

## WORK PACKAGE 7

# Safety Assessment: Precis



# WP7 SAFETY ASSESSMENT

The Hy4Heat Safety Assessment has focused on assessing the safe use of hydrogen gas in certain types of domestic properties and buildings. The evidence collected is presented in the reports listed below, all of which have been reviewed by the HSE.

The summary reports (the Precis and the Safety Assessment Conclusions Report) bring together all the findings of the work and should be looked to for context by all readers. The technical reports should be read in conjunction with the summary reports. While the summary reports are made as accessible as possible for general readers, the technical reports may be most accessible for readers with a degree of technical subject matter understanding.

## **Safety Assessment:**

### **Precis**

An overview of the Safety Assessment work undertaken as part of the Hy4Heat programme.

## **Safety Assessment:**

### **Conclusions Report**

**(Incorporating Quantitative Risk Assessment)**

A comparative risk assessment of natural gas versus hydrogen gas, including a quantitative risk assessment; and identification of control measures to reduce risk and manage hydrogen gas safety for a community demonstration.

## **Safety Assessment:**

### **Consequence Modelling Assessment**

A comparative modelling assessment of the consequences in the event of a gas leak and ignition event for natural gas and hydrogen gas.

## **Safety Assessment:**

### **Gas Ignition and Explosion Data Analysis**

A review of experimental data focusing on natural gas and hydrogen gas ignition behaviour and a comparison of observed methane and hydrogen deflagrations.

## **Safety Assessment:**

### **Gas Dispersion Modelling Assessment**

A modelling assessment of how natural gas and hydrogen gas disperses and accumulates within an enclosure (e.g. in the event of a gas leak in a building).

## **Safety Assessment:**

### **Gas Dispersion Data Analysis**

A review of experimental data focusing on how natural gas and hydrogen gas disperses and accumulates within an enclosure (e.g. in the event of a gas leak in a building).

## **Safety Assessment:**

### **Gas Escape Frequency and Magnitude Assessment**

An assessment of the different causes of existing natural gas leaks and the frequency of such events; and a review of the relevance of this to a hydrogen gas network.

## **Safety Assessment:**

### **Experimental Testing - Domestic Pipework Leakage**

Comparison of leak rates for hydrogen and methane gas from various domestic gas joints and fittings seen in typical domestic gas installations

# WP7 SAFETY ASSESSMENT

## **Safety Assessment:**

### Experimental Testing – Commercial Pipework Leakage

Comparison of hydrogen and methane leak rates on a commercial gas pipework system, specifically the gas meter and equipment contained within the Plant Room of a MOD site.

## **Safety Assessment:**

### Experimental Testing - Cupboard Level Leakage and Accumulation

Comparison of the movement and accumulation of leaked hydrogen vs. methane gas within cupboard spaces in a typical domestic property.

## **Safety Assessment:**

### Experimental Testing - Property Level Leakage and Accumulation

Comparison of the movement and accumulation of leaked hydrogen vs. methane gas within a typical domestic property.

## **Safety Assessment:**

### Experimental Testing - Ignition Potential

Investigation of the ignition potential of hydrogen-air mixtures by household electrical items and a comparison with the ignition potential of methane-air mixtures.

Hy4Heat

Safety Assessment Precis

1.0 | 5 May 2021



Department for Business, Energy & Industrial  
Strategy

## Hy4Heat

# Safety Assessment Precis

ARP-WP7-GEN-REP-0002

1.0 | 5 May 2021

This report takes into account the particular instructions and requirements of our client.

It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

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## **Hy4Heat Safety Assessment Precis**

The aim of the Hy4Heat programme is to establish if it is technically possible, safe and convenient to replace natural gas with hydrogen in residential and commercial buildings. The programme is intended to enable the government and industry to determine whether to proceed to community trials. This summary document provides an overview of the safety assessment undertaken as part of the programme to further the objectives below and inform GDNO site-specific safety cases for proposed community demonstrations.

**Contents**

**Hy4Heat Safety Assessment Precipis ..... 1**

**1 The objectives of the Hy4Heat safety assessment..... 4**

**2 Scope of the Hy4Heat safety assessment..... 5**

2.1 Key assumptions ..... 5

2.2 Gas properties and behaviour differences between hydrogen and natural gas ..... 6

2.3 Current safety framework ..... 6

2.4 Odorant..... 7

2.5 Colourant..... 7

**3 Scope of risk assessment ..... 8**

**4 Methodology of risk assessment..... 9**

4.1 Overall approach to the safety assessment ..... 9

4.2 Uncertainty in assessment ..... 10

**5 Likelihood assessment..... 11**

**6 Data analysis: relevant historic, existing and new data ..... 12**

6.1 Historic gas incidents involving injury ..... 12

6.2 GDNO data collection..... 12

6.3 New experimental data..... 12

6.4 Pipework leak testing..... 12

6.5 Dispersion and accumulation testing ..... 13

6.6 Ignition potential testing ..... 15

**7 Consequence assessment..... 16**

7.1 Data analysis..... 16

7.2 Consequence modelling ..... 16

**8 Risk assessment results ..... 19**

8.1 Addition of safety risk mitigation measures..... 20

8.2 Risk comparison (natural gas vs hydrogen) ..... 21

**9 Risk assessment summary..... 23**

9.1 Recommended risk reduction measures from quantitative risk assessment..... 23

9.2 Recommended safety measures, management and best practice ..... 23

9.3 Competence and training..... 26

9.4 Monitoring of health and safety performance ..... 26

9.5 Other considerations for initial community trial..... 26

**10 Conclusion..... 27**



## Tables

Table 1: Total injury results for natural gas .....	18
Table 2: Total injury results for hydrogen gas.....	18
Table 3: Risk results for natural gas.....	19
Table 4: Risk results for hydrogen gas.....	19
Table 5: Risk results for hydrogen gas (+EFVs) .....	21
Table 6: Comparison of predicted number of injuries for the natural gas base case hydrogen base case and the hydrogen gas case with two EFVs installed*.....	22

## Figures

Figure 1: Overall safety assessment illustrative approach .....	9
Figure 2: QRA process.....	11
Figure 3: Simple, illustrative event tree .....	11

## **1 The objectives of the Hy4Heat safety assessment**

- Conduct a generic safety assessment; assessing and evaluating the generic safety risks inside the property (supported by a quantitative risk assessment, (QRA)), taking into consideration a range of locations, property types and consumers in order to inform safe decision making, the development of appropriate safety management systems for hydrogen and provide the evidence to support potential hydrogen community trials
- Determine if the safety risks of conveying hydrogen inside residential and commercial buildings can be managed such that they are no greater than the accepted risk level associated with the current use of natural gas
- Develop a Safety Annex that summarises the generic safety assessment conducted for conveyance of hydrogen inside residential and commercial buildings. The Safety Annex will also include associated safety mitigation and management recommendations to support the Safety Case submission required by the GDNO (gas distribution network operator) for any proposed community demonstrations
- Obtain a generic ‘letter of assistance’ from the Health and Safety Executive (HSE) to the Safety Annex to support the relevant GDNO Safety Case
- Provide evidence to support wider policy decision making around possible widespread conversion of the natural gas network to hydrogen

