the current natural gas system.

Please note that the results presented in this report do not represent the final assessment of Great Britain. There are further updates to the risk assessment methodology planned during 2023 and the first half of 2024.

The project also successfully worked with Leeds Beckett University to extend the social science learning from the H21 NIC Phase 1 consumer perception research, along with work by Newcastle University for HyDeploy, to develop educational resources and a range of communication materials that can be used to inform, educate and enhance consumers' understanding of the benefits of a change to 100% hydrogen conversion. Consumer inclusion in this journey is paramount to the overall success of future conversion projects.

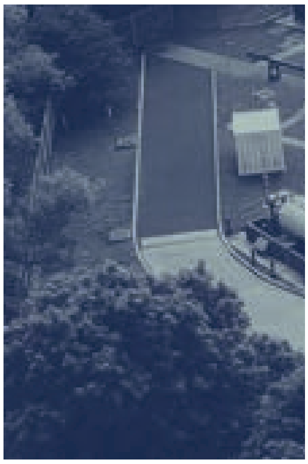
2

PROJECT BACKGROUND

The current Great Britain (GB) gas distribution network transports natural gas (predominantly methane) which is used by businesses and over 22 million homes across the UK. Whilst natural gas produces carbon dioxide when burnt, hydrogen does not, meaning a hydrogen conversion for the gas network could be compatible with legislation to tackle the effects of climate change and ensure the public and industry can continue to enjoy the benefits of a gas supply in addition to other clean energy solutions.

2.0

PROJECT BACKGROUND



The UK was legally bound to make ambitious carbon reductions under the terms of the Climate Change Act (2008). In 2019, the UK government went further, committing to a legally binding target of Net Zero carbon emissions by 2050. This means the UK must tackle decarbonisation at pace and change the way energy is produced, transported and consumed to achieve this goal.

In 2021, 41%[1] of the UK's electricity generated was supplied by natural gas. Natural gas dominates domestic energy demand, supplying 66%[2] of total domestic energy demand and increased by 7.4% in 2021, compared with 2020. Heat demand is highly variable, and, compared with electrical alternatives, natural gas is readily capable of meeting peak instantaneous heat demand, in extreme weather.

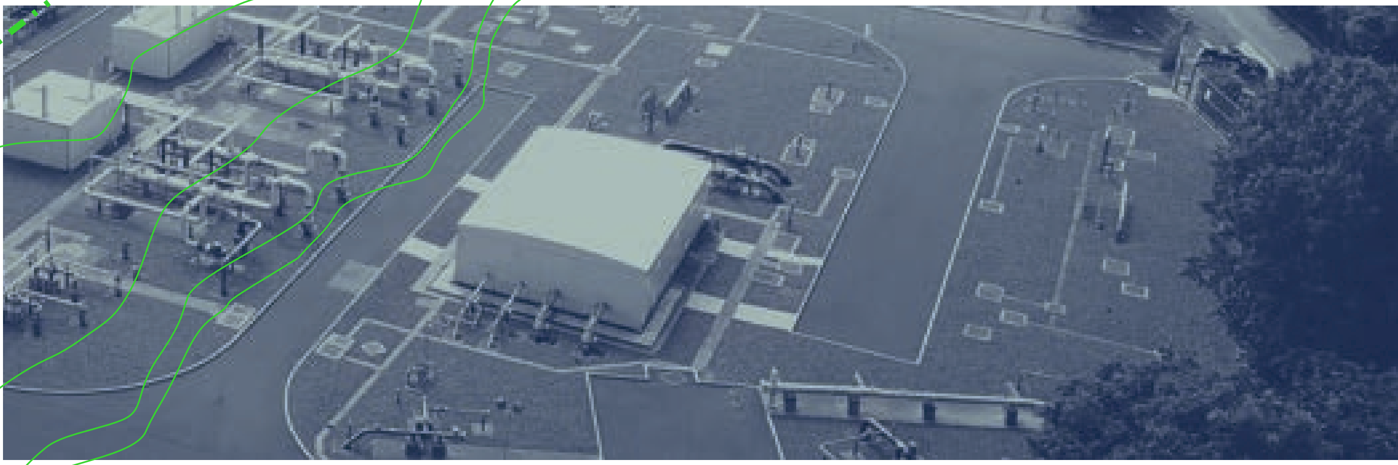
Therefore, there is a huge focus on finding a cleaner alternative to natural gas that can be stored in equivalent volumes to meet this swing in demand. Alternative clean energy solutions for heating buildings presents consumers with choice suited to their individual preferences and requirements.

The objective of the H21 programme is to assess the feasibility of converting the below 7 barg gas distribution network to transport 100% hydrogen, providing quantified, safety-based evidence. The H21 programme follows the work of the 2016 H21 Leeds City Gate (LCG) and the 2018 North of England (NoE) studies, as well as the H21 Phase 1 NIC project, which established a hydrogen conversion is technically possible and economically viable.

The objective of the H21 programme is to reach the point whereby it is feasible to convert the existing natural gas network to 100% hydrogen.

[1] Digest of UK Energy Statistics Annual data for the UK (DUKES). (2021) Electricity fuel use, generation and supply. Table 5.6. Accessed at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094460/DUKES_5.6.xlsx

[2] Digest of UK Energy Statistics Annual data for the UK (DUKES). (2021) Accessed at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1135950/DUKES_2022.pdf



The H21 programme builds on the Government's £25 million 'downstream of the ECV' hydrogen programme (Hy4Heat), which examined using hydrogen as a potential heat source in the home, with focus on the system downstream of the network emergency control valve.

Phase 2 of the H21 programme continues to be a collaborative project involving all the GB Gas Distribution Networks (GDNs) along with National Gas and includes an assessment of the impact of conversion both on the distribution network and downstream of the ECV.

The H21 Phase 2 research will provide vital evidence towards the hydrogen village and potential town scale pilots and provides vital evidence to the Government which is aiming to make a decision about the use of hydrogen for home heating around 2026.

It is also the first stage in understanding the training requirements of skilled workers in the conversion, operation and maintenance of a hydrogen distribution network by providing evidence to support the updating of standards and procedures that will underpin hydrogen network training, and competency programmes.

The aims of H21 Phase 2 are:

- To **appraise key changes** to any procedural controls and demonstrate safe live network operations and maintenance procedures for use with 100% hydrogen on the Microgrid.
- To **undertake unoccupied network trials** on an aged, repurposed network of low-pressure distribution pipes, following the key outputs from the above.
- To **develop a combined distribution network and downstream QRA** for 100% hydrogen utilising the QRAs and data from H21 Phase 1 and Hy4Heat QRAs.
- To **develop a range of information** and educational materials that will reinforce consumer engagement.

3

PROJECT SCOPE

This H21 Phase 2 NIC project will provide confidence in the operations undertaken on the distribution networks to be able to undertake live trials, keeping pace with the research on hydrogen safety, and effectively determine ‘can we manage the network and the conversion process safely’.

3.0

PROJECT SCOPE

The key objectives of the H21 Phase 2 NIC project is to further develop the evidence base supporting conversion of the natural gas distribution network to 100% hydrogen.

The key principles of H21 NIC Phase 2 were to:

- **Confirm how we can manage and operate the distribution network safely** through an appraisal of existing network equipment, procedures, and modelling tools.
- **Validate network operations and modelling software** on a purpose built below 7 barg network as well as an existing, unoccupied, buried network and provide a platform to publicise and demonstrate a hydrogen network in action.
- **Develop a combined distribution network and downstream end-to-end Quantitative Risk Assessment (QRA) for 100% hydrogen conversion** by further developing the work undertaken on the H21 Phase 1 QRA and the Hy4Heat 'downstream of ECV' QRA.
- Continue to **understand how customers could be engaged** with ahead of a conversion.

This H21 Phase 2 NIC project will provide confidence in the operations undertaken on the distribution networks to be able to undertake live trials, keeping pace with the research on hydrogen safety, and effectively determine 'can we manage the network and the conversion process safely'.

The H21 project team have been, and continue to, liaise closely with other industry decarbonisation projects including the Government's Hy4Heat project, SGN's H100 and the Village Trials projects, looking at 100% hydrogen supply to ensure knowledge gaps in the holistic approach are identified and that there is no unnecessary duplication of effort.

This programme will be split into four phases which are described in more detail below:

- **Phase 2a – Appraisal of Network Operations**
- **Phase 2b – Unoccupied Network Trials**
- **Phase 2c – Combined QRA**
- **Phase 2d – Social Sciences**

This H21 Phase 2 NIC project will provide confidence in the operations undertaken on the distribution networks to be able to undertake live trials.

3.1 Phase 2a – Appraisal of Network Operations

In order to carry out demonstrations on a previously untried entity, a Basis of Safety (BoS) must be established, and the development of hydrogen safety and operational standards and procedures must be completed as part of the enabling works to any live public network conversion. An assessment of the procedures and equipment that currently underpin all operations across the distribution network is needed to understand how to manage operational safety during and following conversion.

The SGN H100 innovation project and the H21 NIA Field Trials project had initiated this, undertaking a triage review of the existing networks' operational procedures to determine the procedures that may be affected by 100% hydrogen. Where procedures were likely to be affected by a hydrogen conversion, further investigation into the BoS and further testing of the procedures was undertaken in Phases 2a and 2b of the H21 NIC at DNV Spadeadam and South Bank respectively.

A Master Test Plan (MTP) of operations was developed alongside the detailed design of the H21 Spadeadam micro-grid for network operation trials. This was to ensure there is a simulated representative network available to accommodate full-scale network parameters and typical network components to run with 100% hydrogen or natural gas between 0-7 barg.

The micro-grid test facility at Spadeadam was built to carry out the tests and demonstrations as defined in the Phase 2a MTP to validate safe network operational procedures and further demonstrate the network's capability and suitability for hydrogen conversion. The data from these trials provided safety-based evidence that resulted in technical reports being produced which are to be used by networks to update their existing standards and procedures prior to any conversion of their natural gas distribution systems.

There were several key objectives for Phase 2a – Appraisal of Network Operations, which are defined below:

I. HSE's Science & Research Centre to review NGN's distribution procedures and identify those that should be suitable for a 100% hydrogen network, and those where further evidence and validation will be required.

II. DNV to build a gas demonstration network to facilitate full-scale network parameters and typical network components to transport either 100% hydrogen or natural gas to allow conversion style purging to be undertaken. The demonstration network will leave a legacy future training and R+D facility beyond the H21 NIC project to support further network decarbonisation projects.

III. To demonstrate the procedures identified in HSE's Science & Research Centre review on the purpose-built gas demonstration network at Spadeadam, working with technicians from DNV and operational personnel from NGN and other industry suppliers.

IV. To validate hydrogen network modelling software predictions for pressures and flows on the gas demonstration network and identify any further refinement on these.

3.2 Phase 2b – Unoccupied Network Trials

Nationally and internationally, operational hydrogen experience and expertise is limited to industrial applications, and there are no gas distribution networks supplying 100% hydrogen to homes at present. For live community trials to progress, it is essential that this gap is addressed, and a programme of testing is developed and agreed by all project partners. The programme will also look to resolve any remaining engineering risks that may occur at the time of live community trials and subsequent conversion.

In order to progress with confidence onto live community trials, a trial of conversion and operation of an existing, in-situ, gas network under controlled conditions (unoccupied) is imperative. The H21 NIC Phase 1 testing was vital to understand what assets can be confidently considered for conversion, as well as the consequence of failure of such assets. The Phase 2b – Appraisal of Network Operations will validate and further develop the learning from previous phases by converting and operating a real, in-situ, unoccupied, re-purposed natural gas network in a controlled environment.

Of the numerous hydrogen projects currently being undertaken in the UK, none are undertaking physical demonstrations of 100% hydrogen operations on a fully comparable existing live network asset. The H21 NIA Field Trial determined the selection criteria and location for an unoccupied network site and identified any modifications to the new site, along with a rationale for the selection process. A suitable site with a sufficiently representative example of assets in situ with no end users connected was selected at the South Bank area of Teesside.

This stage will be critical in the development of the competencies required of operational colleagues, to ensure that the operation and maintenance of a re-purposed hydrogen network is as safe as it is today running on natural gas.

There are several key objectives for Phase 2b – Unoccupied Network Trials, which are defined below:

- To **demonstrate the findings from Phase 1 and Phase 2a on an existing unoccupied site** demonstrating network operations in terms of conversion, new connections, network leakage, detection, and repair on a wider representative network.
- **Validate model network flows and pressures.**
- Provide a platform to publicise and **demonstrate hydrogen network operations in action,** including engagement with current third-party specialist suppliers.
- **Odorization of hydrogen in a repurposed network** used to supply new hydrogen appliances and the impact of any other network contaminants on the performance of such appliances.

3.3 Phase 2c – Combined QRA

Raising public awareness of hydrogen for heat and the potential of 100% hydrogen conversion must be a priority for both industry and government.

Hy4Heat have conducted a QRA for downstream 'after the ECV' and, in order to provide a full overview of risk for the conversion to hydrogen, this project shall review, analyse and develop a combined network and end user QRA from the H21 Phase 1 project and Hy4Heat project. This needs to be completed to ensure compatibility of the adjoining systems (upstream/downstream of the ECV) to provide a full overview of risk prior to commencing live community trials.

The outcome of the combined QRA may be used to determine additional safety control measures which could be considered for live community trials.

The key objective for Phase 2c is defined as follows:

- **Developing an end-to-end Quantitative Risk Assessment (QRA) for 100% hydrogen** utilising the QRAs and data gathered from the H21 Phase 1 and Hy4Heat projects to get an overall view on risk and assessing a range of potential control measures for their effectiveness.
- Further **refine the existing natural gas models** developed by DNV and its predecessors with up-to-date data from full scale testing, as well as network and downstream recent and historic incident data. To extend the models to incorporate pure hydrogen into the systems using a consistent methodology and set of models.

3.4 Phase 2d – Social Sciences

Support and acceptance by the public of a gas network conversion to 100% hydrogen will be crucial to its success. Research to date has found that public knowledge of low carbon heat technologies is relatively low, and that these low carbon alternatives – when compared to current heating systems – are viewed with scepticism when cost and disruption are factored into the public's consideration. Therefore, raising public awareness of hydrogen for heat and the potential of 100% hydrogen conversion must be a priority for both industry and government.

Building on research completed during the H21 NIC Phase 1 project, Phase 2d – Social Sciences will explore the public's latest awareness and perceptions of a potential hydrogen conversion.

There are several key objectives for Phase 2d – Social Sciences, which are defined below:

I. **Explore how best to communicate how hydrogen would be produced, stored, transported to, and used in, consumers' homes**, and the meaning of certain key terms such as decarbonisation, carbon capture and storage.

II. **Development of key messages and preferred communication methods** required to explain a conversion to hydrogen to different groups of the population across a range of demographics.

These research questions require a mix of qualitative methods – to generate depth of understanding, and quantitative methods – to provide statistical detail and modelling of how different groups respond to different types of information.

4 PHASE 2A APPRAISAL OF NETWORK OPERATIONS PROCEDURES

The Phase 2a scope included the HSE Science and Research Centre (HSE S&RC) led review, testing and making recommendations to amend the current natural gas operational and maintenance procedures required to operate a network on 100% hydrogen, below 7 bar, safely. It also makes recommendations towards any new, recertification or modifications to network tooling and equipment.

This section contains information collated from the HSE S&RC reports listed in Section 9.0 References. All graphs, visuals and photos have been reproduced by kind permission of, and are attributable to, the relevant report author.

4.0

PHASE 2A APPRAISAL OF NETWORK OPERATIONS PROCEDURES

The Phase 2a scope included the HSE Science and Research Centre (HSE S&RC) led review, testing and making recommendations to amend the current natural gas operational and maintenance procedures required to operate a network on 100% hydrogen, below 7 bar, safely. It also makes recommendations towards any new, recertification or modifications to network tooling and equipment.

The Phase 2a review of operational and maintenance procedures followed on from the preceding work undertaken by the HSE S&RC under the Phase 2 Field Trials NIA project. The NIA project report – H21 Phase 2 Technical Approach and Test Strategy – identified, following the review of over 680 network procedures, which key topic areas relating to procedures should be addressed in Phase 2a. The report identified 8 key common areas for further review and testing:

1. **Purging & Venting**
2. **Ignition Sensitivity**
3. **Personal Protective Equipment (PPE)**
4. **Risk Assessment – The EMT, operational safety distances and minimum evacuation distances**
5. **Human Factors**
6. **Gas Characteristics**
7. **Software and Models**
8. **Flow Stopping**

The outputs from the reviews were incorporated into the Master Test Plan (MTP) and testing was undertaken at the Phase 2a Spadeadam site on the Microgrid and at Phase 2b Unoccupied Trials site at South Bank, and specific tests were witnessed by the HSE S&RC. The HSE S&RC review of the 8 common areas is provided in the following sections.

The aim of this review by the HSE S&RC was to assess the implications to the operational procedures when switching from natural gas to hydrogen.

4.1. Purging and Venting

4.1.1. Scope

The aim of this review by the HSE S&RC was to assess the implications of switching from natural gas to hydrogen on purging/venting procedures in the gas distribution network and provide the evidence for suitable safe purging/venting procedures with hydrogen.

4.1.2. Recommendations

Direct Versus Indirect Purging

The HSE S&RC undertook a literature review which identified the need for more evidence to support direct purging with 100% hydrogen.

→ There is more potential for hydrogen to ignite during direct purging operations, since:

  - Electrostatic ignition inside the pipeline cannot be ruled out;
  - Typically, there are three to four incidents per year on the gas network, of which one ignites; and
  - Experience shows that hydrogen vents have increased propensity to ignite (as compared to natural gas vents), mainly due to electrostatic discharge, and the flame could potentially travel back through the flammable mixture into the pipeline.
  - There is a lack of wider hydrogen industry evidence, experience, and literature of directly purging hydrogen pipework and vessels.

→ The consequences of ignitions during direct purging operations could be severe:

  - They could rapidly run-up to detonation and produce overpressures of tens of bar, which could damage pipes and produce high overpressures near vent exits.

For these reasons, it was decided to only recommend and test indirect purging by complete displacement when purging mains from air to hydrogen and vice versa, and conversion purging (natural gas directly to hydrogen). Indirect purging prevents the interface of hydrogen and air, using an inert gas, which avoids producing a flammable cloud inside the pipeline. Complete displacement removes the risk of air and hydrogen mixing by using nitrogen to displace all the air prior to commissioning and hydrogen when decommissioning.

Future projects may review the feasibility of direct purging of hydrogen pipelines and identify conditions necessary for it to be conducted safely. This project did complete some direct purging of mains for comparing velocities, purge efficiency, and overpressures but further research would be required.

Further work on direct purging should include:

→ Tests involving ignition of stoichiometric hydrogen gas mixtures in various lengths of pipeline (of various diameters) to quantify the maximum length of pipeline that could be purged directly without giving rise to damaging overpressures. This may need to consider tests with different configurations to examine pressures generated by reflected shocks, e.g., from pipe bends. This work would essentially mirror the work previously undertaken by British Gas on natural gas.

→ Tests involving ignition of hydrogen released from vents and ejectors to examine the potential for flames to travel upstream into pipelines and ignite flammable mixtures inside the pipeline during direct purges between hydrogen and air (this is not a concern when purging indirectly, since the gas mixture in the pipeline should be non-flammable at all times).

- Tests involving flowing gas mixtures (stoichiometric hydrogen concentrations) with suspended matter, e.g., rust particles, in pipelines to assess the likelihood of electrostatic ignition. This would need to involve a range of pipeline materials (PE, cast iron, and potentially transitions between one material and another) and a range of flow speeds and particle types and densities. One of the challenges in conducting such tests is that the aim would be to prove a negative, i.e., that electrostatic ignition is impossible. However, the tests would only be able to prove that ignition did not occur in the particular configurations tested experimentally (if indeed ignitions did not occur). If the tests demonstrated that ignition occurred, it could further support the use of indirect purging.

Vents and Rider Pipes

It was expected that riders and vents would need to be larger in both diameter and tapping size to ensure that the required higher purge velocities can be achieved, but upon carrying out the minimum purge velocity experiments on the Phase 2a Microgrid, it has been proven that it is possible to achieve an efficient purge using current vent and rider sizes for indirect purging of low, medium and intermediate pressure hydrogen pipes with diameters not exceeding 36" or 900 mm. The NGN procedure on main and service laying (NGN/PM/MSL/1[3]) provides a table of rider and vent sizes, and after completion of the minimum purge velocity experiments, it is confirmed that the existing NGN/PM/MSL/1[3] table in Section 27.3.2, is suitable for indirect purging of hydrogen pipes.

Nominal pipe diameter or equivalent pipe diameter	Recommended rider and vent diameters (mm) for rider inlet pressures of					Minimum distance for release of squeeze-off from the fully closed position (mm)
	21mbar	30mbar	75mbar	350mbar	2bar	
0 to 150mm (0 to 180mm PE) (0-6in.)	32	32	32	32	32	15
151 to 200mm (8in.)	63	63	63	32	32	15
201 to 250mm (10in.)	63	63	63	63	63	30
251 to 301mm (12in.)	63	63	63	63	63	30
301 to 450mm (18in.)	90	90	90 (2x63)	63	63	45
451 to 600mm (24in)	180	180 (1x125)	125 (2x90)	90 (2x63)	63	60
601 to 900mm (36in)	180	180 (2x25)	180 (2x25)	125 (2x90)	90 (2x63)	-
901 to 1200mm (48in)	-	250 (2x180)	250 (2x180)	180 (2x125)	90 (2x63)	-

Table 4.1: Recommended rider and vent sizes as used in the current natural gas operations (reproduced from NGN/PM/MSL/1, Section 27.3.2)

[3] Northern Gas Networks. (May 2017) Management procedure for main laying and service laying. NGN/PM/MSL/1.

The high molecular diffusivity of hydrogen has a beneficial effect and improves the purging efficiency.

Purge Velocities

Distribution pipelines are purged using the displacement method, rather than pressure-swing purging, due to their low operating pressure. It is important to avoid gases forming layers (stratifying) during purging operations, since this can result in an incomplete or inefficient purge. Current British and American Gas Association (AGA) guidelines for the minimum purging velocity for natural gas pipelines are designed to ensure the flow of gas remains turbulent and non-stratified. The required minimum purging velocity depends on the pipe diameter, and is calculated to achieve certain threshold values of Reynolds and Froude numbers. Hydrogen is more buoyant than natural gas and therefore has a greater tendency to stratify. Due to its density and viscosity, it is also more likely to produce laminar flow. This would suggest that it may be necessary to purge hydrogen pipelines at a higher velocity than is currently the case for natural gas.

However, the pipeline purging experiments showed that the high molecular diffusivity of hydrogen has a beneficial effect and improves the purging efficiency, such that relatively low purging velocities can be used in practice. Results from a programme of experiments conducted at the Phase 2a Microgrid show that stratification does not occur when purging hydrogen through nitrogen, even at low Reynolds and Froude numbers. Tables of the expected modelled purge velocities can be found in Appendix A – Tables and Figures, in the DNV H21a: *Minimum Purge Velocity Report*[4].

Since indirect purging is the proposed approach, at least for the forthcoming hydrogen village trials, the use of an appropriate purging velocity is primarily a logistical and cost issue, rather than one of safety. The gas mixture in the pipeline should not be flammable at any time. Using an appropriate purging velocity is primarily about ensuring an efficient purge to minimise the use of nitrogen and to ensure that operations are not prolonged.

End Points

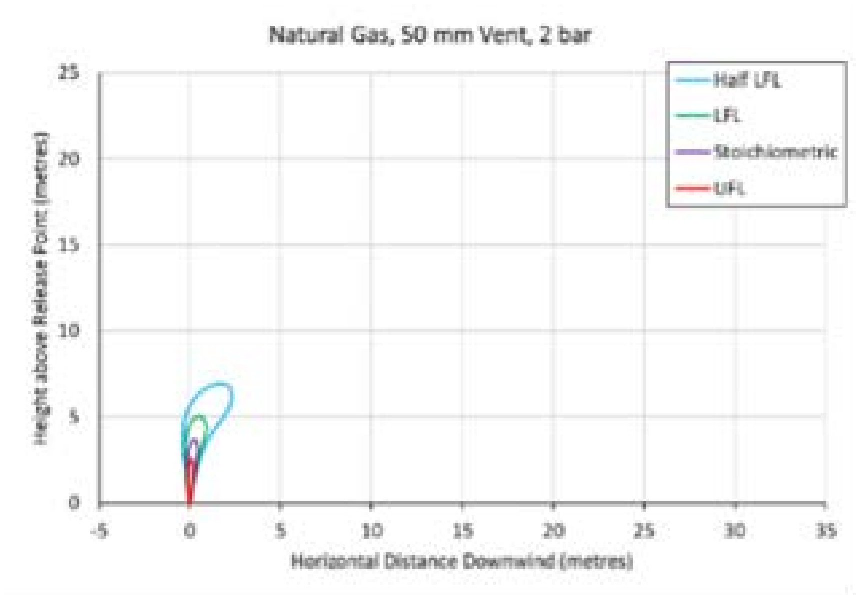
Safe endpoints for indirect purging of hydrogen are already specified in the IGEM/SR/22[5] standard, which incorporate a 30% safety factor, and it is not proposed to alter these.

Venting and Purging Safety

When hydrogen is released from a pipeline through a vent into the atmosphere, a flammable airborne cloud will be generated as the hydrogen disperses into the air. The current natural gas standards require vents to be located at least 5 m downwind from possible ignition sources, a minimum of 2.5m above ground level and located such that any vented gas is unlikely to drift into buildings through air intake grilles, air conditioning units, open doorways and windows. Adequate protection must be given for the general public within the designated hazardous areas, i.e., at least 5 m upwind of any possible source of escaping gas. IGEM/SR/23[6] notes that it can be challenging to identify the 'upwind' direction, especially in urban areas where the wind may recirculate in wakes around buildings. In practice, this could mean that an exclusion distance of 5 m should apply in all directions from the vent stack.

