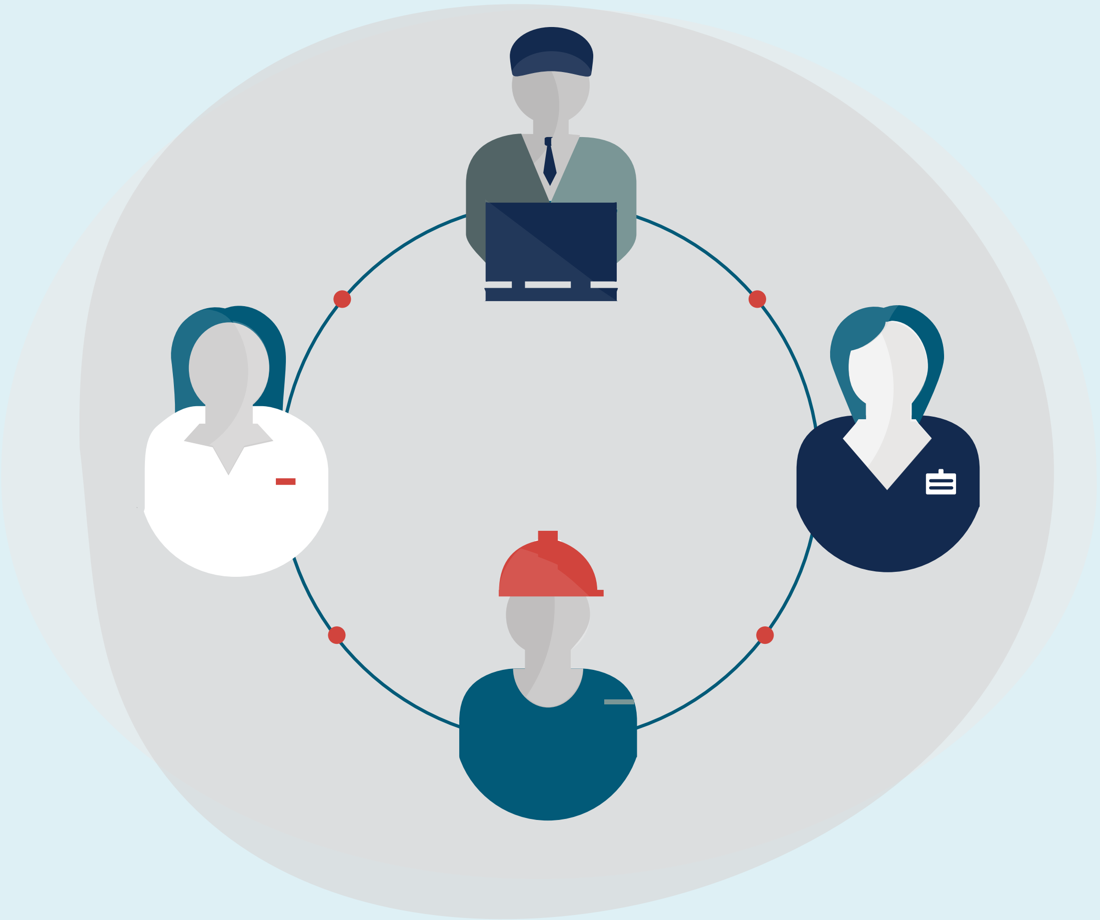
Hy4Heat
demonstrating
hydrogen for heat

Department for
Business, Energy
& Industrial Strategy

WORK PACKAGE 7

Safety Assessment:
Conclusions Report
(Incorporating Quantitative Risk Assessment)



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 Conclusions Report incorporating Quantitative Risk Assessment

1.0 | 1 May 2021

ARUP

Department for Business, Energy & Industrial Strategy

Hy4Heat

Safety Assessment Conclusions Report incorporating Quantitative Risk Assessment

ARP-WP7-GEN-REP-0005

1.0 | 1 May 2021

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Contents

Tables

Figures

Executive Summary

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. This will enable the government to determine whether to proceed to community trials.

The safety assessment covers leaks occurring downstream of the emergency control valve (ECV). The assessment is valid for masonry-built terraced, semi-detached, or detached properties. This includes homes and 'light' commercial premises such as corner-shops. This covers the majority of domestic settings and is believed to be sufficient for a broad range of potential community trials. Note that blocks of flats, houses in multiple occupation, those with mechanical (forced) ventilation, prefabricated and high-rise buildings are excluded from the assessment and so should not be considered as subjects for hydrogen trials, until further work is undertaken.

To support the safety assessment to determine whether it is technically safe to replace natural gas with hydrogen within residential and 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 resulting from a gas leak within a building.

In order to compare the safety risks associated with each gas (i.e. natural gas and hydrogen gas), a QRA (quantitative risk assessment) 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 risk with the use of hydrogen should be 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.

The key findings from the risk assessment are as follows:

- It is understood from historic data that a significant cause of current fires and explosions (about 40% of all of those occurring downstream of ECV) is due to the absence of flame failure devices (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 (97% of reported leaks are from holes no larger than two millimetres) do not create sufficiently large flammable clouds to produce injuries and all can be readily smelled.
- Medium sized leaks (from holes between three and seven millimetres in size) can produce flammable gas clouds in small rooms, notably those with the door closed and / or rooms with poor ventilation. From data collected for Hy4Heat, it is understood that these leaks are most often caused by third party damage and so generally the appropriate steps are readily taken to stop the development of the leak i.e. opening windows, closing the ECV and alerting the gas company. Leaks such as these rarely occur spontaneously.
- Large leaks (from holes greater than seven millimetres) are the size conventionally expected to produce high gas concentrations in large areas of a house. From historic data and data collected by First Call Operatives (FCOs), a significant percentage of these leaks arise from third party damage, including malicious intent. The introduction of two excess flow valves (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).

Risk reduction measures

The following risk reduction measures are recommended to 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 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
- EFV to limit the flow rate to 20m^3/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
    b. Immediately after the ECV
- Hydrogen gas meter containing an integrated EFV to limit the flow rate to <20m^3/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 mm2, 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^2 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 the ECV):
    a. 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.
    b. A tightness test shall be undertaken to current natural gas standards prior to conversion to hydrogen 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.
    c. 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^3/hr (expected to be exclusively non-domestic), then a conventional interlock automatic isolation valve (AIV) 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^3/h.

- Hydrogen detection alarms should be installed where residents are unable to smell the gas odorant or request such a device

- The same odorant with the same effectiveness is to 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
- Existing competent Gas Safe engineers must be upskilled for facilitation of the community trial, including installation, testing and commissioning, having undertaken an appropriate training course (and subsequent assessment) for working with hydrogen gas. Existing competent FCOs with appropriate training in hydrogen gas should be used for responding to any reported incidents.
- During the community trial, data shall be collected to further inform and improve the hydrogen safety management system and procedures. 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, safety case and 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.

These measures are considered to be an appropriate starting point for defining the safety requirements for wider network conversion. Beyond early community trials, further work is recommended to develop safety measures specific to premise types currently outside the scope of this assessment.

It should be noted that cost-benefit analysis to weigh the expected cost of one or more risk mitigation measures against the expected safety benefits has been excluded from the risk assessment scope.

Abbreviations

AIT	Autoignition Temperature
ALARP	As Low As Reasonably Practicable
BSI	British Standards Institute
CO	Carbon monoxide
ECV	Emergency control valve
EFV	Excess flow valve
FCO	First call operatives
FFD	Flame failure device
GAR	Gas Appliances (Safety) Regulations
GDNO	Gas Distribution Network Operator
GSIUR	Gas Safety (Installation and Use) Regulations
GSMR	Gas Safety Management Regulations
HSE	Health and Safety Executive
IGEM	Institute of Gas Engineers and Managers
PE	Polyethylene
QRA	Quantitative risk assessment

Glossary

ALARP - A concept within a framework for deciding whether further onsite control measures are required, which describes the tolerability of risk (ranging from risks which are sufficiently low to be broadly acceptable, to risks that are so high that they are intolerable). In the intermediate 'ALARP' region, risks are tolerable only if they have been reduced As Low As Reasonably Practicable

Burning velocity – the velocity of a flame front relative to the unburnt mixture ahead of it. Laminar burning velocity is a fundamental property of the gas-air mixture

Contact factor (c) – Likelihood of a released flammable fuel gas / air mixture coming into contact with an ignition source

Deflagration – Combustion which propagates at subsonic velocity

Detonation – Combustion which propagates at supersonic velocity

Dispersion - The process of dilution of a hazardous substance by the surrounding fluid

Explosion – general term for an accelerated release of energy, generating overpressure (deflagration or detonation). Overpressure is generally generated by confinement or congestion

Flammable mixture – mixture of flammable gas and air that is capable of supporting combustion

Flash fire – subsonic combustion (deflagration), generally due to late ignition of the flammable cloud, without generation of significant overpressure

FN curve - A plot showing, for a set of specified hazards, the frequency of all events causing a stated degree of harm to N or more people, against N

Frequency - The number of occurrences per unit of time

Ignition potential (p) – Likelihood of a flammable fuel gas / air mixture igniting if it comes into contact with an ignition source.

Likelihood of ignition (i) – Likelihood of a released flammable fuel gas / air mixture igniting.

Lower flammability limit (LFL) – fuel lean concentration below which a flame will not propagate.

Upper flammability limit (UFL) – fuel rich concentration above which a flame will not propagate.

Risk - The likelihood that an event will actually cause harm. The likelihood of a specified undesired event occurring within a specified period or in specified circumstances. It may be either a frequency (the number of specified events occurring in unit time) or a probability (the probability of a specified event following a prior event), depending on the circumstances.

Societal risk – The relationship between the frequency of a specified event and the number of people suffering a specified level of harm in given population. (The number of people affected to a specified level of harm by a specified event in a given population).

Source count (N) - Number of potential ignition sources within flammable area.

Stoichiometric mixture – the theoretically optimum mixture (i.e. there is just enough oxygen to burn all the fuel)

1 Introduction

1.1 Hy4Heat programme

The Department for Business, Energy & Industrial Strategy appointed Arup+ in 2017 to be the programme manager for the Hydrogen for Heat (Hy4Heat) programme to establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances, to enable the government to determine whether to proceed to community trial.

Arup is working with technical and industry specialists: Kiwa Gastec, Progressive Energy, Embers and YoEnergy. Together the group forms **Arup+** and oversees the management, including the technical management, of the entire programme.

The programme consists of ten work packages, one of which is the safety assessment (work package 7).

Figure 1 below shows an illustration of the work packages under the Hy4Heat programme.

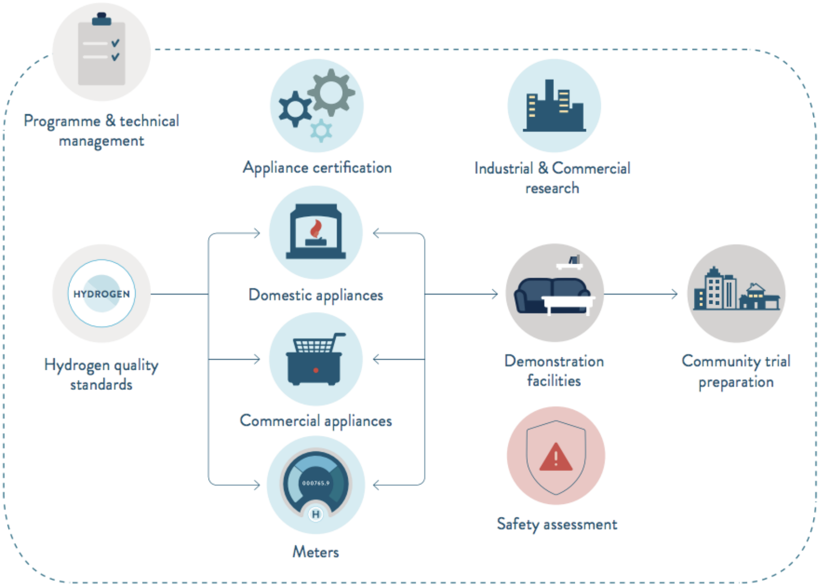


Figure 1: Hy4Heat Work Package Overview

1.2 Safety assessment objectives

The purpose of the safety assessment is to:

- Determine if the safety risks of conveying hydrogen inside residential and commercial buildings can be minimised such that they are no greater than the accepted risk level associated with the current use of natural gas
- Identify any associated safety mitigation and risk reduction measures to control and manage the safety risk of conveying hydrogen to the accepted level
- Enable a safety annex to be produced to support the Safety Case submission required by the

Gas Distribution Network Operator (GDNO) for any proposed community trial

- Provide the evidence to support wider commercial/business and/or policy decision-making around widespread conversion of the natural gas network to hydrogen.

1.3 Safety assessment approach

To meet the Hy4Heat programme objectives, a safety assessment has been conducted. This includes a quantitative risk assessment (QRA) to compare the safety risk of hydrogen against the current use of natural gas within residential and commercial buildings. The QRA is supplemented with the consideration of relevant good practice in engineering, operation and safety management, and is validated against incident data from the use of natural gas. Together, the QRA and these other components comprise the wider safety assessment.

The safety assessment is based on a two storey, masonry-built, terraced house with a basement and a loft conversion. This type of property has been selected because it comprises the single largest proportion of houses in the domestic housing stock in Great Britain, and is considered to be one of the most susceptible forms of construction in relation to gas explosion risks in domestic properties. This is because they are, in general terms, the least robust, due to historic or non-existent building regulations being used in the design and construction. They are often of unknown quality and could include substantial owner/occupier modification. They are also the type of home where historically the majority of deaths and injuries have occurred and where the differences in properties between methane and hydrogen indicate that the risks from hydrogen by comparison with methane are likely to be exacerbated. The assessment considers leaks downstream of the ECV.

The safety assessment adopts a safety case approach to evaluate and examine the safety risks arising from gas leaks in a systematic and structured way, and takes a proactive approach to reducing those risks to a level accepted for the conveyance of gas to domestic and commercial consumers.

A safety case approach is generally accepted as to representing best practice in health and safety management, used in hazardous industries such as oil and gas production and nuclear power generation. In contrast, the use of natural gas in the domestic setting has evolved, based on precedent, acceptance of tolerable risk over time as incidents have occurred and as safety standards have improved, and regulation introduced to support and embed established practice. As an example, flame failure devices are now required in new domestic appliances but are a safety innovation that has emerged through the use of natural gas in the domestic setting - rather than being introduced as a result of a safety case evaluating the risks associated with explosion or asphyxiation arising from flame failure and recommending such a device. Similarly, the materials used in piping natural gas and the regulation of gas installers to assure quality and competence has evolved over time, improving standards and reducing risks.

A safety case approach will generally set out to demonstrate that risks are managed to a level which is as low as reasonably practicable (ALARP). ALARP is a principle articulated in Health and Safety Executive (HSE) Reducing Risks, Protecting People (R2P2) [4], which provides the framework for decision making to manage the safety risks to the public.

However, the current accepted level of risk for the use of natural gas in the domestic setting is not based on an ALARP assessment. Therefore, the starting point for the adoption of hydrogen is not solely that the system should be ALARP. Instead, it is that the adoption of hydrogen should not exacerbate the current level of risk associated with the use of natural gas for heating and cooking in the home. This current level of risk is broadly taken as tolerable by government and the public.

Therefore, the current level of risk accepted for natural gas is defined as the risk acceptance criteria for the risk comparison component of this safety assessment. This safety assessment comprises of a safety assessment for the use of natural gas, and a parallel safety assessment for the use of hydrogen. The safety assessment for the use of natural gas is compared against historical incident data, to give a level of confidence that the model aligns with observed incidents.

To ensure there is a robust safety justification underpinning the use of hydrogen in the domestic setting, at each step of the safety assessment we have adopted a cautious best estimate, considering the comparative nature of the assessment. Where expert judgement has been required, a 'worst-case conservative estimate' has been used for hydrogen and a 'cautious best estimate' has been used for natural gas. This ensures the appropriate level of uncertainty is considered in the risk estimate.

This approach ensures that, as the degree of uncertainty increases (i.e. for hydrogen compared to natural gas), the tendency to err slightly on the side of caution (i.e. the worst case estimate of the outcome or parameter values) means the decision-making takes into account consideration of the level of uncertainty in the estimated risk.

This approach to handling uncertainty in the assessment ensures that the outcome is skewed to derive a demonstrably more onerous environment in which hydrogen is to be considered. Given the objectives of the assessment, hydrogen must in this context be shown to expose the public to no higher risk than the risks from using natural gas. As a result, we derive a cautious best-estimate of the risks associated with the use of natural gas and an over-conservative estimate of the risks associated with the use of hydrogen. The *comparative risk* (the risk due to the use of hydrogen, less the risk due to the use of methane) is therefore also conservative, and the actual risks associated with the use of hydrogen are expected to be lower than we calculate in the assessment.

A number of assumptions are made in the safety assessment. The key assumptions, and the principal reasons why the assumption has been made in the way it has, are as follows:

- The internal pipework and fittings for hydrogen gas are the same as for natural gas. There is no evidence to suggest that pipework requirements will need to be amended for the conveyance of hydrogen. The assessment also assumes that the pipework and fittings fully comply with any regulatory requirements.
- The causes of an initiating leak event (e.g. pipework damage, third party interference) will be unchanged from natural gas to hydrogen gas. This is because these are, broadly, independent of the gas being conveyed.
- Consumer behaviour is assumed to remain unchanged from natural gas to hydrogen gas, including their response to a suspected leak, because the same odorant will be used for hydrogen gas. This will ensure that the familiar smell people are used to responding to is unchanged.
- No centrally added colourant is added in the distribution network. This is because the technical and logistical issues with introducing a colourant into a network are significant and not fully understood and may introduce additional risk without significant benefit.
- Appliances are all safety certified in accordance relevant legislation and with guidance from PAS 4444 and include FFDs fitted on all appliances. This will reduce the likelihood of any appliances

being, unwittingly, left on and unlit. There is a related assumption that conversion to hydrogen will require replacement of all domestic appliances, and thereby those older appliances which were manufactured before FFDs were adopted as standard will be removed from the system.
- Competent installers will all be Gas Safe certified for hydrogen. This will ensure any hydrogen system is installed to the same standard of safety as current natural gas standards require.
- Principles from the IGEM Hydrogen Reference Standard are to be applied during any potential community trial, because these standards outline the key differences associated with hydrogen gas compared to natural gas and how to manage these safely.
- All gas service pipes supplying properties are installed to current natural gas standards to ensure they are in line with the current recommended standard of safety.

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. As a result, hydrogen is more buoyant, leading to larger convective forces, and consequently hydrogen dispersing more quickly than methane.
- The flammability range of hydrogen (about 4 to 74%) is greater than methane (5-15%)
- 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 gases differ therefore in the relationship between average gas concentration in the flammable mixture and the explosion overpressures resulting from the explosion, based on how close the average gas concentration is to being stoichiometric (but also see note relating to laminar burning velocity below).
- In hydrogen compared to methane explosions, the consequences of the explosion have the potential to be worse in the case of hydrogen. This is because 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).

This safety assessment is considered to only be applicable to particular house typologies in Great Britain (GB) and excludes Northern Ireland (NI). This is due to the difference in the nature of the gas distribution network and the available data in GB and NI.

The house typologies to which the safety assessment is considered to be applicable are standard common building types, namely:

- Properties that are masonry-built terraced, semi-detached, or detached homes of normal types.
- Properties that are compliant with current Building Regulations regarding ventilation and installation of appliances. Minimum levels of permanent ventilation required are detailed in Section 14 of this document.
- 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.

There will be properties on the periphery of these categories, and these will need to be considered on an individual basis to ensure they are not substantially larger or more complex than those listed.

For the reasons set out above, the basis of the QRA (being a two-storey terraced house), is considered to be conservative relative to the risks in the other applicable housing typologies. Extension of the findings from the QRA to these other housing typologies is therefore considered to be conservative.

This assessment does 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 Section 14.
- Buildings that use mechanical (or forced) systems for background ventilation.

A separate safety assessment would be required for such properties.