## 2 Scope of the Hy4Heat safety assessment

The safety assessment covers leaks occurring downstream of the emergency control valve (ECV). The Hy4Heat analysis has focussed on standard common U.K. building types. A community trial relying on the evidence gathered in this assessment should be confined to the property types, gas operating conditions, pipeline configuration and building layout/typology which the evidence supports, namely:

- Properties that are masonry-built terraced, semi-detached or detached homes of normal types (whilst the QRA has been conducted for a ‘two up, two down’ terraced house, the principles can be assumed to be extendable to encompass the additional properties listed)
- Properties that are compliant (or made to be compliant) with current Building Regulations regarding ventilation and installation of appliances. Minimum levels of permanent ventilation required are detailed in Section 10.2
- Commercial properties, where buildings are similar to domestic, providing the total gas usage (i.e. total usage of all appliances including those used as part of the business) does not exceed 100kW
- Properties that are up to two storeys but may include, for example, a basement/cellar and/or a loft conversion
- Properties fed by service pipes with maximum operating pressures of 75mbarg

The Hy4Heat assessment did not include the following building types and so these should not be included in community trials until further risk assessment work has been undertaken:

- Industrial facilities
- Commercial properties with gas usage significantly greater than domestic environment, i.e. installed gas usage greater than 100kW (e.g. sports facility with a swimming pool)
- Houses in multiple occupation, for example blocks of flats or other buildings in multiple occupation
- Any large or prefabricated buildings
- Buildings that do not have continuous natural ventilation in excess of the level specified in Section 9.2
- Buildings that use mechanical (or forced) systems for background ventilation

### 2.1 Key assumptions

The key assumptions regarding the gas system for this assessment are as follows:

- The internal pipework and fittings for hydrogen gas are the same as for natural gas
- The causes of an initiating leak event (e.g. pipework damage, third party interference) will be unchanged from natural gas to hydrogen gas
- Consumer behaviour is assumed to remain unchanged from natural gas to hydrogen gas, including their response to a suspected leak
- No centrally added colourant to the distribution network
- Appliances are all safety certified in accordance with relevant legislation and with guidance from PAS4444 including flame failure devices (FFDs) fitted on all appliances

- Competent installers, all of whom are Gas Safe certified for hydrogen
- Principles from the IGEM Hydrogen Reference Standard are applied during any community trial
- All gas service pipes supplying properties are installed to current natural gas standards

## 2.2 Gas properties and behaviour differences between hydrogen and natural gas

The key differences in risk between hydrogen and natural gas (methane) are associated with their inherent properties and behaviour, these include:

- Hydrogen will leak approximately three times the volume through a given hole size under a given pressure compared with methane
- The energy density of hydrogen is approximately one third lower than that of methane
- The density of hydrogen is approximately one-eighth that of methane
- Hydrogen has a wider flammable range (4 %vol – 75 %vol) than methane (5 %vol – 15 %vol)
- Hydrogen has a lower minimum ignition energy, particularly in the concentration range 10 – 50 %vol
- Hydrogen and methane differ in their stoichiometric concentration (approximately the concentration at which there is the optimum mix of gas and air for ignition). (Hydrogen: ~28.9 %vol, Methane: ~9.5 %vol)
- The laminar burning velocity of hydrogen is approximately eight times higher than that of methane
- Both hydrogen and natural gas (methane) deflagrate (burn) in a broadly similar fashion (in a domestic and commercial situation)

The impact of these properties has been considered in the experimental work, the QRA and the proposed risk mitigation measures.

## 2.3 Current safety framework

The Gas Safety (Management) Regulations (GSMR) shall be used as the overarching guide for hydrogen community trials and provide a suitable framework for dutyholders to develop their Site-Specific Safety Case. However, GSMR does not apply to 100% hydrogen gas networks and so cannot be used by HSE to regulate the operators of the community trials.

The trials are subject to the Health and Safety at Work Act 1974, the Pipelines Safety Regulations 1996 and the Management of Health and Safety at Work Regulations 1999. In practice this means that the GDNO, as the dutyholder, must submit a site-specific safety case (S3C) to the Health and Safety Executive (HSE) for a community trial and this includes compliance with the Hy4Heat Annex.

Additionally, the following guidance will also be referenced:

- Gas Appliances Regulations – Certification of gas appliances
- Gas Safety (Installation & Use) Regulations - HSE and Gas Safe

## 2.4 Odorant

SGN commissioned a report from the National Physics Laboratory to assess the performance of the existing odorant, mercaptan, used to create the distinctive ‘gas smell’ and other odorants when used with hydrogen. The conclusion of the report was that mercaptan operates in the same way in hydrogen as it does in methane, so the same levels of concentration should be used to achieve the same results. Mercaptan and its distinctive smell is well recognised by the public and so will be used in potential community trials.

## 2.5 Colourant

The Hy4Heat programme commissioned a report into the potential need for a flame colourant to be added into the hydrogen gas. This work was undertaken by DNV GL and was carried out in response to concerns that hydrogen flames are less visible than methane flames. This report concluded that there was no case, from the perspective of inside residential and commercial buildings, for a centrally added colourant. There is sufficient visibility of the flame, burner design can enhance the flame visibility and appliances can use flame detection methods that are not reliant on flame visibility.

### 3 Scope of risk assessment

To support the safety assessment to determine whether it is technically safe to replace natural gas with hydrogen within residential and light commercial buildings, the safety risks arising from gas leaks within buildings, downstream of the ECV were assessed and evaluated.

In the absence of an industry standard to conveying hydrogen gas through the existing gas network, a detailed risk assessment has been carried out to assess the specific safety risks. A comparative safety risk assessment was conducted to compare the risks from fire and explosion as a result of a gas leak within a building. The safety risk arising from carbon monoxide (CO) poisoning (due to incomplete combustion of natural gas within household appliances) was excluded, as the absence of carbon within hydrogen gas would eliminate this risk. The level of harm to be assessed and evaluated in the comparative safety risk assessment was defined as deaths or major injury, notifiable under The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013 (RIDDOR).

The risk assessment covers leaks occurring downstream of the ECV, up to and including the appliance isolation valve. This assessment does not consider leaks originating upstream of the ECV, e.g. leaks from service pipes or mains, which are considered external to the building. This is subject to a separate safety risk assessment commissioned by the GDNOs as part of the H21 NIC (Network Innovation Competition) programme. The risk of leaks from appliances has not been assessed in this work. All new methane and hydrogen appliances are required under GAR to have an FFD fitted. This means gas cannot flow through the burner if the gas is not alight. In practice, a community trial would see old appliances pre-dating the requirement for an FFD replaced with new hydrogen appliances that do have an FFD, which would deliver a safety benefit. However, the safety assessment has not included this benefit.

## 4 Methodology of risk assessment

In order to compare the safety risks associated with each gas (i.e. natural gas and hydrogen gas), a QRA was conducted to obtain numerical estimates of the safety risks for each gas from a quantitative consideration of the event probabilities and consequences. The numerical results from each of the QRA for both gases were then compared and evaluated (taking into account any proposed safety mitigation measures) against the risk acceptance criteria. The QRA starts from the premise that the risk with the use of hydrogen should be managed such that it is no greater than the level of risk associated with the current use of natural gas. This assessment does not include the risk from CO poisoning, which cannot occur with hydrogen and as such has been excluded from the natural gas base case.