It was noted that the size of 5 m exclusion zone is likely to increase for hydrogen as compared to natural gas, due to the larger flammable cloud extent. An example of a natural gas vs hydrogen flammable cloud extent from a purging vent is given below. The release point is located at 0 metres on the horizontal axis, the wind is blowing from left to right at 5 m/s and the plumes height is measured above the point of release, not the ground.

[4] DNV/Northern Gas Networks. (23 May 2023) H21 Phase 2A Testing Part A: H21a Minimum Purge Velocity Report. Report No.: 1849804, Rev. 1.0.
[5] IGEM. (Jan 1999) Purging operations for fuel gases in transmission, distribution and storage. IGEM/SR/22.
[6] IGEM. (Jan 1995) Venting of natural gas. IGE/SR/23.



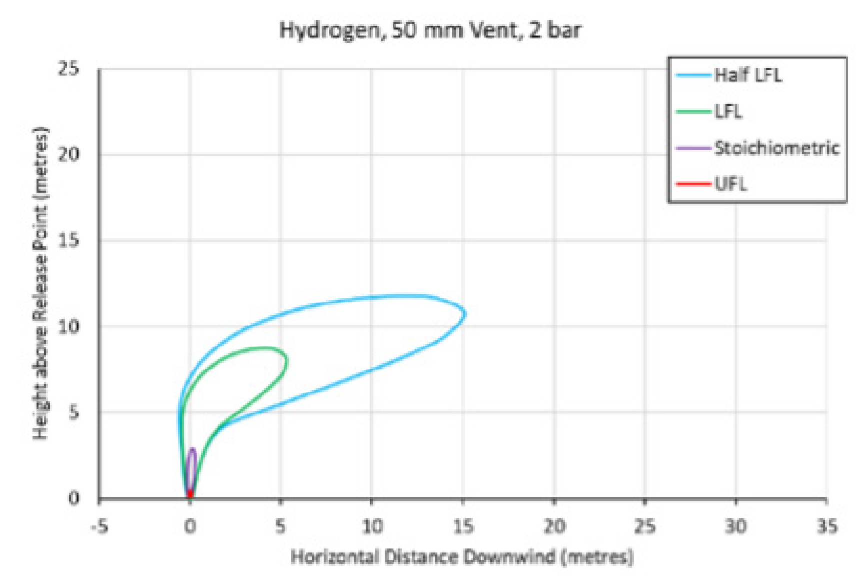


Figure 4.1: Example comparison of a gas cloud from a vent, natural gas and 100% hydrogen

The flammable cloud extent can be assessed with reference to the new hydrogen supplement to IGEM/SR/25[7] on area classification, which provides a look-up table of horizontal dispersion distances for vents (based on the vent diameter and flow rate). When using IGEM/SR/25 to look up the relevant distance, it is necessary to know the flow rate of gas. New guidance on purging velocities for hydrogen distribution pipelines would define the minimum purging velocity.

[7] IGEM (Dec 2022) Edition 2 with amendments 2013 Hydrogen Supplement 1. IGEM/SR/25

In practice, purging velocities are likely to exceed these required values. NGN/PM/MSL/1 provides an indication of the 'typical' purging velocities currently used on the natural gas distribution network. These are mostly within a factor of two of the minimum purging velocity, with the exception of the smallest range of pipe diameters (below 150 mm) where the typical purging velocity is 1.5 m/s, i.e., nearly three times the minimum purging velocity of 0.6m/s.

The typical purging velocities for hydrogen are not yet known but tables of the expected modelled purge velocities can be found in Appendix A – Tables and Figures, in the DNV H21a: *Minimum Purge Velocity Report*[8]. Given that the exclusion distance should be defined on a precautionary basis, it would seem prudent to scale any newly defined minimum purging velocities by a factor of three, and then use the hydrogen supplement to IGEM/SR/25 to look up the relevant distance. This process could be repeated for each vent diameter and then the largest distance chosen to define the new exclusion distance for hydrogen. If this approach proves to be problematic, i.e., because it results in unrealistically large exclusion distances, then it may be necessary to reassess this approach.

Tests have shown that noise levels are higher for hydrogen purging than for natural gas or nitrogen. Engineered solutions (e.g., throttling valves or silencers) need to be considered at MP pressures and definitely required at IP pressures, to manage noise levels for operatives and members of the public. Noise levels should be lower when venting at LP pressures, but even there, the tests suggested that the vent would ideally be located at least 25 m away from sensitive receptors, although this may prove impractical to implement. It is recommended that noise levels be measured during purging operations in future projects, for example the Village Trials, to assess this further.

If the vented hydrogen ignites, tests indicate that the resulting overpressure would be sufficient to break windows at a distance of 5 m from vents operating at 7 barg. Overpressures should be lower at LP and MP pressures. If throttling valves were used to lower pressures on IP and MP purges to LP pressures, to minimise noise issues, this could also help to reduce the potential overpressures from delayed ignitions of hydrogen vents, i.e., mitigating against the effects of noise, potential overpressure and the potentially impracticable increases in exclusion zones.

For sustained fires of vented hydrogen, the thermal radiation is expected to be lower than for the equivalent natural gas fire since hydrogen fires are less emissive. For future projects, such as the Village Trials, it may be useful to supply operatives with thermal cameras, to enable them to see if the vent stack has ignited. The usefulness of thermal imaging is discussed in this report in Section 5.1.3 Ignition of vented gas.

Vents are more likely to ignite for hydrogen than for natural gas, due to the lower ignition energy for hydrogen. New purging procedures should explain the actions to be taken if/when the vent ignites. Flame dip should also be considered when drafting these new hydrogen pipeline purging procedures and training materials, to ensure that operatives are aware that a hydrogen flame could potentially burn back inside the vent pipe (e.g., at the end of a purge) and to consider the use of flame traps to prevent this, however consideration shall be given to any impacts on purging velocity.

[8] DNV/Northern Gas Networks. (23 May 2023) H21 Phase 2A Testing – Part A: H21a Minimum Purge Velocity Report. Report No.: 1849804, Rev. 1.0.

4.2. Ignition Sensitivity

4.2.1. Scope

The HSE S&RC reviewed the differences between the ignition sensitivities of natural gas and hydrogen, and any further precautions that would be required for hydrogen operations. The following cases, where individual considerations of ignition sensitivity need to be considered, were selected from a review of network distribution procedures including:

- Electrical and mechanical powered equipment
- Electrostatic discharges (including stray currents and cathodic protection)
- Friction/impact (including hot surfaces)
- Pyrophoric ignition via oxidation of iron sulphide or 'black dust' (hot particles and exothermic reactions)

4.2.2. Recommendations

4.2.2.1. Ignition topics that should not require alteration with hydrogen

Lower explosive limit (LEL)

A method used to avoid ignitions is to ensure that a flammable atmosphere is not present before conducting certain actions. In order to assess this, LEL criteria are used. The LEL based criteria (20% LEL for the use of non-ATEX equipment, when deciding upon evacuation and other safety precautions, 70% LEL for switching off electrics under emergency conditions, and 5% LEL and falling for reoccupation of buildings) remain fit for purpose with hydrogen; however, these do require accurate hydrogen gas detection.

Damp Cloth Earthing

Damp cloth earthing of PE pipes when cutting was demonstrated experimentally to remain effective in preventing electrostatic discharges and is suitable for use with hydrogen. Protection against electrostatic discharges extends 10 cm beyond the damp cloth.

Continuity Bonds/Cathodic Protection

The continuity bonds used for natural gas remain fit for use with hydrogen. The cathodic protection remains suitable for hydrogen from an electrostatics point of view, although the location of impressed current cathodic protection (ICCP) systems should be in Zone 2 NE (Negligible Extent) areas.

Pyrophoric Ignition

There is little change in the relative risk of pyrophoric ignition, and electrostatic discharge with 'black dust' remains the greatest ignition risk, as is the case with natural gas.

4.2.2.2. Ignition topics that will require alteration with hydrogen

DSEAR

Risk assessments will be needed on the appropriate presence of operators working in Zone 1 areas, given the increased likelihood of ignition of hydrogen compared to natural gas. Based on frictional, electrostatic and other ignition source potentials, hydrogen vents could ignite and therefore the vents shall be designed to withstand this. Work in Zone 1 areas should, as far as reasonably practicable, be avoided where other suitable methods, such as isolation and purging, could be adopted. Where not possible, a robust safety management control system shall be implemented.

ATEX equipment rated to Gas Group IIC (or Group IIB + H2) will be required instead of IIA equipment which is used with natural gas.

BS EN 1127-1:2019 prohibits the use of steel tools in Zone 1 areas with hydrogen gas (i.e., in areas where flammable atmospheres are expected to occur); therefore, non-sparking tools are required.

ATEX equipment rated to Gas Group IIC (or Group IIB + H2) will be required instead of IIA equipment which is used with natural gas.

Electrostatic ignition

Electrostatic discharges from conductors (such as people or small metal tools) that can ignite hydrogen are the same as those that can ignite natural gas; however, charging would only need to occur for 30% of the time, or less, to achieve a voltage that can ignite hydrogen. For personnel, this can be mitigated via appropriate antistatic/electrostatic discharge (ESD) footwear and clothing.

The increased potential for incendive discharges from insulating PE pipe is something that will need to be considered if direct purging was to ever be considered. A limit of 20 m/s would need to be placed on the purge velocity for direct purging in PE pipe. No such flow limit is required from an ignition perspective for indirect purging.

Electrostatic discharges that could ignite hydrogen during mains replacement works were measured during the PE live insertion experiments. The following precautions need to be taken for live insertion:

- There should not be a flammable atmosphere beyond the glandbox when the insertion head is inserted; a proven isolation is required. Confirmation will be required that two bag stops provide an effective isolation for hydrogen and the volume between the bags would need to be vented. The pipe that was cut away to allow for installation of the glandbox will need to have been indirectly purged with an inert gas before cutting takes place to protect against frictional ignition.
- Before the bag stops are removed, the PE pipe to be inserted and volume between the bag stops and glandbox will need to be indirectly purged with an inert gas. Currently direct purging is used.
- The glandbox should have a continuity bond to the metallic pipe and there should be precautions to reduce static on the PE pipe inserted such as wetting down. This is to reduce the likelihood of ignition of any leaks of hydrogen through the membranes of the glandbox through an electrostatic discharge.

Insulated joint testing at >2 kV presents a potential ignition source for hydrogen/air mixtures. Depending on the pressure and location of the pipe, any external leaks may be classified as negligible extent (NE) so testing above 2 kV could only occur on a risk assessment basis. If a zone of NE does not occur, then testing above 2 kV cannot take place. If direct purging were to be undertaken, then testing of insulated joints would present an ignition risk.

Frictional ignition

Hydrogen requires less energy to ignite than natural gas, but still requires temperatures in excess of its auto-ignition temperature of 560°C.

To reduce the risk, the use of non-sparking tools where possible would be a sensible precaution, but they may not entirely eliminate the risks of ignition.

Risk assessments will be required to judge what to do in an emergency situation; these will need to balance the risk of excavating straight onto a leak to stop it as quickly as possible compared to excavating upstream or either side to stop the flow, which might take longer, potentially allowing more time for migration or ignition.

Shot blasting

The procedures for shot blasting should explicitly state that the operation is not to be performed in flammable atmospheres (i.e., where hydrogen is detected above 20% LEL) and cannot be used for cleaning leaking mains other than where isolated and purged first.

Barholing

Barholing is performed using simple hand operated equipment (i.e., no powered moving parts) and as such the equipment is not going to be ATEX rated. A single spark could be generated inside the barholing equipment where the two pieces of metal impact upon each other. It should be ensured that there are no hydrogen gas concentrations above 20% LEL at the level above the ground where the two pieces of metal impact upon each other.

Powered Tools

Table 4.2 includes a list of the powered tools that GDNs regularly use. From this table almost all existing electrical and mechanical equipment will require manufacturers to supply equipment that is rated for use in IIC atmospheres, or subject to a MEIRA assessment, if it is to be used in a potentially explosive atmosphere associated with gas network operations. Only two items of powered equipment are currently suitable for use in hydrogen/air atmospheres. The current zone of use varies, and many are used in non-hazardous atmospheres, meaning that the equipment would still remain suitable in these instances only.

Item Name	Equipment type	Suitability for Hydrogen
Voltstick	Electrical Equipment	Equipment should be sourced which is rated under the ATEX Equipment Directive as being suitable for use in IIC zones A MEIRA under BS EN ISO 80079-36:2016 could be performed for mechanical sources of ignition
Ultrasonic scanner	Electrical Equipment	
Heat shrink gun (Heat gun from PLCS)	Electrical Equipment	
CCTV units for internal joint sealing	Electrical Equipment	
Wolflite handlamp	Electrical Equipment	
Cordless drill/SDS	Electrical Equipment	
Core and Vac	Electrical and Mechanical Equipment (the electrical equipment is outside the zoned area)	
Air Mover	Mechanical Equipment	
Rock Drill	Mechanical Equipment	
Peart branch drill for up to 150mm	Mechanical Equipment	Refer to Drilling Live Mains and Cutting sections for limits on suitability
T101 Drilling machine	Mechanical Equipment	
PE UP Branch Drilling Machine	Mechanical Equipment	
Pneumatic Air Saw	Mechanical Equipment	
Steve Vick Rapid Window Cutter	Mechanical Equipment	
Steve Vick Rapid Rotary Cutter	Mechanical Equipment	
Macaw Pipe Cracker	Mechanical Equipment	
Crackerjack	Mechanical Equipment	
Chalmit Lighting, Evolution Junior	Electrical	Suitable for use with hydrogen
Bartec Impact X 4G Mobile Phone	Electrical	

Table 4.2: Summary of suitability of powered tools identified by NGN

Rock drilling

Rock drilling is performed by pneumatic drills which could be a source of ignition through sparks or hot spots generated within the equipment (i.e., powered moving parts in the motor). In terms of recommendations, rock drilling can be considered under ‘Powered tools’ and one of the three options provided should be used.

Drilling live mains

The motor on powered tools (including electric and pneumatic) could be a source of ignition. There are three options for the continued use of these:

- Have the motor outside of any flammable regions (concentration less than 20% LEL).
- The motors should be Group IIC (or Group IIB + H2) ATEX rated equipment if there is a chance that they could encounter a hydrogen atmosphere within the flammable range.
- Perform a Mechanical Equipment Ignition Risk Assessment (MEIRA) as per BS EN ISO 80079-36:2016 to demonstrate the suitability of the equipment.

Flammable atmospheres may only occur in the drill body for hydrogen at mains pressure in the range of 41 mbarg to 3 barg

Flammable atmospheres may only occur in the drill body for hydrogen at mains pressure in the range of 41 mbarg to 3 barg, or between 46 mbarg to 2 barg for natural gas. Outside of these ranges no flammable atmosphere may occur and no changes in operation are required, although this may be difficult to control and manage for the range of operating pressures present on the networks.

There are three options to achieve negligible extent for the continued use of live mains drilling within the flammable range:

- Use a hand or mechanical vacuum pump to remove the air from the drill body.
- Inert the drill body with an inert gas by pressure swing purging (or flow purging if there are two ports).
- Use a drill that has a maximum allowable working pressure (MAWP) above the overpressure that could be achieved if ignition occurred.

The hierarchy of control should be considered, and more inherently safe control measures such as vacuuming or inerting should be applied if reasonably practicable ahead of mitigation measures such as the drill withstanding the explosion.

For holes drilled for live leak repairs such as anaerobic injection or live metallic service isolations, the drill tip speeds should be limited to below 0.7 m/s.

Cutting

Cutting operations on metallic pipe containing hydrogen are not allowed by BS EN 1127-1:2019 without additional controls in place. The option for cutting metallic hydrogen pipes is to purge the line, following positive isolation, and the use of non-sparking blades.

Proven isolations, such as double block and bleed, alongside indirect purging, will be required to use multi-sparking tools. Confirmation will be required that current isolation techniques provide an effective isolation for hydrogen.

Whilst cutting into PE pipe does not present a direct sparking hazard, due consideration should be given to the potential flammable volume within the pipe that could be released in the event of any cutting operation (assuming the pipe section to be cut has not been purged). To achieve a negligible extent (NE), the pipe while depressurised to ambient pressure would need to have a volume of less than 0.002 m3 (2 litres).

Simple Mechanical Equipment

The ATEX Equipment Directive Guidelines (2020) provide a definition of simple mechanical equipment which is paraphrased as equipment which does not have its own source of ignition, i.e., does not have its own source of any of the 13 ignition sources listed in BS EN 1127-1:2019.

Simple mechanical equipment used in an area with a potentially explosive atmosphere must have a mechanical equipment ignition risk assessment (MEIRA) (BS EN ISO 80079-36:2016) documented to show that it is suitable for hydrogen. To aid in this MEIRA, BS EN 1127-1:2019 states that single-sparking equipment i.e., steel tools, should be allowed Zones 1 (Zone 1 – a place in which an explosive atmosphere is likely to occur in normal operation occasionally) for Group IIA & IIB gases and Zone 2[9] for Group IIA, IIB & IIC gases. Note that it specifically states that single-sparking tools should not be used in Zone 1 hazardous areas for Group IIC gases such as hydrogen.

Electrical & Mechanical Equipment Summary

ATEX equipment rated to Gas Group IIC (or Group IIB + H2) will be required instead of IIA equipment which is used with natural gas. Manufacturers of equipment (of both powered and hand tools) should be engaged with to ensure that equipment is suitable for use with hydrogen. Tools that could be used in Zone 1 areas (e.g., in the vicinity of a leak) should be replaced with non-sparking ones where possible.

The networks will need to assess which simple mechanical equipment (i.e., hand tools) are suitable for use with hydrogen. One option is to work with suppliers to produce ignition hazard assessments against BS EN ISO 80079-36:2016, to ensure equipment is suitable for use with hydrogen.

In instances where suitable equipment cannot be sourced, the current equipment may be brought into potentially explosive hydrogen atmospheres under safe conditions, ensured by implementation of a permit-to-work (PTW) scheme. See paragraphs 306-352 of the DSEAR Approved Code of Practice ACOP (HSE, 2013)[10].

4.3. Personal Protective Equipment (PPE)

4.3.1. Scope

An examination of personal protective equipment (PPE) use and appropriateness in the transition from natural gas to hydrogen is vitally important. What follows is a detailed discussion related to safety shoes, heat and flame-retardant PPE and breathing apparatus (respiratory protective equipment, RPE), required for working with natural gas and hydrogen. This work was undertaken by HSE Science & Research Centre (HSE S&RC).

The use and provision of RPE and PPE is an underlying narrative throughout most of the NGN procedures reviewed and links into many of NGN's business as usual activities. Two policies, and one specification directly relating to the provision of RPE and PPE are used as a basis of consideration:

- → NGN/PM/EHS/11 – Personal Safety Equipment & Personal Protective Equipment
- → NGN/PR/DIS/3.1.1 – Work Procedure for use of breathing apparatus in the UK
- → NGN/SP/E/52 – Engineering Specification for Breathing Apparatus

A procedural review was performed by HSE S&RC and NGN and yielded several topic areas for review:

- → Assess RPE, specifically breathing apparatus (BA), currently in use by NGN and discuss best practice for safe working within oxygen-deprived, natural gas and hydrogen environments.

[9] HSE. (2013) Dangerous Substances and Explosive Atmospheres Regulations 2002: Approved Code of Practice and Guidance. Second Edition.
[10] HSE. (2013) Dangerous Substances and Explosive Atmospheres Regulations 2002: Approved Code of Practice and Guidance. Second Edition.

- Assess heat and flame PPE currently in use by NGN and discuss best practice for safe working within natural gas and hydrogen environments.
- Assess antistatic PPE currently in use by NGN and discuss best practice for safe working within natural gas and hydrogen environments.
- Provide information and references, including relevant British standards, to allow NGN to assess the suitability of their existing range of PPE for both natural gas and hydrogen environments.

NGN's current PPE provision was therefore assessed for its efficacy as appropriate protective equipment in a hydrogen working environment. A list of PPE items, excluding BA, available to NGN staff was provided for this review.

The items of heat and flame-retardant PPE were assessed against the requirements of the following standards:

- BS EN ISO 11612:2015: Protective clothing for industrial workers exposed to heat.
- BS EN ISO 14116:2015: Protection against flame, limited flame spread materials, material assemblies and clothing.
- BS EN 1149-5:2018: Protective clothing - Electrostatic properties, Part 5: Material performance and design requirements.
- BS PD CEN/CLC TR 16832:2015: Selection, use, care and maintenance of personal protective equipment for preventing electrostatic risks in hazardous areas (explosion risks).
- PD CLC/TR 60079-32-1:2018 - Explosive atmospheres Electrostatic hazards, guidance.

The RPE were assessed against the requirements of the following standards:

- BS EN 137:2006: Respiratory protective devices. Self-contained open-circuit compressed air breathing apparatus with full face mask. Requirements, testing, marking.
- BS EN 138:1994: Respiratory protective devices. Specification for fresh air hose breathing apparatus for use with full face mask, half mask or mouthpiece assembly.
- BS EN 14594:2018: Respiratory protective devices. Continuous flow compressed air line breathing devices. Requirements, testing and marking.
- PD CLC/TR 60079-32-1:2018 - Explosive atmospheres Electrostatic hazards, guidance.

The safety footwear items were assessed against the requirements of the following standards:

- BS EN 20345:201: Personal protective equipment – Safety footwear.
- PD CLC/TR 60079-32-1:2018: Explosive atmospheres Electrostatic hazards, guidance.

4.3.2. Recommendations

4.3.2.1. Heat and/or flame PPE

Table ** identifies PPE provided by NGN and discusses its use in natural gas and hydrogen environments. In terms of heat and/or flame PPE provision, the change of flammable gas from natural gas to hydrogen does not influence the garment requirements but, because they have different hazard area classifications, the scope of when and where PPE is required will change.

Most heat and/or flame PPE currently provided by NGN for natural gas environments comply with NGN's legal obligation at this time. However, three items were found not to comply with the required electrostatic standards, though two of these items are undergarments and therefore not required to comply so long as the outer layer does comply. The Long Sleeve Zipped Waistcoat Yellow did not comply with the required antistatic standards. The waistcoat was only ever intended to be worn by non-operational staff, but due to the risk of it being used incorrectly, a decision was made to immediately recall and replace the item.

Heat and/or flame PPE found suitable and adequate for NGN to use in natural gas environments are also suitable and adequate for use in hydrogen environments. All items that comply with BS EN 1149-5:2018 also comply with PD CLC/TR 60079-32-1:2018[11] when they are used as part of a total earthed system with resistance of less than $10^8\,\Omega$.

Item	Heat and/or flame		Electrostatics	
	Suitable for Natural Gas	Suitable for Hydrogen	Suitable for Natural Gas	Suitable for Hydrogen
Hi-Vis ARC Polo	Yes	Yes	Yes	Yes
Hi-Vis ARC Coverall	Yes	Yes	Yes	Yes
Navy/Sky ARC Polo	Yes	Yes	Yes	Yes
Hi-Vis FR/AS Rain Jacket	Yes[1]	Yes[1]	Yes	Yes
Navy ARC Fleece Jacket	Yes	Yes	Yes	Yes
Double-Layer Fire suit	Yes	Yes	Yes	Yes
Hi-Vis FR/AS Winter Anorak	Yes[1]	Yes[1]	Yes	Yes
Navy ARC Cargo Trouser	Yes	Yes	Yes	Yes
FR/AS Round Neck Sweatshirt	Yes	Yes	Yes	Yes
FR/AS Thermal Long Sleeve T Shirt	Yes	Yes	No[2]	No[2]
Hi Vis FR/AS Bib and Brace	Yes[1]	Yes[1]	Yes	Yes
FR/AS Protal Hi Vis L/S Vest	Yes	Yes	Yes	Yes
FR/AS Long Sleeve Zipped Waistcoat Yellow	Yes[1]	Yes[1]	No[2]	No[2]
FR/AS Formal Shirt – Sky	Yes	Yes	Yes	Yes
FR/AS Button Neck Sweatshirt	Yes[3]	Yes[3]	Yes	Yes
FR/ARC Protal Corporate Trouser Navy	Yes	Yes	Yes	Yes
Protal FR Thermal Long Johns	Yes	Yes	No[2]	No[2]
FR/AS Bib and Brace Yellow	Yes[1]	Yes[1]	Yes	Yes
FR/AS Balaclava	Yes	Yes	Yes	Yes

1 Limited flame spread only, suitable as an outer layer worn over other heat and flame PPE
2 Does not comply with any electrostatic standard
3 Complies with a standard superseded by 11612

Heat and/or flame PPE found suitable and adequate for NGN to use in natural gas environments are also suitable and adequate for use in hydrogen environments.

Table 4.3: Summary of heat and/or flame PPE provided by NGN in terms of use with natural gas and hydrogen

4.3.2.2. Antistatic safety footwear

Working with both natural gas and hydrogen systems requires safety footwear that not only protect the wearer from impact but are also antistatic to prevent the user becoming isolated and hence becoming a potential ignition source. Antistatic safety footwear, as described in BS EN 20345:2011, stipulates that antistatic safety footwear should be worn to prevent electrostatic build-up and ensure it is discharged effectively.

All safety footwear provided by NGN stated they are compliant with BS EN 20345:2011 and are suitable and adequate for use in most natural gas environments, the exception being high risk hazardous zone 0 areas. In order to be electrostatically safe in hydrogen environments, this safety footwear must also be compliant with PD CLC/TR 60079-32-1:2018. In order for NGN to demonstrate their safety footwear is compliant with the resistance threshold of less than $1\times10^8\,\Omega$ as stated in PD CLC/TR 60079-32-1:2018, there are two options:

[11] BSI Standards Limited. (2018) Explosive atmospheres electrostatic hazards guidance. BS PD CLC/TR 60079-32-1:2018.