This safety assessment and its conclusion are bounded by the scope, assumption, and the adoption of relevant good practice in engineering, operational and safety management as detailed and recommended in this document. It is considered appropriate for community trials, and useful at informing the relative risks of a wider scale re-purposing but this assessment should be revisited after more practical feedback is available from the community trial.

1.4 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. 1 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.

1.5 Historical data

1.5.1 GSMR

In accordance with the Gas Safety (Management) Regulations 1996 (GSMR), the GDNOs must report gas escape incidents which occur within their network. This includes escapes from domestic gas fittings and escapes from the gas conveyor's network (i.e. upstream of the consumer's ECV). This assessment only considers data which is related to incidents occurring downstream of the ECV.

This data provides an insight into the types of events which tend to lead to injuries in the current natural gas network. This provides a means of assessing whether the natural gas model is producing sensible results, in line with the known annual incident and injury numbers.

The following table is a summary of all downstream GB gas incidents involving injury over the past 4 years. The full list of incidents is provided in Appendix A.

Table 1: Current incident data (from HSE GSMR records Apr-16 to Mar-20)

Incident cause	**Number of fire/explosion incidents which caused injury (period Apr-16 to Mar-20)**
Third party	18
Corrosion	5
Appliance	27
House Fire	4
Unknown	7

This is a total of 62 incidents, or about 15 per year. The largest cause of fire/explosion incidents is appliances (many of which are attributed to appliances without flame failure devices that have been left unlit), followed by third party damage (such as DIY accidents).

Third party data does not distinguish between accidental (e.g. DIY/builder damage) and malicious damage. It can be inferred from GSMR data that the overwhelming majority of incidents are accidental, then a small category of criminal irresponsibility (for example incompetently trying to by-pass the gas meter or attempting theft of copper pipe with the gas left on) and then those few with positive criminality. One of the latter was included within the data incident data set collected for Hy4Heat (see section 5.2.2), but this was smelt and safely addressed.

Further analysis is detailed in section 5.2.1.

1.5.2 HyDeploy incident data review

A review of recent historical incident data has been undertaken by HSE Science division on behalf of the HyDeploy project [51]. The work comprises an analysis of known natural gas incidents which have led to a fire and/or explosion and the consequences of those incidents to life and property. This summary includes commentary on the high-level findings gained from reviewing this incident data.

The data presented in the review summarises the incidents into four injury categories. The term casualty is used to encompass both injuries and fatalities:

- 0 casualties
- 1 casualty
- Between 1-3 casualties
- Greater than 3 casualties

The number of incidents which fall into each of these four categories is recorded, along with a small number of incidents for which the injury level was unknown.

Additional data was provided through further correspondence, which categorised these incidents by the size of the leak.

It should be noted that the data set used in this review is limited to those incidents which required attendance by either HSE or DNV GL to conduct an investigation. Therefore, the sample is not representative of the entire population of gas incidents but can be considered reasonably representative of those incidents which lead to ignition.

The data categorised the injury level per incident related to the estimated size of the leak, as summarised below.

Table 2: Summary of HyDeploy incident review data (received in email correspondence)

	Number of incidents			
Number of injuries	**Large leak**	**Medium leak**	**Small leak**	**Unknown size leak**
0	3	2	5	5
1	13	3	5	12
Between 1-3	10	3	1	6
>3	4	0	1	2
Unknown	0	0	1	1

The leak categories in Table 2, correspond to the hole sizes used throughout this report (see section 5.2.4 for description) in the following way:

- Large leak incorporates the ''large' and 'very large' leak category
- Medium leak represents the 'medium leak' category
- Small leak incorporates 'very small' and 'small' leak categories

Table 3:Injury categories by leak size

	Number of incidents per injury level			
Leak size	**0 Injuries**	**1 Injury**	**Between 1-3 injuries**	**>3 Injuries**
Very small	0	0	0	0
Small	0.2	0.2	0.04	0.04
Medium	0.5	0.75	0.75	0
Large	0.5	2.2	1.7	0.7
Very large	2.1	9.1	7.0	2.8
Total estimated number of incidents per year:	3.3	12.3	9.5	3.5

From Table 3, it can be seen that the majority of predicted incidents would be expected to result in one injury. Of the 29 predicted ignited events per year, 12.3 of these predicted events are estimated to result in one injury and a further 9.5 of these are estimated to result in between one and three injuries. This accounts for 72% of the total predicted number of incidents. It is estimated that 3.5 incidents per year result in more than three injuries.

2 Gas safety management

Under the Gas Safety (Management) Regulations 1996 (GSMR), gas conveyors, such as GDNOs, are required to prepare a safety case containing the information required by Schedule 1 of the Regulations.

The safety cases should contain sufficient information to demonstrate that the GDNO (duty holder)'s operations are safe and that the risks to the public and employees are as low as reasonably practicable. Safety cases will not be considered for acceptance unless they contain all the particulars specified in the GSMR. The format of the safety case is structured to include:

a. Factual information about the operation
b. The safety arrangements, safety assessments and other details required by the GSMR, including those relating to the management system, its audit, assessment of risks and risk control measures, and arrangements for handling supply emergencies
c. A summary covering the main features of (b) above

This safety case must be submitted to the HSE and formally accepted by them before the network can be used to convey natural gas (methane) to domestic customers and other consumers.

The regulation also mandates that any revision made to a safety case to address proposed changes to the operation of the gas network must be resubmitted to the HSE for acceptance before the changes are made.

In the case of conveyance of 100% hydrogen gas in the gas network, GSMR does not apply as the regulation is only applicable for the conveyance of natural gas (methane). However, it is recognised that the framework and preparation of a GSMR 'style' safety case are good practice that should be adopted to demonstrate that the safety risk to the public associated with the conveyance of 100% hydrogen gas are at the level of risk accepted for natural gas.

Therefore, the objective of this safety assessment is to provide the necessary evidence to support the GDNO in building the appropriate GSMR style safety case for the conveyance of 100% hydrogen gas to enable a community trial to take place.

3 Risk assessment approach

3.1 Outline

In the absence of an industry standard on conveying hydrogen gas through the existing gas network, a detailed risk assessment has been carried out to assess the specific safety risks arising from gas leaks within buildings, downstream of the ECV. A comparative safety risk assessment was conducted to compare the societal risks from fire and explosion as a result of a gas leak within a building. 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 quantified in this work (see section 3.5.1). 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, essentially delivering a safety benefit. However, the safety assessment has not quantified this benefit. That is, a qualitative assessment of appliances is discussed but the QRA does not quantitatively include this.

It should be noted that cost-benefit analysis to weigh the expected cost of one or more risk mitigation measures against the expected safety benefits has been excluded from the risk assessment scope.

3.2 Scope

Figure 2 illustrates the overall safety assessment approach, including the quantitative risk assessment (Quantitative Risk Assessment (QRA)) methodology, key data inputs and experimental evidence and links to other parts of the Hy4Heat programme.

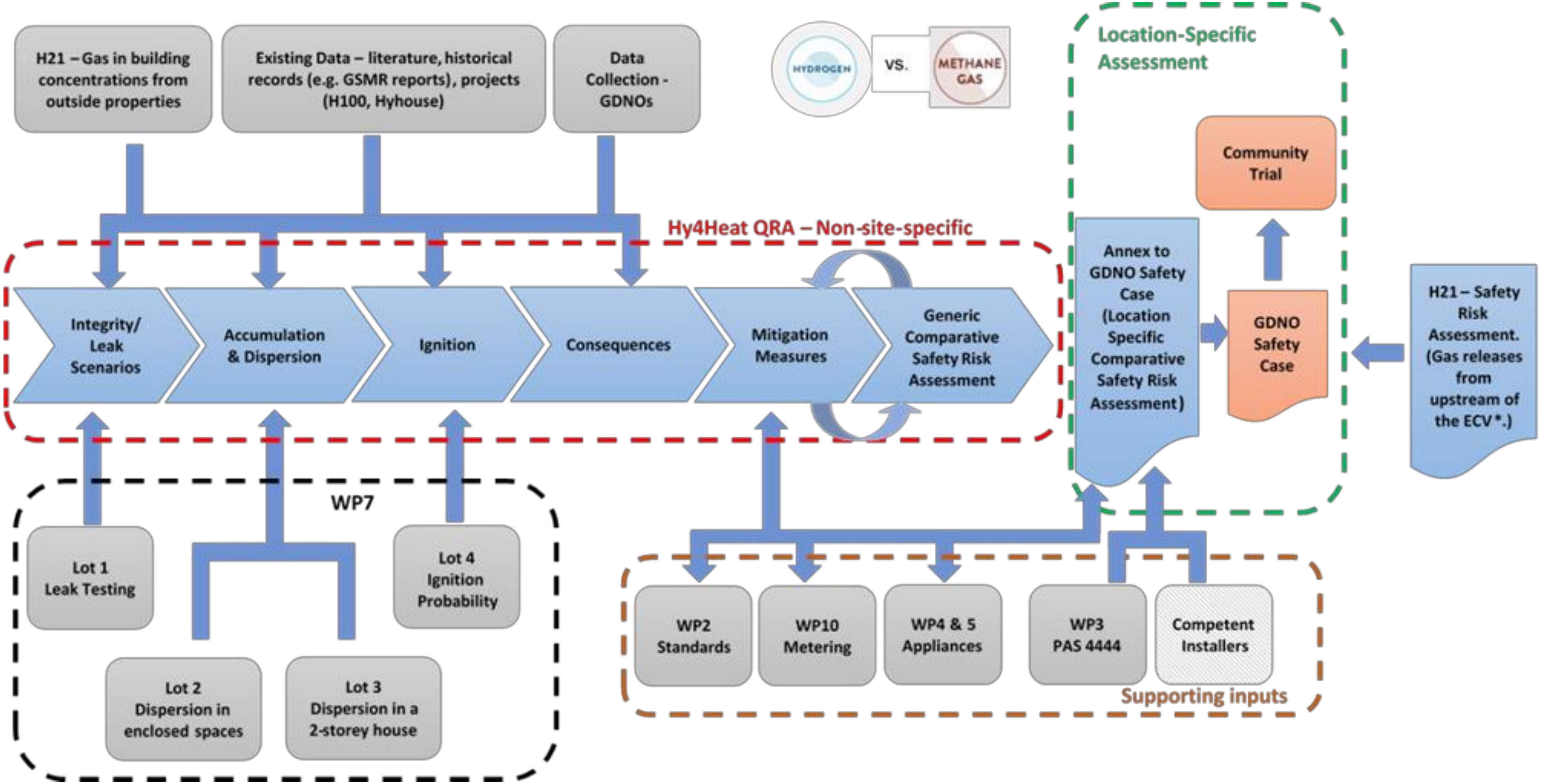


Figure 2: Overall Safety Assessment Approach

3.3 Installation pipework and gas fitting

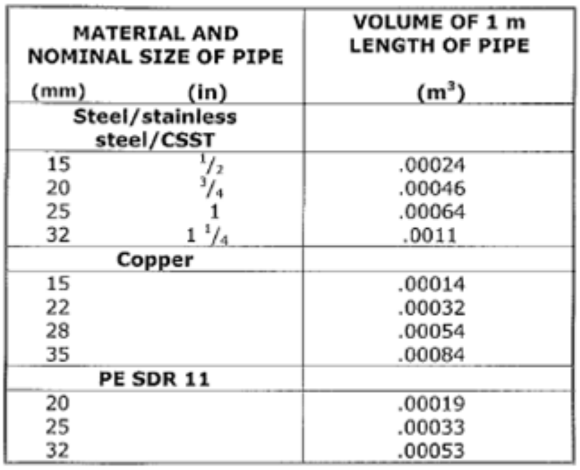
3.3.1 *Existing configurations*

The existing configuration within a domestic environment has been assumed through analysis of BS 6891:2015 Specification for the installation and maintenance of low-pressure gas installation pipework of up to 35 mm (R1¼) on premises [38]. An illustration of this configuration is shown in Figure 3. The existing configuration includes an ECV, gas regulator, gas meter and appliance isolation valve prior to the connection to the gas appliance(s).

3.3.2 *Existing pipework and existing gas working pressure*

Within the domestic environment the piping material is predominantly made from copper, in some cases there may be steel. PE piping is generally not permitted for internal above ground use. The nominal diameter size of these pipes varies as shown in Table 4, this is with an assumed volume of one metre length of pipe.

Table 4: Material and nominal size of pipe [39]



MATERIAL AND NOMINAL SIZE OF PIPE (mm)	(in)	VOLUME OF 1 m LENGTH OF PIPE (m^3)
Steel/stainless steel/CSST		
15	½	.00024
20	¾	.00046
25	1	.00064
32	1 ¼	.0011
Copper		
15		.00014
22		.00032
28		.00054
35		.00084
PE SDR 11		
20		.00019
25		.00033
32		.00053

The operating gas pressure downstream of the regulator is nominally 21 mbar above atmospheric pressure [38]. Therefore, for this assessment, the most conservative and worst-credible assumption is to consider the operating pressure downstream of the gas regulator within the piping as 21 mbar. The maximum operating gas pressure upstream of the gas regulator is up to 75 mbar for low pressure gas distribution network. There is a short length of piping between the ECV and the regulator. For simplicity, for leaks that occur within this length of piping an equivalent hole size at 21 mbar is calculated. To clarify, the calculated leak rate from a specific hole at 75 mbar would be translated to an equivalent hole size at 21 mbar which represents the same flow rate. Therefore, the operating pressure of all releases is assumed to be 21 mbar within the property.

For example, a five-millimetre hole at operating pressure of 75 mbar has a calculated flowrate of 6.3 m^3/h for natural gas and 17.8 m^3/hr for hydrogen. A seven-millimetre hole at operating pressure of 21 mbar has a calculated flowrate of 6.4 m^3/h for natural gas and 18.0 m^3/hr for hydrogen. Therefore, a five-millimetre hole at 75 mbar would be modelled as a seven-millimetre hole with an operating pressure of 21 mbar.

For hydrogen, choked releases occur when the absolute operating pressure is 1.9 times larger than the atmospheric pressure into which the release occurs, otherwise the flow is subsonic. For methane, the ratio is 1.8.(i.e. 1900 mbar for hydrogen and 1800 mbar for methane) Due to the operating pressure being significantly lower than that required for a choked release for both gases, the internal leaks will be subsonic for both natural gas and hydrogen gas. Therefore, leak scenarios for both gases will be characterised as unchoked gas release. This is discussed in detail within the 'Hy4Heat Dispersion Modelling Report' [19]

Table 5: Pipework size and operating pressure [38]

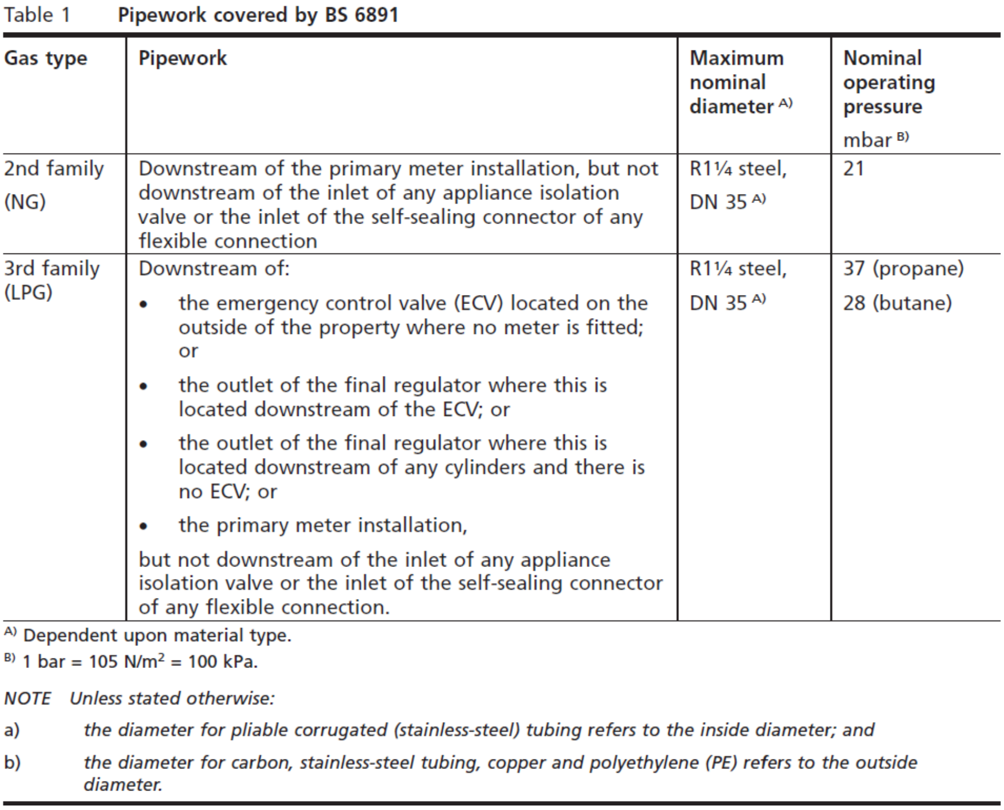


Table 1 **Pipework covered by BS 6891**

Gas type	**Pipework**	**Maximum nominal diameter** [A)]	**Nominal operating pressure** mbar [B)]
2nd family (NG)	Downstream of the primary meter installation, but not downstream of the inlet of any appliance isolation valve or the inlet of the self-sealing connector of any flexible connection	R1¼ steel, DN 35 [A)]	21
3rd family (LPG)	Downstream of: • the emergency control valve (ECV) located on the outside of the property where no meter is fitted; or • the outlet of the final regulator where this is located downstream of the ECV; or • the outlet of the final regulator where this is located downstream of any cylinders and there is no ECV; or • the primary meter installation, but not downstream of the inlet of any appliance isolation valve or the inlet of the self-sealing connector of any flexible connection.	R1¼ steel, DN 35 [A)]	37 (propane) 28 (butane)

[A)] Dependent upon material type.

[B)] 1 bar = 105 N/m^2 = 100 kPa.

NOTE Unless stated otherwise:

a) *the diameter for pliable corrugated (stainless-steel) tubing refers to the inside diameter; and*

b) *the diameter for carbon, stainless-steel tubing, copper and polyethylene (PE) refers to the outside diameter.*

3.3.3 Boundary

This safety assessment covers risks associated with downstream of the ECV, including the appliance. The QRA specifically considers areas of existing pipework from the outlet of the ECV up to and including the appliance isolation valve. This boundary has been highlighted in Figure 3. This assessment does not take into account leaks originating upstream of the ECV (e.g. leaks from service pipes or mains). This is subject to a separate safety risk assessment commissioned by the GDNOs as part of the H21 NIC programme.