An underlying principle of this risk assessment has been that where expert judgement has been required, a ‘worst case estimate’ has been used for hydrogen and a ‘cautious best estimate’ has been used for natural gas. This ensures that the risk assessment takes into account the appropriate level of uncertainty in the risk estimate. This approach ensures that as the degree of uncertainty increases (e.g. for hydrogen compared to natural gas), the results err slightly on the side of caution (i.e. the worst case estimate of the outcome or parameter values) to conservatively control the level of uncertainty in the estimated risk.

### 4.1 Overall approach to the safety assessment

Figure 1 below shows the overall safety assessment that has been developed, including the QRA and the inputs that have been used. These include existing historical records, peer reviewed papers and academic models, new experimental testing, new data collection, use of expert judgement and consideration of proposed safety mitigation measures.

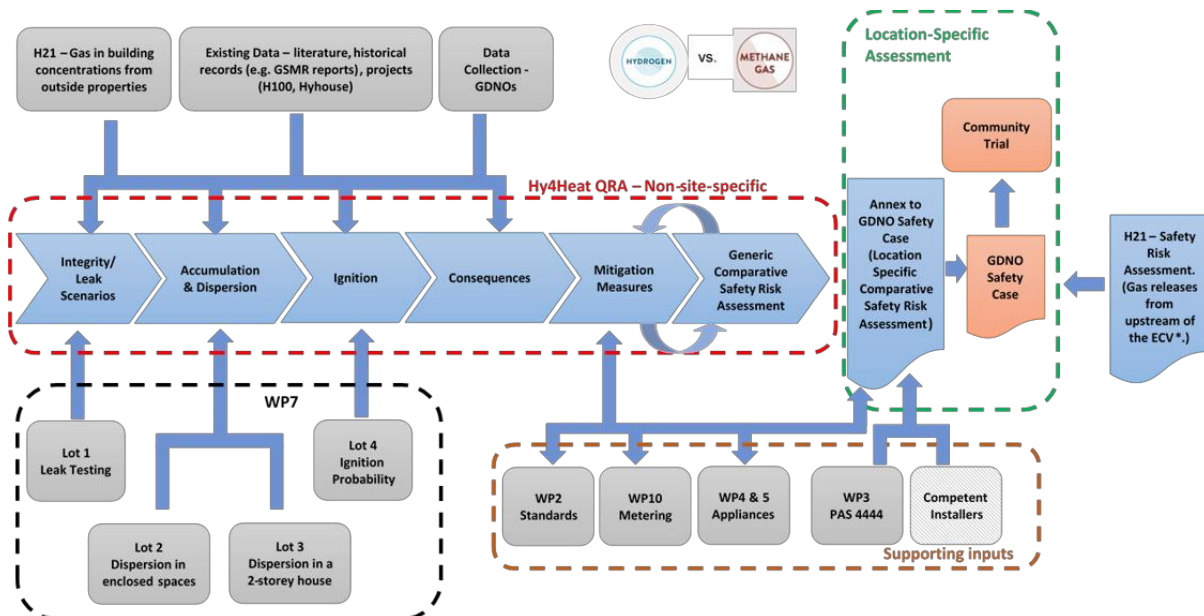


Figure 1: Overall safety assessment illustrative approach

## 4.2 Uncertainty in assessment

The quantitative risk analysis carried out as part of this safety assessment is based on a number of connected assumptions.

These assumptions are largely based on engineering judgement, supported by the analysis of available data collated from gas incidents reported to date and further experiments conducted under the current Hy4Heat programme.

The rarity of incidents in a domestic environment, which occur approximately 20 times per year (i.e. one fire per million homes per year) make them difficult to deduce probabilities relevant to the quantitative risk modelling that are statistically significant (i.e. the rarity of the incident compounded by the limitation of the data collated makes it hard to make assumptions and derive data that will give us confidence that the assumed probabilities reflect reality). In addition, the data available is insufficient to break down these events into their constituent parts with absolute certainty.

Therefore, it is important to acknowledge that there is uncertainty surrounding the values used within the QRA and that uncertainty exists in the assumptions made within the model which at present are not 100% supported by relevant datasets.

There are a number of recommendations made for further work to improve the confidence in the data used within the model.



## 5 Likelihood assessment

To estimate the likelihood of fire and explosion as a result of natural gas or hydrogen gas leaks, the following steps, as illustrated in Figure 2 below were taken:

- Determine failure (leak) scenarios
- Estimate leak sizes and frequencies using collected data
- Estimate release rates and characteristics for the selected leak sizes
- Estimate gas dispersion associated with the release rates
- Estimate probability of ignition based on the dispersed gas concentrations when in equilibrium

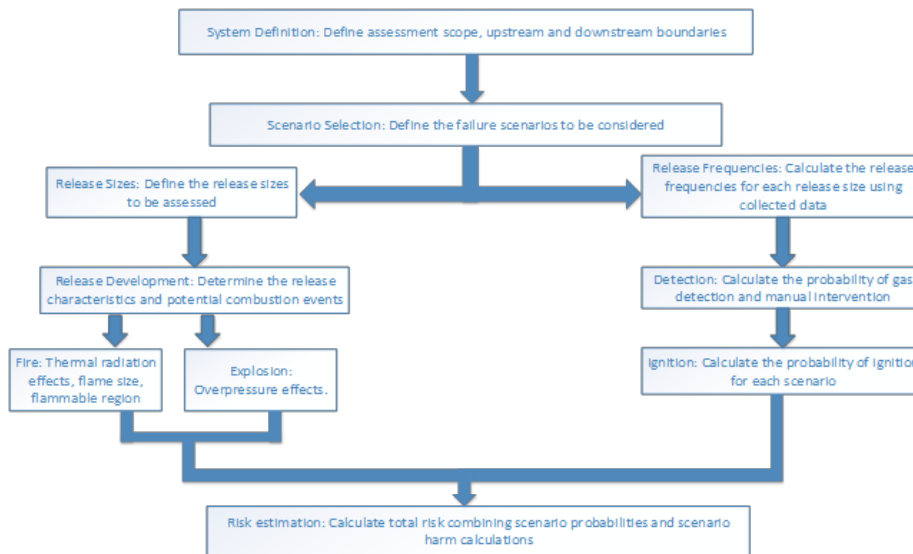


Figure 2: QRA process

Detailed fault and event trees were developed using specialist modelling software (Isograph Reliability Workbench package) to estimate the frequencies of fire and explosion for a range of leak scenarios. A simple event tree is shown in Figure 3 for illustrative purposes.