1. Upon purchasing safety footwear rated as antistatic to BS EN 20345:2011, check it frequently using a boot-checking resistance measurement device, or a personal earthing monitor, (set to $1x10^8\,\Omega$ threshold) and record the results obtained by the safety footwear over time; or

2. Purchase safety footwear that is ESD compliant in BS EN 61340:2016, or has a stated resistance that is suitable, and is compliant to all other requirements in BS EN 20345:2011.

In both cases, the safety footwear will require periodical testing using a boot-checking resistance measuring device, or a personal earthing monitor, and the results recorded in order to demonstrate compliance to PD CLC/TR 60079-32-1:2018.

4.3.2.3. Breathing apparatus

The conversion from natural gas to hydrogen does not impact the BA requirements. All types of BA are suitable and adequate for use in areas with inhalation hazard contaminants where there is no flame engulfment hazard. However, BS EN 137:2006[12] , type 2 self-contained breathing apparatus (SCBA) is the only suitable and adequate RPE for use in hydrogen working environments where there is a flame engulfment hazard or possible flash-over scenario and where other control measures are not available to reduce the dependence on PPE.

4.3.2.4. Recommendations

The following recommendations have been made:

1. For both natural gas and hydrogen, the minimum heat and flame PPE specifications should be:
    - For limited flame spread PPE, to be worn over other heat and flame PPE, BS EN ISO 14116: Index 3, and EN ISO 1149-5.
    - For heat and flame PPE, BS EN ISO 11612: A1, B1, C1, and EN ISO 1149-5.

2. Immediate removal from use of the Long Sleeve Zipped Waistcoat Yellow that does not comply with BS EN 1149-5, and which would be used as the outer garment layer. This item is unsuitable for use within any explosive atmospheres. It is noted that this item is already not intended for use in an explosive atmosphere.

3. Issue a notice to all PPE wearers identifying the two items of undergarments that do not comply with BS EN 1149-5. The notice should state that these items are suitable to be worn as a base layer but should always be worn underneath other PPE that complies with BS EN 1149-5.

4. Issue a notice to all PPE wearers identifying the four items of limited flame spread PPE that comply with BS EN 14116 and BS EN 1149-5, the notice should state that these items should be worn on top of other heat and flame PPE only and should never be worn as a single layer of protection.

5. Provide suitable gauntlets, that prevent handheld tools from become electrically isolated, and are resistant to heat and flame penetration, as discussed in NGN/PM/EHS/11. If the use of gauntlets has been risk assessed and deemed unnecessary the statement in NGN/PM/EHS/11 regarding the wearing of gauntlets should be updated to reflect the new risk assessment.

6. For both natural gas and hydrogen, the minimum safety footwear specifications should be:
    - BS EN 20345 checked for electrostatic compliance with BS PD CLC/TR 60079-32-1.

7. Provide ESD compliant safety footwear, or boot-checking facilities, and update procedures regarding safety footwear, to demonstrate the resistance threshold of all safety footwear is compliant with BS PD CLC/TR 60079-32-1:2018. Any new safety footwear procedure should be imbedded into NGN's culture prior to the gas changeover.

[12] BSI Standards Limited. (2006) Respiratory protective devices – Self-contained open-circuit compressed air breathing apparatus with full face mask – Requirements, testing, marking. BS EN 137:2006.

8. For both natural gas and hydrogen, the minimum BA specifications should be:

   - For oxygen deficient environments BS EN 138 FABA with antistatic hoses that comply with BS PD CLC/TR 60079-32-1.
   - For potential flame engulfment environments BS EN 137: type 2 SCBA.

9. Review the current BA policy to confirm that the provision of FABA is suitable and adequate for all environments where it is currently in use.

4.4. Risk Assessment – Escape Management Tool and Safety Distances

4.4.1. Scope

The HSE S&RC reviewed three aspects of safety raised during the procedural review undertaken on the current below 7 barg operating procedures of Northern Gas Networks (NGN). The aspects assessed were as follows:

Escape Management Tool (EMT): A field engineer investigating a gas leak on the distribution network may conclude that the situation does not require immediate action to repair the leak. In this case, the leak location must be regularly visited by NGN personnel to monitor the situation, until the network has been repaired. The frequency of these follow-up visits is determined by use of the Escape Management Tool (EMT) created by GL Noble Denton.

Operational Safety Distances: NGN procedures refer to numerous safety distances which must be observed by NGN personnel working on the network or investigating leaks.

Evacuation Distances: NGN emergency procedures specify safety evacuation distances relating to leaks detected on high-pressure (>7 barg) transmission pipelines.

4.4.2. Escape Management Tool Recommendations

The current form of the EMT is a critical method of safely managing risk and relatively simple tool for operatives to use in the field in order to decide whether a leak fits into a 1-, 4-, or 7-day re-check. It is expected that after conversion from natural gas to hydrogen, operatives will still need this tool to assess these escapes.

It is recommended that there should be a change to the 100% lower explosion limit (LEL) value (Band 1) in the Escape Management Tool from 5% Gas-In-Air (GIA) to 4% GIA. Without further information on how the other three bands (2–4) were set, no further changes have been proposed. Further research into the original basis for the existence of the four GIA bands and the reasons for the limits of the bands may provide rationale for adjusting the GIA bands.

The project also suggests making use of the CONIFER modelling tool to explore the following:

→ Effect of pressure regime on the risk of an incident for hydrogen

→ Effect of the presence of cellars on the likelihood of an incident

The EMT was based upon 5 years of historical data of natural gas leaks. All recommendations relating to the EMT should be reviewed once there is enough data relating to gas in building incidents from a hydrogen network: this could potentially be done using field data but again this would have to be determined.

4.4.3. Revisions to safety distances

It is recommended that the following revisions to safety distances are implemented:

Specific distance	Current natural gas distance (m)	Hydrogen equivalent safety distance (m)	Comments
Ignition prevention minimum distance			
Around the survey area for standard bar holing (NGN/PR/EM/72) (NGN/PR/EM/74)	5	5	No change.
Use of non-ATEX powered tools within the vicinity of an escape (NGN/PR/EM/72) (NGN/PR/EM/74) (NGN/PR/EM/74a) (NGN/PR/SL/1)	5 (upwind)	5 (upwind)	No change.
Positioning of vehicles (NGN/PR/ML/1)	5 (upwind)	5 (upwind)	No change, it should be noted than in other procedures such as EM72 and EM74, the requirement is only for the vehicle to be upwind.
Distance vents are sited from potential ignition sources when undertaking purging (NGN/PR/ML/4)	5 (downwind)	Distance variable depending on release conditions. Refer to distances from the IGEM/SR/25 hydrogen supplement .	Refer to section 4.1.2 for further information on methodology to calculate distance.
Live gas operations where there is potential for a flammable atmosphere to form (NGN/PR/SL/1) (NGN/PR/ML/1)	5 (upwind)	15 (upwind) when working on a25 mm diameter pipe. 22 (upwind) when working on a 50 mm diameter pipe.	Networks to determine what constitutes a potentially gaseous atmosphere for general main and service laying operations (suggest anything that requires the wearing of breathing apparatus i.e., atmospheres >20% LEL).
From the exhaust of the Tornado bar hole evacuation tool (NGN/PR/EM/74)	5	15	This assumes that the minimum diameter of piping inside a Tornado tool does not exceed 25 mm. On this basis the recommendation is conservative.
Minimum distance of pipe feature from buildings			
Temporary repair (NGN/PR/EM/72) (NGN/PR/EM/74a)	2	2	No change based on a small leakage rate from an open excavation, conservative already for NG.
Cut-off of metallic service pipes – minimum distance of fitting from building (NGN/PM/MSL/1)	2	2.2	Change based on backfilled repair/connection leaking. Live cutting of metallic pipes containing hydrogen is not recommended.
Grout sealed mains insertion (minimum distance from building to end of grouting) (NGN/PR/ML/6016)	2	2.2	Change based on backfilled repair leaking.
Minimum evacuation distances			
Medium pressure pipeline (NGN/PR/EM/72) (NGN/PR/EM/74)	12	34 (unignited) 12 (ignited jet)	Distances based on release state on First Call Operative (FCO) arrival at scene i.e., if the release is ignited or not.
Minimum distance from electrical equipment (which could function as potential sources of ignition) (NGN/PR/SL/1)	25	55 (unignited) 25 (ignited jet)	Distances based on release state on FCO arrival at scene i.e., if the release is ignited or not.

Specific distance	Current natural gas distance (m)	Hydrogen equivalent safety distance (m)	Comments
MP meter vent pipe tips			
Minimum distance of vent pipe tip from opening into building (NGN/PR/SL/1)	1	3	Recommend this is brought in line with distance to non-ATEX electrical equipment (below).
Minimum distance from electrical equipment (which could function as potential sources of ignition) (NGN/PR/SL/1)	1.5	3	Change based on 2022 update to IGEM SR25 hydrogen supplement - non-ideal impeded vent pipe terminations.
MP boundary regulators			
Minimum distance from boundary regulator to building (NGN/PR/SL/1)	3	See Comment.	It is recommended a full HAC is performed using the IGEM SR/25 hydrogen supplement. If the distance generated does not exceed 3 m building burning distance, then this should become the limiting distance.
Distance criteria for immediate response			
Gas detected within 500 mm of a building (NGN/PR/EM/72)	0.5	0.5	No change as the location of the leakage source is not specified, gas is just ‘detected’. This is not the case for a leaking non-LP pipe so increased ground migration is valid.
Leaking non-LP pipe within 5 metres of building (NGN/PR/EM/72)	5	7	Due to potential increased range of underground migration.
Surveys on high-risk pipes			
Within 30 metres of building (NGN/PM/LC/18)	30	30	No change.
Survey along leaking pipe			
15 metres from leak (NGN/PR/EM/72)	30	30	No change.

Table 4.4: Recommended changes to safety distances

4.4.4. Transmission Pipeline Evacuation Distances Recommendations

The thermal radiation hazards arising from a leak on a hydrogen transmission pipeline would not be greater than those from a natural gas transmission pipeline. Where there is a significant time delay between the start of the leak and the arrival of a First Call Engineer at the site of a large leak, the thermal radiation hazard ranges arising from a leak on a hydrogen transmission pipeline would be lower than that for natural gas.

Overpressure arising from a hydrogen fire does not present a hazard at distances in excess of the hazard distance for thermal radiation when the ignition of the leak is immediate. This is less certain if delayed ignition of a large-scale release of hydrogen were to occur. A separate study, outside the scope of this project, FutureGrid, is examining the impact of delayed ignition of a large-scale high-pressure release.

4.5. Human Factors

4.5.1. Scope

The integration of Human Factors considerations into the conversion of the UK gas networks to carry 100% hydrogen is fundamental to developing future safe systems of work.

Rather than expecting Operatives to adapt to new designs that may unintentionally 'force' them to make errors and/or to work in an uncomfortable, stressful, or dangerous manner, early Human Factors integration seeks to understand how the workplace or system where hydrogen is used should be designed to suit the Operatives who need to use it. Design refers to the design of competence management systems, how tasks are designed (e.g., staffing levels, workload), plant, equipment and component design, the design of the operational environment, and the design of procedures. This proactive systematic approach to the application of a hierarchy of control (HoC) of measures aims to manage and support the performance of Operatives in safety critical work. Application of HoC not only enables more robust controls to be considered, but will also provide key decision-making information which may be required from a regulatory perspective.

The scope of the Human Factors programme of work was therefore to gain understanding of how and why the safety management system should be designed for Operatives when transitioning to work with 100% hydrogen. In designing safety management systems, human performance must be considered in all parts of that system, including task and equipment design, the design of the operational environment, the design of procedures and training and the design of the competence management system.

To do this, the following four research questions were addressed:

1. What factors influence the safety of Operatives when carrying out safety-critical work with natural gas?
2. Based on current understanding, what are the potential challenges to new ways of working required for Operatives transitioning to working with 100% hydrogen?
3. What are the potential implications of challenges/new ways of working for Operatives working with 100% hydrogen in a specific scenario?
4. What actions are recommended to promote the safe design of work with hydrogen?

To answer these questions, the objectives were:

a) Review a sample of incidents/ audits involving natural gas.

b) Consult with Operatives in a variety of workstreams and with different levels of experience about their safety critical work with natural gas.

c) Consult with experts in the H21 team (HSE S&RC and NGN) to identify potential safety implications associated with hydrogen work.

d) Identify an appropriate scenario involving natural gas and consider the applicability of a relevant procedure for working with hydrogen.

e) Deliver findings in a technical report.

There were four main sources of data collection:

1. A desk-based high-level review of a sample of accident/incident reports and associated documentation.

2. Consultation with a representative range of NGN Operatives/Team Leaders in a series of one-to-one interviews.

3. Review of H21 Health and Safety Executive Science Division (HSE S&RC) Team findings into the implications of working with hydrogen.

4. 'Escape Locate Repair' scenario talk-through using NGN procedure, EM74[13] and EM72[14] and informed by accident/incident reports.

4.5.2. Recommendations

Many challenges in transitioning to hydrogen lie in Human Factors Integration activities to ensure Operative-centred design of work systems. Anticipated changes in task design mean that NGN need to employ methods including Function Allocation, Task Analysis, Application of Ergonomics Standards and Human Reliability Analysis to assess and predict 'work as done' with hydrogen operations. These methods will involve understanding opportunities for human failure, including physical and cognitive errors (e.g., negative transfer), intentional, and unintentional actions on safety critical tasks. User involvement is key in these processes and will help identify design solutions, which are important given negative transfer type errors cannot be prevented through training and competence. It is possible that such human failure types will be more likely during a transition period (e.g., whilst natural gas and hydrogen are both utilised in parts of the network), and the early days of transition. This is likely due to human nature tending to revert to habitual behaviours.

Challenges and new ways of working were considered in the task of attending a publicly reported gas escape. This represented the type of task that, at high level, might 'look' largely similar to existing natural gas operations, but with numerous changes in sub-tasks. These may relate to amendments to ensure the feasibility of operator positioning, interactions with the consumer, measures to eliminate ignition sources as well as consideration of where and what tools/equipment can be used. Task and Human Reliability Analysis in the field will be required to get a full understanding of the potential for error and how to design the task to minimise this error.

Recommendations to promote the safe design of work with 100% hydrogen are to:

1. Review competence management, accident investigation and the design of procedures for operations with natural gas.

2. Ensure Human Factors competency within NGN and throughout the transition to hydrogen.

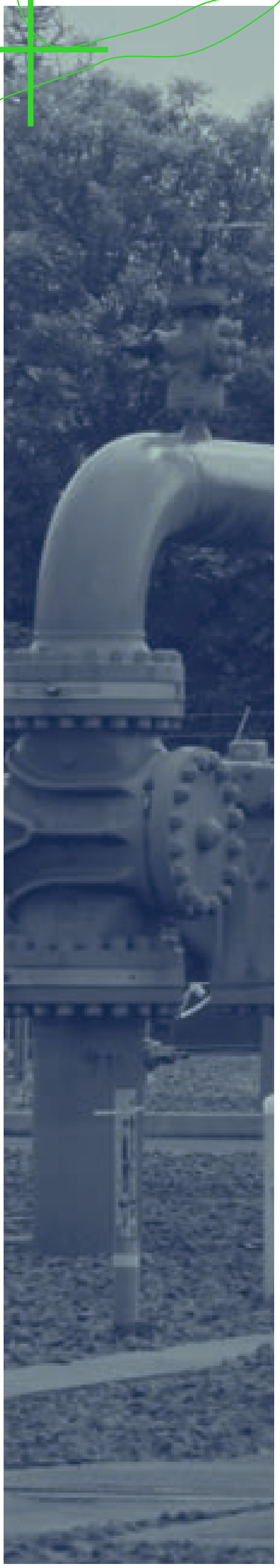
3. Develop a Human Factors Integration plan (HFIP) adopting risk management principles that include key Human Factors in risk assessment activities.

4. Use results of competence management review and HFIP activities to inform development of competence management for hydrogen.

5. Adopt the principle of 'preoccupation with failure' (i.e., attention to and systematic analysis of all incidents/problem areas/warning signals, no matter how trivial) to promote learning and enabling of innovative ways of working with hydrogen.

Many challenges in transitioning to hydrogen lie in Human Factors Integration activities

[13] Northern Gas Networks. Work Procedure for Escape, Locate and Repair Operatives Dealing with Gas Escapes and Other Emergencies.
[14] Northern Gas Networks. Work Procedure for First Call Engineers Dealing with Gas Escapes and Other Emergencies.



4.6. Gas Characteristics

4.6.1. Scope

Understanding the similarities and difference of natural gas and hydrogen enables a deeper understanding of how the transition from natural gas to 100% hydrogen might change the way the gas distribution network is operated and managed. This section covers the issues listed below:

- Identify gas characteristics and physical properties in support of other topic areas.
- Provide information and references in order to allow questions listed under gas characteristics to be answered, which are not covered in other work streams.

4.6.2. Recommendations

Gas Properties

The variation in radiated heat and the potential for a larger hydrogen gas cloud will have a direct effect on some of the safety distances required for a hydrogen network. This may impact on network procedures as safety distances are being reviewed.

Several procedures include statements and tables to demonstrate the behaviour of natural gas in air which will need to be adjusted to include hydrogen, while safety distances will need to be reviewed.

The hazards of working in an oxygen deficient atmosphere will not change, but the likelihood of working in an oxygen deficient atmosphere may change.

If dew points were required to be measured in hydrogen pipelines, and those pipelines operate at different pressures to the current natural gas pipelines a dew point calibration would need to be considered.

The requirement for gas conditioning using heaters will be dependent on the susceptibility of the parts within the system to low temperatures. Where a rapid drop in temperature will negatively impact on a part, such as a regulator, heating will still be required. Existing heaters should be assessed to ensure that they are capable of meeting any additional heat demand.

Gas Detection

Gas detectors and personal monitors currently used to detect natural gas may not be suitable to detect hydrogen or, though unlikely, may need to be re-calibrated for hydrogen. All procedures that require such devices will need to be reviewed and either hydrogen devices made available to hydrogen users, or another basis of safety identified to allow the procedure to be performed. Risk assessments will also need to clearly identify mitigation undertaken in confined spaces work in order to protect workers.

Following completion of a national conversion to 100% hydrogen, there will no longer be a requirement to detect methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), or soot build up in and around appliances. Hydrogen survey detectors will be required for all operational staff working with hydrogen to detect if there is a build-up of unburnt hydrogen gas. It should be noted that the independent detection of CH_4, CO, and CO_2 will still be required during any conversion process from natural gas to hydrogen.

Within legacy networks, and large-scale hydrogen production facilities, carbon containing compounds, such as CO, may be present as impurities in the hydrogen. In addition, operational staff may still be exposed to carbon containing fuels, such as solid fuels or LPG, and they are an emergency service provider for CO incidents. Due to these considerations appropriate CO monitors will continue to be required and used throughout the network.

The networks should consider purchasing new personal CO and CO_2 monitors that are independent or compensated for hydrogen cross-sensitivity issues, as these will still be required due to the other potential sources of CO and CO_2 that may be present, especially in confined spaces.

Close to hydrogen pipelines, dying vegetation may still be able to help identify the location of large leaks but for small leaks, especially those that occur over a long-time frame, dying vegetation cannot be considered a suitable method for identifying potential underground hydrogen leak sites.

Dealing with Fires

Due to the risk of generating a flammable atmosphere, hydrogen flames should always be left to burn themselves out after isolation. Water can be used to cool the surrounding area that may be compromised by the heat and suitable commercial fire extinguishers can be used to prevent the fire spreading while waiting for the hydrogen flame to self-extinguish.

Commercial dry powder fire extinguishers currently used by the networks are suitable for fires in the presence of both natural gas and hydrogen.

Network Flows and Flow Meters

A number of queries were raised from the literature review related to the flow meter function and accuracy and how this would be affected by a change in fuel gas. The review concluded that the non-fiscal meters identified on the natural gas network would function correctly but would require recalibration/recertification for use with hydrogen. This may also include new membrane materials and tapping locations.

A review of meter placement has shown that no changes in entrance length would be required. Network filters prior to flow meters may need replacing due to flow velocities increasing beyond the operating range.

Welding and Brazing

It is strongly recommended that welding trials using gas transmission pipeline and gas distribution steel pipelines containing hydrogen are conducted to establish the revised preheat levels for those grades of steels covering a range of compositions and vintages, thicknesses, welding processes and specific filler metals, etc. The tests should be conducted under a variety of conditions of preheat, thickness etc.

Brazing alloys are likely to absorb atomic hydrogen during the brazing process. The response of the brazing alloys to the presence of hydrogen atoms has not been evaluated and therefore if brazing of steel impregnated with atomic hydrogen is desired, it would be prudent to carry out some brazing trials using similar conditions (e.g., brazing alloy, time, temperature) to that likely to be used in practice.

4.7. Software and Models

4.7.1. Scope

The review of the below 7 bar network operational procedures performed for H21 Phase 2a identified that the change from natural gas to hydrogen raised issues related to software for network analysis. The HSE S&RC undertook an evaluation of software tools for modelling the hydrogen network[15]. This section details which tools can be used for a conversion to hydrogen and whether the equations used in the tools have been validated for hydrogen.

For this evaluation, questions about modelling were of two types.

1. Whether models identified in the review were ready and validated to be used to predict the behaviour of hydrogen.

2. Whether quantities related to modelling would be affected, or need to be altered, changing from modelling natural gas to hydrogen.

All the software tools identified in procedures were developed by DNV. The tools identified, and their use, are listed below:

Name	Application
FALCON	High pressure pipelines (steady state and transient analysis)
Synergi Gas	Large distribution systems (steady state and transient analysis) previously known as SYNERGEE and Synergy Network Analysis
COMPASS	Compressor analysis
SNAP	Design of new housing developments
Toolbox models: OPD Module	Scaling of demands off-peak, not widely used due to data limitations
CONSUS	Tool for determining diurnal storage volumes
PRISM	Detailed analysis of Above Ground Installations (AGIs)
HTREC	Heat recovery tool to investigate temperature recovery of gas in single diameter buried steel pipelines downstream of a pressure reduction station
Xoserve	Xoserve (Central Data Service Provider for Britain's gas market) is the central register of all premises with a gas supply and the repository for meter point Annual Quantities (AQs).

Table 4.5: Software tools identified in procedures

4.7.2. Recommendations

The network analysis tools, Synergi Gas and FALCON include a variety of equations for modelling flow as a function of pressure drop across pipes carrying compressible fluids from low consumer delivery pressures up to high transmission pressure. All equations included have been widely accepted within the oil and gas industry for decades. These products also offer a range of options for calculating the equation of state of a gas, including the expanded viscosity correlations necessary for hydrogen analyses. Synergi Gas and FALCON, therefore, are appropriate tools for modelling hydrogen networks.

When building any hydraulic model, the modeller must make decisions on an appropriate equation of state, friction equation, pipe flow equation and inputs for said equations. Calibration is essential for ensuring that the hydraulic model is a reasonable approximation for a specific network. This may involve determining a value for a quantity such as pipeline efficiency to better reflect the local pipe conditions/construction. The project has conducted testing to gather and analyse data for hydrogen flowing in pipes and these results have been used to validate and refine the inputs to the hydrogen pipeline models (particularly the general valve equation co-efficients for different equipment).

[15] HSE S&RC. (08 April 2021) H21 Phase 2: Evaluation of Software Tools for Modelling. V1.2.

Of the remaining software tools, PRISM can be used to model hydrogen and COMPASS and HTREC are part of the 'roadmap' for conversion for use with hydrogen. SNAP could be updated for hydrogen.

The remaining software tools present specific challenges of relevance or implementation:

- CONSUS uses a statistical engine based on demand data and has no equations for modelling fluid dynamics; the gas type is not relevant.
- OPD is no longer supported by DNV and will be replaced by the deliverables of the Real Time Network project.
- The Demand Derivation System (DDS) uses information from Annual Quantities (AQs) in the Xoserve registry. These measurements will not be available for hydrogen until after the change has been made from natural gas. Where quantities in the DDS are related to volumes or flow rates then these will have to be updated for hydrogen.
- DNV have a replacement product for DDS called IDS, which NGN are currently implementing.

Note: The names used for the network analysis tools software have not remained the same. When the review of procedures was undertaken some procedures used the most recent names while others still used previous names. It is recommended that the procedures are updated with the appropriate names and examples as required.

4.8. Flow Stopping

4.8.1. Procedural Review
4.8.1.1. Scope

The project reviewed the procedures related to distribution pipe isolations and as all procedures use the same basic order of operations the project focussed on NGN/PR/ML/4[16] as this covered the two most commonly used techniques of semi-supported bags and squeeze-off. Figure 4.2 below shows the set-up required by NGN/PR/ML/4 for flow stopping of a metallic main using semi-supported bags.

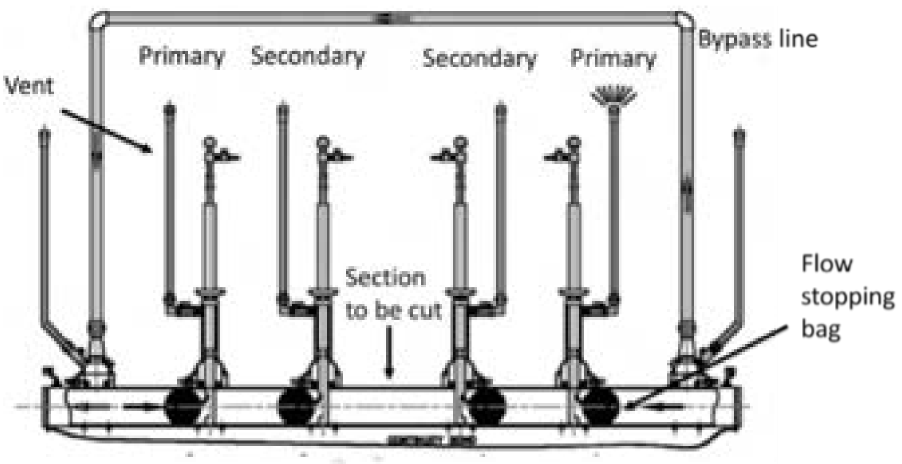


Figure 4.2: A figure taken from NGN/PR/ML/4 showing the set-up for flow stopping of a metallic main using semi-supported bags

[16] NGN/PR/ML/4. Work Procedure for Pipe System Construction, Module 4, PE Main Laying up to and Including 630mm Diameters at Pressure up to and Including 2 bar.