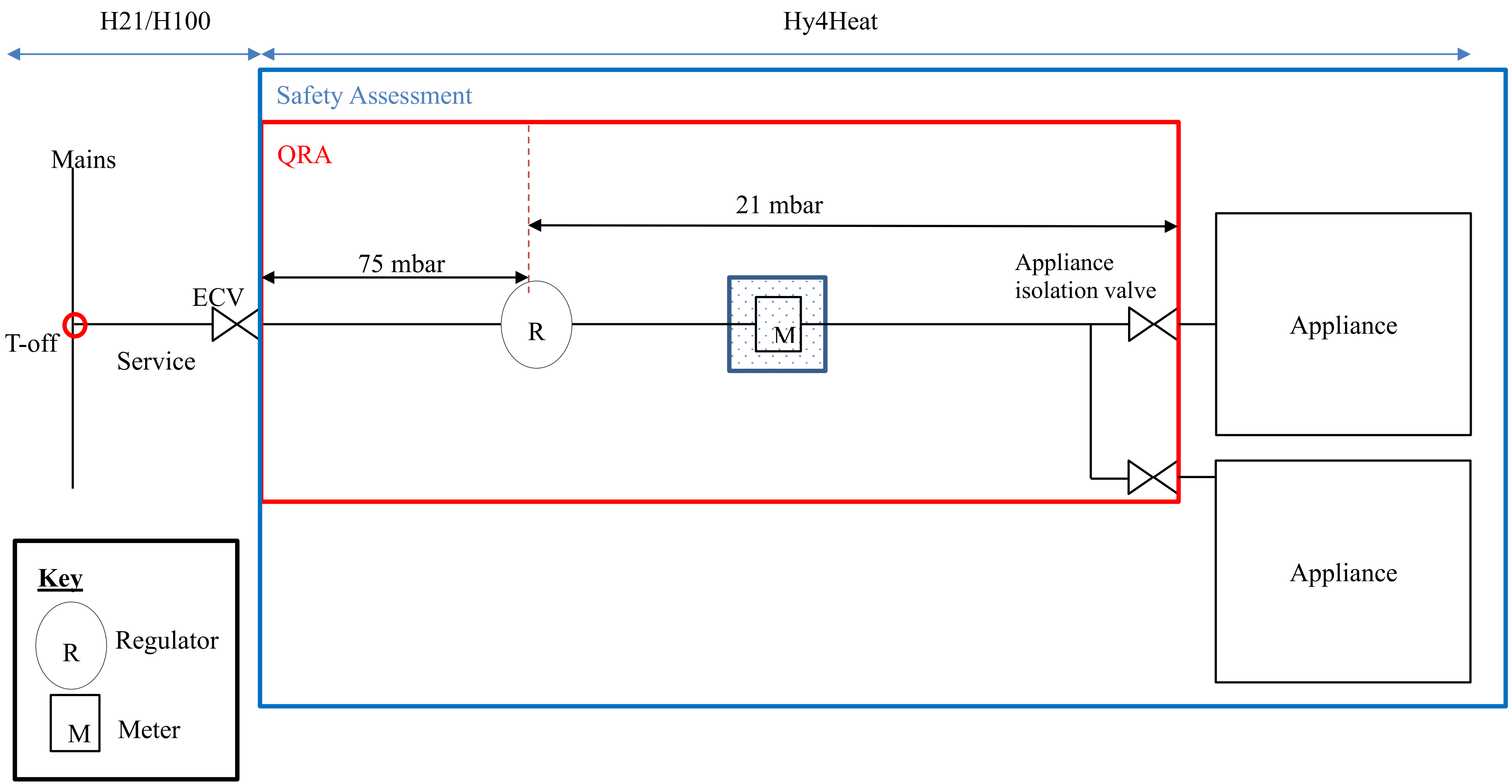


Figure 3: Existing domestic piping configuration [39], safety assessment and QRA boundary

3.4 Quantitative risk assessment (QRA)

A quantitative risk assessment is a logical and systematic approach to numerically estimate the risk associated with certain hazardous events that are more complex and involve novel processes. It is an assessment that uses special quantitative tools and techniques to establish the risk to people from defined scenarios with a given set of parameters. It involves estimating the likelihood and consequences of hazardous events and expressing the findings as risk to people.

Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are techniques used to estimate the event frequencies. Isograph Reliability Workbench software is the modelling tools used to create and conduct the fault tree and event tree analyses for this assessment. These are common and widely used techniques and tools in industry to enable event frequencies to be estimated from numerical data such as accident/event data, failure rates and probabilities. Appendix B details an example fault tree and event tree developed within this assessment.

Event trees were developed to graphically illustrate all possible outcomes following a range of different leak events. It depicts the chronological sequence of events that could occur following the initiating leak event, including escalations and mitigations (e.g. excess flow valves). The structure of the event tree was developed in a series of workshop meetings between Arup and Kiwa, making use of Arup's experience and expertise of producing QRAs with industry accepted modelling software, and Kiwa's knowledge of gas industry specifics and role in producing the QRA for the HyDeploy project.

For specific escalation factors identified in the sequence of events following an initiating leak event, fault trees were developed to derive the probability of failure. This included escalation factors where these are more complex and based on a combination of failures (e.g. system components, safety systems and human reliability), such as determining whether or not a gas leak would be smelt and responded to. The fault trees developed includes all events that contribute to the failure of escalation factor under consideration (the ‘top event’) and graphically illustrates all the logical sequences of sub-events that could result in realisation of the top event, indicating where only one or more than one sub-event needs to occur for the sequence of events to propagate to the top event.

The early development of fault and event trees allows a thorough understanding of the potential escalation paths that could lead to a particular consequence (e.g. fire/explosion) and identify the critical leak events that contribute significantly to the likelihood of these consequences. It also reveals potential gaps or weakness in the escalation or mitigation identified and developed as part of the assessment. This enables further research work based on potential gaps or weakness to be established to further understand gas leaks, dispersion, ignition etc as part of the assessment.

This assessment focused on fire and explosion consequences associated with an uncontrolled release of natural gas or hydrogen within the home. The quantitative risk assessment of fires and explosions follows a systematic sequence. An overview of the methodology used is illustrated in Figure 4 and Figure 5 and the steps taken are as follows:

- 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 characteristics
- Estimate consequences associated with each scenario, including explosion overpressures
- Estimate probability of fatality or other injury, given these events

- Estimate risk reduction effects of layers of protection (It should be noted that some layers of protection are considered and discussed qualitatively outside of the QRA)
- Estimate contribution to the risk profile

This information is incorporated into event trees and the cumulative contribution to the risk profile from each hazardous event is summed.

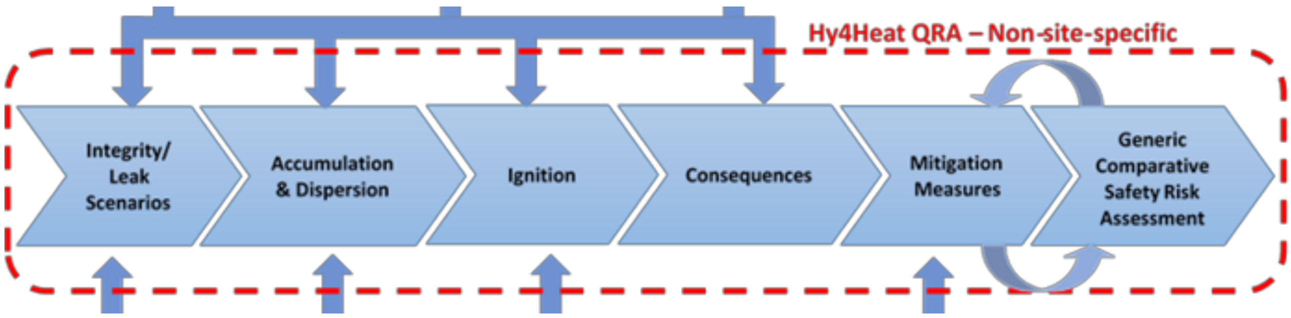


Figure 4: QRA approach

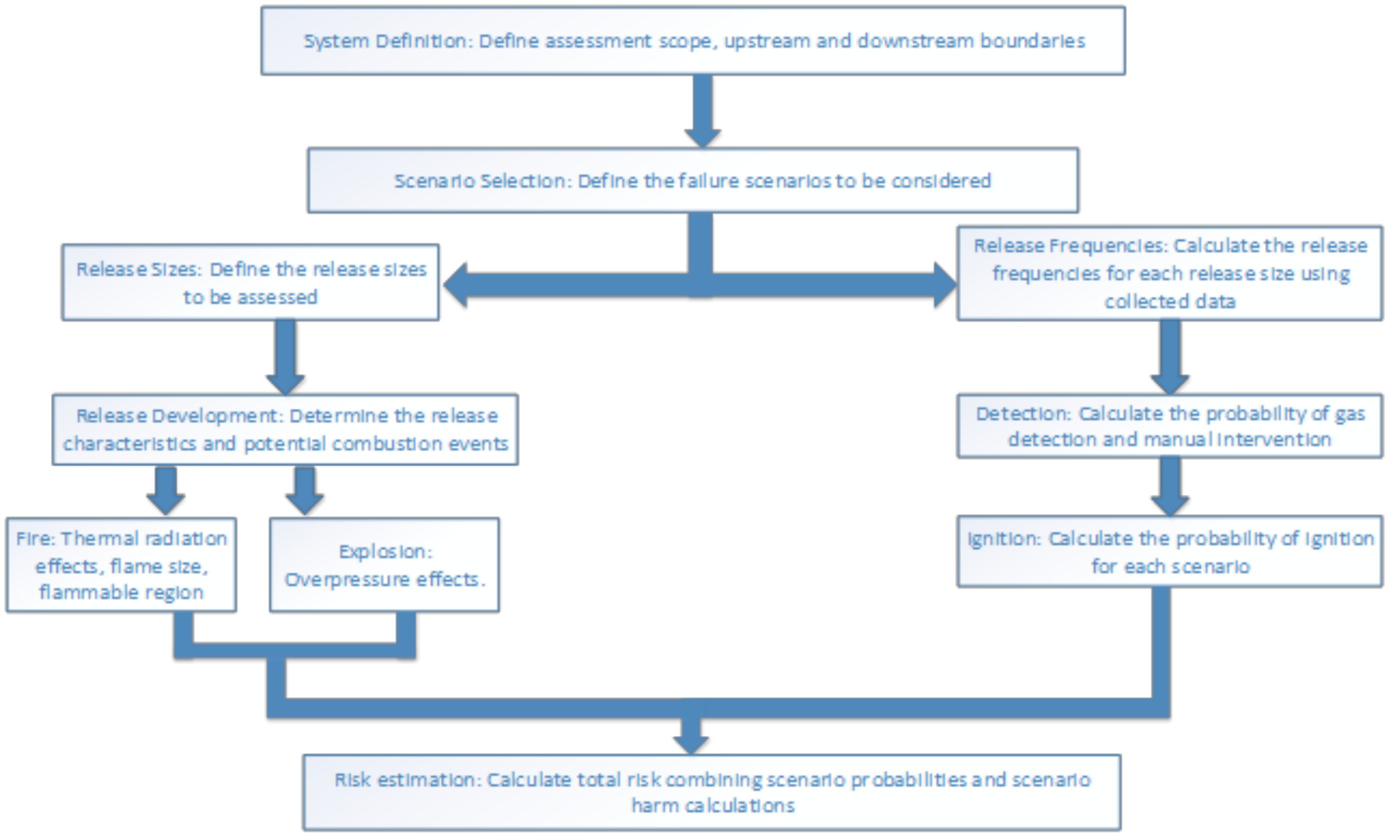


Figure 5: QRA methodology

3.5 Exclusions from QRA

3.5.1 *Appliances*

Uncontrolled gas releases arising from appliances which are faulty or incorrectly operated are not directly considered within the QRA. This is due to the nature of the assessment comparing like for like. Currently, there is a range of gas appliances in use across the GB market, which will vary in terms of modernity and upkeep. Current legislation mandates that all gas cookers within privately rented accommodation must have built-in flame failure device (FFD) functionality, however, the same does not apply to owner-occupied dwellings. Additionally, it is not a requirement to have a valid Gas Safe certificate for appliances in owner-occupied dwellings. In practice, this means that there are expected to be a significant number of households with ageing appliances in use that either do not contain FFD or have an FFD which is faulty.

In the event of any future conversion to a hydrogen gas system, appliances would need to be replaced with those suitable for use with hydrogen gas. Such appliances will be newly developed, and so all of these appliances will contain FFDs. This would effectively be an enforced modernisation for those properties containing old appliances without FFD. The effect of this is further discussed qualitatively in sections 8.2 and 12.

In addition, all future hydrogen appliances will be required to comply with applicable regulation as guided by PAS 4444 [46], developed by BSI as part of the Hy4Heat programme.

3.5.2 Carbon monoxide poisoning

The assessment does not consider the risk arising from carbon monoxide (CO) poisoning due to incomplete combustion of natural gas within household appliances. The absence of carbon within hydrogen gas would eliminate this risk in the event of any future conversion to a hydrogen gas system. This is excluded from the risk assessment (QRA), so that a direct comparison of the risk associated with fire and explosion effects can be made between the two gases. The effective reduction in risk from CO poisoning is discussed qualitatively in section 12.

3.6 Uncertainty in risk assessment

The estimation of risk involves an element of uncertainty. Therefore, it is important to establish and understand the causes of uncertainties in order to account for this within the risk assessment and interpret the estimated risk effectively. This ensures that the credibility of the risk assessment method and process is not undermined. The main sources of uncertainty present in this risk assessment are:

a) Uncertainty in the likelihood, dispersion and consequence models – weaknesses, deficiencies and inadequacies intrinsic to the models which fail to represent reality
b) Uncertainty in the data – quality of data, limited data pool size, potential inaccurate, incomplete and inappropriate data, gaps in data filled through estimation, inference or expert judgement

The assessment outlined in this report is based on the best available data. The nature of QRA requires that assumptions are made in order to best represent reality in a simplified model. There is inherently uncertainty within these assumptions and therefore, the results determined from the model should be read in terms of order of magnitude rather than absolute figures.

The numerical value of this uncertainty is itself an unknown and so attempting to bound each assumption with an uncertainty analysis would introduce further uncertainty and potentially a false confidence in the absolute values derived.

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 ensure the decision making is adequate to control the level of uncertainty in the estimated risk.

A number of sensitivity cases have been modelled where the expert judgement is tested to see the sensitivity of the results to the assumptions made. These are outlined further in Appendix D. Importance analysis of critical assumptions in the QRA is described in Section 12.

3.7 Assessment cases

This QRA aims to provide a comparative risk assessment for a domestic gas system conveying hydrogen compared to the current level of accepted fire and explosion risk for a natural gas system. As such, a number of cases have been considered, described below.

3.7.1 Natural gas base case

The natural gas assessment is intended to baseline the QRA model and provide a basis for comparison with the hydrogen gas case. Therefore, in order to allow a fair comparison, a prediction for risk associated with natural gas is required using the same QRA modelling approach as for hydrogen gas. The safety assessment for the use of natural gas is compared against historical incident data, to give a level of confidence that the model aligns with observed incidents. The approach taken is to assess a 'cautious best estimate' for natural gas, rather than a 'worst case'. This ensures an appropriate comparison can be made with the hydrogen assessment.

3.7.2 Hydrogen gas base case

The hydrogen gas base case uses the model built for natural gas as a starting point. Assumptions which are specific and variable to each gas were then updated in the model. These assumptions include:

- Release rate assumptions
- Gas dispersion assumptions
- Ignition assumptions
- Damage and injury level assumptions

This case assesses the risk associated with hydrogen being conveyed in the current natural gas system as is. This case does not take into consideration the addition of any risk reduction measures that are not present in the natural gas base case.

3.7.3 Hydrogen gas with additional risk reduction measures

A number of risk reduction measures are discussed in section 8 of this report. The risk reduction measures considered quantitatively by the QRA model in this assessment were:

- The installation of two EFVs

A number of other measures were considered out with the QRA model, including:

- Meter location in accordance with best practice
- Ventilation in accordance with regulations
- Provision of gas detection alarms
- Improved appliance safety features

However, whilst these risk reduction measures are qualitatively assessed in this Safety Assessment report, there is a mixture of quantitative and qualitative evidence to support each of these individual measures. The risk reduction measures considered in the QRA model (2 EFVs) and the other risk reduction measures are complementary to provide an overall robust safety assessment.

This is discussed further in sections 8 and 12.

3.7.4 Hydrogen gas sensitivity cases

A number of sensitivity cases have been considered in this assessment to investigate the sensitivity of the assessment to the engineering assumptions made. In particular, sensitivity analysis has been carried out to investigate the gas dispersion and ignition assumptions associated with the hydrogen gas assessment. These are outlined further in Appendix D.

3.8 Risk acceptance criteria

A wide range of factors can affect the risk associated with the use of natural gas and hydrogen in a domestic setting. However, the key common aspect in all quantitative risk assessments is that risk acceptance criteria must be defined. The outcome of the risk assessments is then compared with these risk acceptance criteria to establish whether the risk is acceptable, and whether further safety measures may be practicable to implement.

Risk acceptance criteria for risk to an individual are generally well defined and widely accepted. The key reference for tolerability of risk in the UK is the Health and Safety Executive's Reducing risks, protecting people [R2P2] [4] report.

The annual probability of fatality criteria within are summarised as follows:

- **Unacceptable** – greater than one in 10,000 (10^{-4})
- **Tolerable if ALARP** – one in 10,000 (10^{-4}) to one in 1,000,000 (10^{-6})
- **Broadly acceptable** – less than one in 1,000,000 (10^{-6})

Risk acceptance criteria for past QRAs in the UK (both for oil and gas and more general process applications) are in line with the expectations set out in R2P2 [4]. The current GB Natural Gas industry has on average less than one fatality per year (excluding carbon monoxide poisoning), equivalent to an annual potential loss of life of approximately one in 45,000,000 [43]. This is an estimate based on the number of end users of the GB gas supply and as such is not directly comparable with the above R2P2 individual risk criteria but it is implicitly accepted by the industry and the public.

As described in section 1, a comparative risk assessment approach is used in the Hy4Heat project. This is considered the most appropriate solution as the current risk associated with the domestic natural gas system is much lower than the limit for the broadly acceptable region described above. The current level of risk is accepted by the general public as proportional to the level of benefit gained by society.

Therefore, the criteria chosen for this QRA is to demonstrate whether the conveyance of 100% hydrogen gas in place of natural gas does not pose an increased risk of fire and explosion to the end user and those in close proximity. For the purposes of this assessment, the predicted risk will not be assessed against existing criteria, rather the comparison will be made between the two gases.

The QRA includes only the risk from fires and explosions so as to ensure a fair comparison between the two gases. There are a number of other factors which could be taken into account, such as risk from carbon monoxide poisoning and reliability of energy supply. These factors were excluded from this QRA to avoid the potential for obscuring an increase in risk from one source with a reduction in risk from a different source. However, it will be important to consider the whole range of factors as part of the broader decision-making process for any future conversion to hydrogen.

Specific numerical targets and criteria referenced within legislation, guidance documents, and similar resources may give the appearance of a quantitative assessment process that is fully objective and precise. However, it is imperative to note that the assessment process is still subjective and heavily reliant on engineering judgement and assumptions. Care must be taken when making decisions and values should be taken as order of magnitude rather than as exact. The comparative QRA method is beneficial from this perspective, as it provides a comparison based on the same assumptions and judgements, where practicable, minimising discrepancies.

The measure by which the two gases will be compared is the predicted number of injuries per year. The threshold for injury encompasses major injury and fatality and there is no separation of these within the assessment. This is considered appropriate due to the low frequency of injuries and fatalities which currently occur in the industry. This is reflected through the low number of incidents recorded by the industry.

4 Scenario identification

It is important that a representative, common basis is used for the scenarios studied across the Hy4Heat WP7 document suite. This report undertakes a QRA for a typical ‘two-up, two-down’ UK terraced house, as described in detail in the Hy4Heat Consequence Modelling Report [5, section 4.1]. It is noted that the UK contains a range of housing topologies, and that the actual distribution across these topologies will affect the fit of the QRA model relative to historic empirical natural gas incident data. This is because the housing topology will directly affect parameters such as house airtightness (which influences factors such as dispersion and accumulation, for example) and also number of party walls (which influences consequence analysis results, for example). This is discussed further in section 7.

The variables considered for the specifics of each scenario include:

1. Release cause
2. Release location
3. Airtightness of the property.

4.1 Release causes

The release causes considered in the assessment were informed by data collected from a survey of First Call Operatives (FCOs) designed by Hy4Heat and carried out by GDNOs, as described further in Section 5.2.2. The analysis of this data enabled an understanding of the types of leaks which occur in the domestic environment. The assessment focuses on those leak causes and sizes which have the potential to lead to a fire/explosion incident.

From the FCO data analysis [6], the reported leaks large enough to lead to a flammable atmosphere were limited to those caused by third party damage and corrosion degradation. As discussed in section 5.2.5, other reported leaks, such as those caused by loose connections, were invariably of a size too small to be of concern (<1.5 mm equivalent hole size), and therefore, do not contribute to the risk for a system using either gas.

The FCO data used to inform this assessment was collected on the current natural gas system. However, it is assumed that the initiating event which causes a release of a certain size is independent of the type of gas being conveyed.