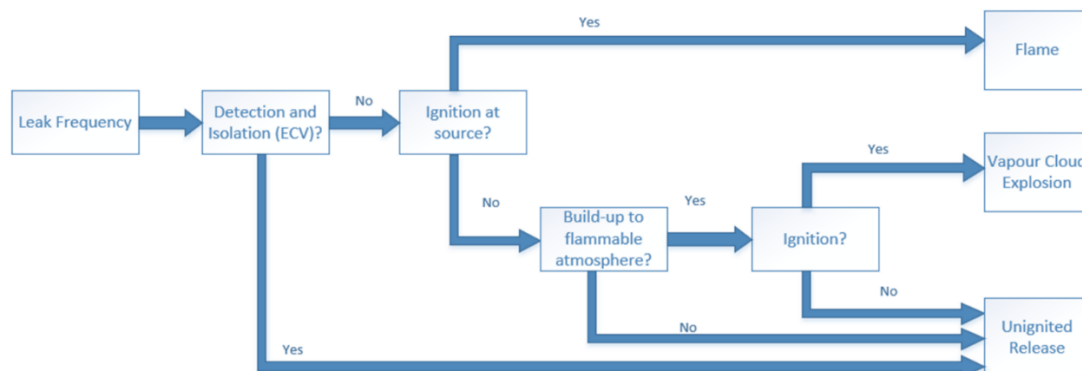


Figure 3: Simple, illustrative event tree

## 6 Data analysis: relevant historic, existing and new data

### 6.1 Historic gas incidents involving injury

Gas incidents which caused injury in the past four years (Apr-16 to Mar-20), recorded by the HSE under the GSMR were reviewed and analysed. A total of 62 incidents i.e. about 15 incidents per year, were recorded, and categorised into five incident causes: third-party damage, corrosion, appliance, house fire and unknown. The largest cause of fire/explosion from gas incidents was appliances (many of which are attributed to appliances without FFDs that had been left unlit), followed by third-party damage (such as DIY accidents). Incidents originating from appliances or house fires have not been taken into account to estimate the frequency of incident leading to injury. This enabled a relevant like-for-like comparison between the historic incident data and the QRA predictions.

### 6.2 GDNO data collection

To address the identified gaps within the available data on gas leaks and their causes, a questionnaire was developed to gather data specifically required for use within the QRA. The questionnaire was completed by the FCOs (first call operatives) of the GDNOs who attend callouts of reported gas leaks. Key information that the survey gathered included the escape location, mechanism and cause. A total of 900 relevant data points were collected and used to inform the leak frequency assessment.

### 6.3 New experimental data

As per Figure 1, four packages of experimental testing were commissioned to inform the Hy4Heat safety assessment. These experiments focussed on comparing a variety of behaviour between methane and hydrogen gas. Given that natural gas is composed predominantly of methane (typically 85-98 %vol), methane was used in all experiments as a surrogate for natural gas for simplicity of both supply and gas analysis.

### 6.4 Pipework leak testing

This experimental testing package, undertaken by Steer Energy Ltd, compared the leak rates of methane and hydrogen from various gas joints and fittings seen in current domestic gas installations. A number of test pieces were assembled, and the leak flows of hydrogen and methane were measured after they were deliberately damaged to induce leakage. Gas fitters were consulted to determine the types of damage they would typically find. The main observations of the tests show that:

- A non-leaking fitting with methane will be non-leaking with hydrogen, therefore none of the fittings or pipes tested have been found to be unsuitable for hydrogen. Equally, a leak with methane will result in a leak with hydrogen. This means that it is considered safe to use the same materials and fittings for internal pipework (as permitted under the GS(I&U)R) for hydrogen as is currently used for methane in the context of a community trial time period

- Small leaks from along threads, loose and damaged fittings have a volumetric leak flow ratio of 1.2:1 between hydrogen and methane i.e. slightly more hydrogen leaks out, but this represents less energy flow because hydrogen has a lower energy density
- Large leaks from accidents such as drilled or nailed holes have a volumetric leak flow ratio of 2.8:1 between hydrogen and methane. i.e. nearly three times more hydrogen leaks. As hydrogen has approximately less than one-third of the energy of methane on a volumetric basis, the amount of energy outflow is slightly less than methane. Despite this large ratio in volumetric leak rates (from the same size hole), the measured concentration of hydrogen (in a domestic room) is usually between 1.3 and 1.8 times that of natural gas. This arises because of the large convective forces driven by the low density of hydrogen i.e. hydrogen dissipates more quickly than methane.

## 6.5 Dispersion and accumulation testing

### 6.5.1 Dispersion and accumulation testing - cupboard level

This experimental testing package compared the movement and accumulation of hydrogen and methane released within confined spaces such as kitchen cupboards in a typical domestic property. The experiments were carried out in a purpose-built row of houses, 'HyStreet', at DNVGL Spadeadam.

This package consisted of two phases:

In **Phase 1**, a programme of 73 experiments was conducted involving 39 releases of hydrogen and 34 of methane into kitchen cupboards and an inset meter box. Releases were from holes ranging from 0.6 mm to 7.2 mm diameter with a pressure of 20 mbarg; the normal pressure downstream of the meter in a domestic property. The test houses have a greater air tightness than most UK housing. Additionally, they do not include kitchen vents (this is contrary to the Building Regulations Approved Document F (England or Wales) (ADF)).

**Phase 2** was an additional set of ten experiments undertaken using hydrogen gas involving some higher release rates and variations in combinations of vent openings in the cupboard and the kitchen wall. The purpose of these experiments was to demonstrate whether an increase in ventilation would reduce the maximum hydrogen concentrations and inventories observed. These experiments utilised the addition of a vent to create this increased ventilation in a controlled manner.

The experiments showed that the addition of a ceiling vent, ducted to the external wall, had the effect of reducing the maximum concentration of hydrogen seen within the kitchen. The results showed that the cupboard vents reduce the concentration of hydrogen in the cupboards. Building Regulations ADJ (England) or regional equivalent, requires ventilation of such cupboards at both top and bottom level. In recent years most manufacturers have sought exemption from this regulation. However, the recommendation of this safety assessment is that, for community trials, venting in any void should be made mandatory in accordance with Building Regulations ADJ (i.e. exemption should not be granted to manufacturers for hydrogen appliances).

### *6.5.2 Dispersion and accumulation testing – property level*

This experimental testing package compared the movement and accumulation of hydrogen and methane released within rooms in a domestic property (HyStreet). The experiments involved releases of hydrogen and methane within a representative two-story domestic property with a basement and a loft conversion.

This package consisted of two phases:

In **Phase 1**, a program of 102 experiments was conducted, involving 53 hydrogen releases, 49 methane releases and variants in release size, flow rate and orientation into both the basement and kitchen boiler cupboard within the house. Releases were from holes ranging from 3.5 mm to 15 mm in diameter. The test houses had a greater air tightness than most UK housing stock; all these experiments were conducted with the property having permeability levels (ventilation) of less than  $\sim 5\text{m}^3/\text{m}^2/\text{h}$  at 50Pa. This is a low value and is equivalent to about 0.25 Air Changes per Hour (ACH). This is considerably below the target ‘as occupied’ ACH of  $\sim 0.4$  as indicated in Building Regulations ADF. This is equivalent to about  $80\text{m}^3/\text{hr}$  for a typical 3 bed property.

**Phase 2** consisted of an additional set of 18 experiments using hydrogen gas with variations in combinations of vent openings in the kitchen and living room. The purpose of these experiments was to demonstrate whether an increase in ventilation would reduce the maximum hydrogen concentrations observed. These experiments utilised the addition of a vent to create this increased ventilation in a controlled manner.