Following a review of NGN's procedures, several recommendations were made on adaptations to the procedures for flow stopping so that they could be used safely and effectively with hydrogen.

The generalised order of actions for flow stopping natural gas are:

- → Install the appropriate number of pipe saddles and drill the live pipe, leaving the slide valves on the saddles closed before removing the drill.
- → Install the bypass line, test, and directly purge the air out of it with natural gas.
- → Open the bypass line.
- → Deploy the secondary stops and check that an adequate seal has been achieved by observing let by at the vents in the section to be cut.
- → Deploy the primary stops and check that an adequate seal has been achieved by observing the vents between the primary and secondary bags.

After the work has finished, the secondary stops are removed before the primary stops, after which the bypass is closed, purged with air and removed.

4.8.1.2. Recommendations

Following a review of NGN's procedures, several recommendations were made on adaptations to the procedures for flow stopping so that they could be used safely and effectively with hydrogen.

Standards of Isolation

Following HSG 253[17] only double isolations are to be used with hydrogen in mains and services. Where this is not practical in services, a risk assessment and ALARP[18] demonstration will be required. Further practical evaluation could be undertaken to determine if this could change, similar to natural gas, where single squeeze offs are allowed on certain diameter LP (0-180mm) and MP (0-63mm) PE mains and services.

Inflation of Bags

Nitrogen should be used as the fill gas for all bags while flow stopping hydrogen, rather than air that is currently generally adopted.

Before/during set up of flow stopping

The bypass line should be indirectly purged with nitrogen following a successful pressure test and the section to be cut after flow stopping between the secondary (inner) stops should also be purged with nitrogen immediately before cutting, please refer to the diagram below. The drill body should also be purged with nitrogen before drilling into the main:

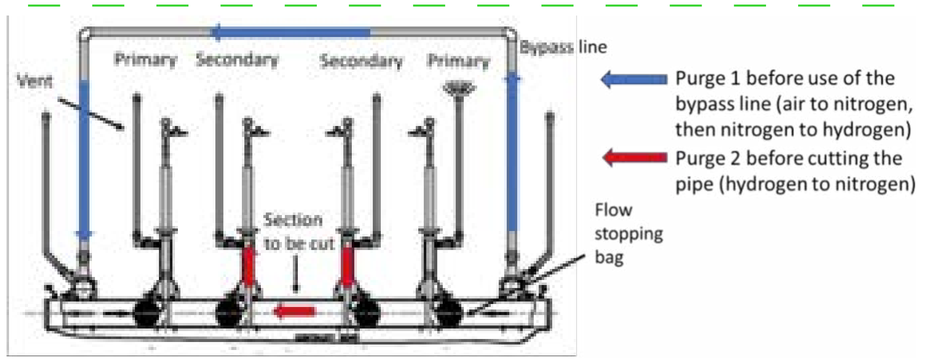


Figure 4.3: The purging required after installation of the flow stops and before the use of the bypass line cutting of the pipe can commence

[17] HSE. The safe isolation of plant and equipment. HSG 253.
[18] ALARP – As Low As Reasonably Practical

After the section is cut and repaired

When reinstating hydrogen after flow stopping, the following method is recommended as shown in the figure below:

- → Before removing the secondary (inner) bags, the cut and repaired section should be purged with nitrogen after works are complete (to remove any air ingress during the repair);
- → After removing the secondary stops, the section between the two primary bags should be purged with hydrogen using the existing direct purging protocol (the section should only contain nitrogen and hydrogen); and
- → The bypass line should be purged with nitrogen before removing it.

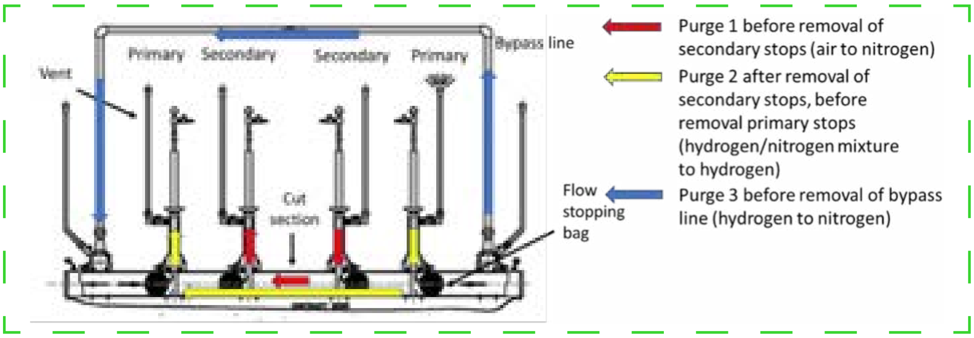


Figure 4.4: The purging required after repair of the cut section and removal of flow stopping equipment

Purging

When re-commissioning the repaired/replaced section back to hydrogen the purging vent needs to be suitably sized. This may require an additional separate vent if the flow-stop saddles vents are not sufficient.

Changing equipment

All equipment should be vented to a safe place away from operators. It is recommended that fixed vents on the equipment bodies should be used for venting as significant free volumes could exist within the equipment body and hydrogen gas could build up in the excavation if released into it. All drills and equipment should be purged with nitrogen before disconnection.

4.8.2. Effectiveness of Flow Stopping

4.8.2.1. Scope

This project reviewed the use of the flow stopping techniques currently used with natural gas mains and services and their continued suitability for use with hydrogen. The scope of work was limited to the low (LP) and medium pressure (MP) mains networks (i.e., up to and including 2 barg), as assets from H21 Phase 1 which are suitable up to 2 barg were re-used. Flow stopping, however, is used in the intermediate pressure (IP) network up to 7 barg. The updated basis of safety will remain valid for the IP network, however, testing of the effectiveness of these methods at the higher pressure will be needed, or validation by the manufacturer.

Figure 4.5: The flow stopping demonstration on a section of metallic main at HSE's Science & Research Centre in Buxton

The following flow stopping methods were undertaken following specific network operational procedures:

- Squeeze Off
- Semi Supported Bags (WASK/Sarco)
- Semi Supported bags (ALH Systems)
- Iris bags (ALH Systems)
- Metallic Line Stop (MLS)
- Lip Seal Plug
- Foam Plug

4.8.2.2. Basis of Safety Recommendations

The basis of safety for the use of flow stops with hydrogen should change from that for natural gas. The basis of safety should now include preventing an ignitable atmosphere in the region to be cut, rather than solely re-pressurisation of the section and/or excessive losses from the network.

A new criterion was developed that relates the backpressure generated by flows up the vent between primary and secondary stops, with the leak rates across the secondary stop to generate an ignitable atmosphere beyond the prescribed time limits. It is recommended that backpressures on the intermediate vent upstream of the section to be cut do not exceed 0.2 mbarg; this new criterion could be measured with pressure gauges by operatives in the field to alert them if a flow stop has not sealed adequately.

The pressure dependence of the flow stopping technique needs to be determined to calculate the pressure at which the prescribed maximum flow occurs. This calculated value from laboratory testing needs to be greater than 0.2 mbarg so that the prescribed maximum flow will not occur in practice. Operatives using flow stopping methods can measure the pressure generated on the intermediate vent, and this should be less than 0.2 mbarg to demonstrate effectiveness. Suitable accurate gauges should be utilised for this purpose.

4.8.2.3. Flow Stopping Methods Recommendations

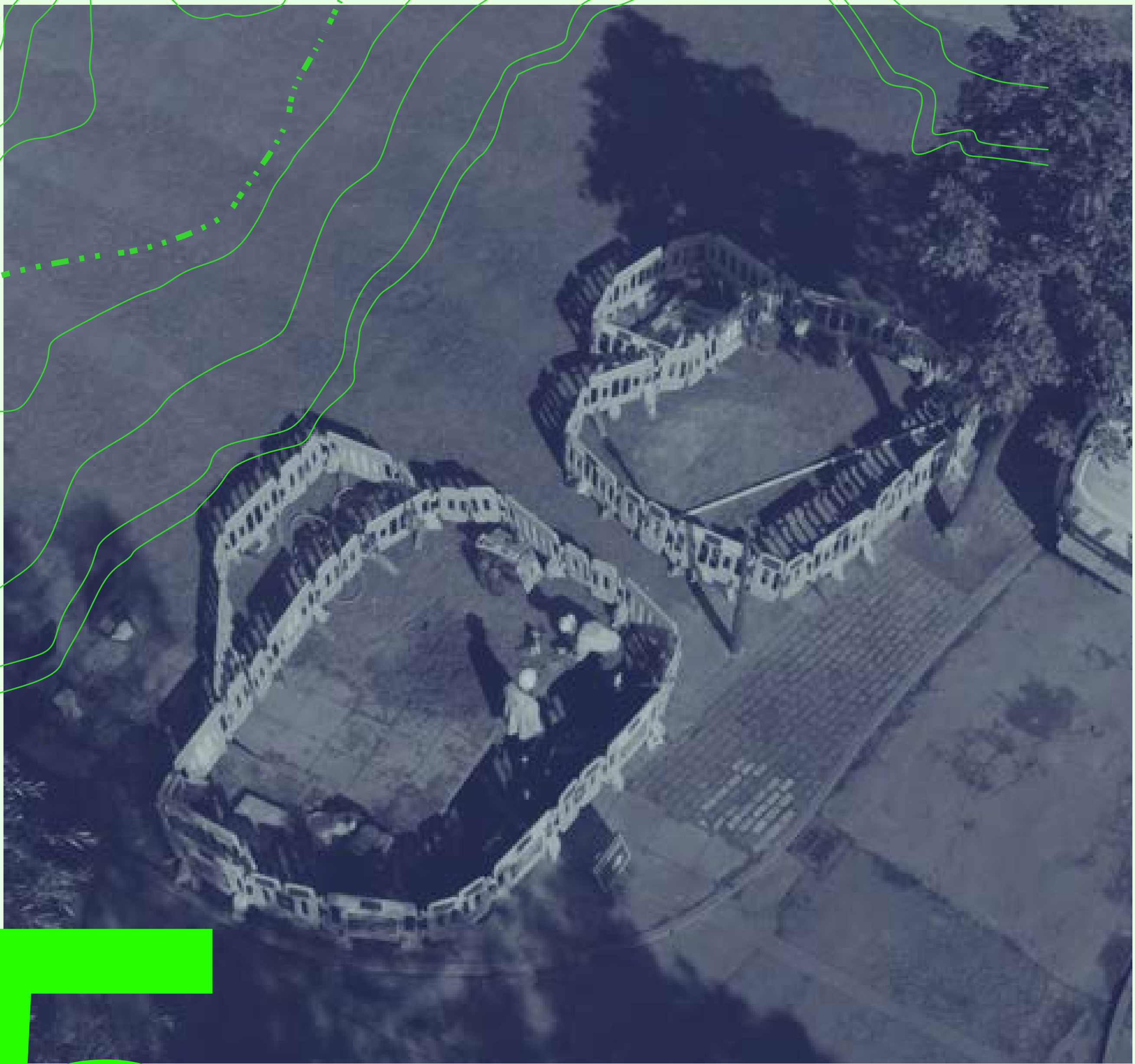
Testing of flow stopping techniques was undertaken following industry and manufacturers' method statements. The results of this testing programme were obtained for particular samples of pipe under particular ambient conditions. Multiple repeats of the flow stopping techniques were not performed, and in most cases multiple different pipe samples of the same size and material were not used. The test results are therefore indicative in nature and serve as a guide as to which stopping methods appear to be effective or not.

The testing results show that squeeze off, MLS, lip seal plugs (Stopple) and foam plugs performed well and met the new criteria. For MLS, lip-seal plugs and foam plugs, so little flow occurred that it was not measurable, and hence no pressure build-up was measured after the flow stop.

GIS/E4 bags (both WASK/Sarco and ALH Systems) need some development to optimise bag inflation pressures to make them suitable for use with hydrogen. New bag technologies could be developed, or the shape and design of bags changed to promote laminar rather turbulent leaks (such as longer bags). Promoting laminar leakage leads to better performance at low pressures, and the leak rate past the flow stop will fall away significantly faster with pressure. This could be done by increasing the contact length and/ or decreasing the diameters of the leakage paths gas passes through.

Flow stopping development work could be undertaken by manufacturers using air, and the flow rates converted to those expected for hydrogen, with the conversion factor dependent on whether laminar or turbulent leaks are observed. However, testing with hydrogen should take place to verify that any developments perform as expected with hydrogen.

Further testing could be undertaken to determine if ignitable concentrations build up in the region to be cut. A possible experiment to measure this in a realistic manner would be to set up the two pairs of flow stopping equipment as per the network procedures. The vents should be open with flame traps attached and hydrogen detectors used to measure if hydrogen builds up between the two pairs of flow stops over the period of several hours. The hydrogen concentrations should be measured after purging of the region between the stops is conducted.



5

PHASE 2A AND PHASE 2B DEMONSTRATIONS

The Phase 2a review by the HSE S&RC involved assessing the full suite of <7 barg procedures for their suitability for use on a 100% hydrogen network. Where suitability and sound basis of safety could not be determined, recommendations for changes to procedures were made and evidence gaps highlighted. A Master Test Plan (MTP) was developed by NGN, in collaboration with the HSE S&RC and DNV to address these gaps in existing network procedures and operations through tests and demonstrations at the Phase 2a Microgrid at Spadeadam and the Phase 2b Unoccupied trial site at South Bank, both managed by DNV.

This section contains information collated from the DNV reports listed in Section 9.0 References. All graphs, visuals and photos have been reproduced by kind permission of, and are attributable to, the relevant report author.

5.0

PHASE 2A AND PHASE 2B DEMONSTRATIONS

A comprehensive review of the operating procedures in use today for managing natural gas in the Northern Gas Networks (NGN) Distribution Network was completed by HSE Science and Research Centre (HSE S&RC) in collaboration with NGN and DNV. The review involved assessing the full suite of <7 barg procedures for their suitability for use on a 100% hydrogen network. Where suitability and sound basis of safety could not be determined, recommendations for changes to procedures were made.

Working on the procedure review recommendations by HSE S&RC, a Master Test Plan (MTP) was developed by NGN in collaboration with the HSE S&RC and DNV to address various aspects of existing network procedures and operations.

Delivery of the MTP was specified to be carried out on two different representative networks, both able to run on natural gas and 100% hydrogen:

→ **Phase 2a:** A full-scale (diameters, pressures and flows, not lengths) 'Microgrid' at Spadeadam. This new build, polyethylene network of gas mains involved all distribution pressure tiers (IP, MP, LP) and a significant range of diameters of PE pipe, and was capable of producing demands of up to 4000 scmh of hydrogen flow through repurposed natural gas pressure reduction equipment. Real network assets in the form of metallic valves, governors and repaired leaking metallic assets were also included.

→ **Phase 2b:** An area of South Bank where a live low pressure ductile iron gas network was still in service but effectively redundant after demolition of the housing some years past. DNV and NGN developed and commissioned a secure, isolated hydrogen distribution network by linking together the existing 4" and 6" ductile iron mains with 180 mm PE cross-links. A high pressure to low pressure hydrogen supply system, complete with a repurposed natural gas MP-LP pressure regulating unit and odorization dosing unit was used to introduce odorized hydrogen into the trial network for completion of the MTP. A 63 mm PE branch was also installed to feed two PE services supplying 100% hydrogen boilers providing hot water and heating for the office and welfare facility on the site.

The review involved assessing the full suite of <7 barg procedures for their suitability for use on a 100% hydrogen network.

The scope for the **Phase 2a Microgrid** site included undertaking the following activities:

- Emergency response and bad practice demonstrations
- Finding leaks
- Accessing leaks
- Assessment of repair techniques
- Planned Live gas operations
- Isolation techniques
- Commissioning and decommissioning activities
- Pressure regulation and maintenance procedures
- Pressure and flow validation

The scope for the **Phase 2b Unoccupied Trial** site included undertaking the following activities:

- Finding leaks
- Assessing leaks
- Planned live gas operations
- Isolations
- Water extraction
- Commissioning and decommissioning activities
- Pressure regulation and maintenance
- Modelling

The following sections of this report provide further details on the demonstrations undertaken and the findings. As some of the activities are of a similar nature, the results have been grouped together from Phases 2a and b where possible.

Phase 2a Microgrid

Commissioned specifically for the Phase 2a activities, the 'Microgrid' at Spadeadam consisted of:

- 48" diameter carbon steel high pressure storage array.
- HP to IP pressure reduction skid, specifically designed and built for 100% hydrogen service.
- 'Microgrid' consisting of various lengths and diameters of PE pipe in pressure tiers separated by pressure reduction equipment taken from natural gas service on existing networks. Standard GIS rated valves were used to isolate the various sections of the Microgrid.
- Vent line, demand valve and stack capable of providing a demand of 4000 scmh flow rate on the network.

The system was heavily instrumented to allow for the pressure, temperature and flow conditions to be well understood under varying loads. Demand on the network was provided at low level by connection to 100% hydrogen boilers in the adjacent HyStreet facility, and at higher levels by the operation of a flow control valve in the vent line to simulate demands up to approximately 4000 scmh.

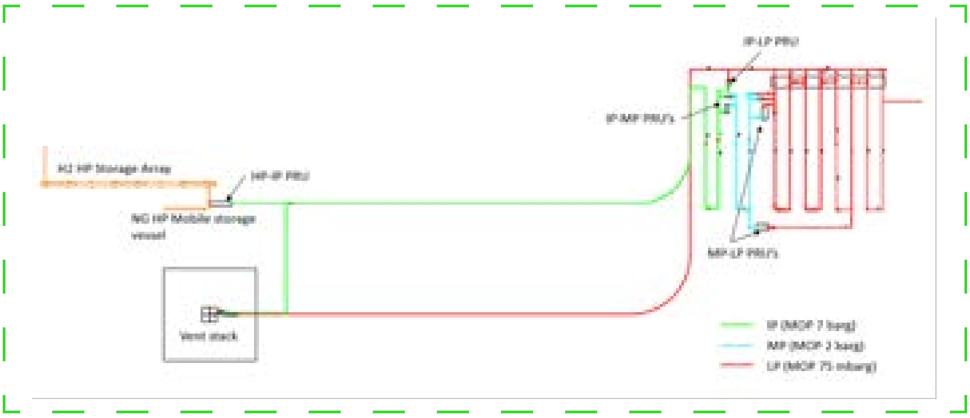


Figure 5.1: H21 Microgrid facility at DNV Spadeadam site

Figure 5.2: Aerial view of H21 Microgrid

H21 Phase 2b: South Bank Test Site

Similarly to the Microgrid at Spadeadam, the Phase 2b facility was built specifically to address the MTP but in a different environment to that at Spadeadam. The site was selected by NGN on the basis that it contained two abandoned and demolished domestic streets where the existing low pressure metallic ductile iron gas mains were still connected to the wider network. The facility involved:

- Erection of a security fence to manage access.
- Isolation and decommissioning of the four gas mains transiting the site.
- Installation of connecting pipework to the ends of each existing main such that a network loop was formed.
- Provision of an internal, secure compound with high-pressure hydrogen storage, odorization system and pressure reduction equipment to provide LP hydrogen to the test network.
- Pressure reduction was achieved using cylinder pack regulators to reduce pressure from HP to MP and then a re-purposed natural gas governor was used to regulate the pressure from MP to LP.
- Site-wide CCTV and gas detection system to enable 24-hour monitoring of safety and security on the site.
- New control room and 'boiler room' to provide control and demand on the network respectively. Demand was provided by a pair of boilers feeding the hot water and heating systems for the site buildings.

This facility provided an opportunity to demonstrate new and existing operational practices as defined in the MTP but also served to build experience and confidence in being able to convert and operate existing network mains on 100% odorised hydrogen for the first time. The project involved the development of a site-specific Safety Management System for the test facility which could serve as a blueprint for further trials of this nature.

The Phase 2b network was smaller than that in Phase 2a and hydrogen demand was set to accommodate the maximum required for the purging operations of the biggest metallic mains on the facility, which were 6" ductile iron. This was up to 1600 scmh and was achieved by operating up to 6 multi-cylinder hydrogen packs in parallel. Baseline demand on the network was provided by two 100% hydrogen domestic boilers, both operating with odorized hydrogen for the first time. Hot water and central heating in the control room was serviced by these boilers in addition to a sink in the boiler room itself. The boilers were in service for the whole operational use of the facility (circa 9 months) and remain available to be recommissioned if the site is recommissioned.

Figure 5.3: Aerial photo of the site with pipe arrangements overlaid; new PE mains in yellow, existing ductile iron mains in red

5.1. Emergency response and bad practice demonstrations

5.1.1. Scope

Demonstrations of the potential consequences from operations not following the recommended change in practices were conducted as 'Bad Practice' demonstrations in the H21 Phase 2a project. Specifically, this involved trials where ignited events in buried pipes and outside vents were conducted to gather both qualitative and some quantitative information on the consequences of such Bad Practice events.

5.1.2. Inadequate commissioning/ decommissioning of mains and services

5.1.2.1. Method

In the first of these demonstrations a stoichiometric mixture of hydrogen and air was purposefully created inside both main and service pipes and ignited. This could occur during commissioning and decommissioning of pipes with hydrogen if newly proposed indirect purging procedures were not followed, and hydrogen was able to mix with air inside a pipe and was subsequently ignited (either outside of the vent or by some mechanism inside the pipe).

Conducted as two separate tests using nominally 10 m lengths of main pipe (180 mm PE) and service pipe (32 mm PE), the flammable mixture was ignited, and internal and external overpressures were measured. The ends of the pipes were left as an open trench to resemble a purging operation where injection and vent points are usually manned. Video footage was taken to illustrate the effects of the internal explosion in open and above ground.

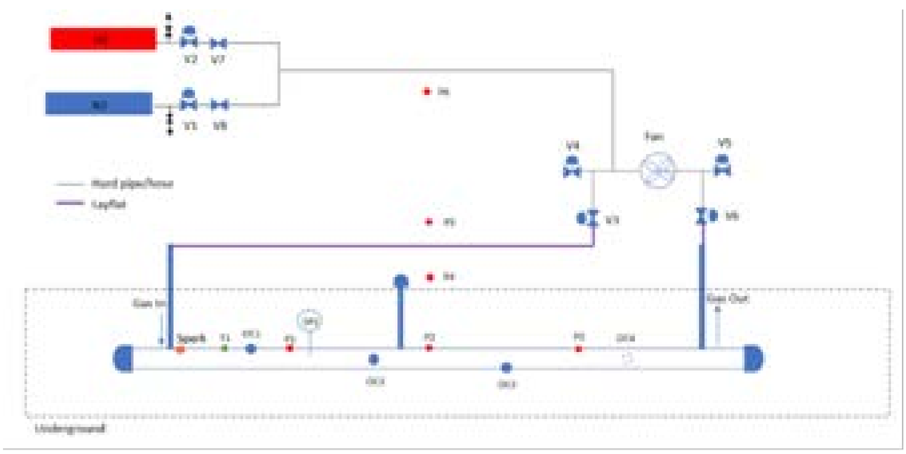


Figure 5.4: Test setup

5.1.2.2. Results

The following results were found:

1. The number of demonstrations was small: one main and one service, but did provide insight into the behaviour of the polyethylene main and service when subjected to a significant internal explosion.

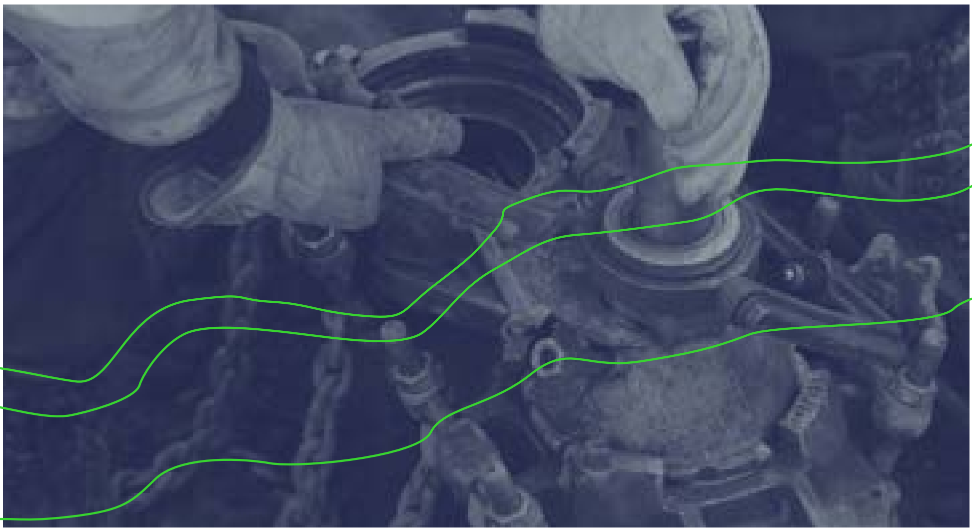
2. For the mains demonstration, the most significant consequence of concern to personnel observed came from that of the failure of an unburied 63 mm electro-fused PE cap end on a branch connection in the pipe being purged – interpreted to have had the potential to cause impact harm to nearby persons and hearing damage to those within a few metres.

    a. The cap end which failed, did so at a pressure of nominally 1 barg. The high pressurisation rate is thought to have been the cause of the apparently brittle failure of the cap, as it would not normally have been expected to fail at the 1 barg level observed.

    b. It was not possible to distinguish this consequence as being significantly different to that of a similar natural gas event, where pressures in excess of 1 barg are also easily generated.