This is intuitive for leaks caused by third party damage, however, for leaks caused by material degradation (e.g. corrosion), it is necessary to consider whether hydrogen would be more likely to cause material degradation than natural gas. A literature review produced by HSE in 2015 concluded that there is little evidence to suggest that materials used for the low pressure distribution system will undergo degradation due to the injection of hydrogen into the network [23]. Steer Energy performed a number of experimental tests as part of Hy4Heat [25] which concluded that for all pipework systems tested, networks that were gas tight with natural gas were also gas tight with hydrogen. Information set out in the IGEM hydrogen reference standard also indicates that there is no evidence of hydrogen posing an issue with common domestic pipework materials. This is also discussed in appendix F. It is recognised that further research is required to determine which specific materials are suitable for use with hydrogen, as discussed in open item 6.

Therefore, the FCO data can be considered representative of the distribution of release causes and hole sizes within the GB housing stock, irrespective of whether the system is transporting natural gas or hydrogen. However, for a given hole size, the volumetric flowrate differs for each gas, with hydrogen having a higher volumetric flowrate than natural gas through any given hole. The methodology for determining flowrates for both natural gas and hydrogen gas is documented in the Hy4Heat Gas Escape Magnitude Report [6].

4.2 Release locations

The assessment considers leaks originating in the kitchen of a standard terraced house. This assumption is considered reasonable as the kitchen is likely to have the highest number of potential leak points and the highest number of ignition sources of any room within a typical home.

Two scenarios are considered with regards to the volume of space in which the release occurs. These are labelled as kitchen door open, or door closed. This is relevant to the dispersion modelling and the volume of space available for a flammable gas cloud to develop. 'Kitchen door closed' refers to a scenario where the gas build-up is confined to the kitchen space in which the leak originated. 'Kitchen door open' refers to a scenario where the gas disperses throughout the property. These two scenarios will give rise to different gas accumulation profiles for the same release type and, ultimately, will have different associated consequences.

In the absence of any tangible data, it is assumed that 50% of the time the kitchen door is open (or non-existent) and 50% of the time the kitchen door is closed.

4.3 Property ventilation level

The air permeability level of a property has a significant impact on the behaviour of gas accumulation within that property. For instance, a property with a high air permeability level has a quicker air exchange rate and flammable gas will not be able to build-up as readily compared to a property with a low level of air permeability.

A study published by Leeds Metropolitan University in 2011 analysed data from BRE's database of air leakage which contains information on 471 properties of different age, size, type and construction [22]. From this analysis a frequency distribution of air permeability ranges in the housing stock has been assumed, as summarised in the table below. Secretary of State approved guidance for Building Regulations (ADF England and Wales) is designed to achieve an 'as occupied' ACH of 0.4. This figure has not changed for many years; the level of uncontrolled ACH has however been lowered to effectively reduce the large percentage of housing stock with high permeability.

The range of air permeability levels across the housing stock is considered to be independent of the type of gas being conveyed. The same assumptions are used for both the natural gas and hydrogen gas models.

Table 6: Air permeability in the housing stock

Air permeability description	**Air permeability range (m3/(h.m2)) @ 50 Pa**	**Air permeability (m3/(h.m2)) modelled (kitchen)**	**Air permeability (m3/(h.m2)) modelled (ground floor)**	**Percentage of housing stock**	**Equivalent air changes per hour (ACH)**
Low (Highly Sealed e.g. no natural continuous ventilation)	2-4	2	1	4%	0.1-0.2
Medium (Moderately Sealed e.g. with continuous ventilation)	5-10	5	5	37%	0.25-0.5
High (Leaky e.g. older houses)	>10	15	15	59%	>0.5

4.4 Scenarios considered

The table below summarises the scenarios considered in the assessment. The probability of these scenarios is assumed to be independent of the gas being conveyed. The same scenarios and associated frequency of occurrence are used for both the natural gas and hydrogen gas models. The leak frequency distribution is presented in section 5.2.5.

Table 7: Range of considered scenarios

Scenarios considered for different release causes and locations		**Release location**			
		Internal pipework (doors open)	**Meter (doors open)**	**Internal pipework (doors closed)**	**Meter (doors closed)**
Release cause	Third party damage	✓	✓	✓	✓
	Corrosion	✓	×	✓	×

Note that all three air permeability bands (Table 6) are considered in each of these six scenarios, giving a total of 18 scenarios.

5 Frequency assessment

5.1 Outline

The frequency assessment aims to estimate the likelihood of occurrence of each scenario, defined in section 0. This requires an assessment of the initiating event frequency (in this case, gas leaks) and an assessment of the likelihood of each of the subsequent variables which could impact the development of each scenario.

This section describes the two main elements of the frequency assessment:

- Leak frequency (section 5.2)
- Ignition probability (section 0)

Further assumptions which are included in the event trees are described in section 6 and 7.

QRA data (including leak frequencies and ignition probabilities) from the process industry are not immediately applicable to the domestic environment. This is due to the significant difference in conditions associated with a domestic system:

- Lower operating pressure – the domestic system operates at only 21 mbar
- Lower flowrate – the design maximum flowrate of natural gas through a typical domestic meter is 6 m^3/hr, although can be higher from a leak around the meter
- Smaller piping – typical domestic piping is a maximum diameter of ~30 mm
- Different materials – copper piping is by far the most commonly utilised material with a domestic system
- Different failure modes – e.g. DIY accidents, such as drilling through a gas pipe would not be expected on a process facility.

5.2 Leak frequency

Several methods for estimating credible and representative event frequencies for natural gas leaks within the home environment have been investigated.

The main areas of investigation into leak frequencies for use in the Hy4Heat QRA have been focused on complementing data analysis of past events with experimental evidence:

- Data source 1: analysis of historic data recorded by GDNOs over the past decade
- Data source 2: analysis of recent data gathered between June 2019 and January 2020 via a Hy4Heat questionnaire provided to GDNO FCOs
- Data source 3: experimental testing conducted by Steer Energy.

A full appraisal of these three data sources is provided in the Gas Escape Frequency and Magnitude Assessment report [6]. A summary is provided in the sub-sections that follow.

5.2.1 Historic data

In accordance with the Gas Safety (Management) Regulations 1996 (GSMR), the Gas Distribution Network Operators (GDNOs) must report gas escape incidents which occur within their network. This includes escapes from domestic gas fittings and escapes from the gas conveyor's network (i.e. upstream of the consumer's ECV). This assessment only considers data which is related to incidents occurring downstream of the ECV.

The granularity of the GSMR reports is not sufficiently detailed to allow conclusions to be drawn regarding the frequency of specific sizes or causes of gas releases.

It is also noted that there is the potential for small leaks which do not lead to an accident to be under reported. Especially as the GDNOs are not required to investigate incidents which occur downstream of the ECV and do not result in, nor have the potential to result in, an injury or fatality. In these instances, the homeowner is responsible for any necessary repairs and so there is no consistent record of the specific causes or sources of these leaks.

This data provides an insight into the types of events which tend to lead to injuries in the current natural gas network. This provides a means of assessing whether the natural gas model is producing sensible results, in line with the known annual incident and injury numbers.

The following table is a summary of all downstream GB gas incidents involving injury over the past four years. The full list of incidents is provided in Appendix A.

Table 8: Current incident data (from HSE GSMR records Apr-16 to Mar-20)

Incident cause	**Number of fire/explosion incidents which caused injury (period Apr-16 to Mar-20)**
Third party	18
Corrosion	5
Appliance	27
House fire	4
Unknown	7

This is a total of 62 incidents, or about 15 per year. The largest cause of fire/explosion incidents is appliances (many of which are attributed to appliances without flame failure devices that have been left unlit), followed by third party damage (such as DIY accidents).

The following assessment excludes incidents originating from appliances or house fires, as the QRA scope is to consider the risk from gas leaks downstream of the ECV up to, but not including, any appliances. From the table above, there are approximately seven incidents which lead to injury per year from these pipework gas leaks.

5.2.2 GDNO data collection questionnaire

To address the identified gaps within the available data, a questionnaire was developed by Hy4Heat, with the aim of gathering the data specifically required for use within the QRA. The questionnaire was intended for use by the GDNO FCOs who attend callouts of reported gas leaks.

Using the questionnaire, data was collected by FCOs from all four of the GDNOs in depots throughout Great Britain.

For the QRA to use this data appropriately, a large enough data set was needed to provide statistical confidence in the interpretation of the data and the conclusions which are subsequently drawn. Of the data collected, approximately 900 data points were considered to be within the scope of the Hy4Heat assessment.

Data collected, via this survey, on release causes and hole sizes has been used to inform the leak frequency distribution within the assessment. The initiating event leading to a particular hole size is considered independent of the type of gas being conveyed and, as such, the same leak frequency distribution is applied to both the natural gas and hydrogen gas models. The leak rates will vary between the two gases, as discussed in the following section.

5.2.3 Experimental testing

Steer Energy was commissioned to carry out a series of comprehensive testing of pipes and fittings for a range of leak scenarios [25].

The objectives were:

- To compare the flow rate of hydrogen gas and natural gas from the same leak scenarios
- To compare the gas tightness of existing pipework and fittings downstream of the ECV for hydrogen gas and natural gas

This data forms the basis for calculating the estimated leak rates of natural gas and hydrogen gas from the same release types. Calculation of leak rates for representative scenarios is detailed within the Gas Escape Frequency and Magnitude Assessment [6]. The leak rates will vary between the two gases, with hydrogen having a greater volumetric release rate than natural gas for any given hole size. (However, hydrogen would have a lower mass flowrate than natural gas from the same hole size).

5.2.4 Equivalent hole size categories

The estimated leak rates, calculated as described above, are used to group the leak scenarios into the following equivalent hole size categories:

- <1.5 mm – negligible
- 1.5-2.4 mm – very small
- 2.5-3.9 mm – small
- 4-6.4 mm – medium
- 6.5-10.9 mm – large
- ≥11 mm – very large

Table 9 describes the hole size categories and the equivalent hole sizes modelled for each case. These categories and hole sizes were chosen based on the FCO data collected.

Table 9: Hole Size Categories

Hole Size Description	Hole Size Range	Hole Size Modelled
Negligible	<1.5 mm	Not modelled
Very Small	1.5 - 2.4 mm	1.8mm
Small	2.5 - 3.9 mm	3mm
Medium	4 - 6.4 mm	5mm
Large	6.5 - 10.9 mm	9mm
Very Large	≥11 mm	13mm

5.2.5 Estimated leak frequencies

There are around 600,000 callouts per year, which require GDNOs to visit places of residence to investigate suspected gas leaks. According to industry, in practice, about 400,000 of these relate to gas leaks and the remaining 200,000 are mostly related to faulty CO and natural gas alarms, faulty appliances and reports of the smell of gas that are not found to be natural gas leaks. Therefore, it has been assumed that the total number of reportable natural gas leaks per year in Great Britain is 400,000 leaks. This is based on discussions with GDNOs and broadly aligns with industry accepted values from the gas industry.

For this assessment, the leak frequencies have been derived using the data collected on natural gas leaks by the GDNOs (see Section 5.2.2). It is assumed that the distribution seen within the collected GDNO data is representative of the whole of Great Britain. This indicates that 34% of leaks are associated with internal pipework, 41% are associated with the meter installation and 17% are associated with appliance connections. A further 9% are associated with appliances themselves but these are excluded from the scope of this assessment.

Table 10 to Table 12 summarise the derived leak frequency distribution for a number of probable leak causes and locations. It can be seen from these tables that the majority of releases are within the <1.5 mm hole size category and, hence, are considered to be negligible.

As described in section 4.1, the GDNO data is considered representative of the distribution of release causes and hole sizes within the GB housing stock, irrespective of whether the system is transporting natural gas or hydrogen. Therefore, the same hole size frequencies are assumed to apply to a system using hydrogen gas as those of a natural gas system.

Table 10: Leak frequencies for leak location – internal pipework

Leak cause	**Leak hole size (hole diameter) mm**						
	< 1.5	**1.5 – 2.4**	**2.5 – 3.9**	**4 – 6.4**	**6.5 – 10.9**	**≥11**	
	Frequency distribution (% of total)						
Third party damage	5.1%	0.6%	0.6%	0.7%	0.4%	0.4%	7.7%
Corrosion/ degradation	11.0%	0.1%	0.1%	0%	0%	0.1%	11.3%
Loose Connection	3.3%	0%	0%	0%	0%	0%	3.3%
Unknown	11.4%	0%	0%	0%	0%	0%	11.4%
Totals	30.8%	0.7%	0.7%	0.7%	0.4%	0.6%	34%

Table 11: Leak frequencies for leak location – meter installation

Leak cause	**Leak size (hole diameter) mm**						
	< 1.5	**1.5 – 2.4**	**2.5 – 3.9**	**4 – 6.4**	**6.5 – 10.9**	**≥11**	
	Frequency distribution (% of total)						
Third party Damage	10.8%	0%	0%	0%	0%	0.2%	11.0%
Corrosion/ degradation	11.6%	0%	0%	0%	0%	0%	11.6%
Flux damage	2.7%	0%	0%	0%	0%	0%	2.7%
Loose connection	4.3%	0%	0%	0%	0%	0%	4.3%
Unknown	11.3%	0%	0%	0%	0%	0%	11.3%
Totals	40.7%	0%	0%	0%	0%	0.2%	41%

Table 12: Leak frequencies for leak location – appliance connections

Leak cause	**Leak size (hole diameter) mm**						
	< 1.5	**1.5 – 2.4**	**2.5 – 3.9**	**4 – 6.4**	**6.5 – 10.9**	**≥11**	
	Frequency distribution (% of total)						
Third party damage	0.1%	0%	0%	0%	0%	0%	0.1%
Corrosion/ degradation	7.6%	0%	0%	0%	0.%	0%	7.6%
Incorrect operation	0	0%	0%	0%	0%	0%	0%
Loose connection	0.3%	0%	0%	0%	0%	0%	0.3%
Unknown	8.5%	0%	0%	0%	0%	0%	8.5%
Totals	16.6%	0%	0%	0%	0%	0%	17%

It should be noted that nearly all internal leaks greater than four millimetres are created by third party damage. In practice, nearly all of these leaks are rendered safe by the same third party (i.e. they open the windows and doors and turn the gas off) before a large explosive gas cloud can occur. This could explain much of the discrepancy between the number of leaks that occur and the number of fires and explosion incidents.

5.2.6 Malicious intent

It is known from historic GSMR reports that malicious intent is a credible cause of a domestic natural gas incident. The frequency of these malicious events is embedded into both the historic data and the new data collected by the GDNOs for Hy4Heat. An investigation into the drivers behind malicious intent, undertaken by Arup and presented in Appendix C, concluded that the current available data is insufficient to judge whether there would be a change in likelihood of malicious tampering when moving from a system conveying natural gas to hydrogen gas. Therefore, this assessment does not attempt to explicitly estimate the likelihood of malicious interference with a domestic gas system. Malicious events are included within the frequency of third-party damage events as outlined above. It is assumed that the likelihood of these events remains constant regardless of the gas being conveyed within the system.

5.3 Ignition probability

5.3.1 Ignition overview

Uncontrolled release of a fuel gas into the atmosphere has the potential to generate a flammable fuel/air mixture. It does not necessarily follow that such a mixture would result in a fire or explosion. It must also be brought into contact with a source of ignition, and the source of ignition must be active and of sufficient energy to ignite the gas.

Ignition of materials is a complex subject at the interface of chemistry, physics, and engineering. At a generic level, it is widely known that the minimum ignition energy (MIE) of a hydrogen-air mixture is significantly lower than the MIE of a natural gas-air mixture. That is, hydrogen is significantly more easily ignited by, for example, a spark than natural gas (see the Consequence Modelling Report [5, Table 2] for further details). This is illustrated in Figure 6 below.

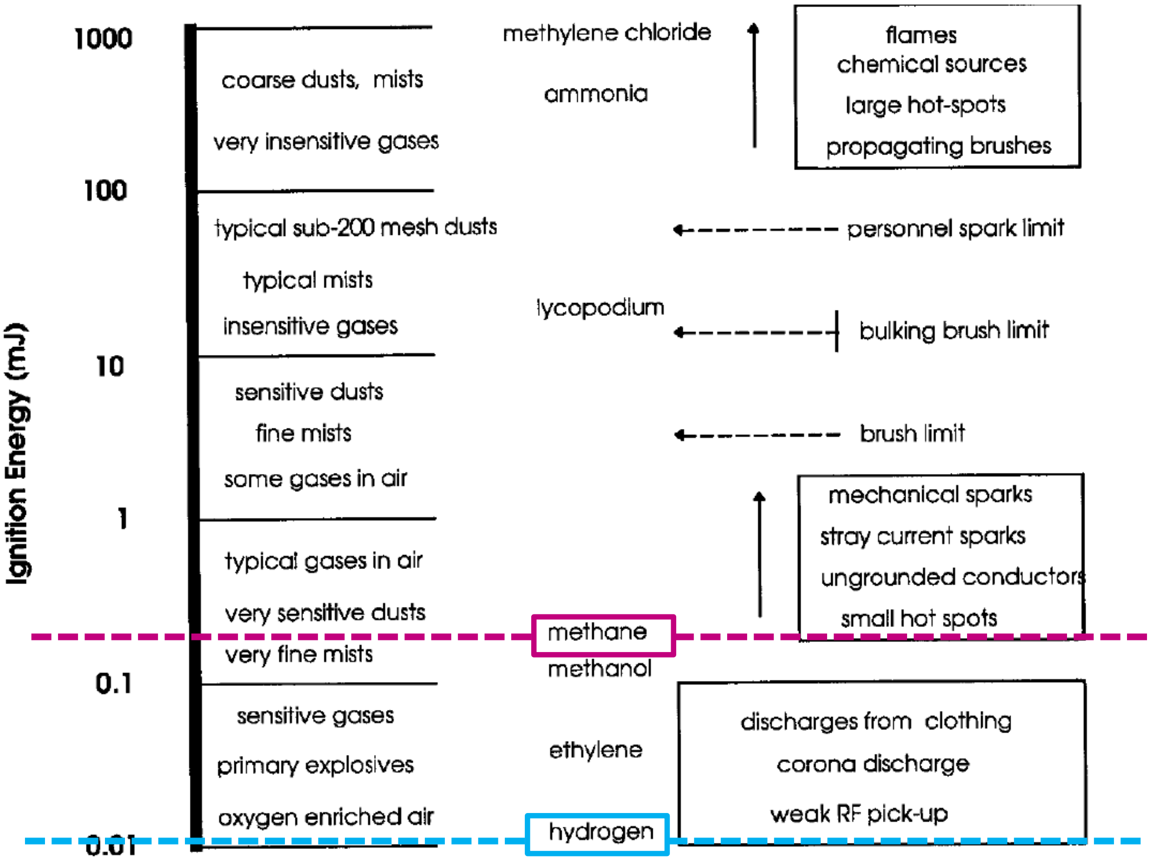


Figure 6. Ignition energies (mJ) of various materials and types of ignition source that may ignite them [7, figure 2.5]

This section seeks to present a balanced level of detail regarding ignition and its associated probabilities, presented from an applied practical (engineering) perspective, to develop a coarse ignition model which is appropriate for use within a comparative QRA.

At a high level, **likelihood of ignition, *i***, was split into two likelihood parameters:

- **contact factor, *c*** – the likelihood of a flammable gas / air mixture, when generated, coming into contact with a potential ignition source
- **ignition potential, *p*** – the likelihood of an ignition source having sufficient energy to ignite a flammable gas / air mixture

$$i = p \times c$$

Ignition potentials are discussed in section 5.3.2. Contact factors are discussed in section 5.3.4.

5.3.2 Ignition potentials

Determination of the above specific likelihoods was challenging due to the limited amount of information that could be consulted. Traditional key literature and sources of past incident data [8][9][10] are largely focused on industrial (rather than domestic) settings, causing the challenges described in section 5.1 of this report.

As a result, it was necessary to use a significant degree of engineering judgement to compensate for the lack of statistical data. This was informed and supplemented by a targeted empirical testing programme commissioned by the Hy4Heat programme and undertaken by DNV GL at the Spadeadam site (see section 5.3.5 for further details).

Parameters such as temperature and pressure have a significant effect on the flammability range of gases. However, the temperature and pressure variations encountered in a UK domestic environment (due to seasonal and diurnal temperature ranges, for example) have a negligible effect on gas flammability ranges.