The experiments showed that the addition of a ceiling vent (ducted to the external wall) had the effect of reducing the maximum concentration of hydrogen seen within the kitchen.

The air bricks added to the basement showed less conclusive results, with some smaller vent tests recording an increase in the maximum hydrogen concentration. The tests undertaken with the larger vent size all demonstrated the expected reduction in maximum hydrogen concentration. However, as the results are inconclusive, the conveyance or use of hydrogen in the basement is not recommended. This could be an area that requires further investigation.

This series of experiments were used in the QRA model to assess the relative likelihoods of explosive mixtures of methane and hydrogen forming.

### *6.5.3 Accumulation and dispersion in the QRA*

A comprehensive analysis of the new experimental dispersion and accumulation data was undertaken. This was supported by analysis of experimental data previously collected by HyHouse and H100 (SGN Network Innovation Allowance) programmes. An identification and validation exercise were carried out for a number of simple dispersion models and as a result, the Linden model has been used to model dispersion within the QRA. This model calculates the mean steady state concentration which develops for a given hole size in a defined space, for both natural gas and hydrogen gas. From the experimental data analysis undertaken, stratification is an observed phenomenon in both gases. The dispersion model results were then compared with HyStreet data to estimate the highest likely gas concentrations for both gases. This was carried out for a range of hole sizes and realistic release geometries, in the kitchen and the downstairs of the house. These peak concentrations were used to inform the consequence modelling undertaken and described below.

## 6.6 Ignition potential testing

This experimental testing package, undertaken by DNV GL, assessed and compared the potential for household electrical items to ignite hydrogen and methane mixtures with air. Electrical items were primarily chosen on the basis that they had at least one of three potential ignition mechanisms; hot surface, electrical contacts, or electrical motors. In addition, some electrical items were also selected because they had none of these mechanisms (as control samples). The items used in the test programme included white goods in new and used condition, plugs and switches, light fittings and extractor fans. The items were placed into a 2.86m<sup>3</sup> explosion chamber and operated for ten minutes at increasing concentrations of hydrogen or methane in air.

It was found that:

- In the majority of tests, no ignition occurred with either hydrogen or methane
- In the majority of tests where hydrogen was ignited, so was methane
- Some domestic appliances caused hydrogen to ignite, but not methane. These include hair dryers, toasters, vacuum cleaners, tumble driers and irons. Nearly all of these appliances can only be used with a human operator present, who would most likely smell a gas release

These results were used in the QRA model to assess and compare the likelihood of an explosive mixture of methane igniting and an explosive mixture of hydrogen igniting.

## 7 Consequence assessment

A comprehensive comparative consequence assessment has been undertaken to determine the level of damage associated with ignition of a hydrogen gas cloud compared to that of a natural gas (methane) cloud.

### 7.1 Data analysis

A review of experimental data and other literature relating to deflagrations of flammable mixtures of hydrogen and methane was carried out. The experiments concerned ignitions within structures constructed from varying types of material such as glass, wood, concrete and metal. Nearly all structures had some means by which the deflagration could be vented, and some experiments contained obstructions within the enclosure. Of particular relevance was available experimental data from the ignition of methane and hydrogen gas in structures similar to that of domestic kitchens.

The relevance of each experimental set-up to a domestic situation was considered. The dataset was refined to provide a range of possible damage outcomes that might occur to a property from an ignition of methane and hydrogen.

The key findings were:

- Data from experiments representative of a domestic property showed that for concentrations of around 10% methane and 15-20% hydrogen the consequence of an ignition would be roughly comparable. Towards the higher end of this concentration band, the hydrogen ignition starts to become more severe than methane. The concentrations taken are uniform average concentrations where experiments are fan-mixed. When it is not fan-mixed then the mid height concentration has been used
- Beyond 20% (up to around 40%) the consequence of a hydrogen ignition gets progressively more severe
- The presence of obstruction within the combustion zone can cause turbulence of flammable gas mixtures leading to increased peak overpressure for both hydrogen and methane. Note that peak overpressures for hydrogen can be higher due to the faster flame speed
- There was no evidence of hydrogen exhibiting a general transition from deflagration to detonation in a pseudo domestic environment. A general detonation was only achieved using chemical detonators

### 7.2 Consequence modelling

Following this data analysis, a consequence modelling exercise was then undertaken informed by the key findings above. The assessment considers the consequences of ignition of a flammable gas cloud (either methane or hydrogen) occurring within a typical two storey, masonry-built, terraced house. The UK housing stock contains a variety of housing topologies and using a terraced house to assess the impact of an explosion is considered conservative due to the proximity to other dwellings.

Data from previous natural gas incidents have shown that more serious injuries per incident arises in terrace houses compared to either semi-detached or detached houses. Knowing the

characteristic of hydrogen explosions compared to methane explosions, it is predicted that this scenario will remain. Therefore, with the addition of appropriate mitigation measures, if the risks in terrace houses from hydrogen can be made comparable to those from methane, then it is appropriate to infer that the same applies to semi-detached and detached houses. In practice, explosions in a detached property are less likely to cause harm to adjacent dwellings.

The consequence assessment considers confined explosions with a level of congestion representative of typical domestic furniture. In confined explosions, the overpressure is generated from the restriction of expanding combustion products due to the presence of a confining enclosure, i.e. the walls, floor and ceiling of a domestic dwelling. The presence of congestion, in the form of household items, also contributes to the generated overpressure. The generated overpressure and impulse associated with ignition of a flammable gas cloud, consisting of either methane or hydrogen, has been estimated using a method for vented combustible explosions developed by Warwick FIRE (University of Warwick multidisciplinary research laboratory). The effects of an explosion depend on the strength and duration of the generated overpressure. The estimated internal overpressures and impulses are used to determine the response of the masonry walls forming the boundary of the domestic enclosure. The methodology identifies whether the load-bearing walls of the enclosure retain their structural integrity when subjected to the estimated overpressure and impulse generated by an explosion.

As the assessment considers explosions generated inside domestic properties, the main causes of harm will be:

- Structural collapse; with the potential to cause injury to any occupants who are inside the affected property at the time of the incident
- Flying debris; (e.g. glass, structural components) with the potential to cause injury to occupants inside the affected property and passers-by external to the property at the time of the incident
- Burns; with the potential to cause injury to occupants inside the affected property and passers-by external to the property at the time of the incident

The assessment considered two key scenarios:

- A ground floor kitchen (4m x 3m x 2.4m). Initially the internal door and window is closed allowing a build-up of gas within the room prior to ignition of the confined flammable cloud
- The downstairs of an open plan terraced house (4m x 8m x 2.4m). Initially, the internal door and windows are closed, and it is assumed the flammable cloud is confined to the downstairs room

Tables 1 and 2 below present the total injury results per incident as predicted by the consequence model for natural gas and hydrogen gas, respectively.