3. Significant pressure over short durations was generated from explosion events within the pipe, with detonations suspected in both demonstrations. The detonations did not cause catastrophic failure of the PE pipes themselves, although components did fail (i.e., the electro-fused cap end). Pipes/components of differing material, construction and geometry, as are present on gas networks, could be more susceptible to catastrophic failure when subjected to comparable events. High flame speeds in both demonstrations meant that very little flammable mixture was ejected from the pipe prior to the flame reaching the outlet. This means that there was no appreciable external explosion outside of the pipe. In neither demonstration was there any evidence of ground heave or movement associated with the explosion event.

4. It is noteworthy that the internal explosion within the pipe in each demonstration showed very little potential for harm to personnel/public as measured at external pressure sensors – the most appreciable consequence was that of the failed end cap in the main pipe demonstration, which failed at a pressure of approximately 1 bar whilst subjected to a high rate of pressure rise.



5.1.3. Ignition of vented gas

5.1.3.1. Method

Three deliberately ignited vent operations were conducted with delayed ignition to gain information and understanding on the risks posed by both thermal radiation and potential explosion overpressure in distribution network level vent operations. The three cases were – 1" NB vent pipe at 2 barg, 1" NB vent pipe at 6.5 barg and a 6" NB vent running at 30 mbar to represent venting from three different pressure tiers. The difference between the visual and thermal camera records of each vent – where the flames were virtually invisible in daylight but highly luminous in the thermal spectrum – is given below:

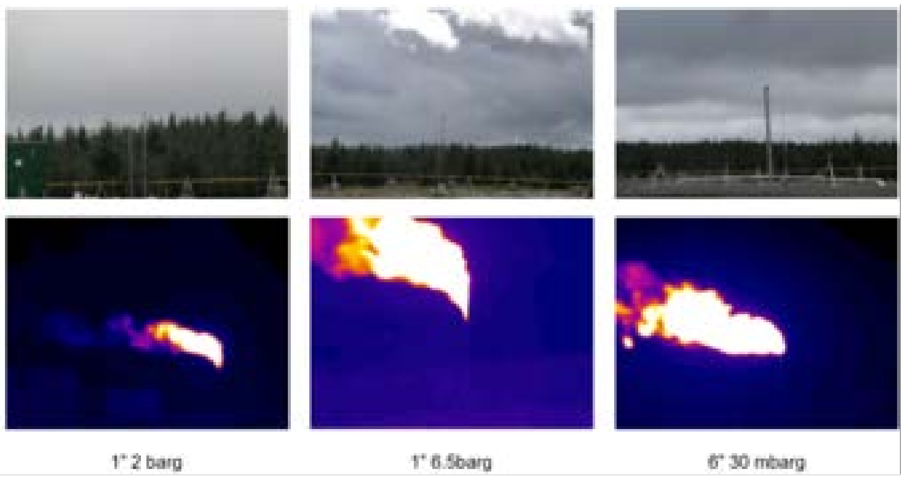


Figure 5.5: Ignited venting operations comparison between visual and thermal camera

Observations by personnel present were that the lower pressure vent was considerably more visible than the higher pressure vents but all vents were audible and exhibited a change in pitch once ignited.

5.1.3.2. Results

The following results were found:

1. Thermal radiation levels from the demonstrations conducted present a low potential for harm near to ground level (1 m above ground level) from the vent for unprotected persons.
    a. The largest thermal field was generated by the low pressure (~30 mbarg) vent through the 3 m long, 6" NB vent pipe with the potential for harm only in sustained exposure at any distance close to ground level and within 15 m.
    b. Smaller vent pipes of similar height in low pressure applications will present significantly less of a thermal hazard - these types of vent operation are most typical of the sorts conducted on distribution networks
    c. The thermal hazard distances observed by the higher pressure, smaller diameter vents were less than for the low-pressure vent. The mass flow rate in the low-pressure vent was similar to that of the intermediate-pressure (6.5 barg) vent whilst the intermediate-pressure vent posed less of a thermal hazard away from the flame.
    d. As with other flammable venting, the impact of the flame and thermal radiation on nearby combustible materials should be considered.

2. Anyone present in any location on the ground around each of the vents demonstrated would have been unlikely to suffer serious thermal injuries in the event of an unplanned ignition, provided that egress was unimpeded.

3. No information is presented on the likelihood of an unignited vent to subsequently ignite, and all vents should be considered to potentially ignite.

4. Noise from 6.5 barg pressure venting has the potential to breach the thresholds of pain for hearing at a distance of 25 m or more, with the ignition event itself providing the highest noise level, albeit for a short duration.

5. Notable changes in pitch and amplitude were audible in all trials after ignition with the ignited portion of the trial providing higher sound levels than the unignited – this change in pitch/amplitude is not inconsistent with what would be expected in similar natural gas vent operations if they were ignited.

6. The lower pressure vented flame was appreciably more opaque and more visible to the naked eye.

5.2. Finding and Accessing leaks

5.2.1. Objectives

The Phase 2a Finding Leaks and Accessing Leak demonstrations were conducted in a controlled environment at the Spadeadam site, which was previously constructed as part of H21 Phase 1b and remote to the Microgrid. Demonstration of the consequence of ignition of underground pockets were conducted as standalone tests in a further separate area in Test Site West.

Finding and assessing leaks tests were also undertaken at the Phase 2b Unoccupied Site at South Bank, utilising the findings from the work completed at Spadeadam. The programme included manned operational demonstrations of leak finding operations (bar holing/rock drilling) prior to accessing leak operations (using various excavation techniques) on hydrogen gas-saturated ground locations near to live leaks.

The programme included the following activities:

Phase 2a Microgrid:

1. Consequence tests in which bar holes over live leaks and pockets of gas under various surfaces were ignited.

2. Manned live leak-finding operations (bar holing/rock drilling) over live leaks.

3. Accessing leaks (using various excavation techniques) on gas-saturated ground locations over an isolated leak.

Phase 2b Unoccupied Trial Site:

1. Introduction and characterisation of various engineered leaks, designed to replicate typical leaks from a network, at different sections of the test facility.

2. Conducting manned leak locating activities on engineered leaks in a real street environment using a variety of techniques and following the recommended changes in procedure.

3. Conduct manned ground-breaking and excavation activities either side of the engineered leaks into ground saturated with hydrogen and subject to some lateral flow from the engineered leak through the substrate.

4. Conduct manned excavation activities onto the engineered leak location after isolation of the gas supply, but whilst the ground remained potentially saturated with hydrogen.

It should be noted that no live leaks were directly excavated on as the likelihood of ignition was anticipated as found in previous demonstrations in Phase 1.

5.2.2. Method

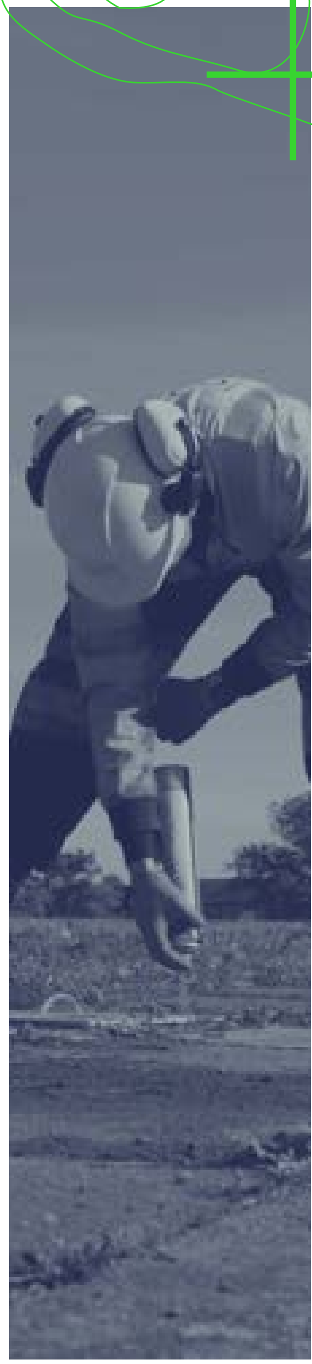
Phase 2a Methodology

The methodology followed to complete the Finding and Accessing Leaks tasks was that of:

1. Assessing the potential consequences of accidental ignition during leak finding activities over live leaks.
    a) Potential of ignition in and around the bar hole and the operative creating it.
    b) Ignition of a small pocket of flammable hydrogen/air mixture beneath the surface by interaction with the manned sample hole creation.
2. Assessing the potential for harm from excavating through potentially hydrogen-saturated ground over a recently isolated leak.

Some of the tests conducted were carried out sequentially, so that test procedures and risk assessments were updated to reflect the outcomes of previous tests. As such, the first tests conducted were consequence tests associated with leak finding operations on live leaks which were ignited by means of a pyrotechnic device or a long pole with an ignited petrol-soaked rag at one end to provide a naked flame. Single bar holes had been pre-installed at each leak location before the leak was initiated. Furthermore, pockets of gas/air mixtures (approximately 2 litres volume filled with a 30% vol hydrogen/air mixture) were ignited under flagged and tarmac areas.

After having broadly assessed the potential consequences of ignitions when conducting manned leak finding activities, the next demonstrations consisted of performing manned rock drilling and bar holing over live leaks, which allowed mapping of gas concentrations around the known leak location. Standard excavation techniques were carried out at leak locations into the gas saturated ground once the leak had been isolated.



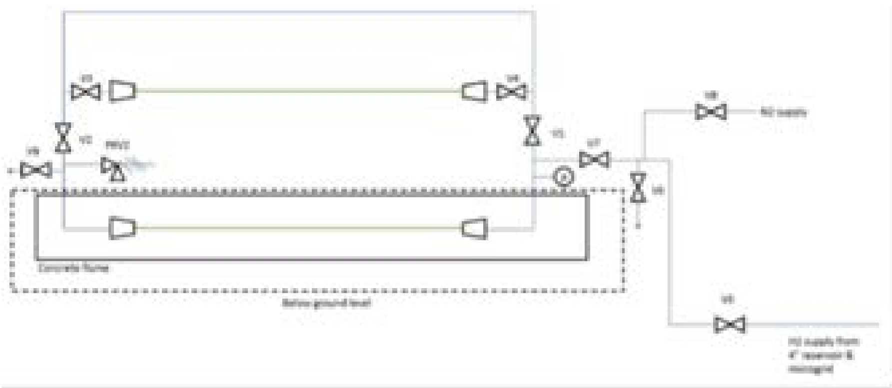


Figure 5.6: Test setup

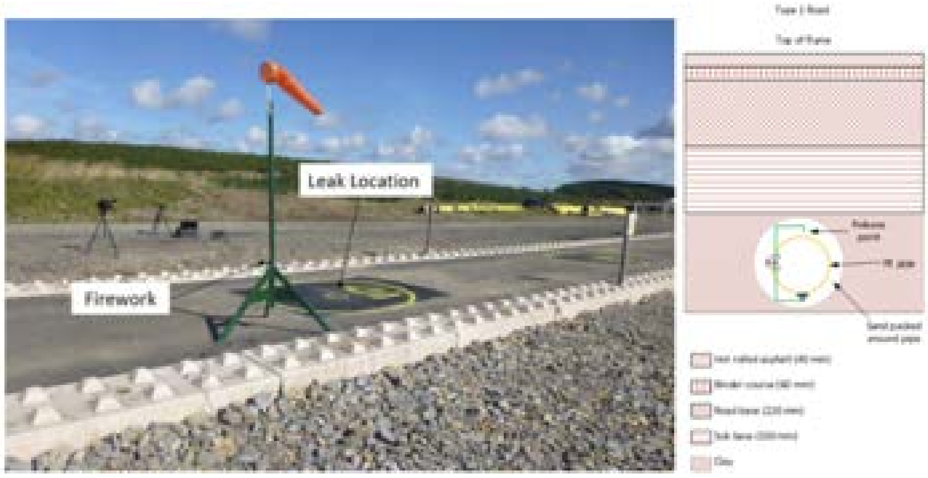


Figure 5.7: Example of Finding Leaks arrangement in Type 1 road

Finding Leak trials were conducted with hydrogen and natural gas.

Phase 2b Unoccupied Trial Site Methodology

As a part of the work undertaken on the Phase 2b Unoccupied Trial site, defined leaks were introduced into the converted LP distribution ductile iron mains within the South Bank test site. These leaks simulated releases at different points within the distribution network, presenting a range of conditions for characterising, locating, and accessing the leaks.

Finding Leak trials were conducted with hydrogen and natural gas. All gas concentrations were monitored using a hydrogen/natural gas GMI Gas Surveyor 700 Gascoseeker developed under a separate project led by SGN. The surveys followed standard operational procedures and utilised the Gascoseeker GS700 and probe connection, which was inserted into the bar holes created in preparation for the surveys.

As part of this project, the flow and migration of both natural gas and hydrogen were measured at various distances from the point of release, under different ground surfaces. Gas concentration measurements at approximate 1 m spacings to a depth of 200 mm were taken north, south, east and west of the release location on multiple occasions during a release. This allowed for a comparison of the in-ground gas migration as it changed with time at varying distances from the release point.

Figure 5.8: Example induced leak on an old service connection plug

5.2.3. Results

5.2.3.1. Phase 2a: Finding Leaks

Demonstration of potential consequences of ignition of hydrogen venting from bar holes on low pressure gas networks was investigated by attempting ignition of pre-installed bar holes over leaks of various types through different types of surface make-up and back-fill materials.

Attempts were made to illustrate any potential consequence should an operative create a sample hole coincident with some unlikely void beneath the surface containing a flammable mixture of hydrogen and air. Ignition of 2 litre underground voids filled with stoichiometric hydrogen:air mixtures failed to generate any appreciable consequence to the operative, beyond a slight movement of the ground.

Once potential consequences were established to be of low impact to personnel and equipment, manned leak finding operations were conducted using both pneumatic rock drill and bar hole techniques over live leaks.

In all cases, accidental or spontaneous ignition was not observed to occur during any of the unmanned or manned leak finding operations. Deliberately ignited bar holes in low pressure demonstrations conducted did result in limited consequence, categorised as 'popping' sounds, sustained flames and the ejection of small stones and debris over short distances (>5 m) on some tests. No direct comparisons with natural gas were conducted, but it is entirely credible and conceivable to generate very similar consequences from bar holes flowing natural gas.

Given the apparent likelihood of these events happening spontaneously or accidentally being low, coupled with the low/negligible consequences, a well-protected workforce working to established procedures and equipped with appropriate PPE is not considered to be exposed to unacceptable risk in these activities on a 100% hydrogen network. Some consideration should be given to the practices of leaving bar holes unattended when producing significant (flammable) gas readings immediately above the hole, to mitigate the risk of public interference (accidental or deliberate).

In summary; the potential consequences of leak finding activities on low pressure (<75 mbarg) hydrogen networks was deemed as low risk when conducted only in non-flammable atmospheres around the personnel and tooling. On higher pressure tier distribution networks, the conclusion likely still holds, provided that the non-flammable atmosphere conditions (< 20% LEL) around personnel and tooling is met. Leaks on higher pressure networks are also treated differently when programmed for repair, such that they are less likely to be left unattended in any case.

5.2.3.2. Phase 2a: Accessing Leaks

Following on from the findings of the preliminary trials conducted in H21 Phase 1b: WBS5 where remotely controlled excavation activities over live leaks led to some unintended ignitions of the hydrogen being vented through the excavation, the activities in Phase 2a were predicated by a requirement not to put personnel in flammable atmospheres – a key recommendation of the HSE S&RC procedure review conducted in H21 Phase 2a. For this reason, the Accessing Leaks demonstrations in Phase 2a were limited to focus on the excavations that would be required in order to effect isolation and after the isolation of a leak itself. Any such excavation would potentially need to be conducted through hydrogen-saturated ground and surfacing, particularly in cases where the surface is sealed and the hydrogen may not dissipate for many hours or days after leak isolation.

The excavation demonstrations in this task were undertaken into hydrogen-saturated ground (typically >30% vol) immediately after the leak was isolated (by operation of a remote valve) and through different surfaces representative of a highway, tarmac and flagstone footpath using a variety of techniques. In all cases, the excavations were successfully completed in close accordance with standard procedures (with the addition of the pre-requisite to isolate the leak first). No ignitions of hydrogen were observed (even with deliberate ignition attempts), and where hydrogen concentrations within and around the excavation were detected to be above tolerable working limits (i.e., > 20% LEL), these were found to dissipate immediately when the ground was disturbed.

As with any risk assessment, consideration should be given first to elimination and engineering controls before people are asked to work in potentially flammable atmospheres. However, the application of appropriate hazard awareness, robust procedures and fit-for-purpose PPE would render the activity acceptable by standard risk assessment methodologies.

5.2.3.3. Phase 2b: Finding Leaks

Engineered leaks in two of the ductile iron mains were subjected to leak finding and accessing activities at the Phase 2b South Bank Test Site. These ranged from a very small leak on a threaded component up to a slot cut through the pipe with a hacksaw simulating a fractured iron main. The slot was cut whilst the main was isolated, depressurised and purged to a nitrogen atmosphere. After reinstating the ground and surface around the engineered leaks, the arrangement at South Bank meant that it was simple to be able to compare firstly the leakage rates from different gases (hydrogen, natural gas or nitrogen) and subsequently the in-ground migration behaviour of the different gases in a real-world scenario utilising realistic survey techniques.

Figure 5.9: Small threaded leak source (left) and large saw-cut leak source (right), cut when main was isolated and purged to nitrogen

These demonstrations served as a proof that the modified leak finding and accessing methods were practicable and no additional problems were identified or encountered during their conduct. In addition, interesting comparative data on the behaviour of each of the natural gas and hydrogen leaks in real, domestic street settings was collected.

Given the complexity of the geometrical arrangements, it is difficult to identify highly correlated trends, but it can be said that the general trends found were as follows:

1. Each of the engineered leaks gave rise to higher flow rates of gas into the ground for hydrogen than they did for methane when run at the same pressure.

2. Concentration in sample holes decayed with distance from the leak in a similar trend for both hydrogen and methane.

3. In the majority of cases, normalising the sample hole measurements for the flow rate of gas meant that the decaying trends for the two gases became closer. This can be interpreted as an indication that the in-ground behaviour has little dependence on the gas properties (namely density and viscosity).

The engineered leaks in this programme of demonstrations were all in a known location, meaning that the determination of leak location purely from the survey data was not required. The observed trends in concentration are all commensurate with what would be expected in real leaks (i.e., decaying sample hole readings with distance from the release) and no obvious discrepancies were observed which would lead to any concerns that the techniques could continue to be used to find leaks on a hydrogen distribution system.

5.2.3.4. Phase 2b: Accessing Leaks

The accessing of the leaks was carried out with the following criteria (where the location of the leak was known):

In order to affect a repair/isolation, the project excavated greater than 1m from the suspected release location and ensured no sustained hydrogen readings greater than 20% LEL was found in and around the area where the excavation technique was being conducted. Excavating on any sample hole (bar hole), regardless of concentration levels, was permitted on the condition that no sustained hydrogen readings greater than 20% LEL were present in and around the area where the excavation technique could cause an ignition. For example, this would include where the digging tool strikes the ground. For this reason, additional gas concentration levels were taken at the base of the excavation as the excavation progressed.

These criteria were developed based on experience from H21 Phase 2a and in discussion between DNV, HSE S&RC and NGN representatives on site at the test site facility. The criteria proved simple to meet and required only moderately more enhanced gas sampling efforts than for a standard natural gas operation. The intention, as recommended from the HSE S&RC work in Phase 2a, is that no work in flammable atmospheres should be undertaken unless it can be demonstrated to present an As Low As Reasonable Practicable (ALARP) risk profile. Knowing where the leak locations were in this programme of demonstrations meant that this could be ensured, but it should be noted in real leak scenarios that the precise location will not be known. It is expected that the excavation criteria developed here will remain practicable in real leak scenarios where the leak location is unknown, in that the operatives conducting the operation should identify if any sustained gas concentrations are present, prior to exposing the leak. If it is possible to excavate directly onto the leak without sustained gas concentrations being present, then it may be possible to demonstrate ALARP for directly repairing small leaks.

Further work could be conducted to identify if the techniques used here could ever be used to safely excavate directly onto leaks if the criteria are continually met up to the point of exposing the leak -- note that there is not enough evidence in this work to recommend this is undertaken on real leaks.

5.3. Assessment of Repair Techniques

5.3.1. Objectives

As part of the work undertaken in Phase 2a, the project undertook repairs of some aged and previously decommissioned assets using various repair techniques, connected the repaired assets to the microgrid and left them in hydrogen service over a period to see if the repairs leaked over time.

5.3.2. Method

Six used cast iron (CI), spun iron (SI) and steel (ST) assets purposely made to present leaks or leak paths were repaired using six commonly used techniques in the current natural gas network including:

- → muffed encapsulation
- → anaerobic repair
- → two-part joint injection
- → polyform repair
- → clamp repair
- → heat shrink sleeve repair.

Repairs were conducted under nitrogen pressurisation where required. The repaired assets were then pressure tested with nitrogen, buried, and connected to the H21 microgrid and commissioned with hydrogen. These were subsequently tested weekly over the course of five months, whilst the rest of the testing programme was being carried out, the assets were individually isolated and checked for reappearance of leakage over time and under service conditions by means of pressure decay tests.

Figure 5.10: Schematic layout of repaired assets

Figure 5.11: Repair assets manifold (prior to backfill)

5.3.3. Results

All of the repair techniques were successfully applied and confirmed at the point of application to be leak free with nitrogen at 50 mbarg. The samples were subjected to hydrogen service for a period of 5 months at pressures between approximately 30 and 85 mbarg.

After approximately 3.5 months from the introduction of hydrogen, small signs of leakage were present on the heat shrink repair, which might be expected with any gas, given that it is specified as a temporary repair for use only up to 75 mbarg. This temporary repair technique would have been repaired by an interim or permanent repair much sooner than 3.5 months on a live network.

Consistently, from the introduction of hydrogen to the end of testing, the two-part injection repair showed signs of leakage, seemingly related to the internal pressure in the sample at the time of the test. No comparisons with natural gas were tested here, so it is conceivable that the equivalent repair could also have leaked in natural gas service.

All other repair techniques were found to remain leak-tight throughout the test period. These tests indicated that the successful repair techniques (Clamp, Anaerobic, Muffed Encapsulation and Polyform repairs) should prove effective in repairing leaks in metallic pipes in low pressure hydrogen networks. Conversely, the two techniques where leakage was observed after the introduction of hydrogen (two-part injection and heat shrink) could be attributed to some fault with the application of the technique, rather than any inherent unsuitability for hydrogen service. All repair techniques were applied in non-flammable conditions and, if pressure was required to achieve the seal, this was provided by applying an internal pressure of nitrogen at the required pressure.

5.4. Planned Live gas operations

5.4.1. Objectives

Live gas operations are essential to maintain and operate the distribution networks and are carried out daily by competent operatives throughout the industry. Demonstrating that these routine operations can be completed safely on a 100% hydrogen network is essential to demonstrate the feasibility of converting the existing below 7 barg gas distribution network to 100% hydrogen.

These works were carried out in controlled conditions, following method statements and current work procedures specifically designed and adapted for use on a 100% hydrogen network. New safety measures and procedural steps were introduced to ensure the safety of those onsite and may be considered for future operations following the success of these trials.

The scope included the demonstration of the following live gas activities:

1. Under-pressure branch drilling of 6" DI main through a bolted Donkin 555 valve
2. Under-pressure branch drilling of 180mm PE to install short PE stub section through both an electrofused 125 mm PE ball valve and metallic Donkin 555 valve.
3. Live service isolation and insertion on 2" and 1" steel services using Steve Vick Live Gas Service Isolator (LGSI), Rapid Service Isolator (RSI) and Live Service Insertion (LSI) techniques.
4. Live mains insertion of 75mm PE into 4" DI section of main using Steve Vick Live Mains Insertion equipment.

All activities were undertaken on the Phase 2b Unoccupied Trial site at South Bank. In all cases, the techniques were modified to include inert purging, remote venting and additional earth bonding where required to accommodate the requirements to avoid ignition of any hydrogen / air atmospheres.

5.4.2. Method

Under Pressure Branch Drilling

Metallic branch drilling is necessary when connection points are identified and taken from the parent main for a new feed of gas without the need for flow stopping and cutting out of the main. They can also be utilised for accessing the main to install temporary flow stop equipment or other equipment such as CCTV. These drillings are undertaken under network pressure and can vary in size. NGN procedure NGN/PR/ML/4[19] covers the drilling of all diameters of metallic mains with an outlet branch size up to 15 inches on live mains operating up to 2 bar.

The NGN procedure, NGN/PR/ML/4 was used for the demonstrations, along with risk assessments and method statement. The procedure followed included new, updated, indirect purging methods to ensure there was no mixture of air and hydrogen within the drilling head itself, causing an ignitable atmosphere. An indirect purge of the under-pressure tee and drilling machine was completed using the dilution method. The purge

All activities were undertaken on the Phase 2b Unoccupied Trial site at South Bank.

[19]NGN/PR/ML/4. Work Procedure for Pipe System Construction, Module 4, PE Main Laying up to and Including 630mm Diameters at Pressure up to and Including 2 bar.

was completed with nitrogen and obtaining a 0.5% oxygen reading was necessary for a successful purge.

Figure 5.12: Drilling of 6-inch DI main

With the drilling completed, the drilling machine was purged with hydrogen. This was completed through the machine's test point connected to a flame arrestor, and two consecutive readings of 100% hydrogen were needed for a successful purge. Once successful, the gate of the valve was closed and a let by check was carried out. No let by was found on passing the valve. Before removal of the drilling machine an indirect purge with nitrogen was once again completed to ensure no ignitable atmospheres within the equipment.