Furthermore, this ignition analysis made the same approximation between natural gas and methane properties as described in the Consequence Modelling Report [5, section 2.1]:

> *"In the past there have been extensive studies on the properties and behaviour of methane as a flammable gas. Natural gas usually contains between 70-90% methane, therefore when describing the characteristics for natural gas; the characteristics can be assumed to be like that of methane. This is reasonable for this study given that when compared with hydrogen, the behaviour of natural gas is similar to methane."*

This was judged to be appropriate when considering the similarity between natural gas and methane, as well as the level of uncertainty associated with the ignition probabilities of each gas considered. The ignition analysis in this report therefore compares the ignition probabilities of hydrogen versus methane, rather than comparing hydrogen versus natural gas, as significantly less data and literature exist for natural gas.

At a high level, the approach used to assess ignition sources' potential for Hy4Heat can be broadly split into two stages: a screening stage (see section 5.3.3) followed by a numerical assessment stage (see section 5.3.3.1).

The screening stage first compiled a long list of ignition sources and then applied a range of screening arguments on a source-by-source basis to determine which ignition sources could be screened out from further (numerical) consideration in the QRA.

The numerical assessment stage then assigned numbers against the remaining ignition sources' contributions to the QRA through the creation of ignition fault trees in Isograph Reliability Workbench FaultTree+ software.

5.3.3 Screening

As described in section 5.3.1, not all ignition sources have sufficient energy to ignite a flammable gas cloud. A wide range of ignition sources can be found in the domestic environment which may be relevant when considering gas leaks. The ignition sources needed to be characterised with respect to ignition mechanism, intermittency, energy, and a range of other key parameters.

To derive an appropriate ignition potential for natural gas and hydrogen, it was important to consider the detail of what ignition involves, and how this theory could be applied to the gases in reality.

At a high level, ignition is the process by which a material capable of reacting exothermically is brought to a rapid state of combustion. At atmospheric temperatures and pressures, flammable mixtures of gases and air will not ignite unless a source of energy is provided [11, p4]. As a result, these gas mixtures generally require heating to some critical extent by an external temperature or energy source, referred to generically in this report as 'ignition sources'.

Ignition sources can be divided into 'soft' and 'hard'[1] ignition sources. 'Soft' ignition sources include the vast majority of ignition sources found in a conventional domestic environment e.g. sparks and flames. 'Hard' ignition sources are defined as providing a significantly higher amount of energy to the gas mixtures than is normal. This occurs through, for example, the detonation of high explosive charges [5, section 2.3] As most typical domestic environments are extremely unlikely to contain such explosives, 'hard' ignition sources were not considered further in this report.

Figure 7 provides a simple generic graph showing the relationship between rate of heating and spatial dimensions of various ignition sources. At the left-most part of the curve, the source is very small in size but with a very high rate of heating. Here the key parameters of interest are energy density of the ignition source and the minimum ignition energy of the gas mixture. At the right-most part of the curve, the source is very large in size but with a small rate of heating, with the emphasis being on the ignition temperature of the gas mixture.

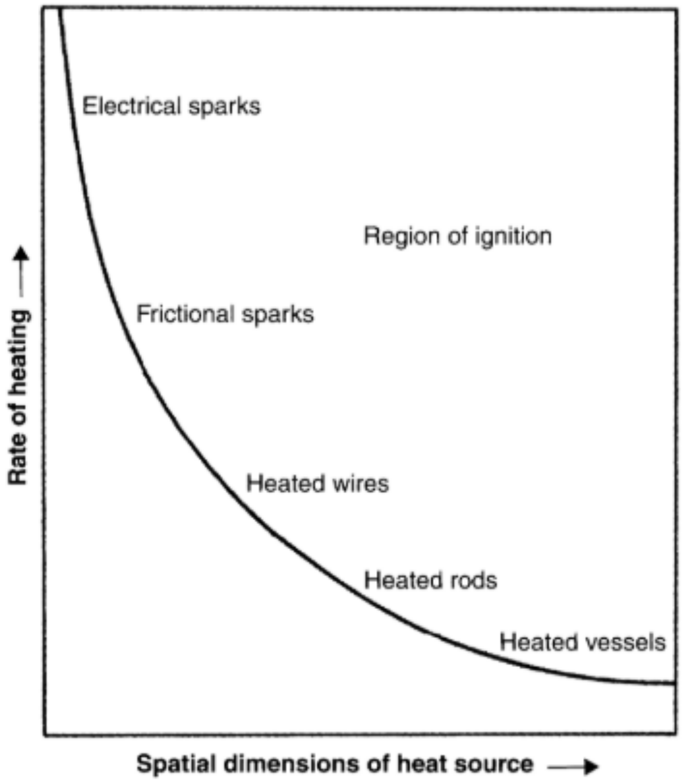


Figure 7. Spatial and heating characteristics of various ignition sources [13, Figure 1.2]

For gases, ignition occurs most easily when the energy is delivered fast (on the order of microseconds) and into a small volume [12, p44].

Potential ignition sources were broadly categorised as follows:

- flames
- hot surfaces
- sparks

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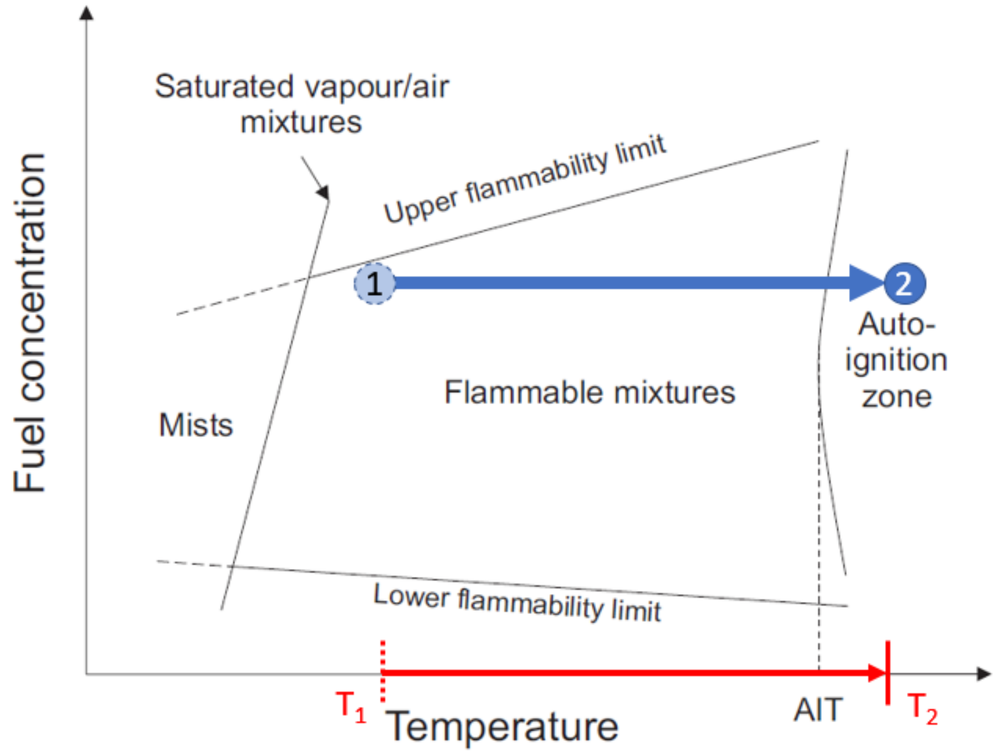
[1] Note that these are distinct concepts to 'weak' and 'strong' ignition sources, which are discussed in detail in section 5.3.3.1.

- spontaneous heating

Table 13 provides a basic description of each, as well as some high-level statements regarding whether they are applicable to the domestic environments that were considered as part of this work.

Table 13: Ignition category descriptions

Category	**Description**
Flames	A flame is the gaseous (and generally visible) part of a fire. Open flames produce hot gases which can cause ignition via heating up of cold flammable mixtures and reacting with them (via free radical chemical reactions, sustaining combustion) [11, section 2.1.6]. Flames can be either non-pre-mixed (diffusion) flames or pre-mixed flames. The former occur where the oxidiser (e.g. oxygen in air) and the fuel (e.g. natural gas or hydrogen) do not mix until they react in the flame sheet (in e.g. candles). The latter occur, as the name implies, where the oxidiser and the fuel are already mixed ahead of being lit (in e.g. gas burner). Pre-mixed flames are the more common type of flame in a domestic environment, as pre-mixed flames (by definition) tend to be those introduced purposefully and in a controlled manner.
Hot surfaces	As introduced in the Consequence Modelling Report [5, Table 2], "[…] *auto-ignition temperature is the temperature at which a flammable gas will initiate combustion* [without an external source of ignition] *and it varies with pressure. In the context of an unburnt combustible vapour cloud at atmospheric pressure in a domestic setting, the cloud would start to undergo combustion if the edge, or any part of the cloud came into contact with a surface that was hotter than the auto-ignition temperature of the gas.*" Hot surface ignition takes place to the right of the flammable mixture region on a generic flammability diagram (see Figure 8, which illustrates the heating of a flammable mixture from temperature T_1 to temperature T_2 such that it ignites due to exceeding its auto-ignition temperature (AIT)).  Figure 8. Movement into auto-ignition zone on generic flammability diagram (annotated on [31, figure 2.2])

Category	Description
	Hot surface ignition requires a very significant temperature, ranging from 540 °C [14] to 595 °C [15, Table 3.1] for methane, and 400 °C [14] to 560 °C [15, Table 3.1] for hydrogen, noting auto-ignition of gases is a complex topic in its own right and a wide range of factors heavily influence it [32, p3]. Traditionally, it was assumed that any surface at a temperature at, or above, the AIT of the flammable gas would ignite it [37, p16/59]. This is still reflected in some modern-day codes and standards governing maximum allowable temperatures of machinery. However, due to the heat losses involved, the actual hot surface itself must be at an even higher temperature than the AIT of the gas in question. Babrauskas' Ignition Handbook proposes a rule of thumb of a hot surface temperature being 200°C in excess of the material's AIT before ignition can occur [12, p43]. A range of literature summarised in the HySafe Biennial Report on Hydrogen Safety [36, p56] quotes the range of AIT for a hydrogen-air and hydrogen-oxygen mixtures as 640 °C to 930 °C. Furthermore, it is important to note that local ignition of a cloud of gas via auto-ignition does not necessarily mean that a flame will propagate through the cloud. Such flame propagation is affected by a wide range of factors [24] and is difficult to accurately predict, other than when there is a significant temperature excess above the gas' AIT. Examples of potential domestic hot surfaces are space heaters, electrical equipment, and lights.
Sparks	A spark can be generically defined as a localised source of thermal or electrical energy capable of igniting combustible material [16]. Sparks can be generated: • mechanically (via e.g. mechanical friction or mechanical impact), in which case they are burning / incandescent particles • electrically (via e.g. electrostatic discharge or sparking in electrical equipment), in which case they are electrical discharges through ionised air. A static hazard is generated through build-up (and subsequent discharge) of electrical charge through friction of dissimilar materials or substances [18, Annex G]. Static is one of the main ignition sources where there is a significant difference between the behaviour of natural gas and hydrogen
Spontaneous heating	This ignition mechanism is one where combustion occurs due to self-heating arising from exothermic internal reactions. This is only observed in scenarios such as e.g. peat fires or landfill fires, where oxidation or bacterial fermentation under specific conditions initiate a runaway self-heating event leading to ignition and combustion, or in the presence of very specific chemicals normally only found in a controlled laboratory or industrial environment. As a result, spontaneous heating was not considered relevant to the domestic environment and was excluded from further consideration in this report.

The ignition potential of flammable gas clouds has been extensively studied by a wide range of respected safety practitioners, with their conclusions subject to peer review. The majority of these studies have been undertaken for industrial (high hazard) applications. Nevertheless, some of the findings were determined to be applicable to domestic environments too so long as the caveats in section 5.1 were appropriately accounted for.

A range of small, individual studies are available in the wider literature. In 2004, the HSE commissioned a literature review to determine the likelihood of ignition on high hazard sites (Research Report 226 [2]). This HSE report contains a comprehensive review of many different sources of information on ignition probabilities, and has therefore been used (in conjunction with Babrauskas' Ignition Handbook [24]) to inform the development of ignition probabilities in this report.

Following on from the categories described in Table 13: Ignition category descriptions, Table 14 compiles an initial long list of domestic ignition sources which may be relevant to the QRA, taking cognisance of the ignition hazards listed in BS EN 1127-1 [17] and RR226 [2]. It groups them according to the high-level categories in Table 13: Ignition category descriptions and undertakes a screening exercise to determine which ones should be considered further in the QRA. **Note that this is not the same as determining which ones are credible / reasonably foreseeable** – see open item #3 in section 15 for further discussion.

Furthermore, it is also crucial to note that one of the key differences between ignition sources is whether human action is directly required to generate them**.** It is important to determine whether an ignition source could occur only whilst an occupant or third party is actively generating it (when e.g. smoking), or whether it could occur in the absence of any actions (e.g. older type boiler with a flame open to the room via an open flue). This is important as this aspect of an ignition source has the largest influence on whether there can be a causal relationship between the generation of an ignition source during a gas leak. This was considered in Table 14 when making screening justifications.

Where both gas-fired and electric versions of appliances are possible, it was assumed that the house contains the gas-fired versions of the appliances. This was judged to be appropriate because:

- the type of home being studied is only likely to contain electric versions of appliances if it has undergone a significant renovation, with natural gas generally being the default energy source for heating and cooking in non-new-build homes
- the ignition potential of a flame is identical for both gases being studied, and implementing further granularity in appliance type (resulting in the introduction of new hot surface ignition hazards from e.g. electric hobs) would not result in a significant difference in the comparative QRA results as the AIT of both gases being studied is very similar. Sparks can be a source of significant difference in natural gas and hydrogen ignition risk but sparking of an electric hob or electric oven such that the spark makes contact with leaked gas was considered extremely unlikely

Table 14: Theoretical domestic environment ignition sources

Ignition source description	**Ignition source category**			**Ignition source sub-category**	**Considered further in QRA?**	**Justification**
	Flame	**Hot surface**	**Spark**			
Sparks from stationary appliances	-	-	✓	Electric sparks	**Yes**	Appliances can pose an electric spark hazard both via malfunction or mis-operation and during normal operation. Generally, a significant degree of deterioration is required before an electrical appliance malfunctions in a way that creates sparking. Furthermore, it was considered very unlikely that an appliance in an average home has been incorrectly wired or is counterfeit (such that it does not meet the required safety standards for safe operation in the UK). As a result, the conditional probability of such sparking occurring during the same timeframe as a gas leak in the home was judged to be sufficiently low that it could be considered negligible with respect to other sources and excluded from the QRA. Some appliances or devices may occasionally spark even during normal operation. A simple example of this is the sparking of a light switch or connections to a light fitting when the switch is operated. Generally, switches can only act as an ignition source during the short window of time when they are being operated. However, when considering all electrical appliances and devices within a typical home, it was considered credible that an electric spark may coincide with the presence of a gas leak. This is in part due to the potential for a *causal* relationship between the two, where the detection of a gas leak may prompt the occupant(s) of the home to take actions which may, as a result of habit or necessity (e.g. night-time gas leak), still include actions such as operating a light switch. **This was considered further in the numerical assessment (section 5.3.3.1).** Appliances or devices that may occasionally spark during normal operation but that are not human-initiated (such as automatic bimetallic strip thermostats for controlling heating) were screened out from further assessment. This was on the basis that operation of the source has no causal link with the gas leak cause, the frequency of operation is anticipated to be low, the prevalence of these sources throughout the domestic environment is low, and the location of the source is very unlikely to be within the flammable cloud, thus representing a negligible contribution to the QRA's ignition risk relative to other (more significant) sources. NOTE: an electric spark flame igniter on a gas cooker is technically a small stationary electrical appliance designed to generate a spark during normal operation. However, it is generally only operated when switching on a gas cooker. Its ignition potential was judged to be greatly outweighed by the subsequent gas flame created, to the point where the individual contribution of the electric spark flame igniter to the overall QRA was considered negligible.

Ignition source description	Ignition source category			Ignition source sub-category	Considered further in QRA?	Justification
	Flame	Hot surface	Spark			
Hot surfaces of stationary appliances	-	✓	-	-	No	Appliances can pose a hot surface hazard both via malfunction or mis-operation and during normal operation. Generally, a significant degree of deterioration is required before an electrical appliance malfunctions in a way that creates a hot surface when its normal operation does not usually involve creating one in the first place. Ovens and gas cookers have hot surfaces when operating normally, but the ignition potential contribution from their hot surfaces is significantly outweighed by the accompanying open flame (and electrical spark flame igniter, when first switching on) ignition sources posed during their operation, and thus the individual contribution to the risk was considered negligible.
Flames from stationary (gas-fired) appliances	✓	-	-	Open pre-mixed flames	Yes	The pre-mixed flames generated by gas cookers and gas boilers, in conjunction with the potential for these flames to be present for multiple hours each day, meant that **this was considered further in the numerical assessment (section 5.3.3.1).**
Hot surfaces of portable appliances / tools	-	✓	-	-	No	Appliances such as irons have hot surfaces during normal operation. However, the temperatures achieved are generally significantly below the AIT of either methane or hydrogen (see Table 14). As an example, the typical maximum surface temperature of a hand iron (in normal operation) is 200°C based on the maximum setting recommended on fabric labels [26]. Two notable exceptions to this are toasters and hair dryers, whose filaments grow red-hot when operating (i.e. the filament temperatures are likely to be in excess of 600 °C). This is also reflected in the empirical testing undertaken (see section 5.3.5), where both led to immediate ignition of hydrogen but not of methane. However, occupants would likely notice the smell of accumulating gas well before a flammable concentration could be achieved. It is noted that the empirical testing indicated that hydrogen ignition during testing of the iron was likely to have been due to an *electrical* ignition source rather than the hot surface itself. It is credible that appliances' malfunction could lead to excess heating of their components. However, it is considered very unlikely that temperatures could reach the AIT of either methane or hydrogen, as it is very likely the appliance would fail prior to reaching these temperatures, stopping the heating process. The conditional probability of hot surface creation occurring during the same timeframe as a gas leak in the home such that a portion of a flammable gas cloud is raised above its AIT was judged to be sufficiently low that it could be considered negligible and excluded from the QRA.