Table 1: Total injury results for natural gas

Peak concentration range (vol%) and scenario	Total number of people injured (kitchen scenario)	Total number of people injured (whole downstairs)
5.0% to 7.5% (kitchen door closed)	0.35	n/a
7.5% to 14.0% (kitchen door closed)	2	n/a
14.0% - 15.0% (kitchen door closed)	0.35**	n/a
5.0% to 6.5% (kitchen door open)	n/a	0.9
6.5% - 11.0% (kitchen door open)	n/a	5.5
11.0% - 15.0% (kitchen door open)	n/a	0.9**

*\*\* This could be interpreted as meaning that larger leaks and greater methane inventories are less dangerous than smaller leaks with lower methane concentrations. In terms of actual injuries, this is unlikely to be the case. This result arises because the consequence modelling has assessed the level of damage and, hence, the injuries likely to occur from the primary deflagration in the originating room. In practice a large gas inventory (several kg) may well create secondary fires and explosions in adjacent rooms which will cause further damage and injury. This is an example of natural gas being assigned a cautious low risk to ensure a relative QRA with a pessimistic view of hydrogen.*

Table 2: Total injury results for hydrogen gas

Peak concentration range (vol%) and scenario	Total number of people injured (kitchen scenario)	Total number of people injured (whole downstairs)
5.0% to 14.0% (kitchen door closed)	0.35	n/a
14.0% to 23.0% (kitchen door closed)	2.3	n/a
>23.0% (kitchen door closed)	7.4	n/a
5.0% to 13.0% (kitchen door open)	n/a	0.9
13.0% to 21.0% (kitchen door open)	n/a	5.5
>21.0% (kitchen door open)	n/a	9.4



## 8 Risk assessment results

The estimated risk values from the risk assessment combine the output from the frequency assessment, (which aims to estimate the frequency of a range of leak events) with the consequence assessment (which estimates the level of harm associated with the leak events). The risk assessment only considers the risk from fires and explosions and, as such, the risk from CO poisoning has been excluded from these results.

The estimated number of injuries per year for the range of scenarios for natural gas and hydrogen are illustrated in the tables below.

Table 3: Risk results for natural gas

Peak concentration range (vol%) and scenario	Likelihood (Estimated number of events per year (GB population))	Consequence per incident (Estimated number of people injured)	Risk (Estimated number of individuals injured per year: GB)
5.0% to 7.5% (kitchen scenario)	3.5	0.35	1.2
7.5% to 14.0% (kitchen scenario)	2.2	2	4.4
14.0%-15% (kitchen scenario)	0*	0.35	0
5.0% to 6.5% or 11%-15% (whole downstairs)	1.5	0.9	1.4
7%-11% (whole downstairs)	1.8	5.5	10.1
Total	9	n/a	17

\*The likelihood as predicted by the QRA for the scenario of a 14-15% natural gas explosion is 0. This is due to the use of a steady state dispersion model, none of the scenarios modelled in the QRA lead to a flammable atmosphere of exactly 14 or 15% at steady state. In order to provide a conservative comparison to hydrogen, if the steady state model predicts a concentration of >15% natural gas (i.e. above upper flammability limit (UFL)) then it is assumed not to ignite.

Table 4: Risk results for hydrogen gas

Peak concentration range (vol%) and scenario	Likelihood (Estimated no. of events per year (GB population))	Consequence per incident (Estimated number of people injured)	Risk (Estimated number of individuals injured (per year GB))
5.0% to 14.0% (kitchen scenario)	20.0	0.35	7.0
14.0% to 23.0% (kitchen scenario)	2.8	2.3	6.5
>23.0% (kitchen scenario)	2.8	7.4	20.4
5.0% to 13.0% (whole downstairs)	11.4	0.9	10.2
13.0% to 21.0% (whole downstairs)	0.4	5.5	2.4
>21.0% (whole downstairs)	2.0	9.4	18.8
Total	39	n/a	65

The results in Table 3 and Table 4 show both a high estimated number of large natural gas and hydrogen incidents. The increased number of injuries per incident for hydrogen inevitably leads to an increased value for annual injuries, which is considerably larger than

that predicted for natural gas. This is because of the more serious consequences predicted by the Warwick FIRE model for the higher concentration hydrogen explosions.

Recent publications (during 2019 and 2020) by the HSE have also highlighted the degree of uncertainty over the accuracy of all hydrogen deflagration models, including the Warwick FIRE model which, as a single room, single vent model, does not reflect the mechanism of failure of domestic property. The model has purposely been used in a conservative manner and is permitted to predict overpressures much larger than will occur in UK domestic properties. This single vent model can predict overpressures above 1000mbarg; in practice nearly all UK housing has failed below 200mbarg and the most robust buildings by 600mbarg.

In practice when experiencing either a methane or hydrogen fire the speed of the pressure build-up within a room is much slower than the speed of mechanical failure of a window, door or even standard brick wall.

However, as this is a relative QRA, and the same model is used for both gases, the over-conservatism within the consequence model is considered to not affect the predicted relative risk between the two gases.

## 8.1 Addition of safety risk mitigation measures

As per the results in Table 3 and Table 4, the QRA estimates an increase in the frequency of ignited events and an increase in the overall risk to people for conveyance of hydrogen gas within the existing domestic gas system, with no additional control measures in place.

Additional control measures were therefore considered, and Excess Flow Valves (EFVs) were considered through the QRA model. EFVs are devices that automatically respond to excessively high rates of flow, by closing off the supply of gas. EFVs have been proposed as additional control measures to reduce the risk to a comparable level to that of the natural gas case.

The original hydrogen QRA was reassessed to consider the impact of introducing two EFVs into the domestic gas system:

- One upstream of the meter installation
- One located within the smart meter installation

The use of two EFVs is considered as it increases the overall reliability. The combination of a conventional physical EFV, in addition to a specifically designed gas meter, containing the instrumented valve, will result in a system with a higher reliability than one relying on a single device. The two valves are assumed to not any have common cause failures, as they are different types of valve and would operate independently of each other. The valve in a gas meter is a conventional actuated valve, such as an on-off ball valve whereas an EFV operates using purely physical phenomena resulting from gas flow.

It is assumed that both of these EFVs are set at a flowrate of 20m<sup>3</sup>/hr. This value is based on the maximum flow of hydrogen gas that could be reasonably expected to be needed (e.g. if a large combination boiler, gas fire and hob were in operation at the same time). In practice, it is envisaged that the EFV located in the smart meter could be calibrated to a lower flowrate and could be available in a range of pre-set capacities.

The estimated number of injuries per year for the range of scenarios for hydrogen with EFVs are illustrated in Table 5 below.

Table 5: Risk results for hydrogen gas (+EFVs)

Peak concentration range (vol%) and scenario	Likelihood (Estimated number of events per year (GB population))	Consequence (Estimated number of people injured)	Risk (Estimated number of people injured per year: GB)
Kitchen explosion (5-14 vol%)	18.5	0.35	6.5
Kitchen explosion (14-23 vol%)	0.4	2.3	1.0
Kitchen explosion (>23 vol%)	0.05	7.4	0.3
Whole downstairs explosion (5-13 vol%)	6.5	0.9	5.8
Whole downstairs explosion (13-21 vol%)	0.4	5.5	2.4
Whole downstairs explosion (>21 vol%)	0.03	9.4	0.3
Total	26	n/a	16

The QRA thus shows that the introduction of 2 EFVs for hydrogen gas substantially reduces the predicted number of annual injuries and brings the risk in line with that of the natural gas case. This is due to the reduction in frequency of large and very large leaks which have the potential to lead to the worst-case explosions.