PE Under Pressure Branch Drilling

PE branched connections are connection points made to parent PE mains for new feeds of gas. These connections are made by electrofusion branch saddles. The NGN procedure NGN PR/ML/4 covers the installation of PE electrofusion branch saddles on 125 mm and 180 mm PE mains, operating at pressures up to and including 2 bar.

The NGN procedure, NGN/PR/ML/4 was used for the demonstrations, along with risk assessments and method statement. The procedure followed included new, updated, indirect purging methods to ensure there was no mixture of air and hydrogen within the drilling head itself, causing an ignitable atmosphere.

A 180 mm PE main was drilled using two different techniques for this demonstration:

- Drilling through a Donkin 555 valve connected to an electro fusion saddle.
- Drilling through a 125 mm PE Ball valve assembly and drill connected to the ball valve by wrap clam shell.

Figure 5.13: Wrap clam shell fitted to 125mm valve

To ensure there was no creation of an ignitable atmosphere, an indirect purge of the valves, saddles and drilling machines was completed by using a nitrogen source to cycle nitrogen through the equipment. The purge is required to be completed with nitrogen to remove all the air from the equipment, and obtaining a 0.5% oxygen reading is necessary for a successful purge. The length of time to purge the full rigs to 0.5% oxygen was approximately five minutes.

Live Service Isolation and Live Service Insertion

Live service isolation and live service insertion are important methods for adoption with 100% hydrogen. Steel gas services are isolated daily in the industry for replacement purposes. Live metallic service isolation was carried out on 1-inch and 2-inch steel services using two different techniques (Live Gas Service Isolator and Rapid Service Isolator). The Rapid Service Isolator (RSI) is a method of injecting a sealant through a drilled hole on the service pipe. There is no curing time for the sealant, and it provides a gas-free seal on natural gas systems.

The Live Gas Service Isolator (LGSI) uses an under-pressure tee designed to clip onto the service and provide a gas tight connection to the outer diameter of the service. Prior to any drilling taking place, the under-pressure tee had to be indirectly purged to nitrogen to ensure no ignitable atmosphere within the equipment. This was achieved by introducing nitrogen via the test point valve on the body of the drill and venting through the stopper body to achieve 0.5% oxygen. This step may be removed in the future if the volume of the under-pressure tee is deemed negligible.

Using the under-pressure tee allowed operatives to drill a hole into the live service under gas-free conditions. Once drilling was completed, there will be a small volume of hydrogen within the under-pressure tee. This is to be vented via the valve on the ¼ turn valve on the drill body once the drill has been retracted; this also ensures the valve on the under-pressure tee is functioning correctly and there is no let by. On completion of drilling and venting, the correct sized stopper was then inserted into the live service through the newly drilled hole.

On completion of isolation, the Live Service Insertion (LSI) operation was carried out. LSI is the method used to upgrade old metallic services by inserting new PE pipework while the carrier pipe remains live. This is completed after the isolation step and the PE service is fitted with a nose cone which has multipurpose features, allowing the new PE service to be fed while sealing off the gas to the metallic carrier pipe, allowing a sealant to be injected into the annular space, and in turn decommissioning it while the PE stays live. The carrier pipe is cut behind the temporary stopper position, allowing the insertion kit to be attached prior to inserting the pipe.

Live Main Insertion

Live mains insertion is a main laying technique similar to that of dead insertion with the beneficial difference of keeping consumer supplies on throughout the insertion process. By using a glandbox, the old main is kept live while the new PE main, fitted with a perforated nose cone (live head), is inserted, commissioned, and re-connected. The consumers are then supplied by the annular space between the inserted and carrier mains until convenient to transfer services onto the new inserted PE main, using proven foam flow stop technology.

The NGN procedure NGN/PR/ML/4 was followed onsite along with a risk assessment and method statement. These were adapted to include new, indirect purging of pipe and equipment to ensure the prevention of air and hydrogen mixing, causing an ignitable atmosphere.

The live main insertion was undertaken after isolation of the existing metallic main has been undertaken. Isolation was completed by using GIS/E4 ALH bags on a WASK double bagging off system, isolating a section of 4-inch main. Prior to cutting the section of main being removed, the space between the secondary bags was purged with nitrogen to a reading of 0.5% oxygen before the cold cut could take place.

Once the section was cut, the Steve Vick live insertion glandbox was installed to the open end of the pipe where insertion would be taking place. The area of main where the glandbox would be fitted was cleaned and the glandbox was attached to the main. Once secured, the bags were slowly deflated and the glandbox was checked with a GascoSeeker to ensure tightness; no readings were obtained on the check.

A live head was installed into a 75 mm PE pipe coil and inserted into the glandbox, passing through the polyethylene gas tight burst seal within the gland sitting in front of the secondary flow stopping bag. Indirect purging of the coil to nitrogen via a 32 mm rider from the WASK bypass dome along the 75 mm to the vent stack at the tail of the PE pipe coil was completed to ensure no ignitable atmospheres were present in the new PE main to be inserted.

A further purge to a 100% hydrogen was carried out via a purge rider connected upstream of the flow stopping equipment to allow hydrogen to purge through the 75 mm PE pipe coil without pulling large volumes of hydrogen from the metallic main. Once two consecutive readings of 100% hydrogen were obtained at the end of the PE coil, insertion was carried out once the flow stopping equipment had been removed.

To complete the live main insertion demonstration, the Insertion Seal Foam Bag was used to show its capability of sealing the annular space between the carrier main and new inserted PE main on a pressurised hydrogen network.

5.4.3. Results

Metallic Branch Drilling

The demonstration of the under-pressure branch drilling conducted on a 6-inch ductile iron main can be considered successful. Following the amended procedures and method statements, which centred around introducing indirect purging on equipment being used, there were no further observations throughout the process that caused concern. The drilling was undertaken safely and without any unexpected release of hydrogen and successful extraction of the drilling coupon.

Undertaking a metallic branch drilling on a 100% hydrogen network will include new added measures that ensure ignitable atmospheres are avoided using indirect purging of the equipment to 0.5% oxygen via an inert gas.

A recommendation made is that modifications to the drill body would benefit the efficiency of the operation. This would include the location of pressure/vent points, helping to facilitate an easier method of purging, allowing shorter purging times. This modification could be considered when designing future hydrogen-specific drills.

PE Branch Drilling

The two demonstrations of the under-pressure branch PE drillings conducted by Radius (drilled through a Donkin 555 valve) and ALH (drilled through a 125 mm PE ball valve) both on a 180 mm PE main would be considered successful, following the amended procedures and method statements, which centred around introducing indirect purging on equipment being used. There were no further observations throughout the process that caused concern.

Undertaking a PE branch drilling on a 100% hydrogen network will include new added measures to ensure ignitable atmospheres are avoided using indirect purging of the equipment to 0.5% oxygen via an inert gas.

It is recommended that a double block and bleed valve setup should be used for drilling operations, and it is noted that the 125 mm PE Ball valve method does not include this.

Live Service Isolation and Insertion

The demonstrations of the Live Gas Service Isolator (LGSI) on the diameters of 1 and 2 inches would be considered a success. Each under-pressure tee provided a tight seal and drilled each service without issue. The valves currently on the under-pressure tee allow for safe and efficient indirect purging steps to be introduced into procedure, ensuring no ignitable atmospheres occurred.

The rubber stoppers selected stopped hydrogen flow downstream and provided the necessary seal to allow further work to be carried out without added risk. Importance of the added steps of indirect purging shall be emphasised to protect operatives' wellbeing and prevent ignitable atmospheres occurring within the equipment. The added assurance of drill speeds confirming they were within the recommended RPM as not to cause an ignition was confirmed by the demonstrations.

It was observed during the demonstration that using the LGSI took an extended time to cut off the services when using the system, and that, in an emergency situation, the RSI would be the preferred method of isolation.

Following the LGSI, the Live Service insertion (LSI) demonstration provided useful evidence on what material would be suitable for use within a hydrogen network. LSI was unsuccessful on new galvanised steel pipework, due to new manufacturing techniques to form the pipe. The nose cone would be cut by the seam within newer pipework and would be unable to provide an adequate seal to allow the injection of annular foam sealant. Given this type of steel is not commonly buried on the network, this is not expected to present an issue in the future. However, when deployed in older and yellow wrapped service pipe the nose cone performed well and provided a seal against hydrogen, allowing for the sealant to be injected and the demonstration to succeed. This would suggest that, providing that the correct indirect purging of equipment was added into procedures and method statements, the use of LGSI and LSI on correct material would be safe for use on 100% hydrogen networks.

The Rapid Service Isolator performed well and was carried out exactly how it would be on a natural gas system. The rubber glanding system provided a 100% seal against the steel services and had no issues of passing hydrogen during the drilling process. The sealant injection performed correctly and had no passing of hydrogen. All let by tests were successful and this method shall now be considered the preferred form of isolation in emergency situations.

Live Main Insertion

The Live Mains Insertion demonstration of 75 mm PE main being live inserted up a 4-inch DI main was successful, following the amended procedures and method statements, which centred around introducing indirect purging on mains and equipment ensured no ignitable atmospheres occurred. There was no further let by, leakage or other unexpected observations.

Additional tappings to provide safe indirect purging points when decommissioning the carrier main were discussed and put in place at the time of demonstration. The indirect purging of the insertion main, the section to be cut, and equipment were each important changes to the procedures and, once implemented, shall provide safe working practices when working on a 100% hydrogen system.

The insertion seal foam and the end seal were carried out successfully on a hydrogen pressurised system without issue, and can confidently be used on such systems in the future.

5.5 Isolation techniques

5.5.1. Objectives

Isolation operations are essential to the distribution network and are carried out daily by operatives throughout the industry. Proving these operations can be done safely on a 100% hydrogen network is essential to demonstrate the feasibility of converting the existing below 7 barg gas distribution network to 100% hydrogen.

Isolation operations demonstrations were carried out on both the Phase 2a Microgrid and the Phase 2b Unoccupied Trial site at South Bank in controlled conditions, following method statements and current work procedures specifically designed and adapted for the use on 100% hydrogen network. New safety measures and procedural steps were introduced to ensure the safety of those on site, and may be implemented for future operations following the success of these trials.

Demonstration tests were carried on both sites as the Phase 2a Microgrid is built from new pipes, valves etc., (as new) whilst the Phase 2b Unoccupied Site utilises existing network pipes and valves, demonstrating an older, existing network.

The techniques were all conducted with the introduction of nitrogen inerting steps to avoid hydrogen and air mixing within any confined geometries and nitrogen was used to inflate bags.

Phase 2a Microgrid Demonstrations:

Flow stopping tests were conducted in the H21 Microgrid at DNV Spadeadam. The flow stopping techniques demonstrated included: a metallic stopple, squeeze off, ALH bag off, and an MLS bag off.

The flow stopping/live gas techniques demonstrated on the Microgrid were:

- Metallic stopple and 3-inch drilling: inserted into 12-inch steel section of main fed from the MP section of the Microgrid.
- Squeeze off: double squeeze offs applied to a 180 mm SDR11 PE100 main in the IP section of the Microgrid (the effectiveness of single squeeze off was also checked during these demonstrations).
- ALH bag offs: double ALH bag offs applied to a 630 mm SDR21 PE100 main in the LP section of the Microgrid (the effectiveness of single ALH bag was also checked during these demonstrations).
- MLS bag offs: double MLS bag offs applied to a 180 mm SDR17.6 PE80 main in the MP section of the Microgrid (the effectiveness of single MLS bag was also checked during these demonstrations).

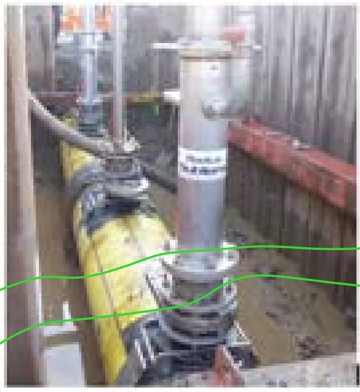


Figure 5.14: Various flow stopping techniques demonstrated on the Phase 2a Microgrid

Phase 2b Unoccupied Trial Site

Flow stopping tests were conducted on the Phase 2b Unoccupied Trial site in South Bank using the existing pipework from the test site. The following tests were undertaken:

- 80 mm Isolation using ALH Twinbag Flowstop System
- 180 mm PE Isolation Using MLS System and Double Squeeze Off
- 4-inch Metallic MLS Flowstopping Operation
- 4-inch Metallic Flowstopping Operation (WASK Isolation kit)

Figure 5.15: Various isolation techniques in practice at H21 Phase 2b South Bank

5.5.2. Results

Phase 2a Microgrid Demonstrations

Demonstration of the implementation of Squeeze Off, Stopples and Bag Off techniques on representative network components running on 100% hydrogen were successful in isolating the flow down to very low levels in the examples considered. Let by past single and double isolation techniques varied between the pressure tiers and techniques, but in the cases of double-block-and-bleed arrangements, the let by rates were demonstrably low. The success of the double isolations gives confidence that the techniques can be employed on a hydrogen distribution network.

Notwithstanding the potential for explosion within the vent pipes and voids, the let by is generally considered to be of low consequence potential when directed up elevated vent pipes in outdoor scenarios – the flammable region it is possible to generate is small and any thermal radiation or explosion overpressure outside of the vent would be low in magnitude and certainly equal to or less than the venting conducted during, for example, purge operations. Effective management of atmospheres in the vents and voids would effectively eliminate the risk of explosion within the pipework.

It is proposed to use flame traps on in-service hydrogen vents (water traps were used in Phase 2a). These water flame traps and/or flame traps have the potential to cause some back pressure on the vent line. This back pressure has, in turn, the potential to influence the let by rates in double isolation scenarios resulting in more flow into the section to be isolated/cut, and should be carefully considered in the development of operational procedures.

Phase 2b Unoccupied Trial Site Demonstrations

The following results were obtained:

Title	Isolation Type	Applied to	Test Description	Nominal Leakage Rate
ALH DS Bas Only 4 PSI	ALH Bag, ALH Base	180 mm PE	Downstream (D/S) bag only deployed at 4 PSI N2 fill, monitored pressure accumulation in D/S leg.	0.5 – 0.8 l/min between 46 and 52 mbar differential pressure
ALH DS Bag Only 6 PSI	ALH Bag, ALH Base	180 mm PE	D/S bag only deployed at 6 PSI N2 fill, monitored pressure accumulation in D/S leg.	0.5 – 0.8 l/min between 46 and 52 mbar differential pressure
ALH US + DS 4 PSI No Vent	ALH Bag, ALH Base	180 mm PE	Up Stream (U/S) and D/S bags deployed at 4 PSI N2 fill, monitored pressure accumulation in D/S leg. No vent between bags	0.04 l/min max at 52 mbar differential
ALH US + DS 4PSI Bleed Open	ALH Bag, ALH Base	180 mm PE	U/S and D/S bags deployed at 4 PSI N2 fill, monitored pressure accumulation in D/S leg. Vent between bags open to atmosphere	0.04 l/min at 52 mbar differential
Squeeze Between SO	Radius hydraulic squeeze off	180 mm PE	U/S and D/S squeeze-offs deployed. Monitor pressure accumulation between squeezes, no vent.	0.002 l/min at 51 mbar differential
MLS Between Bags	MLS bag, Wask Base	180 mm PE	U/S and D/S bags deployed. Monitor pressure accumulation between squeezes, no vent.	0.005 l/min at 50 mbar differential
Between SO-BO	MLS bags one side, Squeeze off other side	180 mm PE	U/S and D/S bags deployed, U/S and D/S squeezes deployed. No vents open	0.03 l/min at 50 mbar
ALH Bags onto 4” Metallic	ALH bags, Wask Base at both ends	4-inch Ductile Iron	U/S and D/S bags deployed at both ends. Time to reach main pressure monitored as leakage rate too high.	0.2 l/min at 26 mbar (i.e., mid-point for full pressure swing 0-51 mbar in isolated section)
MLS Stopper Kit	MLS Stoppers Shoe Size 1	4-inch Ductile Iron	Secondary D/S and U/S stoppers deployed at 8 PSI N2. Monitor pressure accumulation between secondary stoppers, no vent.	Zero pass observed

Table 5.1: Isolation operation performance

Leakage rates have been acceptable in all but one method of isolation used in South Bank. The specialised methods of isolation undertaken by contractors (MLS stoppers and ALH Double bag) showed successful seals and suitability of use on 100% hydrogen networks.

The demonstration of GIS/E4 bags inserted in to a 4-inch DI main resulted in an unacceptable pass from the flow stopping equipment. The bags were inflated to 600 mbar, the isolated section of main was vented down to 0 mbar and a let by test of the bags was undertaken over 5 minutes with the vents on the bag tubes in the closed position. Once the five minutes were observed, the section of main had recovered to mains pressure of 51 mbar. This indicated a poor seal of the bags and an unsuccessful isolation operation. Testing by the HSE S&RC at Buxton of GIS/E4 bags was undertaken and reached the same conclusion that further work was needed for the GIS/E4 bags to make them suitable for use with hydrogen, refer to section 4.8 of this report.

5.6. Commissioning and Decommissioning activities

5.6.1. Phase 2a Indirect and Conversion Purging

Indirect and conversion purging of all diameters and pressure tiers on the Phase 2a Microgrid were conducted at Spadeadam. In addition, indirect branch purges and the direct purging of MP and LP services with and without excess flow valves was demonstrated. In conducting this extensive (but not exhaustive) set of demonstrations, operational experience of the procedures and technical aspects of the techniques was gained by DNV and NGN. Whilst the facility was not designed to deliver full model validation datasets, the demonstrations were able to give some insight into the practicalities of real purging operations and form a basis for the development of purging procedures for future hydrogen trials, with the following considerations needing to be taken forwards.

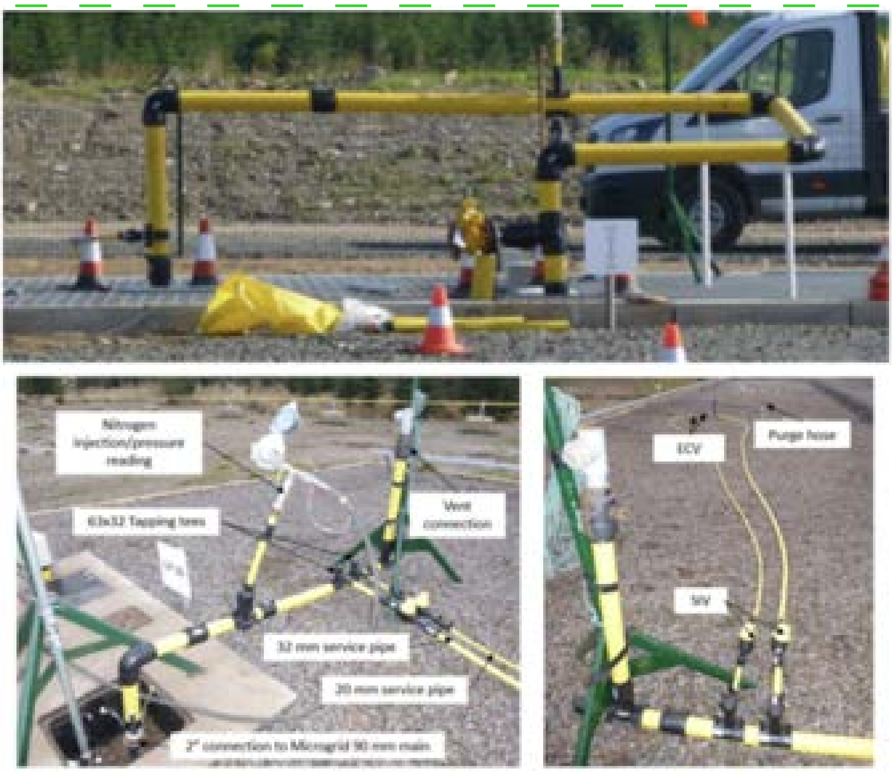


Figure 5.16: Purging and venting of various sized mains and services on the H21 Phase 2a Microgrid

Results

1. Successful purging of air from pipes using high-pressure nitrogen cylinder packs was achieved according to a strict test procedure. The introduction of nitrogen to the system being purged needs careful consideration in terms of managing the risks of over-pressurisation, high-pressure systems, asphyxiation, etc. In addition, the practical implications of the volumes of nitrogen required at each purge site need further consideration.

2. Indirect and conversion purging of mains using purge rider and vent sizes as currently used for natural gas purges (defined in NGN/PM/MSL/1[20]) appears to be adequate.

3. Direct purging of services was found to be successful utilising a test procedure and hazard exclusion zone. Further work could look to define the particular hazard associated with each operation in terms of ignition of flammable volumes in the services pipes and purge hoses.

The demonstrations were not specified for the production of model validation data and further work was required to fully validate a model for predicting purge success/failure/efficiency without additional checks on the main. This need for further work was the basis on which the idealised purge experiments discussed in Section 5.6.2 were commissioned.

5.6.2. Phase 2a: Minimum Purge Velocity

The objective of the experimental work was to determine the minimum purge velocity required to avoid stratification when purging pipes with 100% hydrogen. In accordance with the HSE S&RC findings, only indirect purging is considered suitable on hydrogen networks (where, traditionally, natural gas distribution networks are purged directly between air and natural gas). After significant indirect purging demonstrations were undertaken to gain experience in the practicalities of indirect purging, further purging experiments were undertaken to investigate the dependency of purge efficacy upon flow velocities, such that recommendations could be made on required purge and rider sizes for future purge operations.

Failed or inefficient purging is a result of stratification in the pipe where the densities of the two gases differ and the lighter gas tends to pass over the top of the denser gas to some extent. The avoidance of stratification is expected to be dependent on the Froude number, which is a dimensionless number dependent on the ratio of inertial and buoyancy forces. As the buoyancy forces increase with the addition of hydrogen, it is expected that the minimum purge velocities would need to increase to keep the Froude number constant and avoid stratification. A Froude number of 0.7 is used as a threshold to avoid stratification, above which it is said not to occur.

A dependence on the turbulence of the flow is also theorised such that a Reynolds number of 4000 or more is also suggested to enable suitable levels of mixing in the pipe. This has the implication that small pipe diameters require much higher purge velocities in theory than larger pipes. For natural gas:air purges, this is not particularly consequential as these larger velocities are generally easy to achieve. The lower density of hydrogen means that significantly higher flow speeds are required to achieve the same Reynolds number, and this has the potential to make purging of smaller pipes impractical if this requirement is to be achieved.

A programme of idealised purge experiments was undertaken utilising a 100 m long test rig consisting of both 125 mm and 315 mm PE test pipes, above ground and connected to the Phase 2a Microgrid via appropriate riders and a buffer section of 315 mm PE pipe. The downstream end of each test pipe was equipped with a remotely operated vent valve and vent pipe. The vent valves were proportional control ball valves, such that specific flow rates could be achieved. Each test pipe, rider and vent was instrumented so that information on the gas conditions within the pipe could be gather in real time as the purge operations were completed.

[20] Northern Gas Networks. (May 2017) Management procedure for main laying and service laying. NGN/PM/MSL/1.

Figure 5.17: Rider sections of the pipe bridging from the buffer pipe to the 125 mm and 315 mm test sections

Results

In this experimental programme 32 tests were undertaken, which investigated stratification and the extent of mixing zones formed during the purge of the gases in pipe in relation to the purge speed. A purge was considered complete when the operator at the vent measured over 99% gas in two consecutive measurements using a calibrated hydrogen GascoSeeker; this is in line with actual practice in existing distribution purge operations (where 90% vol is used as a threshold).

As an extra measure this was simultaneously confirmed by the measurements reported on the thermal conductivity detectors (TCD) in the vent of each purge before stopping the purge. In all experiments there was no notable discrepancy between the GascoSeeker readings and the TCD reading in the vent. In this programme, a purge was defined as successful when there was no 'start' gas left over in the pipe as indicated by all TCDs in the pipe reading higher than 99% vol 'end' gas.

It was found that:

- All purges were successful even with speeds significantly lower than those required by current guidance (i.e., exceeding both a Froude number of 0.7 and a Reynolds number of 4000).
- In both the 125 mm and 315 mm pipe dimensions, increasing the purge gas velocity marginally reduced the length of the mixing zone which is consistent with previous experiments. The mixing zone size was increased with decrease of the purge speed. However this does not present a safety issue as purging was undertaken with an inert gas.
- Efficiency of the purging was found to be relatively insensitive to the speed at which the purge was carried out. In the smaller diameter, 125 mm pipe purges, the efficiency of the purge was observed to decrease with increasing purge speed – although this could be a function of instrumentation time delays.

→ Analysis of the experimental data, comparison with theory and previous natural gas experiments supports the following:

- Indirect purging of low, medium and intermediate pressure hydrogen pipes with diameters not exceeding 36" or 900 mm can be safely and efficiently conducted using the same size riders and vents as those already used for natural gas direct purge operations.
- Commissioning and decommissioning with nitrogen as an intermediary should be done at a minimum pressure (into the rider) of 75 mbar.
- Conversion purging from natural gas to hydrogen can also be conducted safely and efficiently using the same rider and vent size combinations as used for natural gas purge operations today.
- When provisioning for quantities of nitrogen required for a purge operation, the efficiencies noted in the present work suggest that a factor of 3 times the volume of the main to be purged is considered conservative.