Ignition source description	Ignition source category			Ignition source sub-category	Considered further in QRA?	Justification
	Flame	Hot surface	Spark			
Electrical sparks from portable appliances / tools	-	-	✓	Electric spark	**Yes**	Portable appliances can pose an electric spark hazard via malfunction or mis-operation. Generally, a significant degree of deterioration is required before a portable appliance malfunctions in a way that creates electric sparking. Furthermore, it is considered very unlikely that a portable appliance in an average home has been incorrectly wired or is counterfeit (such that it does not meet the required safety standards for safe operation in the UK). As a result, the conditional probability of such electrical sparking occurring during the same timeframe as a gas leak in the home was judged to be sufficiently low that it can be considered negligible and excluded from the QRA. This was further supported by ignition testing undertaken by the H21 project [28], where ignition sources simulating a realistic mobile phone were unable to ignite either natural gas nor hydrogen. A modified mobile phone ignition source setup achieved ignition by introducing significant conservatisms through manipulating the spark generating circuit, but it was concluded that "*ignition is […] theoretically possible but in practice extremely unlikely.*" However, as described in the justification for stationary appliances posing a spark ignition source, switches or plugs operated normally can pose a spark ignition source, and this is relevant for portable appliances / tools too. This is particularly the case as a spark can be triggered when switching off or unplugging an appliance. This means that if an occupant who is using such an appliance smells gas, they may trigger a fire or explosion through taking an action which they mistakenly feel makes the situation safer but in reality increases the risk of the leaked gas igniting. **This was considered further in the numerical assessment (section 5.3.3.1).**
Mechanical sparks from portable appliances / tools	-	-	✓	Friction spark Impact spark	**No**	Portable appliances and tools such as hand-held drills or hammers can theoretically pose a mechanical (friction or impact) spark hazard when being used. In some gas leak scenarios, it is possible that a causal relationship exists between the initiation of the gas leak (e.g. accidental drilling into a gas pipe) and the generation of friction sparks when a flammable atmosphere is forming. However, in practice the materials that are likely to be involved in such friction / impact are unlikely to generate sparks as generally the key source of impact or friction sparks would be the contact of iron on iron. Furthermore, even in the very unlikely event of spark generation and ignition (e.g. through the head of a hammer creating a spark when hitting the head of a nail), this would occur almost immediately after the generation of a gas leak, leading to a fire rather than an explosion. As a result, the conditional probability of

Ignition source description	Ignition source category			Ignition source sub-category	Considered further in QRA?	Justification
	Flame	Hot surface	Spark			
						generating a mechanical spark igniting a flammable cloud in the home was judged to be sufficiently low such that it could be considered negligible and excluded from the QRA.
Gas leak	-	-	✓	Electrostatic discharge spark	No	Operational experience has shown that flammable fluid leaks via orifices in industrial settings can ignite due to electrostatic discharge sparks. The probability of ignition of such leaks increases with increasing flowrate (which in turn is linked to increasing pressure). A significant effort has been undertaken by industry to quantify the ignition probabilities in such scenarios, and information to date is reported in literature such as that produced by the International Association of Oil & Gas Producers on the subject [8], including suggested ignition calculation methods such as those in HSE's pipeline risk assessment tool MISHAP. However, such electrostatic discharge sparks are generally only credible when considering industrial high-pressure releases significantly above the pressures encountered in a domestic setting (21-75mbar). A further risk factor for this type of ignition is multi-phase flow (e.g. where release of a flammable liquid via a leak results in some of the liquid flashing off into the gas phase), which again is not encountered in a domestic setting. The risk of immediate or delayed ignition of released gas in a domestic setting as a result of static discharge generated by the leaked gas' flow itself is therefore judged to be sufficiently low that it can be considered negligible and excluded from the QRA.
Friction of dissimilar materials	-	-	✓	Electrostatic discharge spark	Yes	As is the case for light switches (considered earlier in this table), there is the potential for a causal relationship between a gas leak and generation of the ignition source, where the detection of a gas leak may prompt the occupant(s) of the home to take actions such as walking from one area of the house to another via a carpeted surface or moving off of furniture made of materials which encourage the generation of electrostatic discharge sparks (e.g. rubber feet). This is of particular interest to Hy4Heat as it is likely that the large difference between methane MIE and hydrogen MIE results in electrostatic discharge sparks igniting hydrogen but not methane. **This was considered further in the numerical assessment (section 5.3.3.1).**

Ignition source description	Ignition source category			Ignition source sub-category	Considered further in QRA?	Justification
	Flame	Hot surface	Spark			
Smoking materials (lighter and cigarettes)	✓	-	-	-	**No**	The open flame from a lighter or match and the incandescent end of a cigarette during (and shortly after) smoking poses a credible ignition source in the home. However, basic fire safety such as not smoking when being able to smell gas can be considered ingrained in the wider population even without specific training on the subject. As a result, it is considered extremely unlikely that an occupant would begin smoking within the timeframe when a flammable cloud had formed in the home after a leak and they had detected it via smell. Furthermore, tests such as those performed for the H21 programme [28] have shown that the cigarettes themselves are unlikely to pose an ignition hazard even for hydrogen, and that instead it is only the open flame from a lighter or matches that is a concern (which is equally likely to ignite both gases once in contact). It is conceivable that a gas leak may occur whilst an occupant is already smoking, but it is very unlikely that a gas leak in the home could form a flammable atmosphere in the limited time that someone would be smoking a cigarette (where they had already started to smoke prior to the initiation of the gas leak). Furthermore, even in this case it is most likely that the occupant would smell the gas prior to it accumulating to a flammable level and would extinguish their cigarette. The conditional probability of an occupant smoking during the same timeframe as a gas leak forming a flammable cloud in the home was judged to be sufficiently low such that it could be considered negligible and excluded from the QRA.
Candles	✓	-	-	-	**No**	Candles found in the home are a source of open diffusion flames. However, given the widespread availability of electricity in modern society, candles in the present day are generally only likely to be used as decorative items in the housing types being considered for the community trial. Use of candles within the home is judged to be relatively rare, and unattended use (where the occupant would not smell a gas leak and extinguish the candle) even more so, in large part due to extensive fire safety campaigns on the subject. Whilst it is widely known that a significant number of fire casualties across the UK are a result of improper candle use, this is as a result of the candles setting nearby solid materials on fire, and is not directly relevant to the gas leak scenarios being considered in this report.

Ignition source description	Ignition source category			Ignition source sub-category	Considered further in QRA?	Justification
	Flame	Hot surface	Spark			
						The conditional probability of a lit candle being present during the same timeframe as a gas leak forming a flammable cloud in the home was judged to be sufficiently low that it could be considered negligible and excluded from the QRA.
Other use of naked flames	✓	-	-	-	No	There may be other use of naked flames around the home outside of smoking materials and candles, both assessed earlier on in this table. It is most likely that these sources would be present in a garage (e.g. welding equipment), although some may be present inside the home itself e.g. chef's blow torch or small soldering iron for electronics. These sources have been excluded from consideration in the QRA for the same reasons detailed for candles and smoking materials above.
Electromagnetic waves	-	-	✓	-	No	The basic principle is that electromagnetic waves produced by radio-frequency transmitters (e.g. radio, television and radar) will induce electric currents and voltages in any conducting structure on which they impinge. Furthermore, components which are normally in contact may break or separate momentarily (e.g. due to maintenance), which could generate a spark if the induced current and voltage are sufficiently large [30]. A range of home appliances/devices emit and receive electromagnetic waves (primarily radio-frequency ones). This includes mobile phones and WiFi routers. Furthermore, at any given point there are also other signals passing through the home from emitters external to the house. However, radio transmissions from individual portable electronic devices are generally too low to induce dangerous electric currents in nearby equipment and the risk of incentive sparking from the battery is low [29]. Radio-frequency transmitters are generally only a concern when looking at industrial settings where the sources are likely to be significantly stronger than in a domestic environment, and sensitive safety-critical equipment may be vulnerable to certain types of electromagnetic interference. Even in the unlikely event that this caused ignition in a domestic environment, the other sources of sparks from the same appliance(s) would be much more likely to pose an ignition hazard. This would greatly outweigh any ignition contribution from the electromagnetic waves themselves.
Lightning strikes	-	-	✓	Electrostatic discharge spark	No	Theoretically, there may be a causal link between lightning and a gas leak (e.g. due to a storm resulting in lightning discharge whilst also damaging a gas main outdoors). However, for the gas leak causes of interest

Ignition source description	Ignition source category			Ignition source sub-category	Considered further in QRA?	Justification
	Flame	Hot surface	Spark			
						for this ignition model (internal third party damage and internal corrosion/degradation), no causal link has been identified. Lightning strikes have been discounted as an ignition sources on the basis of their extremely low frequency in the context of other, much more frequent, domestic ignition hazards.
Vehicle	-	✓	✓	Hot surface Electric spark	**No**	Vehicles such as cars may pose both a hot surface hazard (e.g. exhaust pipe when the car is left running for an extended period of time) and an electric spark hazard (e.g. spark plug operation for petrol-powered cars or malfunction of the electrical systems such that a spark is generated). However, the scope of this QRA is limited to that described in section 3.2. As a result, ignition sources posed by vehicles are excluded from consideration in this QRA.
Malicious acts	✓	✓	✓	-	**No**	As discussed in section 5.2.6, there is no difference anticipated between the likelihood of malicious acts related to natural gas and malicious acts related to hydrogen. Both are extremely unlikely and their contributions to the ignition probabilities of the QRA are negligible when compared with ignition sources' other contributions.

Individual examples of many of the above sources causing ignition are rare but have been recorded for natural gas. Some are widely known in the gas industry due to their uncommon nature. Some of the incidents can be directly related to location and year (e.g. rats attacking lead pipe North Shields 2007), but such occurrences (and the subsequent anecdote) are so infrequent they cannot be meaningfully used within a QRA. This screening only considered delayed ignition of leaks leading to explosions. Immediate ignition of a leak *can* physically occur, leading to a small flame which might be sustained in the case of hydrogen (whereas for methane it would likely lift off). This has been demonstrated in separate sets of experiments undertaken by DNV GL and Kiwa Gastec [60] [61]. However, this was discounted from analysis due to the low immediate consequence, the very low likelihood of such immediate ignition (due to the very small gas jet volume within which an ignition source would have to be present to cause immediate ignition of the released gas), and the identical maximum credible consequence for both hydrogen and methane (a house fire).

5.3.3.1 *Numerical assessment*

The numerical assessment in this section focused on characterising the ignition sources within the kitchen door open scenario to provide a breakdown of ignition sources and their individual contributions to the ignition probability of a flammable gas/air mixture.

The kitchen was judged to be a particularly key area from an ignition perspective as there are many ignition sources with a high ignition potential (e.g. appliances which pose a flame type ignition source).

As described in the qualitative screening, the ignition potential of flammable gas clouds has been extensively studied by a wide range of respected safety practitioners. HSE Research Report 226 [2] not only discusses characterisation of ignition sources, but also reviews methodologies for the calculation of ignition likelihood.

The HSE report [2, Table A.7] assesses the estimated strength of various ignition sources on a qualitative basis, with Table 15 reproducing the domestic ignition sources listed in the HSE report:

Table 15: Domestic ignition sources and estimated parameters

Ignition source	Type	Potential	Activity
Electrical equipment, switches etc	Electrical	Weak	Intermittent
Heaters, boilers etc	Flame	Strong	Intermittent
Gas cookers etc	Flame	Strong	Intermittent
Smoking materials	Flame	Strong	Infrequent

Potential refers to the strength of the ignition source i.e. the ease with which it ignites a flammable gas/air mixture if brought into contact with it. Activity refers to the fraction of time that the ignition source is live. For example, a light switch which is in good condition and has been correctly wired generally only acts as an ignition source, at most, during the short window of time when it is being switched from one position to another.

Quantitative estimates for the value of qualitatively described ignition potentials are described later in the HSE report [2], with live flames having a potential of one and other strong sources having a potential between 0.5 and one, and weak sources having a potential of 0.05. These sources only act as potential ignition sources for the fraction of the time that they are in operation, and it is therefore technically possible for a constant moderate potential ignition source to make a bigger contribution to ignition likelihood than a strong (high potential) infrequent ignition source.

Background ignition sources' contribution to the overall ignition potential were characterised by the product of three factors (broadly developed based on the methodology described in HSE RR226 [2]):

- individual source ignition potential (probability of source having sufficient energy to ignite the gas)
- operation fraction (fraction of day that the source is active)
- ignition source number multiplier (to account for what fraction of homes each ignition source is present in, and how many instances of the ignition source are present)

The approach taken for human initiated ignition sources was a variation of the above. The approach was different to take into account the potential for causal links to exist between human initiated ignition sources and the original gas leak cause.

Human initiated ignition sources' contribution to the overall ignition potential were therefore characterised by the product of two factors:

- individual source ignition potential - same as for background sources
- conditional probability of ignition source being generated, which was heavily dependent on engineering judgement and aimed to take into account both the technical/physical aspects of the ignition source, and also the human behaviour causing the ignition sources (which may be linked to the original gas leak cause)

The key difference between the natural gas and hydrogen ignition models is the increased ignition potential of weaker ignition sources. The ignition potential of weak electrical sources (electrostatic discharge spark and electrical spark) was assumed to increase by one qualitative strength category in HSE RR226 i.e. from weak (for natural gas) to medium (for hydrogen). This represents an increase in ignition potential from 0.05 to 0.2 i.e. a four-fold increase. A sensitivity case was also modelled (see Appendix D – Sensitivity analysis for more details).

The flame ignition sources' ignition potential increases slightly from the natural gas case to the hydrogen cases (discussed further in entry 4 of Table 16). The ignition potential of flames from a hydrogen-fired appliance, versus those from a natural-gas-fired appliance, was assumed to be the same.

As described in section 4.2, two key scenarios were identified and modelled for the ignition fault trees:

1. Kitchen door open (or non-existent)
2. Kitchen door closed

The key difference between the ground floor configurations was assumed to be a reduction in the type and number of ignition sources for the 'door closed' configuration, as the leaks were assumed to take place in the kitchen. It was assumed that the door seals sufficiently well such that the minimal amounts of leaked gas in the kitchen that might escape into the living room/hallway/staircase around the door would be very significantly diluted to the point where ignition could not occur within the living room/hallway/staircase, and therefore the gas would not make contact with ignition sources found in this part of the downstairs area.

The following ignition sources were assumed to only be present in the living room, and therefore were assumed to not contribute to the overall ignition probability of leaks occurring in the 'door closed' configuration:

- carpeted surface
- gas fire

Although there are differences between the physical properties of natural gas and hydrogen which result in differences in the way dispersion occurs, it is difficult to directly link the effect of these to changes in ignition probability. This is captured as an 'open item' in section 15.

The above was used to inform the ignition fault trees that were created in the FaultTree+ module of Isograph Reliability Workbench (see section 3.4 for an overview of the software) based on the assumptions and modelling decisions described in Table 16, including the final list of ignition sources screened in during the initial screening exercise.

Table 16: Ignition fault tree gate/event details

No.	Fault tree gate/event	Comments and assumptions
1	Tumble dryer - electrostatic discharge spark (background ignition source)	This was the key background electrical ignition source that was screened for further assessment during the screening. **Operating fraction: 0.042** **Source multiplier: 1.0** It was assumed that 100% of households have a tumble dryer (located in the kitchen), and that the tumble dryer operates for one hour per day (i.e. operating fraction of 0.042). **Ignition potential** Natural gas: 0.05 Hydrogen base case: 0.2 Hydrogen sensitivity case: 0.5
2	Carpet or furniture - electrostatic discharge spark (human initiated ignition source)	**Conditional probability of generation** Kitchen door closed: 0.2 Kitchen door open: 0.3 A causal link was assumed between the detection of gas and electrostatic discharge sparks that occur during the presence of a flammable atmosphere. This was via e.g. an occupant moving across a carpeted surface, or off a piece of furniture, towards a different part of the house. This could be to investigate the smell, to open windows and/or doors, and/or to evacuate from the house. The value was reduced from the 0.3 estimate to 0.2 for the kitchen door closed scenarios to discount the contribution of carpeted surfaces (and other living room static sources) towards the risk. **Ignition potential** Natural gas: 0.05 Hydrogen base case: 0.2 Hydrogen sensitivity case: 0.5
3	Electrical switch or electrical outlet - electrical spark	**Conditional probability of generation** Third party leak cause scenarios: 0.3 Corrosion/degradation leak cause scenarios: 0.5

No.	Fault tree gate/event	Comments and assumptions
	(human initiated ignition source)	A causal link was assumed between most electrical sparks that occur during the presence of a flammable atmosphere and the detection of gas. This was via e.g. an occupant potentially needing to switch on a light during a night-time leak to be able to see in the darkness after waking up and detecting gas, or pro-actively unplugging an electrical appliance after detection of gas under the mistaken assumption that this reduces the risk of ignition. This may be exacerbated by the occupant feeling disoriented immediately after waking up. The value was increased from the 0.3 estimate to 0.5 for the corrosion/degradation leak cause scenario to account for the increased potential for the leak to occur during night-time (versus third party cause scenarios where it is unlikely that third party work is being undertaken during the night). **Ignition potential** Natural gas: 0.05 Hydrogen base case: 0.2 Hydrogen sensitivity case: 0.5
4	Gas boiler – partially open flame (background ignition source)	**Operating fraction**: 0.3333 **Source multiplier**: 0.1 It was assumed that: • 100% of the homes that are being studied have one boiler, located in the kitchen. It is noted that in some properties do have boilers located in cupboards elsewhere; in these cases, accumulation to a flammable range would be faster, however ignition within the cupboard would have significantly smaller consequences; • 100% of the boilers are gas-fired rather than alternative boiler types / heat sources which do not result in the use of flames; • The majority of natural-gas-fired boilers are room-sealed, and therefore only 10% of all natural-gas-fired boilers has an open flame which the leaked gas can make contact with. This is either due to the boiler being of an open flue type, or the boiler being room-sealed but with a leaky case seal; • All hydrogen-fired boilers are room-sealed, but the case seal failure rate was conservatively assumed to be 10% i.e. the same ignition source multiplier was used for both natural-gas-fired boilers and hydrogen-fired boilers; and • A gas boiler operates for eight hours per day (i.e. operating fraction of 0.3333), with seasonal variations averaged. **Ignition potential** Natural gas: 0.75 Hydrogen base case: 1.0 Hydrogen sensitivity case: 1.0 The natural gas ignition potential was not judged to be as high as 1 (normally used for open flames) due to the enclosed environment making it more difficult to ignite any leaked gas which is taken into the boiler. The hydrogen ignition potential was increased from 0.75 to 1 to account for hydrogen's higher diffusivity and lower MIE than natural gas, even when considering the added ignition difficulty in the closed environment.

No.	Fault tree gate/event	Comments and assumptions
5	Gas cooker/hob – open flame (background ignition source)	**Operating fraction:** 0.042 **Source multiplier:** 1.0 It was assumed that: • 100% of the homes that are being studied have one cooker, located in the kitchen; • 100% of the cookers are gas-fired rather than electric/induction/etc. which do not result in the use of flames; • A cooker operates for an average of one hour per day (i.e. operating fraction of 0.042). **Ignition potential** Natural gas: 1.0 Hydrogen base case: 1.0 Hydrogen sensitivity case: 1.0 Judged to be 1.0 for all natural gas and hydrogen cases due to the ignition strength of open flames.
6	Gas fire – open flame (background ignition source)	**Operating fraction**: 0.042 **Source multiplier (kitchen door open):** 0.1 **Source multiplier (kitchen door closed): 0** It was assumed that: • 10% of the homes that are being studied have one gas fire, located in the living room; • 100% of gas fires are fully open to the room atmosphere; • A gas fire operates for an average of one hour per day (i.e. operating fraction of 0.042), with seasonal variations averaged. **Ignition potential** Natural gas: 1.0 Hydrogen base case: 1.0 Hydrogen sensitivity case: 1.0 Judged to be 1.0 for all natural gas and hydrogen cases due to the ignition strength of open flames.

The fault trees reproduced in Appendix B then combined the ignition potentials (section 5.3.2) and contact factor (section 5.3.4) to calculate the overall ignition probabilities reported in Table 17, which were used as an input to the QRA model.

Table 17: Overall ignition probabilities used in QRA model

Scenario	**Natural gas**	**Hydrogen (ignition base case)**	**Hydrogen (ignition sensitivity case)**
Ignition (third party – kitchen door open)	0.09	0.17	0.31
Ignition (corrosion/degradation – kitchen door open)	0.11	0.23	0.42
Ignition (third party – kitchen door closed)	0.09	0.15	0.27
Ignition (corrosion/degradation – kitchen door closed)	0.10	0.21	0.39

5.3.4 *Contact factors*

When considering the likelihood that a flammable gas / air mixture would come into contact with an ignition source, the location within a room was considered. Due to typical gas pipe routing and the dispersion and consequence models considering the maximum steady state gas concentrations and volumes, it was assumed that any release reaching steady state would come into contact with the potential ignition sources in the room.

As a result, a **contact factor of one was used**. The overall three-dimensional spatial arrangement of ignition sources was not considered within the models, other than considering whether the ignition sources were most likely to be in the kitchen, the remainder of the downstairs, or both – see open item 1 in section 15 for further discussion of this.

It was also assumed that where ignition occurs, it propagates through the full gas cloud. In reality, there is a potential difference when comparing methane and hydrogen in that ignition in a hydrogen cloud concentration at the lower end of the flammability range (~4% to ~8%) is less likely to propagate through the hydrogen cloud (due to insufficient energy) than an equivalent scenario for methane at similar concentrations [53]. However, this difference reduces at higher concentrations and ignition is expected to propagate through both gas types. Furthermore, the gas concentrations where the difference in propagation may manifest itself are the ones which lead to the smallest consequences (and therefore risk contributions). Therefore, for the purpose of this QRA, this difference was judged to be negligible.

5.3.5 *Empirical testing*

An empirical testing programme was undertaken for Hy4Heat by DNV GL at the Spadeadam site. Further details can be found in the dedicated DNV GL report [35], and a summary of the results is provided in Table 18.