## 8.2 Risk comparison (natural gas vs hydrogen)

Table 6 shows the injuries predicted from fires and explosions for all three cases (natural gas, hydrogen, and hydrogen with EFVs), which takes into account the behavioural responses (such as ECV closure / opening window and doors when gas is smelled) upon detection of the leak. The higher level of predicted injuries from all three cases relative to the GSMR data is a consequence of the conservative estimates of the presence of large and very large holes with the potential to leak gas at a high rate. As hydrogen gas has never been operational in the GB domestic gas network, there is no historic injury data for hydrogen incidents. There is also limited data for natural gas injuries due to the low number of annual incidents. The rarity and complexity of these events therefore makes it difficult to reduce this conservatism.

It is important, therefore, that these results are compared on a relative likelihood basis, rather than as absolute values, due to the uncertainty and overprediction inherent in the assessment described above.

EFVs are assumed to have a high level of reliability (derived based on the HSE failure rate guidance) that can respond very quickly to shut off the supply of gas when flow is too high. The combination of a conventional physical EFV with hardware and software monitoring in a specifically designed gas meter will result in a system with a higher reliability than one relying on a single device. The addition of EFVs would have the greatest impact on reducing the frequency of large and very large leaks, bringing the overall level of risk to a comparable level to natural gas.

It is acknowledged that medium sized leaks (in small rooms of low ventilation) may offer some increase in risk. However, the overall level of risk for hydrogen with EFVs is considered to be comparable to the natural gas base case.

Table 6: Comparison of predicted number of injuries for the natural gas base case hydrogen base case and the hydrogen gas case with two EFVs installed\*

	<b>Indicative average annual number of injuries</b> (HSE GSMR Data 2016-2020**)	<b>Natural Gas</b> Predicted number of individuals injured (per year: GB)	<b>Hydrogen Base Case</b> Predicted number of individuals injured (per year GB)	<b>Hydrogen + 2EFVs</b> Predicted number of individuals injured (per year GB)
<b>Total estimated no. of injuries per year***:</b>	<b>12</b>	<b>17</b>	<b>65</b>	<b>16</b>

*\*These numbers should be considered a general relative basis rather than absolute values*

*\*\*Value calculated from GSMR incident data (excluding appliance and general house fire incidents) and HyDeploy analysis of injuries per incident is used as a representative value for comparison with the QRA predictions. (HyDeploy is an energy trial to establish the potential for blending hydrogen, up to 20%, into the normal, natural gas supply)*

*\*\*\*It should be noted that the predicted total number of injuries per year have not been adjusted against the total housing typology type and are based on consequences should every leak occur in a typical 'two-up, two-down' UK terraced house (as per the scope of this assessment)*

## 9 Risk assessment summary

The following paragraphs summarise the findings of the risk assessment.

It is understood from historic data that a significant cause of current fires and explosions (~40% of all of those downstream of ECV) is due to the absence of FFDs, particularly on hobs. All hydrogen appliances will have FFDs, therefore, reducing the likelihood that appliances can be, unwittingly, left on whilst unlit.

From the dispersion analysis undertaken, small leaks (<2mm hole and about 97% of reported leaks) do not create sufficiently large flammable clouds to produce injuries; all are readily smelled, especially as hydrogen has a large volumetric leak rate.

Medium sized leaks (2-6.5mm) can produce flammable gas clouds in small rooms, those with the door closed and/or rooms with poor ventilation. From the FCO data collected, it is understood that such leaks are often created by 3<sup>rd</sup> party damage and therefore appropriate behaviour to stop the development of the leak are undertaken, i.e. by opening windows, closing the ECV and alerting the gas conveyer. Such leaks very rarely occur spontaneously.

Large leaks (>6.5mm) are the size conventionally expected to produce high gas concentrations in large areas of a house. From historic data and FCO data collected, a significant percentage of these arise from third-party damage (including malicious intent). The introduction of two EFVs will significantly reduce the likelihood of leaks of this size developing into a hazardous scenario (i.e. the flow of gas will be stopped before a flammable atmosphere can develop).

### 9.1 Recommended risk reduction measures from quantitative risk assessment

It is shown that the estimated risk of injury associated with conveying hydrogen gas in an existing domestic system with the addition of two EFVs, is no greater than the estimated risk of injury associated with the current existing natural gas system.

Therefore, in the event of any future community trial, it is recommended that two EFVs are installed:

- One upstream of the meter installation
- One located within the smart meter installation

### 9.2 Recommended safety measures, management and best practice

The following risk reduction measures should be put in place for a community trial:

- The following regulations and standards shall be complied with:
  - a. Gas Safety (Installation & Use) Regulations
  - b. IGEM Hydrogen Reference Standard (IGEM/H/1) or equivalent hydrogen specific amendments to existing IGEM natural gas standards
  - c. As and when it is completed, the BSI PAS Installation Standard – pipework and ventilation, and other relevant IGEM standards
  - d. All hydrogen appliances must be new (domestic or commercial), certified by a Notified Body in accordance with Gas Appliances (Enforcement), Miscellaneous

Amendments Regulations with the use of PAS 4444 including Flame Failure Devices (FFDs) fitted on all appliances

- e. Installed hydrogen smart gas meters must be new, certified by a Notified Body (for metrology and safety), and be SMETS2 compliant.
- Excess Flow Valve (EFV) to limit the flow rate to 20m<sup>3</sup>/hr in the service pipe. This is either to be installed as a retrofit or as part of new installation. The installation of this mechanical excess flow valve should conform to the functionality of the standard ASTM F2138 - 12(2017) (Standard Specification for Excess Flow Valves for Natural Gas Service) or similar publicly acknowledged industry standard. It shall be located in either of the following locations:
  - a. In the service pipe itself, or
  - b. Immediately after the Emergency Control Valve (ECV).
- Hydrogen gas meter containing an integrated Excess Flow Valve (EFV) to limit the flow rate to <20m<sup>3</sup>/hr or set at a lower value that is related and proportionate to the maximum usage of appliances installed within the individual property. Minimum values for the setting of this should be agreed with appliance manufacturers.
- Meter connections shall comply with the “Specification for gas meter unions and adaptors” upgraded from the Natural Gas specification (BS 746:2014) for use with hydrogen.
- Hydrogen gas meter location: Hydrogen gas meters should be installed outside of the property\* and comply with current best practice and BS6400-1:2016. *\*Where it is inappropriate to install the meter outside the property, then the GDNO shall conduct a full risk assessment for the individual property and ensure that any installation is within two metres of the service pipe entry.*
- Ventilation:
  - a. Whole property: Rooms with gas appliances or substantial pipework installed should have non-closable vents with equivalent area of 10,000 mm<sup>2</sup>, located as close to the ceiling level as possible and no more than 500 mm below ceiling level.

Such vents can most readily be assessed in conjunction with the requirements for the ventilation of new properties 2021 draft of Building Regulations Approved Document F (England or Wales) (or regional equivalent), but with the additional requirement of proximity to the ceiling.