Nominal pipe diameter or equivalent pipe diameter	Recommended rider and vent diameters (mm) for rider inlet pressures of					Minimum distance for release of squeeze-off from the fully closed position (mm)
	21mbar	30mbar	75mbar	350mbar	2bar	
0 to 150mm (0 to 180mm PE) (0-6in.)	32	32	32	32	32	15
151 to 200mm (8in.)	63	63	63	32	32	15
201 to 250mm (10in.)	63	63	63	63	63	30
251 to 301mm (12in.)	63	63	63	63	63	30
301 to 450mm (18in.)	90	90	90 (2x63)	63	63	45
451 to 600mm (24in)	180	180 (1x125)	125 (2x90)	90 (2x63)	63	60
601 to 900mm (36in)	180	180 (2x25)	180 (2x25)	125 (2x90)	90 (2x63)	-
901 to 1200mm (48in)	-	250 (2x180)	250 (2x180)	180 (2x125)	90 (2x63)	-

Table 5.2: Recommended rider and vent sizes as used in the current natural gas operations (reproduced from NGN/PM/MSL/1, Section 27.3.2)

Further Work

Two elements of this idealised purging work could be considered for potential further work:

Method and required volumes of nitrogen required:

i. Under test conditions it was possible to use multi-cylinder packs, manifolded together to achieve the required flows, but significant procedural steps were required to be able to use readily available cylinder regulators. Further work could be considered for methods and equipment to achieve the safe and efficient flows of nitrogen in real purge operations where the volumes required may be considerably higher.

ii. The idealised purging experiments pointed to a nominal purge efficiency not normally lower than approximately two, i.e., the required volume of nitrogen to achieve the purge was, in general, no more than twice the volume of the pipe being purged. This volume needs to be delivered at the specified flow rates, so care should be taken around the use of depleted cylinders.

Direct purging of smaller diameter pipes:

i. The implication of the findings in this work might lend themselves to a critical look at the risks involved in direct purging of smaller mains and services. At present there has been no focus on direct purging as it was considered to be untenable for hydrogen operations, but there is the potential to re-visit this using the information gained.

5.6.3. Phase 2b: Indirect and Conversion Purging

Similarly to the Phase 2a purging activities, indirect and conversion purging of all the various legs of the Phase 2b network was performed. The system afforded the opportunity to perform relatively complex, 2- and 4-branch purges in addition to the long-length ‘outer-loop’ purges.

A Duomo Small Flare Unit (SFU) complete with flame arrestor was procured for use on the Phase 2b network. Acknowledging that the flare unit was undersized for the direct purging of mains (it was originally designed for natural gas/air purge operations up to 2” in diameter but was fitted with a flame arrestor for hydrogen service), its use formed an opportunity to investigate the impact on indirect and conversion purging at rates considerably below those which would be considered safe in direct purge operations.

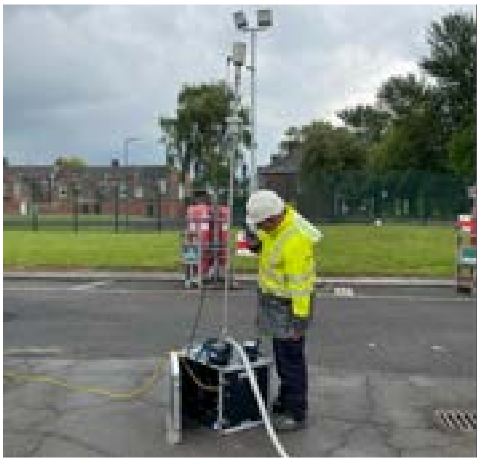


Figure 5.18: Use of mobile flare unit

More than 30 different purge configurations of pipes, branches, gases, operating pressures and vent/flare combinations were demonstrated at the Phase 2b South Bank site.

Results

General observations are as follows:

1. The demonstrations were very repeatable: flow rates and GascoSeeker readings were notably consistent between direct repeats.

2. In all cases, either a measurable change in flow rate or an audible change in pitch/volume of the vent indicated the arrival of the purge gas at the vent or flare, confirmed by near simultaneous readings from GascoSeeker instruments at the same position.

3. All purges conducted resulted in a complete purge being indicated at the measurement point in the vent(s).

4. Checks on final concentrations at the mid-point of purged pipes revealed no evidence of failed purging (i.e., the checks only ever served to confirm the measurements made at the vents).

5. Decreasing the flow rate by introduction of the flare unit at the vent had the effect of increasing the time to purge. The effect on purge efficiency (how much gas used to complete the purge) does not seem to be great in this instance.

6. Two and four vent branch purges were successfully completed both in commissioning and decommissioning style purges. Two vent branch purges were successfully completed in conversion style purges (natural gas to hydrogen and vice versa).

7. The GMI GascoSeeker instruments were found to be reliable in measuring between natural gas and hydrogen (and air:nitrogen). It was noted that the addition of an oxygen measurement on the same unit would be beneficial in any mass roll-out to prevent the requirement for additional units when purging nitrogen.

8. Demonstration of the use of a flare unit in these purge operations gave operational experience of using such a unit, and no significant issues around its use were found, apart from the significant reduction in flow rate and time taken to complete a full purge. As would be expected at these flow rates, the thermal radiation from the flare when used at 30 or 50 mbarg with hydrogen or natural gas was not found to be significant to observers operating the unit at its base.

Figure 5.19: 30 mbar hydrogen at 30 scmh flow rate through flare unit thermal image versus normal video

5.7. Pressure regulation and maintenance procedures

5.7.1. Objectives

NGN undertook the opportunity to monitor the performance of the pressure regulation units (PRU) present on the H21 Microgrid at Spadeadam and the Unoccupied Trial site at South Bank, whilst they were in use with 100% hydrogen. Full standard maintenance procedures for the PRUs (functional checks, major overhaul) were carried out. Pressure regulation and maintenance operations are essential to the distribution network and are carried out daily by operatives throughout the industry. Proving these operations can be done safely on a 100% hydrogen network is essential to demonstrate the feasibility of converting the existing below 7 barg gas distribution network to 100% hydrogen.

Phase 2a Spadeadam

The units were in operation during the testing phase of the project between June 2021 and February 2022 and were routinely used to support the testing activities in the test facility. Additionally, two hydrogen-ready boilers installed in the HyStreet houses were fed continuously with hydrogen, at which time selected PRUs were in continuous operation. The PRUs were commissioned and decommissioned (indirectly, using nitrogen followed by hydrogen or vice versa), hydrogen gas circulated through the PRUs daily at various set pressures and flows, and some of the units underwent major overhauls and filter replacements.

Figure 5.20: HP–IP pressure reduction unit at Spadeadam

Pressure Tier	Unit Type	Inlet Pressure	Outlet Pressure	Max flow NG (scm/h[21])
HP-IP	Fiorentini Twin Stream	9 bar–80 bar	7 bar	4000
IP-LP	Elster Instromet (Orpheus 1000125315 Below Ground)	2 bar–7 bar	25–50 mbar	3200
IP-MP	Elster Instromet (Orpheus 1000125315 Below Ground)	2 bar–7 bar	350 mbar–2 bar	3200
IP-MP	Bryan Donkin RMG SN 9249913 (Above ground)	2 bar–7 bar	350 mbar–2 bar	1500
MP-LP	ERS Module (Underground)	350 mbar–2 bar	22–47 mbar	3400
MP-LP	Elster Instromet (Orpheus 1000078664 Below Ground)	350 mbar–2 bar	30–50 mbar	4900
MP-LP	Bryan Donkin RMG G2–TR-T14W (Above ground)	350 mbar–2 bar	30–50 mbar	3000
MP-LP	Unknown unit type Regulators 3-inch Donkin 280s (Backfeed, Above ground)	350 mbar–2 bar	30–50 mbar	4500 (approx.)

Table 5.3: PRU specifications

Phase 2B Unoccupied Trial Site – South Bank

The Twin Stream regulator was supplied by Honeywell and purchased by NGN and was designed for use with natural gas. The regulator has an inlet pressure range of 0.35 to 2 barg, and is capable of an outlet pressure of 30 to 50 mbar while having a maximum flow rate of 796 m3/h.

It was installed on the Unoccupied Trial network with a total volume of 6.227 m3, which included PE and DI gas mains. On a day-to-day basis, it maintained the regulation of hydrogen to the network allowing various demonstrations to be undertaken while feeding two hydrogen installations within the compound. A maximum demand of 420 m3/h was placed on the rig during the South Bank trial.

Figure 5.21: MP–LP pressure reduction unit at South Bank

[21]scm/h – Standard Cubic Metres per Hour

The pressure reduction unit at the unoccupied site was subject to the following checks/maintenance on both the working and standby streams:

- Routine check
- Functional checks
- Major overhaul

5.7.2. Results

The pressure regulation units ran continuously, feeding a small demand on the Microgrid at Spadeadam HyStreet and the Unoccupied Trial site without any issue during the length of service. No loss of supply was experienced, and no performance issues noted.

There were no incidences of over-pressurisation or nuisance slam-shut activation from any of the installations. In turn, no deterioration of setpoints was found during routine and function checks.

Throughout the routine checks, functional checks and major overhaul, no significant issues were found. Soft parts and general condition of components were found in an acceptable state. There was slight water corrosion in reliefs and diaphragms and minimal damage and light water discolouration to the main relief valve, but it was agreed these observations would not necessarily be caused by the presence of hydrogen. The majority of components were in good working condition and soft parts were flexible and could be used again in service.

Performance levels of the pressure reduction skids when running on hydrogen at the demand levels demonstrated in this project are very similar to those when running on natural gas. There are few discrepancies between the two gases, and the overall performances produced by the pressure reduction skids are very similar in both noise pollution and flow rates: thereby no reason for concern in the use of hydrogen for these pressure systems. This project did not investigate the performance of the PRUs when subjected to flows greater than 4000 scmh, as might be the case to meet a 4000 scmh natural gas energy demand (i.e., ~12000 scmh hydrogen flow).

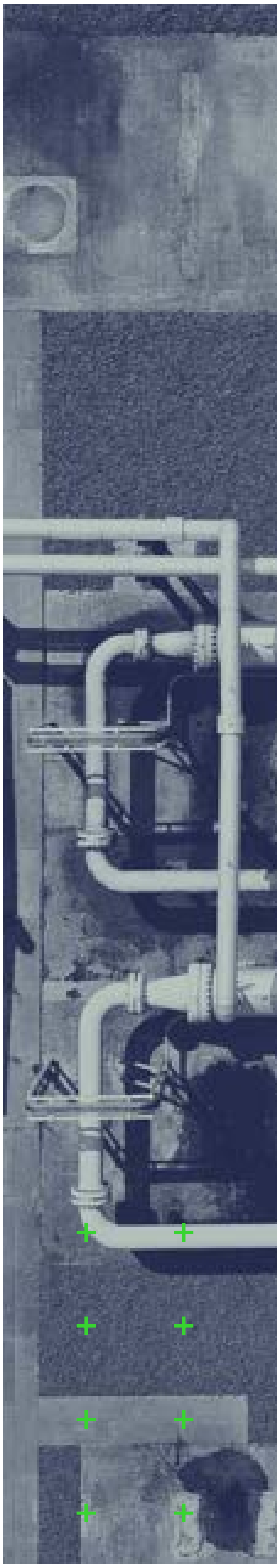
It should also be noted that no dust or debris was found in the filter within either stream.

5.7.3. Recommendations

It is important to feedback indirect purging techniques and procedures to pressure regulator manufacturers, noting the need for indirect purging to nitrogen and the lack of adequate pressure points and vent points on current systems. Additional purge, pressure and rider points will allow more efficient decommissioning and commissioning in future installations and this change will be easier to implement in manufacturing stage. The indirect purging requirement will also need to be incorporated into procedures, method statements and work instruction.

It is also recommended that further, larger trials, especially on villages/towns, begin with enhanced maintenance regimes to allow for variety of usage and service times. This project lasted 9 months and had extremely low demand given what the installations are normally subjected to out on the network. It would therefore be sensible to increase maintenance schedules and requirements to gain knowledge about the long-term effect, if any, of transporting hydrogen through these pressure regulation installations. These trials would need to be supplemented with flow and pressure metering telemetry near to the regulator.

Performance levels of the pressure reduction skids when running on hydrogen at the demand levels demonstrated in this project are very similar to those when running on natural gas.



5.8. Pressure and flow validation

5.8.1. Objectives

As part of the Phase 2a Microgrid tests, there was a requirement to confirm that the network analysis assumptions for analysing natural gas networks would work for hydrogen networks. Therefore, a network model would be built and first calibrated with four of the natural gas flow and Microgrid flow configurations. Then the gas would be replaced in the network model with hydrogen, and the results then compared with the Microgrid pressure results for four different flow configurations.

There are currently two products being used in the UK for distribution network analysis, GBNA and Synergi Gas. As Synergi Gas is used by a majority of the four GDNs in the UK, this product has been used for the modelling of hydrogen and natural gas in the Microgrid.

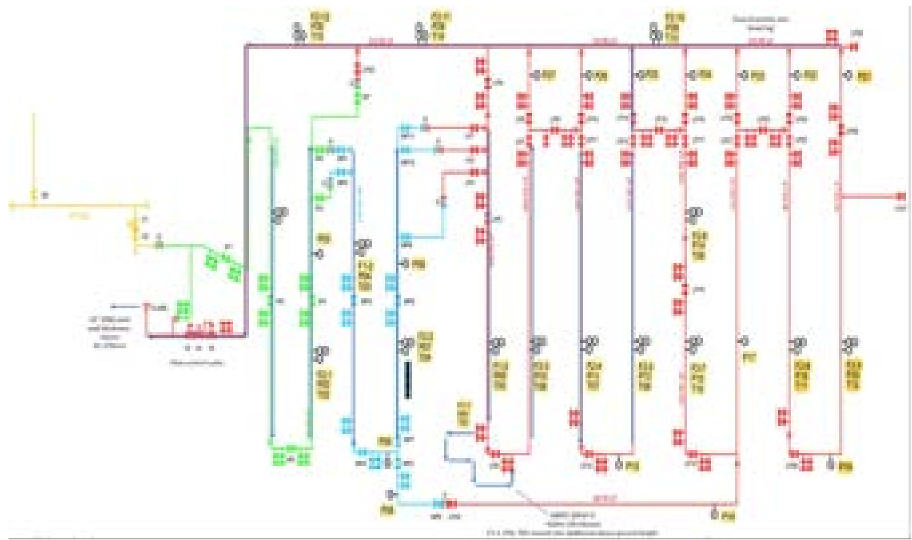


Figure 5.22: Example from Synergy mode

Four scenarios were modelled for natural gas and hydrogen using different lengths of the Microgrid (long & short) and differing flow scenarios. All sections of the H21 Microgrid were fitted with instrumentation to monitor pressure, temperature, and flow data. Pressure readings were taken at various locations across the Microgrid, dependent on whether the short or long Microgrid was used for the test.

Similarly to the works completed in Phase 2a on the Microgrid at Spadeadam, some further pressure and flow model validation trials were undertaken on the unoccupied site at South Bank. The existing network provided the opportunity to flow hydrogen at various rates through a mixture of used metallic pipes and newly installed valves and PE pipe. Utilising the isolation valves around the network it was possible to induce flow along a wide variety of flow paths to a vent located on the site. Two different flow paths were selected, and steady-state flow tests were conducted at four different flow rates by moderation of the valve on the vent pipe. The tests were firstly conducted when the network was operating at 30 mbar (controlled via the district governor feeding the network) and then repeated at the higher pressure of 50 mbar.

5.8.2 Conclusions

The overall conclusion is that network models that have been validated for natural gas can be utilised for hydrogen analysis as long as any valves or regulators using the General Valve equation have corrections for valve coefficients due to the change in specific gravity.

If the General Valve equation or Check Valve equation is used for valves and regulators in a network model, then the coefficient values (Cgmax) used for natural gas would need to be corrected for the variance in specific gravity when converted to hydrogen. The specific gravity of hydrogen is much lower than that of natural gas, so for the same pressure drop, the flow rate of hydrogen will be higher than natural gas. Therefore, to convert a model from natural gas to hydrogen using General Valve equations will require the Cgmax values to be increased by the square root of the ratio of the specific gravity of the natural gas over the specific gravity of hydrogen: a ratio of 2.95 for the gases on test. This correction is not required for any of the other valve equations such as the Reliance, Fisher, Mokveld or Valtek equations. So, the recommendation for the UK gas industry is to replace any General Valve equations in their network models with more flexible valve equations such as the Reliance equation.

Therefore, to convert a model from natural gas to hydrogen using General Valve equations will require the Cgmax values to be increased by the square root of the ratio of the specific gravity of the natural gas over the specific gravity of hydrogen: a ratio of 2.95 for the gases on test. This correction is not required for any of the other valve equations such as the Reliance, Fisher, Mokveld or Valtek equations. So, the recommendation for the UK gas industry is to replace any General Valve equations in their network models with more flexible valve equations such as the Reliance equation.

5.9. Water Extraction

5.9.1. Objectives

When operating low pressure networks, ingress of water can be problematic in a variety of ways – crucially, low pressure networks do not have the required pressure to lift any significant water head and relatively small accumulations of water can lead to blockages. It was therefore deemed necessary to demonstrate that water could be safely and effectively removed from low pressure networks when running on 100% hydrogen. This was demonstrated for mains and service water ingress incident mock-ups at the H21 Phase 2b facility in South Bank.

5.9.2. Method

The works were carried out in controlled conditions, following method statements and current work procedures specifically designed and adapted for the use on 100% hydrogen network. These additional measures were namely the inert purging of the extraction equipment such that a flammable fuel:air mixture could not be generated within the equipment or hoses when extracting water.

Two items of equipment were tested where the manufacturer was able to produce hydrogen specific operating procedures and risk assessments. Other, more popular techniques (e.g. Alan Taylor units) were not trialled in this programme as suitable risk assessments and hydrogen specific procedures were not available.

Mains Water Extraction

Mains water extraction is a method of removing water from network pipework through a tee set (metallic) or top tee (PE) attached to the affected gas main. The Synthotech M-V1 water extraction system (WexTech) was used in the South Bank demonstration and involved the removal of 30 litres of water from a 4-inch ductile iron main. The WexTech is designed for use in both metallic (4-inch up to 10-inch) and PE mains (90 mm to 250 mm) using the Synyocam 3 CCTV camera system to identify the location of water within mains for extraction, operating on pressures up to 75 mbar

Figure 5.23: M-V1 site set up

Service Water Extraction

Service water extraction is a method of removing water from network service pipework through the ECV attached to the affected gas service. The Synthotech S-1.0 water extraction system was used in the South Bank demonstration and involved the removal of 2 litres of water from a 20 mm service. The S-1.0 is designed for use in PE and Serviflex services ranging from 20 mm to 32 mm, using the Synthotech services camera. The equipment operates on pressures up to 75 mbarg.

Figure 5.24: Service water extraction demonstration set up

5.9.3. Results

Mains Water Extraction

The demonstration of the Synthotech M-V1 water extraction system (WexTech) proved successful in the extraction of 30 litres of water within a 4-inch main. Following adapted method statements and the addition of indirect purging of the equipment ensured no occurrences of ignitable atmospheres within the equipment or work area. One observation was the requirement for the pump to be flushed and primed before water extraction.

The water extraction step itself was completed efficiently and successfully, demonstrating that the M-V1 has the capability to extract a large volume of water from a metallic main with the same effectiveness as it would on a natural gas network.

Other water extraction equipment, such as Alan Taylor units and large tanker type water extraction methods, will need to be assessed for suitability for use with hydrogen which, for example, could be achieved through a MIERA assessment.

Service Water Extraction

The demonstration of the Synthotech S1.0 water extraction system proved successful in the extraction of 2 litres of water from a 20 mm gas service. Following adapted method statements and the addition of indirect purging of the equipment ensured no occurrences of ignitable atmospheres within the equipment or work area.

The water extraction step itself was completed efficiently and successfully, showing the S1.0 has the capability to extract a volume of water from a PE service with the same effectiveness as it would on a natural gas network.

6

PHASE 2C COMBINED QRA

The scope of **Phase 2c** built further upon the work previously undertaken in both the H21 Phase 1 QRA and the BEIS Hy4Heat QRA for quantification of the comparative risk between a 100% hydrogen distribution network and end usage, versus that of an equivalent system conveying natural gas.

The CONIFER QRA model developed in Phase 1 was extended to include releases downstream of the Emergency Control Valve.

This section contains information collated from the DNV reports listed in Section 9.0 References. All graphs, visuals and photos have been reproduced by kind permission of, and are attributable to, the relevant report author.

6.0

PHASE 2C COMBINED QRA

6.1 QRA Model Development

The updates made to the CONIFER QRA Model as a part of Phase 2 included the following:

- The failure frequencies associated with mains and services were reviewed and updated in a few cases.
- The hole size distributions applied to mains and services were reviewed and modified. This removed one of the most significant areas of uncertainty in CONIFER that was identified in Phase 1.
- The gas ingress probabilities and the proportion of gas reaching a building that enters it has been modified to better compare the behaviour of natural gas and hydrogen.
- The possibility of the delayed ignition of a vapour cloud in the open, generating significant overpressure has been included.
- Release frequencies and hole size distributions were derived for releases downstream of the Emergency Control Valve (ECV). This includes releases from meter installations, downstream pipework and appliances within domestic properties.
- An outflow model was developed to apply to releases into free air inside buildings.
- The response of people to gas ingress into buildings was reviewed, to take account of differences between external releases percolating into buildings and releases inside buildings.
- The gas accumulation model within buildings was updated in order to more accurately model the differences between natural gas and hydrogen releases directly into buildings.
- The model that predicts the severity of explosions in buildings has been modified to reduce the conservatism in its predictions for hydrogen.
- Harmful and damaging effects outside the building where an explosion occurs have been included. This includes the ejection of debris into the surrounding area, and the effects of overpressure upon people and nearby buildings.
- The vulnerability assumptions for fires and explosions have been reviewed. This includes the prediction of non-fatal injuries.
- Multiple changes were made to the detailed application of various aspects of the model, to improve general performance and to capture the differences between natural gas and hydrogen.

The QRA model developed by the H21 Phase 1 project, CONIFER, was extended to include releases downstream of the Emergency Control Valve.

As part of the CONIFER update process, the predictions at various stages of the calculation were benchmarked against historical performance of the natural gas distribution network ensuring that the version of CONIFER used to produce risk predictions are realistic.

The combinations of control measures evaluated during Phase 2c show that it is possible to operate a hydrogen distribution network with a total predicted societal risk no higher than that posed by the current natural gas network.

Please note that the results presented here do not represent the final assessment of Great Britain. There are planned updates to the risk assessment methodology during 2023 and the first half of 2024 including the following:

- Inclusion of commercial and other non-domestic buildings.
- Inclusion of multi-occupancy buildings, including high rise buildings.
- Review of several parts of the CONIFER package to address comments from the HSE Evidence Review Group. This includes, but is not limited to, the failure frequencies applied to iron mains, the treatment of gas movement through the soil, the accumulation of gas within buildings, and the modelling of vulnerability to people exposed to explosions.
- Review of several parts of the model following receipt of additional information or evidence from several gas industry projects that are ongoing or planned.
- Review of the modelling of risk mitigation measures, and their associated benefits.

6.2. Overall Quantitative Risk Assessment

A Quantitative Risk Assessment (QRA) was carried out using the updated CONIFER package, which contains a series of detailed models that use statistical data and representations of physical processes to predict the risks to the general public from the operation of a gas distribution network. It can be used to quantify the risks associated with natural gas and hydrogen networks, and can be used to compare different designs or operational cases, and to assess the benefit of control measures. The risk calculations include releases upstream (distribution network, below 7 barg assets) and installations downstream of the Emergency Control Valve (ECV), within houses.

For the purposes of this assessment, the 2032 distribution system carrying hydrogen is compared with the 2020 distribution system carrying natural gas case, to demonstrate that a hydrogen network can be operated at a risk level that is no greater than the current natural gas network. The 'distribution system' includes the upstream distribution mains, services and governor kiosks as well as meters, pipework and appliances downstream of the ECV.

The representation of the 2032 gas distribution system is based on projections supplied by NGN and factors in the current Iron Mains Risk Replacement Programme, started in 2002, for planned replacement of metallic pipes.

The Iron Mains Risk Replacement Programme data used for the 2032 gas distribution system is as follows:

Pressure	Diameter Tier	Portion of Mains replaced by PE						
		Within 30 metres of building			More than 30 metres from building			Any distance
		Cast iron	Ductile iron	Spun iron	Cast iron	Ductile iron	Spun iron	Steel
LP	1	1	1	1	0.1676	0.7186	0.2959	0.7976
LP	2	0.1693	0.1836	0.1738	0.7916	0.4618	0.6338	0.7976
LP	3	0.3719	0.2342	0.3865	0.4694	0.1714	0.4727	0.7976
MP	1	1	1	1	0.3029	0.0077	0.2172	0.4278
MP	2	0.2525	1	0.4596	0.1209	0.0694	0.1257	0.4278
MP	3	0.5282	1	0.8544	0.287	0.0302	0.1393	0.4278
IP	All	0	0	0	0	0	0	0

Table 6.1: Iron Mains Risk Replacement Programme Data – 2032 Projection

This includes the following:

→ All Low Pressure (LP) and Medium Pressure (MP) iron mains with diameters up to 8 inches within 30 metres of buildings will be replaced with PE.

→ All MP ductile iron mains within 30 metres of buildings will be replaced with PE.

→ Between 16.9% and 38.7% of LP cast iron and spun iron mains within 30 metres of buildings will be replaced with PE, with some variation across diameters and the two materials.

→ Between 25.3% and 85.4% of MP cast iron and spun iron mains within 30 metres of buildings will be replaced with PE, with some variation across diameters and the two materials.

→ All domestic metallic services will be replaced with PE.

→ There are no changes to releases downstream of the ECV.

6.2.1. Base Case Risk Predictions

Detailed risk calculations were carried out for many thousands of combinations of mains, services and building types. When carbon monoxide poisoning and unburnt gas exposure is included, the total societal risk of fatality from releases in the 2032 hydrogen case (unmitigated), although extremely low, is higher than the total societal risk of the 2020 natural gas case. The graph below also shows the predictions for the 2032 natural gas network and the 2020 hydrogen (unmitigated) network for comparison purposes.