The results were largely used to inform the screening process, and in a minority of cases, some of the numerical assessment assumptions.

The key aspect to note is that most tests showed ignition of either both gases or neither gas. It was only in a minority of cases where hydrogen ignited but methane did not. The small sample size of the data (and therefore its relatively low statistical significance) was factored into its use. The results informed the development of the ignition model, and were used for partial validation of certain assumptions, but were not relied on heavily.

It is also noted that a sharing session took place with the H21 project regarding ignition probability development. Whilst the discussion was relatively brief to ensure that the approaches remained independent, it was a positive session and there was broad alignment between the ignition assessment approaches of the two programmes, with similar aspects of ignition (particularly background vs. human initiated sources) having been highlighted as most important.

Table 18: Summary table of DNV GL ignition tests

Equipment	**Notes**	**Hydrogen**		**Methane**	
Small extractor fan 1 (new unit)	Manrose 11640	-	No	-	n/a
Small extractor fan 2 (old unit)	Manrose XF100S	-	No	-	n/a
Medium sized extractor fan 3 (old unit)	Vent Axia 17104020E	-	No	-	n/a
LED light fitting (new)	Sylvania 6412X LED ceiling light 24 W	-	No	-	n/a
Bayonet light fitting (old)	LED Filament bulb	-	No	-	n/a
	60 W bulb	-	No	-	n/a
	LED Filament bulb (smashed)	-	No	-	n/a
	60 W bulb (smashed casing)	Immediate	L1	Immediate	L1
Fluorescent light fitting (old)	Old but working	-	No	-	n/a
	Old with faulty starter	-	No	-	n/a
Hair drier (old)	Babyliss S190A, 2 kW	Immediate	L1	-	No
Vacuum cleaner (old)	Art Miele	20 sec	L1	-	No
Microwave oven (new)	Tesco Microwave	-	No		n/a
Tumble drier (old)	Hotpoint Aquarius TVM570	9 min	L1	Equipment damaged so unable to test	
Fridge unit (door closed) (old)	LEC R-RD40F	-	No		n/a
Fridge unit (door open) (old)	LEC R-RD40F	-	No		n/a
Iron (new)	Tesco's £10 Iron	8 min	L4	Equipment damaged so unable to test	
Toaster (new)	Tesco's £7 toaster	Immediate	L1	-	No
Electric hob	Cooke & Lewis CLCER60A	5 sec	L1	10 sec	L2

The key outcomes were that:

- The extractor fans or light fittings in normal operation did not cause ignition in either gas; this is of particular interest as lights and extractor fans are almost the only potential sources of ignition likely to occur routinely near the ceiling of a kitchen
- For the range of white goods tested, the majority of items showed no significant difference between gases; Such white goods will nearly always be on a work top (i.e. mid height) in the case of kettles, microwaves and ovens, or floor mounted in the case of tumble dryers or washing machines. This will tend to reduce the risk for hydrogen which accumulates towards higher levels in a room
- When ignition occurred, the hydrogen ignitions were loud and fast when compared with methane ignitions at similar equivalence ratio. The methane ignitions were more luminous, quieter and of a longer duration. This in accord with expectations

5.3.6 Ignition probability summary

A wide range of ignition sources relevant to methane and hydrogen were screened. For those deemed most relevant, an ignition potential value was assigned for the purpose of the QRA model. This was in some cases informed by the empirical testing mentioned above.

The analysis showed an increase in ignition likelihood for hydrogen compared to natural gas of 50-100%, depending on the exact scenario being considered. The most important factor contributing to this was the increase in ignition potential assumed for weak ignition sources (e.g. sparks arising from static and sparks arising from e.g. triggering of switches or unplugging of a device from a mains socket). For the hydrogen ignition base case, the flame ignition potential contributions were most significant, whereas in the hydrogen ignition sensitivity case, the balance shifted towards the ignition potential contribution of the electrical sources. The QRA model end results have a linear relationship with the derived overall ignition likelihoods.

Similarly to the Consequence Modelling Report [5], it is recognised that there are many limitations to the modelling undertaken here and that there are many simplifications of complex effects along with variation in input parameters that have a significant impact on the results. It is difficult to measure some input parameters and their variation without creating hundreds of iterations of models, particularly given the generally low control over domestic ignition sources and their extremely high variability. However, the assessment undertaken in this section does provide a means with which to compare hydrogen with methane when looking into probability of ignition in a domestic setting, and the open items explicitly captured in section 15 discuss some of the limitations of the model and their impact on the use of the end results.

6 Leak detection and isolation assumptions

6.1 Gas detection assumptions

The current GB gas network contains an odorant which enables consumers to quickly identify a gas leak, prior to dangerous levels of gas accumulating. This acts as an important measure to reduce the risk from a gas leak as, once a leak has been detected, appropriate further action can be taken to either stop the leak from developing (i.e. by closing the ECV) or to reduce its potential consequence (e.g. by opening windows and doors).

Natural gas in the current gas network contains an odorant that can be detected by the human olfactory system at less than 20% of the lower flammability limit [20]. This corresponds to a volume concentration in air of ~1%. In practice, this allows even very small leaks to be identified through smell. It is assumed that the odorant is 99% effective at identifying gas leaks, provided a person is present at the time of the leak.

The likelihood of someone detecting a leak in sufficient time to stop it from escalating is dependent on the type of leak that has arisen. For instance, a leak caused by third party damage has a high probability of detection due to the inherent nature of the leak being caused by a person.

The existing odorant used within the GB gas distribution network is Odorant NB (New Blend). Work undertaken by the National Physics Laboratory concludes that the existing Odorant NB would also be suitable for use within a 100% hydrogen network [21]. Their testing indicates that this odorant meets the current network requirements for odorants used in natural gas systems. The odorant provides the same, familiar characteristic gas smell at the same intensity and there was no indication of additional risk or damage to pipelines or appliances (in comparison to natural gas). Therefore, the assumptions described above, based on natural gas experience, are also applied to the hydrogen gas assessment.

The table below outlines the assumed probabilities for different leak types.

Table 19: Leak detection probabilities (third party damage)

Description	**Probability**	**Comments**
Probability of gas detection by occupant (third party damage)	0.97	Leaks caused by people, therefore, inherently someone present. Small proportion of people wouldn't smell a leak
Probability of gas detection by passer-by (large leaks)	0.80	Large leaks (6.5-11mm) will be strong smelling and therefore, a neighbour, visitor or passer-by could smell gas and report it. This is known to happen from past incident data recorded through GSMR
Probability of gas detection by passer-by (very large leaks)	0.90	Very large leaks (>11mm) will be very strong smelling and therefore, a neighbour, visitor or passer-by could smell gas and report it. This is known to happen from past incident data recorded through GSMR

Table 20: Leak detection probabilities (other leak causes)*

Description	Probability	Comments
Probability of gas detection by occupant (other leak causes*)	0.6	This takes into account the proportion of time that people would be out of the house or asleep.

**There is no accounting for detection by neighbour in this leak category as the largest applicable leak size is 'medium leaks'*

It is worth noting that there is a time element associated with the generation of large spontaneous leaks, such as those due to degradation, which increases the likelihood of detection. For instance, corrosion leaks often start out small and develop over time into a larger, more hazardous, hole. This development allows more time for detection compared to a release caused by third party damage which would happen instantaneously.

It is important to note that these assumptions are based on engineering judgement rather than analysis of a statistically significant dataset. Therefore, there is inherently some uncertainty surrounding these values. It is recommended that further data collection and analysis be carried out to investigate the probability that a gas leak is detected in time to prevent an incident. This should provide a higher level of confidence in the values to be used here. (See Open Item 7). Given the nature and rarity of gas incidents, any data collection undertaken would need to be an extensive exercise. This difficulty is likely to be compounded by the high level of human involvement in nearly all large downstream leaks. People (including both 3rd parties and householders) tend to be embarrassed about such actions or anxious about legal implications.

6.1.1 Occupancy

It should be noted that unoccupied scenarios are included inherently in this assumption based on the likelihood that someone is present in the property at the time of the leak (as described in the consequence assessment report). For unoccupied scenarios, the probability of detection is assumed to be zero and the actions described in the following sections are assumed to not be executed. Except in the case of large or very large leaks, where it is assumed that neighbours could smell and report a gas leak in the absence of any occupants doing so. There is evidence from GSMR incident data which supports this.

Accounting for the typical time a person spends outside of the home, for example, at work, average occupancy is assumed to be 74% [5]. This is the occupancy factor which has been used to calculate the number of persons at risk within houses that are impacted by an explosion[2].

In terms of detection, the potential for leaks to go unnoticed whilst occupants are sleeping needs to also be considered. Therefore, it has been assumed that occupants sleep for seven hours per day and that 50% of the time they will wake up due to the smell of gas and 50% of the time the leak will go unnoticed. Combining this with the proportion of time that people are out of the house, gives an overall probability of a person being present and awake of ~60%.

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[2] It is noted that these occupancy averages have been derived based on pre-covid assumptions around work patterns and behaviours. Further review in the future will need to reflect any changes as a result of the long-term impact from covid.

Intuitively with higher occupancy, more people are at risk but the likelihood of a potential leak being identified is also higher, therefore the overall impact may not be significant – this would need to be studied.

6.2 Behavioural response assumptions

The UK population have been educated to respond to the smell of gas by undertaking certain actions which aim to control the risk associated with a potential gas leak. These actions are dependent first on the gas having been smelled. Therefore, if the gas leak is not detected, the probability of any of the following actions taking place is zero.

As the odorant is assumed to be the same for both a natural gas and hydrogen gas system, it is assumed that peoples' responses would be the same regardless of the gas being conveyed in the system. Therefore, the probability assumptions described in the following sections are assumed in both the natural gas and hydrogen gas models.

6.2.1 Ventilation

The first action taken by most people is to open windows and/or doors in order to provide extra ventilation. This allows the gas to escape and prevents gas accumulation within the home.

A domestic environment is much simpler than a high-pressure industrial control room environment. People are generally well aware of the action to take upon smelling gas and given the action of opening windows or doors is simplistic for the majority of people, the likelihood of a person responding in the 'correct' manner is high.

It is assumed that if a gas leak is detected, as per assumptions outlined in section 6.1, appropriate action is taken to provide extra ventilation 95% of the time. This is discussed further in Open Item 8.

The effect of this extra ventilation is to provide sufficient pathways for air exchange into the property, hence, preventing the build up to a flammable concentration of gas inside the home.

Therefore, it is assumed that, if ventilation is provided in this manner, the leak does not develop into a hazardous situation.

6.2.2 Manual ECV closure

The most effective way to prevent the continuation of any gas leak is by closure of the manual emergency control valve (ECV).

This action is less intuitive and generally follows on from the triage process that GDNOs employ when a leak is reported. During this triage procedure, consumers will be instructed to close their manual ECV if it is deemed necessary by the telephone operator.

Based on data provided by Cadent for reported leaks, it is assumed that, once a leak is detected, the ECV is successfully closed in sufficient time to prevent a hazardous situation, 70% of the time. The time available for closure of the ECV to be effective is dependent on the size of the leak. Once the manual ECV is closed, it is assumed that the flow of gas to the property is stopped and, as such, the release is prevented.

The table below summarises the behavioural response assumptions within the QRA.

Table 21: Behavioural Response Assumptions (within both QRA Models)

Description	**Probability**	**Comments**
Probability of ECV closure, if gas detected	0.7	Engineering judgement – supported by GDNO data
Probability of opening windows and doors, if gas detected (increasing ventilation)	0.95	Engineering judgement based on small proportion of people who may choose not to open windows/doors or be unable to do so

Again, it is important to note that these assumptions are based on engineering judgement rather than data analysis. Therefore, there is inherently some uncertainty surrounding these values. It is recommended that further data collection and analysis be carried out to investigate the likelihood that people respond in this manner when confronted with a gas leak and, hence, provide a higher level of confidence in the values to be used here. (See Open Item 8). Given the nature and rarity of gas incidents, any data collection undertaken would (again) need to be an extensive exercise.

6.2.3 Response time

This assessment does not quantitatively assess the time taken to build up to flammable atmosphere, after the onset of an uncontrolled gas release. The dispersion model, as briefly described in section 7, is a simple model which calculates the maximum steady state concentration that could be reached for a given set of conditions.

The probability of the response actions above assume that the action is taken in appropriate time to prevent build up to the steady state concentration.

The success of the above behavioural responses at preventing an incident depends on the underlying assumption that it takes time to build up to a flammable mixture once a release of gas occurs.

Simplistically, the much higher volumetric release rates of hydrogen compared to natural gas (times 2.8) would lead to an expectation that hydrogen concentrations would rise much more quickly and the time to a dangerous concentration would be much shorter. A study was undertaken to investigate the time taken for hydrogen and natural gas to reach set concentrations based on the Hy4Heat dispersion data set [57]. The study found that, for all hole sizes, both gases reach 1% GIA (the concentration at which you could expect to smell the gas) in a similar time period. There is a trend for hydrogen to reach LFL (4.5% GIA) and 8% GIA slightly quicker than natural gas at the mid and top points of the room.

Care must be taken when drawing conclusions regarding the time taken to build up to the concentrations shown in the results from the Hy4Heat dispersion trials. This was a post factum analysis rather than forming part of the original specification of trials, and therefore the monitoring approach used was not ideal for purposes of determining the development of concentration profiles over time, with an eight-minute sampling interval at each analytical point. Consequently, the development of the concentration during the time between samples can only be approximated.

Very small/small leaks with a steady state concentration just above the lower flammable limit will take a long time – in excess of an hour – to reach a flammable mixture whether natural gas or hydrogen is leaking. The sufficiency of time available for human response to leaks would not be altered by the gas in this case.

Conversely, large leaks will result in short response times with either gas. Figure 9 illustrates times to 8% gas in air for hydrogen and methane gas from a 7 mm leak (shown as 65kW). Both methane and hydrogen will exceed 8% gas in air in less than 10 to 20 minutes.

The differences between natural gas and hydrogen arise in the intermediate zone, between small leaks that give extended reaction times and large leaks that give short reaction times with either gas. A certain proportion of failure modes would be expected to present a materially shorter response time with hydrogen than with natural gas.

When assessing the impact of these modes, the distribution of leak rates associated with holes as considered during the FCO data collection and analysis part of this work should be revisited. The majority of leaks (~97%) encountered were of the small size that would give long response times with either gas. Reduced response times would only be expected to affect a very small subset of incidents. These medium sized leaks (around 3 mm – 7 mm) have been looked at in more detail below (Figure 9).

For a 3.5 mm leak, the concentration of hydrogen rises much more quickly than methane, although the methane rate of build-up is much more dependent upon the location of the leak. Typical methane times to 8% for the high-point are 30 to 160mins, whereas hydrogen is 5 to 50mins.Typical methane times to 8% for the mid-point are 70 to 230mins, whereas hydrogen is 45 to 60mins. The reasons for this are unclear and requires further work. These relatively large leaks are almost exclusively caused by 3rd party accidental damage or malign; and certainly, in the context of 3rd party damage, the difference between these times is minimal. The 3rd party still has plenty of time to respond appropriately. The smell and sound of a gas leak will be apparent almost instantaneously, alerting the person who caused damage to the need to respond to the incident. This would be independent of the leaking gas.

On the rare occasion where such leaks are from corrosion, there are three possibilities: the householder is present and calls the gas emergency number and makes safe; the householder takes no action and the gas builds up until it is smelt by a returning householder or passer-by; or there is nobody present and the gas builds up until it is smelt by a returning householder or passer-by. If the house is empty, there is a lower risk of an ignition source (except from the boiler). In the context of ‘empty house’ it is suggested that the difference between the two most rapid cases (i.e. 5 minutes for hydrogen and 30 minutes for methane) is small.

For a 5 mm leak, timings to hazardous concentrations are again shorter for hydrogen compared to methane (<5 minutes compared to 20 minutes). If the leak is caused by 3rd party, then there is time for a response in both cases. If there is no householder present, then the difference in timing is too small to be meaningful. There is little chance of a passer-by or neighbour reporting such a leak within the time to flammable concentration for either gas.

Based on the above, it is assumed that there is no significant difference in the time available to respond to a gas leak for hydrogen or methane gas.

It is acknowledged that these assumptions are predominantly based on engineering judgement. Therefore, it is recommended that further work be carried out to comprehensively investigate the difference in response time available between methane and hydrogen gas leaks (See Open Item 9).

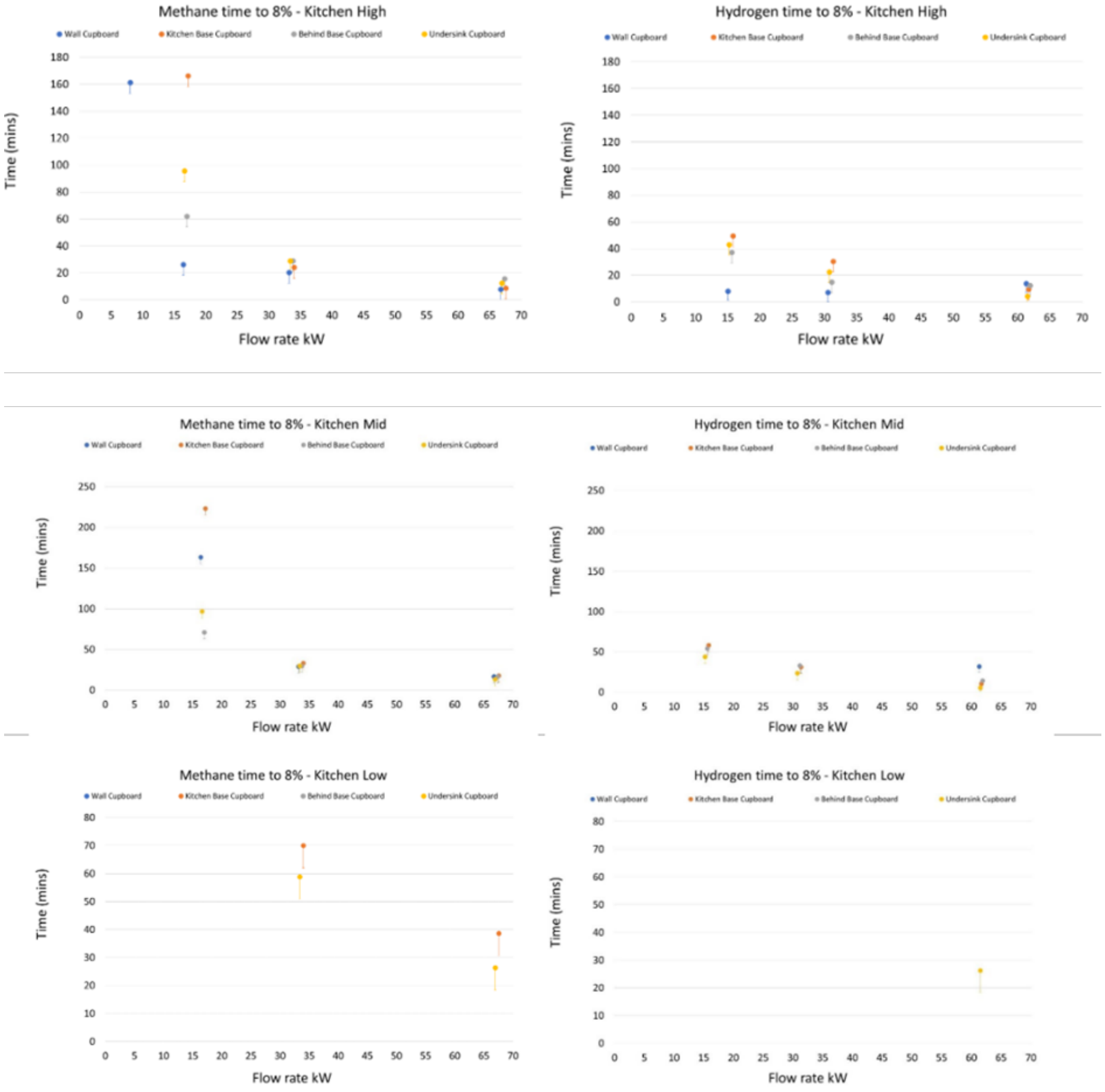

Figure 9: Graphs indicating time to 8% gas in air for methane and hydrogen (3.5 mm = 15 kW; 5 mm = 30 kW; 7 mm = 65 kW) (Graphs taken from KIW-WP7-REP-002 [57])

7 Consequence assessment

7.1 Outline

The consequence assessment aims to predict the behaviour of both natural gas and hydrogen in the event of an uncontrolled release. The detail of this assessment is contained within other reports [5], [19] and this section provides a brief overview and the context in which the consequence assessment was integrated as part of the risk assessment.