However, it should be noted that these regulations were not introduced with the intention of controlling the build-up of flammable gas.

Particular care should be taken regarding:

- Compliance with undercutting of internal doors in accordance with 2021 draft of Building Regulations Approved Document F (England or Wales) (or regional equivalent),
- Vents that can be fully closed, either automatically or manually shall not be used. The use of stops to ensure provision of at least 10,000 mm<sup>2</sup> could be considered.
- Mechanically ventilated buildings are excluded from the trial

- b. Hydrogen appliances in rooms: Compliance with appropriate product ventilation standards (domestic or commercial) is also required and/or manufacturers installation instructions.
  - c. Hydrogen appliances in cupboards and other appliance compartments (e.g. boilers): All appliances in cupboards shall be vented in accordance with Building Regulation ADJ (England or Wales) or equivalent regional documentation; and exemptions shall not be permitted. Manufacturers' guidance should take precedence if larger vents are required. Building Regulation ADJ Para 1.18 should be followed regarding co-compliance with both ADJ and ADF. In this context, equivalent regional legislation is Scottish Building Regulations guidance document 'Building Standards Division – Domestic Ventilation' and 'Building standards technical handbook: domestic buildings'.
  - d. Pipework in ducts: All ventilation of pipework in ducts shall be confirmed as complying with BS 6891 Specification for the installation and maintenance of low-pressure gas installation pipework of up to 35mm (R114) on premises.
- Internal pipework (downstream of ECV):
    - e. Shall be visually inspected where this can be done without disturbance to the fabric of the property and remedial work undertaken where it does not comply with current natural gas standards.
    - f. A tightness test shall be undertaken to current natural gas standards prior to conversion and subsequently prior to commissioning by a second person. The tightness test shall be assessed in accordance with IGEM/H/1 or other installation standards (e.g. BSI). Where this is not the case, then the pipework shall be replaced to meet current natural gas standards.
    - g. Any cast iron components found during the inspection shall be removed or replaced.
  - For larger 'light' commercial properties up to 100kW, i.e. where demand is in excess of 20m<sup>3</sup>/hr (expected to be exclusively non-domestic), then a conventional interlock (AIV – automatic isolation valve) system shall be installed in accord with IGEM UP/2 7.9.8 and associated Appendix 11. This shall cut off the supply to the building in the event of a leak being detected. An excess flow valve shall also be installed to limit peak flow to <30m<sup>3</sup>/h.
  - Hydrogen detection alarms should be installed where residents are unable to smell the gas odorant or request such a device.
  - Same odorant with the same effectiveness must be added to hydrogen as is currently used for natural gas (Odorant NB).
  - Each property (meter point) considered within the community trial shall be assessed for its suitability to accept hydrogen according to this guidance. The reasons should be recorded, including properties that have been assessed but deemed unsuitable for the initial community trial.
  - Householder agreement shall be in place and shall agree to ensure appropriate safety management of appliances and other infrastructure, including maintaining the system and appropriate reporting of incidents throughout the trial period. This should also include any information about the use of hydrogen that is considered relevant

The precise means of implementing these measures shall be site specific.

### 9.3 Competence and training

Existing competent Gas Safe engineers must be upskilled for facilitation of the community trial, including installation, testing, commissioning, inspection and maintenance having undertaken an appropriate training course (and subsequent accredited assessment) for working with hydrogen gas.

Existing competent First Call Operatives with appropriate training in hydrogen gas should be used for responding to any reported incidents.

### 9.4 Monitoring of health and safety performance

During the community trial, data shall be collected to further inform and improve the hydrogen safety management system and procedures.

This should include data and information on:

- The practicalities of conversion especially the location of gas meters and the accurate assessment of building ventilation
- Ease of repair of existing hydrogen pipework carcass and the ability of fitters to render such systems gas tight
- The occurrence and reporting of hydrogen leaks
- Any arising incidents, or near misses, even if below the RIDDOR threshold

This information should then feedback into the safety assessment to enable further refinement, modification and amendments of the assessment to ensure the robustness of the QRA, Site Specific Safety Case and dutyholder safety management systems. This will ensure that the hydrogen gas system still meets the objective of risks being no greater than the existing natural gas system.

### 9.5 Other considerations for initial community trial

For an initial (first) community trial, it is concluded that:

- Basements/Cellars – The installation of gas pipework and appliances in cellars should not be permitted as part of an initial community trial
- Appliances – All appliances (domestic and commercial) shall be specifically confirmed by their Original Equipment Manufacturer (OEM) that the appliance has been approved by a UKCA to participate in a hydrogen neighbourhood demonstration. Feedback shall be provided to the OEM on the performance of their equipment
- Gas service pipe upstream of ECV – all service pipes shall comply with the Pipelines Safety Regulations 1996 and current natural gas installation standards and shall be of appropriate and approved material. *(In the context of this Hy4Heat assessment, upstream of the ECV, this means that the service pipe shall be a plastic pipe where it is underground. The dutyholder shall be responsible for assessing the site-specific case)*
- A detailed method statement shall be prepared for each stage of the installation and commissioning of either a new hydrogen network or repurposing of an existing natural gas network



## 10 Conclusion

This safety assessment has demonstrated that, with appropriate measures, the risks to consumers and the public from fire and explosions in a hydrogen system are comparable to the risk from the current natural gas system. The scope of this assessment only includes the risks inside properties, arising from leaks downstream of the emergency control valve.

It should be recognised that the use of >98% hydrogen as a domestic fuel source in community trials is a first of a kind application. Good practices and lessons learnt on assessing safety risk from a range of industries (e.g. nuclear, rail, offshore and petrochemical) have been used in this assessment. Sensitivity analyses have also been undertaken to test the impact of a number of parameters in the safety assessment.

The safety assessment has been made transparent throughout to allow for robust peer review:

- Scope, aims, objectives, boundaries, assumptions made throughout the safety and risk assessment process have been clearly stated and justified
- The best available existing data and peer reviewed academic models have been used in this assessment and clearly referenced throughout the work
- The use of historical and experimental data has been clearly justified
- To handle uncertainty in the assessment, expert judgement has been used and clarified
- Details of the way in which the risks have been evaluated and a decision reached as to what additional actions (if any) are clearly documented

We are confident that the safety assessment and current proposed risk reduction measures will ensure the safety risk is managed to the current acceptable level. The assessment is expected to form an integral part of the community trial's safety management system.

It should be noted that this safety assessment was conducted as a one-off activity but should be part of a process of continuous improvement. Periodic review of the safety assessment and safety management procedures are required and further work is anticipated as part of planning for larger scale trials and considering wider roll-out, particularly with respect to building types that have been excluded from the Hy4Heat safety assessment. Any relevant new information available from the following sources should be taken into consideration for future updates:

- Community trial findings
- Safety management experience
- Advances in manufacture and supply of material and equipment

This safety assessment work has been led by Arup and Kiwa Gastec, with support from DNV GL and Steer Energy. The consideration of domestic hydrogen use has involved the extensive collaborative efforts of the GDNOs, regulatory bodies (HSE), government (BEIS), academics and a wide group of industry experts.



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