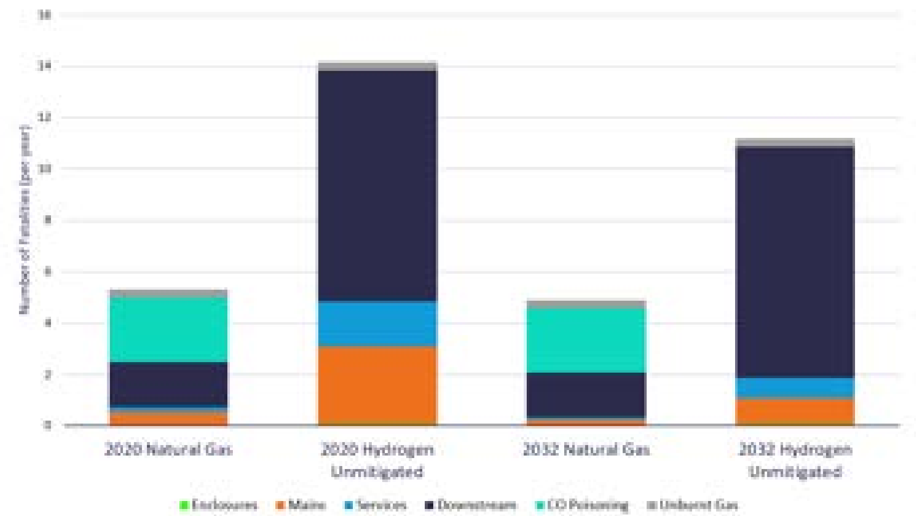


Figure 6.1: Predicted numbers of fatalities occurring across Great Britain – 0-7 barg distribution network and downstream of the ECV

The graph shows that additional control measures will be required to bring the risk of hydrogen to as low, or lower than, natural gas.

The releases downstream of the ECV pose the majority of the societal risk when considering fatalities or non-fatal injuries. This suggests that control measures that affect downstream releases are more likely to be beneficial.

When non-fatal injuries are considered, the 2032 hydrogen societal risk prediction decreases to around 15% of the 2020 natural gas societal risk. This is mainly due to the removal of carbon monoxide poisoning incidents that occur from the use of natural gas.

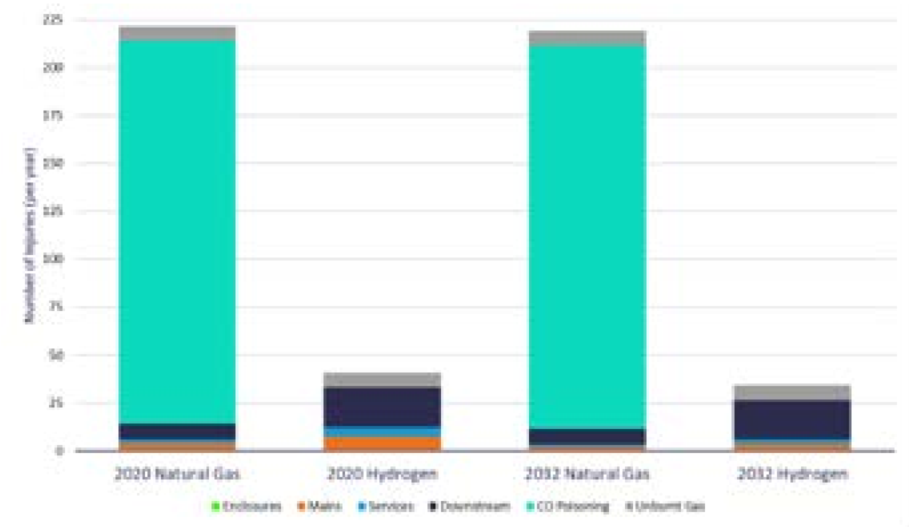


Figure 6.2: Predicted numbers of non-fatal injuries occurring across Great Britain

6.2.2. Predicted Numbers of Incidents

The results below summarise the predicted numbers of fires and explosions, that cause damage to buildings or other assets only, for the four operational cases, pre-control measures.

Hazard Type	Leak Source	Number of Events (per year)			
		2020 Network		2032 Network	
		Natural Gas	Hydrogen	Natural Gas	Hydrogen
Fires Outdoors	Mains	54.79	63.04	23.90	30.40
	Services	35.26	44.41	35.26	44.41
	Total	90.06	112.44	59.16	74.85
External Meters Ignited Releases		3.50	12.61	3.50	12.61
Explosions in Enclosures		0.18	0.41	0.18	0.41
Explosions in Houses	Mains	4.83	9.71	1.56	3.24
	Services	2.59	6.34	1.12	2.79
	Downstream of the ECV*	22.11	41.73	22.11	41.73
	Total	29.53	57.78	24.78	47.76

Table 6.2: Predicted numbers of hazardous events (fires and explosions) occurring across Great Britain

* Includes ignited downstream leaks that produce very low overpressures, so are localised fires.

The overall number of predicted fires on mains and services decreases from the 2020 natural gas case to 2032 hydrogen case

These results of the CONIFER calculations show the following, before any additional control measures are applied. However, it must be noted that the appropriate combinations of control measures show that a hydrogen distribution network can be operated with a total societal risk no higher than that posed by the current natural gas network.

- The overall number of predicted fires on mains and services decreases from the 2020 natural gas case to 2032 hydrogen case due to the influence of the planned iron mains replacement programme.
- Many of the fires are very small. The predicted numbers of potentially severe fires are similar for both gases.
- The frequency of predicted explosions from releases upstream of the ECV decreases from the 2020 natural gas case to the 2032 hydrogen case. This is also due to the planned iron mains replacement programme.
- However, without additional control measures, the frequency of explosions from releases downstream of the ECV approximately doubles from the 2020 natural gas case to the 2032 hydrogen case.
- Examination of the explosion severity model suggests that the number of severe explosions over 70 mbar overpressure (resulting in minor structural damage), is predicted to remain around the same as currently experienced if the planned iron mains replacement programme is completed. However, the number of severe explosions, over 200 mbar overpressure (expected to severely damage houses), is predicted to be higher.
- In addition, without control measures, around double the frequency of minor explosions is predicted in the hydrogen case, which would be unlikely to result in fatalities, but may still cause some property damage.

6.2.3. Control Measures

Potential control measures were identified in Phase 1 of the H21 QRA, which were reviewed and assessed as part of this project, and 10 measures were selected for evaluation. The control measures listed adjacent were also reviewed but not included, as they were found to provide only a small reduction in societal risk compared to the others. These control measures included:

- Increased concentration of odorant
- Increased number of first call operatives
- Reduction in network operating pressures
- More frequent leakage surveys
- Stricter immediate action criteria to repair small leaks

The table below details the 10 control measures assessed.

Description		Reduction in PLL	
		Fatalities per year	% of Hydrogen Base Case
Increased ventilation in buildings	Example 100 mm diameter vent	3.676	32.8
Gas detection inside buildings	Local alarm only	2.996	26.7
	Local alarm and alarm at emergency call centre	7.156	63.9
Installation of excess flow valves	Closing only for leaks exceeding 20 m3/hour	1.611	14.4
	Closing for leaks exceeding 20 m3/hour and some smaller leaks when other appliances operating	2.414	21.5
	Additional risk reduction when EFV close to main (reducing risk from service leaks)	0.336	3.0
Replacement of metallic mains	8-inch diameter and smaller steel mains	0.071	0.6
	10-inch and 12-inch diameter metallic mains	0.198	1.8
	All metallic mains	0.375	3.3
Replacement of metallic connections on services	50% reduction to spontaneous failures of PE services	0.364	3.2
Protection of distribution mains	90% reduction to interference damage of all mains	0.173	1.5
Inspection and replacement of weak PE pipe joints	50% reduction to spontaneous failures of PE mains	0.220	2.0
Move internal meters to external walls	All internal meters relocated	2.177	19.4
Inspection of downstream pipework and equipment	20% reduction to spontaneous failures from all downstream sources	1.519	13.6
Compliance with regulations leading to improved appliances	50% reduction to spontaneous failures from appliances	1.273	11.4

Table 6.3: Potential control measures with benefits upstream and downstream of the ECV

These results show that the different options have varying benefits, but that there is the potential to make significant reductions in the societal risk. When considered individually, the installation of gas detectors linked to automatic reporting of leaks to the national call centre (at concentration levels exceeding half the Lower Flammable Limit (LFL)) alone reduces the total societal risk for hydrogen in 2032 to a level below the 2020 natural gas societal risk.

The effect of combining control measures has been examined in order to investigate the possibility of bringing the 2032 hydrogen societal risk level below the 2020 natural gas level. Ten examples have been evaluated, as summarised in Table 6.4, adjacent. The cases are intended to represent broadly increasing levels of effort to implement the measures.

There is the potential to make significant reductions in the societal risk.

Case	General Measures [1]			Measures Downstream of the ECV[1]			Measures Upstream of the ECV[1]		
	Increased Ventilation	Gas Detection[2]	Excess Flow Valves[3]	Move Internal Meters	Inspect Downstream Equipment	Improved Appliances	Metallic Pipe Replacement[4]	Protection of Mains	Reduction in PE Joint Failures[5]
A	No	Local, 100%	At meter	No	No	Yes	As planned	No	No
B	No	No	At meter	Yes, 50%	No	Yes	As planned	No	No
C	No	Local, 50%	At meter	Yes, 80%	No	Yes	As planned	No	No
D	Yes, 50%	No	At meter	Yes, 80%	No	Yes	As planned	No	No
E	Yes, 25%	Local, 50%	At meter	Yes, 50%	No	Yes	As planned	No	No
F	Yes, 50%	Local, 50%	At meter	Yes, 80%	Yes	Yes	As planned	No	No
G	Yes, 50%	Local, 50%	At meter	Yes, 80%	Yes	Yes	Additional	No	Some
H	Yes, 50%	Local, 100%	At meter	Yes, 80%	Yes	Yes	As planned	No	No
I	Yes, 50%	Local 100%, remote 50%	At meter	Yes, 80%	Yes	Yes	As planned	No	No
J	Yes, 100%	Local 100%, remote 100%	At main	Yes, 100%	Yes	Yes	All LP and MP	Yes	Yes

Table 6.4: Summary of combined mitigation measure cases

Table notes:

1. Comments such as 'Yes, 50%' indicate that the measure has been applied to 50% of properties (or 50% of properties with internal meters for that measure, so 25% of properties overall as half of the meters in operation are already external).

2. 'Local' and 'remote' in the gas detection column indicates where the alarm sounds. Remote alarms report gas detection automatically to the national call centre. Note that the presence of gas detectors does not guarantee that the presence of gas will always lead to an alarm.

3. Excess flow valves are assumed to be located in or near the meter in most cases, case J includes an EFV at the meter and at the upstream end of the service.

4. The 'As planned' is the reduction in risk that is achieved through the metallic mains replacement programme that is already planned. The 'Additional' replacement corresponds to replacing all LP and MP steel mains with a diameter of 8 inches or less which are within 30 metres of domestic properties, and the replacement of LP and MP metallic mains with diameters of 10 inches and 12 inches so that 90% of the metallic mains population in 2020 (irrespective of distance from property) is replaced by 2032. 'All LP and MP' corresponds to replacing all metallic LP and MP mains.

5. 'Yes' indicates that the PE Joint spontaneous failure rate is reduced to 50% of the base case value, and 'Some' indicates a 10% reduction of the base case value.

These cases are intended to represent the following approaches:

→ **Case A** is a low disruption case with only planned mains and service replacement upstream and no significant alterations downstream of the ECV. This avoids work that homeowners might not approve, or that might be impractical – such as moving internal meters, introducing extra ventilation, or excavating services to install EFVs.

→ **Cases B to E** represent various combinations of control measures downstream of the ECV that involve some disruption but are realistic. For example, it is assumed that there are some internal meters that cannot be moved outdoors for practical reasons.

→ **Cases F and H** represent slightly more ambitious approaches, with greater proportions of houses receiving control measures than assumed in Cases B to E. Again, the focus is on leaks downstream of the ECV.

→ **Case G** is similar to Case F but includes additional metallic pipe replacement.

→ **Case I** was developed to show the influence of remote alarms being triggered upon gas detection. As discussed below, this gives around the same overall risk as the 2020 natural gas case without CO poisoning or unburnt gas exposure being included.

→ **Case J** is not intended to be realistic, but shows the level of societal risk that could be obtained by implementing all the control measures simultaneously.

Note that all the cases include improvement of domestic appliances, so that all appliances have flame-out devices fitted. This is expected to be the case for all new hydrogen appliances. In addition, all the cases include the installation of a pair of excess flow valves, such that they always isolate the gas supply to equipment downstream of the excess flow valves when called upon. In Cases A to I, the pair of EFVs is immediately upstream of the meter, or included within the meter. In Case J, one of the pair of valves is at the upstream end of the service, such that large releases from the service are isolated too.

Figure 6.3 shows the societal risk predictions for these combinations of risk mitigation measures.

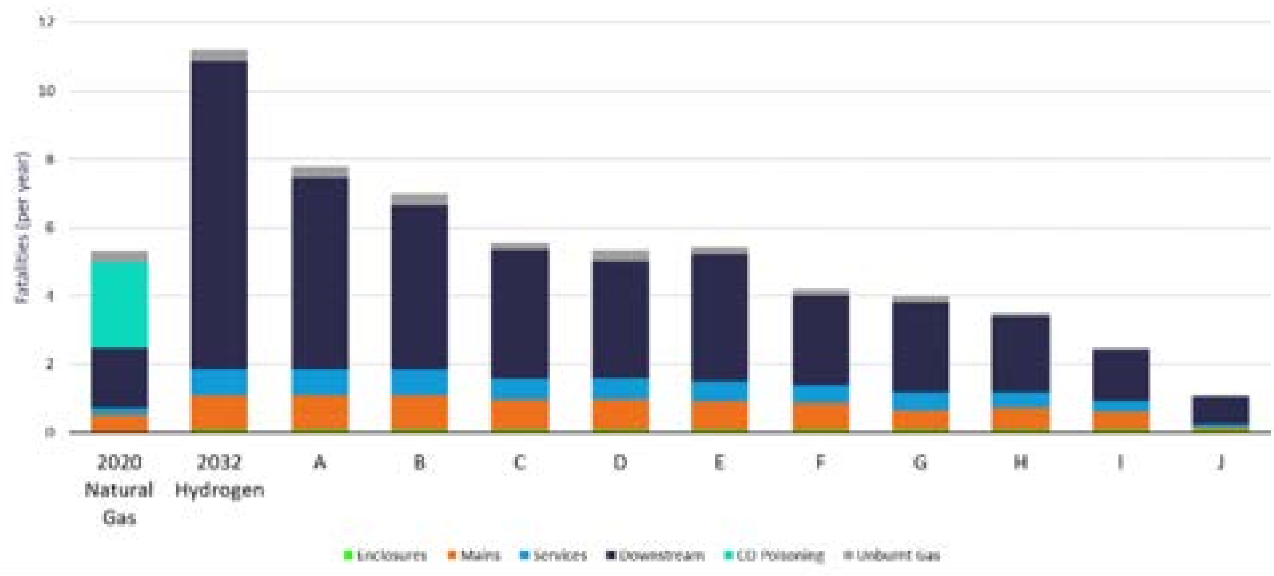


Figure 6.3: Influence of combinations of risk reduction measures for the societal risk across Great Britain

The combinations of risk mitigation measures evaluated above show that it is possible to operate a hydrogen distribution network with a total societal risk no higher than that posed by the current natural gas network.

6.2.4. Risk Mitigation Summary

The safety benefits of ten potential control measures have been evaluated. Some of these calculations include the assessment of multiple variants. The following results were obtained:

- The influence of the iron mains replacement programme that is already planned is included in the base case risk predictions and has a significant benefit.
- Measures that affect both upstream and downstream releases generally provide a significant level of risk reduction. Improved ventilation of rooms, installation of gas detection and installation of excess flow valves were considered.
- Measures that affect only upstream leaks from mains and services typically result in a small risk reduction. Additional mains replacement (beyond that already planned under the iron mains replacement programme), replacement of metallic connections on services, protection of distribution mains against impact damage, and inspection of PE joints are considered.
- Measures that affect only the leaks downstream of the ECV have a moderate influence. Moving internal meters to outdoor locations, inspection of downstream pipework and equipment, and improvements to appliances are considered.

None of these control measures in isolation reduces the 2032 hydrogen case societal risk to the level predicted in the 2020 natural gas case – with the exception of gas detectors that automatically report a potential leak to the national emergency call centre. To address this, ten additional example cases involving multiple control measures being implemented simultaneously were considered. Two of the combined cases give hydrogen risk levels that are very similar to those posed by the 2020 natural gas network, and five cases produced predicted risks that are even lower.

These are intended to be examples, rather than recommendations, as different control measures could be appropriate depending on the circumstances. However, this demonstrates that it is possible to convert to 100% hydrogen at the same or lower risk level than the natural gas system. This applies to the overall risk, including leaks upstream and downstream of the ECV.

The benefits achieved from each control measure could be refined even further in the future as designs/ products become more developed.

7

PHASE 2D SOCIAL SCIENCES

Phase 2d extended the learning from the H21 NIC Phase 1 consumer perception research, to develop educational materials and a range of communication materials that can be used to inform, educate and enhance consumers' understanding of the benefits of a change to 100% hydrogen conversion.

Consumer inclusion in this journey is paramount to the overall success of the conversion.

7.0

SOCIAL SCIENCES

7.1 Introduction

The research builds on the insight gained during Phase 1, including that people have little awareness of how their energy is produced and how the current gas supply contributes to carbon emissions and little understanding of terms commonly used when talking about hydrogen as a domestic fuel.

Working with partners from Leeds Beckett University, the project continued to develop the key messaging strategy that will help consumers and stakeholders better understand the impact of a network conversion.

7.2 Objectives

The aim of this Phase 2 social science research is to provide a suite of resources that NGN can use to communicate effectively with the public about a hydrogen conversion. This is achieved through the following objectives:

- → Produce text and a set of communication principles that NGN can use across all its communication materials, such as leaflets, websites, letters, and scripts for door-to-door engagement officers.
- → Produce an animation that explains the reasons for a hydrogen conversion and how hydrogen is produced. This will provide an engaging and easy to understand account of what will happen and why. It therefore forms a valuable resource for consumers who have difficulties reading English. It could be readily translated into several languages.
- → Develop an interactive display that can be used at community engagement events to aid explanations of how hydrogen is stored and transported, and the practicalities of how the conversion is achieved.

To develop these resources, a series of 12 co-production workshops with members of the public and experts from Northern Gas Networks (NGN) and partners was held. These workshops identified the information that people want, and developed and tested information suitable for an information leaflet.

The final stage of the project was a survey designed to test how the animation affects people's attitudes towards, and acceptance of, hydrogen as a domestic fuel, and to learn more about the beliefs that the public have about a hydrogen conversion.

Phase 2 social science research is to provide a suite of resources that NGN can use to communicate effectively with the public about a hydrogen conversion.

7.3 Outputs

7.3.1 Leaflet

Based on discussions in the paired workshops described above, text was produced that could be used in an information leaflet and various other communication resources. The leaflet text includes the following headings:

- Introduction
- What will happen to my bills?
- What will happen to my appliances?
- What will happen to my gas supply?
- What is happening and when will it happen?
- Where will my hydrogen come from?

Further details can be located in Section 3.1 of the H21: Phase 2 Social Sciences Study (2022)[22]

7.3.2 Animation Development

The project used a series of 'storyboard groups' to develop the script and the visuals for the animation on how hydrogen is produced. This was identified in Phase 1 research as a question better answered by a video than by text. The animation does not explain the different domestic energy options that people can choose from, and does not aim to enable them to make an informed choice between domestic fuels. It focusses on how hydrogen is produced, and this script was subsequently adapted for the interactive display.

Based on the discussions in the workshops, review by experts, and discussions with the animator (www.liquidlizard.co.uk) the final animation was produced. It lasts two and a half minutes and shows how blue hydrogen is produced by splitting methane and how the carbon is stored. The animation can be viewed here:

- Animation Video: Why are we looking to transport hydrogen through the gas network in the future?
- NGN YouTube channel

7.3.3 Survey Results

A survey was used to test the effect of the animation and a total of 924 participants completed the survey. People were randomised into viewing the animation (the animation group) or not (the control group). People in the animation group had fewer questions and concerns about a potential hydrogen conversion. They were better equipped to reach an informed view on a potential future conversion. They had stronger beliefs that it is safe, and that it has a positive effect on the environment. They support the change more strongly, and are more accepting of having hydrogen in their homes. Those in the control group were more likely to simply

[22]Leeds Beckett University. (Nov 2022) H21: Phase 2 Social Sciences Study.

respond that they "have no idea" about different aspects of a future conversion. They were left with more uncertainty and residual questions, for example the willingness to support a hydrogen conversion "if it is safe" or "if it has been tested" or "if it won't cost me any more".

The survey results also show how people respond to the prospect of a hydrogen conversion. We identified six broad responses:

- → believing that it is a good idea as it will help tackle climate change
- → concerns about cost, particularly with the recent cost-of-living increases
- → not feeling sufficiently informed to have an opinion
- → questions and concerns – which were markedly lower for people who had viewed the animation – particularly about safety and the process of producing hydrogen and storing carbon dioxide
- → feeling mistrustful of the information; believing conversion would be a bad idea, or assuming it's an excuse to increase bills
- → believing that this is an interesting area that they would like to know more about.

The results indicate people are willing to pay more for hydrogen than natural gas: 8% more for blue hydrogen and 11% more for green hydrogen. The results provide some evidence that people who are open to a change of gas for environmental reasons are more accepting of hydrogen than they were in 2019, although there has been little change in the proportion of people who are not engaged with the topic and have low awareness of hydrogen as a domestic fuel. Survey data were collected in April and May 2022, at a time when energy prices were increasing but had not yet peaked, so it is possible that price increases will not remain acceptable.

The potential increase in the cost of bills that would accompany a hydrogen conversion are a major concern that people have, both for themselves and for the more vulnerable in our society. These concerns are greater now than in 2019 because of the recent increases in the cost of living, especially domestic energy bills. In contrast, where a potential cost increase is not flagged, there can be a perception that hydrogen will be cheaper than natural gas. Projected cost is therefore an area that needs to be explained to the public so that they are not misled. Safety concerns can be addressed by an explanation of how hydrogen is produced, how the safety of carbon storage is ensured, and the testing that has been undertaken on transporting hydrogen and using it in homes.

7.3.4 Interactive Display

The findings from the workshops were also used to inform content for the interactive display. This was built in collaboration with Ay-Pe (https://ay-pe.com) and involved a series of iterations of content which were tested against the communication golden rules and refined by discussions with experts.

Two versions of the software were produced. The first was installed on a series of iPads which can be played in the Hydrogen Home. These focus on the different appliances in the home. The iPads can also be taken on school visits. The second version was installed on a large totem display, (as below) which is suitable for displays or exhibitions.

Figure 7.1: The H21 Team with the interactive display

The interactive display includes details on the following:

- Why change?
- Hydrogen appliances
- Switching to hydrogen
- Your choices
- New opportunities

7.3.5 Golden Rules

Based on findings from the co-production and storyboard workshops, a set of Golden Rules was developed for communicating with consumers before and during the proposed switch of the gas network to hydrogen. While the focus is primarily on verbal communication, the rules also address the use of visuals and voice (for example in animations or videos). The Golden Rules are grouped under three high-level principles.

1. **Enable a genuine conversation with customers**
   - Be clear about what you are going to say
   - Invite everyone to get involved
   - Remove barriers to participation
2. **Tell a story that engages customers**
   - Put yourself in the customer's shoes
   - Reveal the bigger picture
3. **Give balanced information**
   - Explain what's known and what's not
   - Enable people to select their own level of detail
   - Describe changes and anticipate concerns
   - Balance continuity and change
   - Be considered
   - Respect people's desire to do the right thing
   - Address people as adults

8

ACRONYMS

8.0

ACRONYMS

a

AGI
Above Ground Installation

AQ
Annual Quantity

b

BEIS
Department for Business, Energy & Industrial Strategy

c

CI
Cast Iron

CMS
Competency Management System

CO
Carbon Monoxide

CO^2
Carbon Dioxide

CO^4
Methane

CONIFER
Calculation of Networks and Installations Fire and Explosion Risk

d

DI
Ductile Iron

e

ECV
Emergency Control Valve

EMT
Escape Management Tool

g

GDN
Gas Distribution Network

GIA
Gas In Air

GRP
Glass Reinforced Plastic

h

HFIP
Human Factors Integration Plan

HoC
Hierarchy of Control

HSE
Health & Safety Executive

HSE S&RC
Health & Safety Executive Science & Research Centre

i

IMRRP
Iron Mains Risk Replacement Programme

IP
Intermediate Pressure

l

LCG
Leeds Citygate

LEL
Lower Explosive Limit

LFL
Lower Flammable Limit

LGSI
Live Gas Service Isolator

LP
Low Pressure

LPG
Liquefied petroleum gas

LSI
Live service Insertion

LTS
Local Transmission System

m

MAWP
Maximum Allowable Working Pressure

MEG
Mono Ethylene Glycol

MEIRA
Mechanical Equipment Ignition Risk Assessment

MLS
Metallic Line Stop

MP
Medium Pressure

MPLR
Maximum Permissible Leak Rate

MTP
Master Test Plan

n

NB
Nominal Bore

NE
Negligible Extent

NGN
Northern Gas Networks

NIA
Network Innovation Allowance

NIC
Network Innovation Competition

o

OD
Outside Diameter

OFGEM
Office of Gas and Electricity Markets

p

PE
Polyethylene

PLL
Potential Loss of Life

PPE
Personal Protective Equipment

PRU
Pressure Regulation Unit

q

QRA
Quantitative Risk Assessment

r

RPE
Respiratory protective Equipment

RSI
Rapid Service Isolator

s

SCMH
Standard Cubic Metres per Hour

SDR
Standard Dimension Ratio

SI
Spun Iron

ST
Steel

u

UK
United Kingdom of Great Britain and Northern Ireland

w

WBS
Work Breakdown Structure

9 REFERENCES

9.0

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