7.2 Leak outflow

For each of the leak scenarios considered, an estimated flow rate is required for both natural gas and hydrogen gas in order to determine the rate at which gas is released from a given hole.

Experiments commissioned by the Hy4Heat programme and carried out by Steer Energy aimed to compare the leak rates for natural gas and hydrogen from various domestic gas joints, pipes and fittings. The tests were conducted on a range of fixtures and fittings likely to be seen in domestic gas networks, including test pieces that were deliberately damaged to induce a leak. Whilst there are an infinite number of ways to cause damage leading to a leak, these test pieces were intended to represent real scenarios and gas fitters were consulted to draw on their experience of such incidents. The full detailed test programme and results are set out in the Steer Energy report: Safety Assessments for the Suitability of Hydrogen in Existing Buildings [25].

The results from these tests have been used to inform the predicted size of each of the reported leaks within the FCO data set. This enabled the FCO data points to be grouped into equivalent hole size categories in order to develop the assumed leak frequency distribution for different hole sizes, as set out in section 5.2.5.

The considered leak categories are summarised in Table 22 below. Each category represents a range of hole sizes and a representative hole size is modelled for each category. These leak categories are assumed to be independent of the gas being conveyed within the system and are therefore constant between both the natural gas and hydrogen models.

Table 22: Hole size categories

Leak category	Category range (hole diameter, mm)	Modelled hole size (diameter, mm)
Negligible	<1.5 mm	n/a
Very small	1.5 – 2.4 mm	1.8 mm
Small	2.5 – 3.9 mm	3 mm
Medium	4 – 6.4 mm	5 mm
Large	6.5 – 10.9 mm	9 mm
Very large	>11 mm	13 mm

The outflow for each of the above hole sizes is calculated as part of the gas dispersion model, using industry standard theory, as described in the Hy4Heat 'Gas Dispersion Modelling Report' [19].

7.3 Dispersion assessment

The dispersion model used in this assessment is the one vent Linden model [27], which is detailed in the Hy4Heat Gas Dispersion Modelling Report [19], along with the rationale for the model's applicability to this assessment. In short, the model calculates the steady state concentration which develops for a given hole size in a defined space, for both natural gas and hydrogen gas.

The spaces considered are a kitchen (28.8 m^3) and the ground floor of a house (76.8 m^3). These scenarios were chosen as being the most credible cases in terms of leak location and development. A full property fill (two-storey and attic) has not been considered as a credible scenario, as it would take several hours for a leak to develop to steady state throughout a whole two-storey property, by which time either appropriate action can be assumed to have been taken or an ignition has already occurred. The model also takes into account the air permeability of the modelled enclosure. As described in section 4.3, three levels of property air tightness are considered in this assessment.

Table 23 illustrates the scenarios considered, including space dimensions and air permeability levels.

Table 23: Gas leak locations and representative air permeability levels [19]

Gas leak locations	**Kitchen**		**Storey (Downstairs of a terraced house)**	
Space dimensions (width x length x height)	4m x 3m x 2.4m		8m x 4m x 2.4m	
Volume size (in approximation with potential leak locations)	~ 30 m3		~75 m3	
Air permeability description	**Total leak & vent area**	**Air permeability rate estimated @50Pa**	**Total leak & vent area**	**Air permeability rate estimated @50Pa**
Low (Highly sealed e.g. no continuous ventilation)	~ 0.04 m2	2 m3/(h.m2)	~ 0.04 m2	1 m3/(h.m2)
Medium (Moderately sealed e.g. continuous ventilation)	~ 0.08 m2	5 m3/(h.m2)	~ 0.15 m2	5 m3/(h.m2)
Leaky (e.g. older houses)	~ 0.20 m2	15 m3/(h.m2)	~ 0.40 m2	15 m3/(h.m2)

The levels of air permeability rate chosen are roughly aligned to a study published by Leeds Metropolitan University which analysed data from BRE's database of air leakage. As described in Section 4.3, this data contained information on 471 properties of different age size, type and construction [22]. and showed that a very wide range of air permeability rate exists within the UK housing stock.

In addition, it should be noted that the published data stops short of analysing the permeability down to individual rooms such as kitchens, bathrooms and utility spaces where boilers are commonly installed, and a minimum level of ventilation to control damp is required in accordance to Building Regulations Approved Document F (AD(F)) [58].

The Hy4Heat experiments carried out in the purpose-built house, 'HyStreet', at the DNVGL Spadeadam site does provide a means to inform (in a preliminary way) what might be considered normal, in terms of contributors which influence the air permeability level associated with the build and installation of a typical room such as a kitchen. For instance, the kitchen in the 'HyStreet' house has leaks at various levels due to cracks in the floor, drains and other plumbing, incomplete floor seal, electrical fittings e.g. sockets and lights etc.

However, it should be noted that the build of the purpose-built 'HyStreet' house does differ from the typical housing stock in that it does not have a means of continuous ventilation. Therefore, it is assumed in the QRA that the level of background leakage for properties in the "Highly sealed" category (less than 5 m3/(h.m2) – frequency 4%) correspond to the Hy4Heat experiments carried out in the DNV GL 'HyStreet' house, where continuous ventilation in the kitchen is absent. The value of 0.04 m^2 total vent area produced dispersion model predictions that fit well and are comparable with the data observed from the Hy4Heat WP7 experiments in the kitchen of the DNV GL 'HyStreet' house, without any added ventilation (See section 6.3 of Gas Dispersion Modelling Report [19]).

The moderately sealed category is assumed to correspond to kitchens that have similar background leakage to the build of the kitchen in the DNV GL ‘HyStreet’ house but with additional ventilation – which should be continuously available. This assumption is based on the dispersion model results with the value of 0.08 m^2 total vent area, which produced comparable predictions to the results observed from the Hy4Heat experiments carried out with an additional 100mm diameter vent hole above the kitchen door (Figure 29 of Gas Dispersion Modelling Report [19]) in the DNV GL ‘HyStreet’ house.

This means that the results in the QRA have taken into consideration the typical air permeability level applicable to the population of properties which may be subject to the community trial.

The following Figure 10 to Figure 13 summarise the output of the dispersion model for natural gas and hydrogen. The first two figures show the predicted gas concentration for hydrogen and natural gas at different hole sizes within a typical kitchen space. The subsequent two figures illustrate the predicted gas concentration for hydrogen and natural gas at different hole sizes within a typical ground floor of a terraced house.

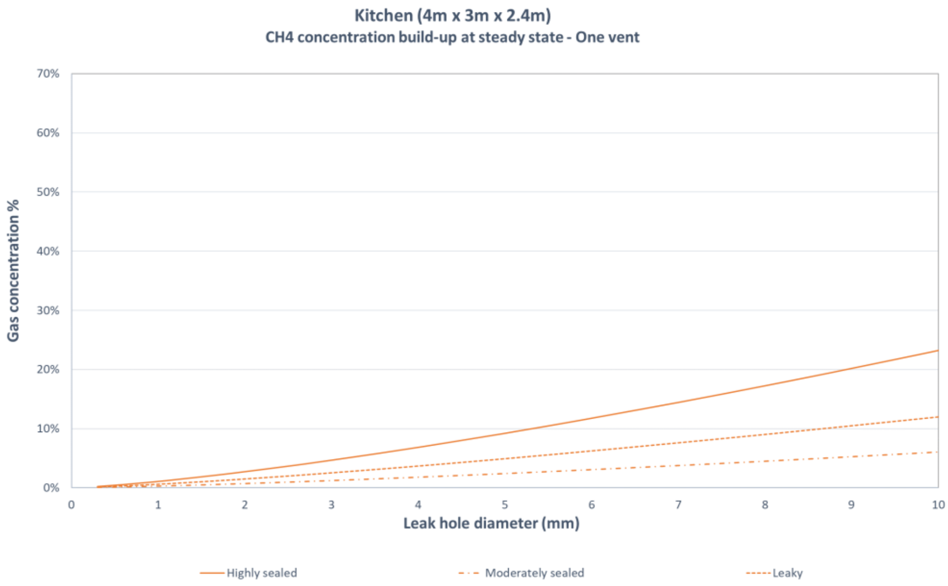

Figure 10: Peak methane concentrations in kitchen for three different levels of air tightness

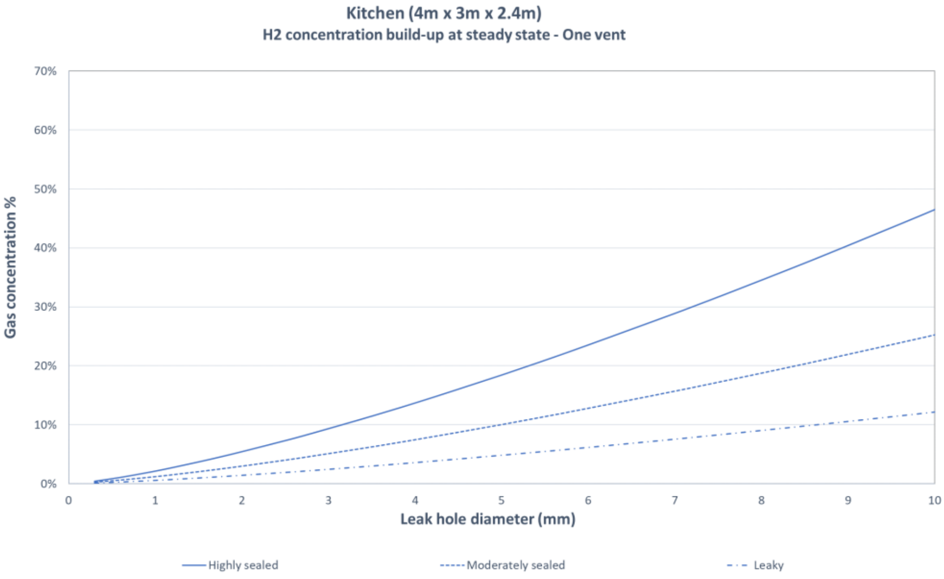

Figure 11: Peak hydrogen concentrations in kitchen for three different levels of air tightness

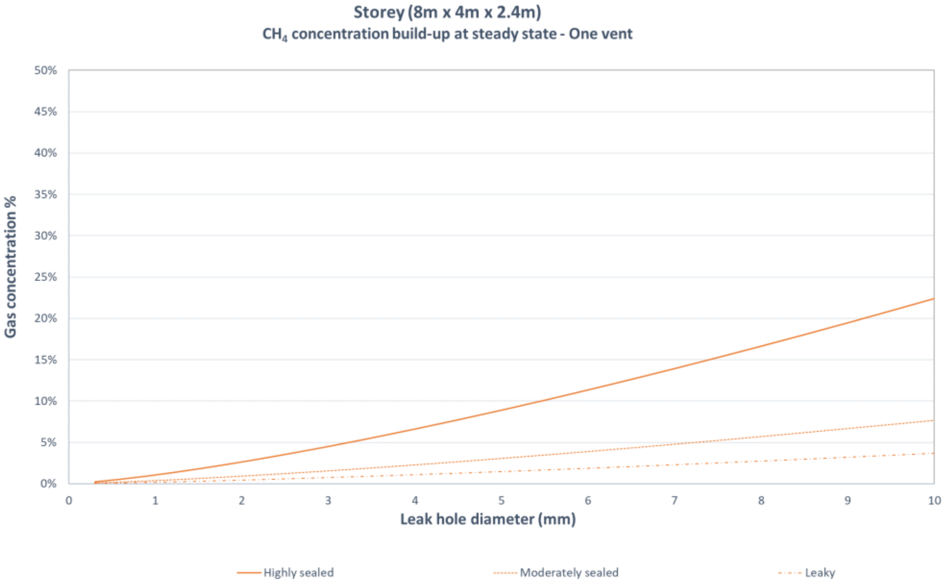

Figure 12: Peak methane concentrations in a ground floor storey for three different levels of air tightness

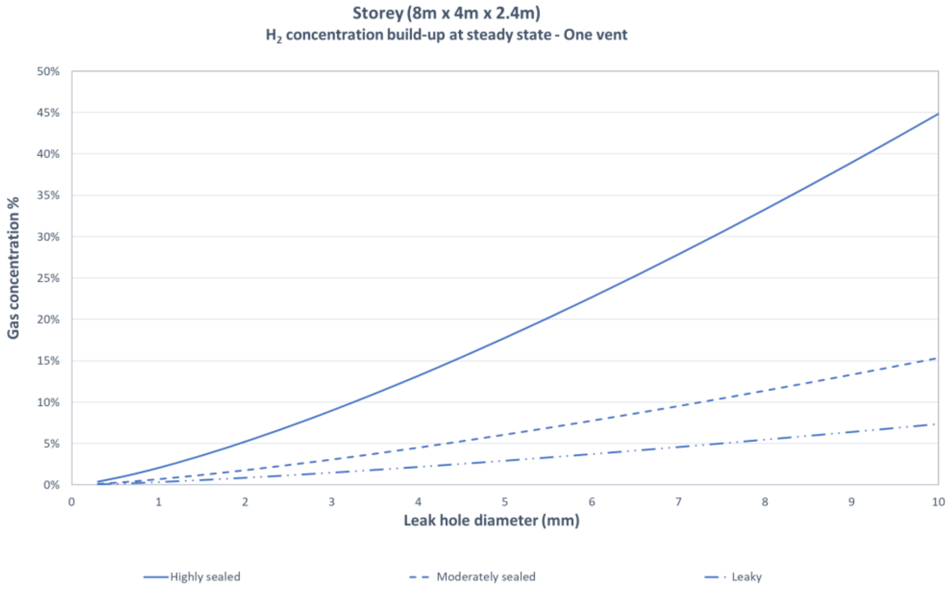

Figure 13: Peak hydrogen concentrations in a ground floor storey for three different levels of air tightness

For each scenario considered (Section 0), the steady state concentration predicted by the dispersion model outlined above is taken forward for input into the explosion assessment, described in the next section.

For example, a 7mm hole occurring within a moderately sealed kitchen space (with the door closed) gives rise to a steady state concentration of 8% with methane gas.

7.4 Explosion (deflagration or detonation) assessment

The explosion assessment considers confined explosions with a level of congestion representative of typical domestic furniture. The assessment methodology and assumptions are detailed in full in the Hy4Heat Consequence Modelling Report [5] and a brief overview is provided here for context.

In confined explosions, the overpressure is generated from the restriction of expanding combustion products due to the presence of a confining enclosure, i.e. 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 natural gas or hydrogen, has been estimated using a method developed by the University of Warwick FIRE research group [33] [34].

The assessment considers the consequences of ignition of a flammable gas cloud (either natural gas or hydrogen gas) occurring within a typical 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.

7.5 Damage and injury assessment

The dispersion and consequence modelling described above estimated flammable gas cloud concentrations and associated overpressures for a number of scenarios.

The effects of an explosion depend on the strength and duration of the generated overpressure. As the assessment considers explosions generated inside domestic properties, the main causes of harm will be structural collapse and flying debris (e.g. glass).

The potential for structural collapse of a property, causing injury to any occupants who are inside the affected property at the time of the incident, dominates the potential for injuries to arise from a domestic gas explosion.

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, as described in the consequence modelling report [5], judges whether the load-bearing wall of the enclosure retains its structural integrity when subjected to the estimated overpressure and impulse generated by an explosion.

Table 24 and Table 25 summarise the estimated structural damage arising from natural gas or hydrogen deflagrations occurring due to a flammable gas cloud filling either a kitchen space or the downstairs of a property. The severity of a deflagration is influenced by the volume concentration of gas in air of the flammable vapour cloud at the time of ignition. The tables detail categories grouped by the estimated extent of structural damage caused by an ignition within a given range of gas in air concentrations and give an indication of the number of people who may have the potential to be affected. The volume concentration ranges in the tables below refer to the steady state peak volume concentration in a stratified mixture, giving the concentration present in the top stratum.

Table 24: Kitchen scenario – structural collapse results

Failure of walls in **kitchen where explosion occurs?**	Failure of walls of **next-door neighbour** kitchen?	Assumed **extent of structural damage**	Number of people **injured due to structural collapse**	Concentration range for this damage level (vol%) 'Peak' concentration **(nat gas)**	Concentration range for this damage level (vol%) 'Peak' concentration **(hydrogen)**
No	-	Structural integrity maintained in dwelling where ignition occurs	0.0	5.0% to 7.5 % and >14.0%	5.0% to 14.0%
Yes	No	Partial collapse of 3 houses	2.0	7.5% to 14.0%	14.0% to 23.0%
Yes	Yes	Total collapse of 3 houses, partial collapse of 2 houses	6.7	n/a	>23.0%

Table 25: Downstairs of a terraced house scenario – structural collapse results

Failure of walls in **house where explosion occurs?**	Failure of **walls of next-door neighbour?**	Assumed **extent of structural damage**	Number of people **injured due to structural collapse**	Concentration range for this damage level 'Peak' concentration **(nat gas)**	Concentration range for this damage level 'Peak' concentration **(hydrogen)**
No	-	Structural integrity maintained in dwelling where ignition occurs	0.0	5.0% to 6.5% >11.0%	5.0% to 13.0%
Yes	No	Total collapse of 3 houses	5.4	6.5% to 11.0%	13.0% to 21.0%
Yes	Yes	Total collapse of 5 houses	8.9	n/a	>21.0%

The injury assessment also accounts for the number of people injured due to exposure to overpressure, burns and glass throw, internal and external to the property. These injury levels can be found in detail in the consequence modelling report [5]. Total injury levels are presented in Table 26 and Table 27 below.

Table 26: Combined injury results for natural gas

Peak concentration range (vol%) and scenario	**Total number of people injured due to overpressure, burns and glass debris throw (kitchen scenario)**	**Total number of people injured due to overpressure, burns and glass debris throw (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 27: Combined injury results for hydrogen gas

Peak concentration range (vol%) and scenario	**Total number of people injured due to overpressure, burns and glass debris throw (kitchen scenario)**	**Total number of people injured due to overpressure, burns and glass debris throw (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

7.5.1 *Severity of Injury*

It should be noted that the threshold for injury within the consequence assessment encompasses major injury and fatality and there is no separation of these within the assessment. As stated previously, the potential for injury is dominated by the associated structural collapse rather than the direct effect of explosion overpressures on individuals. Although hydrogen explosions cause greater overpressures than methane explosions, there is no evidence that the overpressures produced during hydrogen explosions are more likely to cause a fatality than the overpressures produced during methane explosions [59] [54]. However, there is the potential for an increased risk of hearing loss related to hydrogen explosions.

8 Potential risk reduction measures

The effects of a variety of risk reduction measures were considered, including both existing measures and potential future additions. These measures have concerned reducing the likelihood of hazardous situations arising, or reducing the potential consequences that such situations could result in. Measures that could mitigate risk following an explosion, such as explosion relief panels that can be appropriate within process plant, have not been considered in this study.

These risk reduction measures are only being considered for addition to the hydrogen case.

8.1 Excess flow valves

Excess flow valves are devices which automatically respond to excessively high rates of flow by closing off the supply of gas. These are currently installed within domestic natural gas meter installations that are connected to medium pressure supplies but not on more common low-pressure systems. Preliminary testing undertaken within the H100 programme showed that these valves function predictably with hydrogen when considering the gas physical properties, and development of EFVs certified for use in hydrogen service is now underway. It is recommended that an excess flow valve should be installed in the gas supply upstream of the gas meter, either in the service pipe or in the meter installation.

Hy4Heat Work Package 10 is developing smart gas meters for hydrogen service. One of the essential criteria of this package is the implementation of excess flow shutoff functionality within the meter software to drive the integral valve closed if a gas flow greater than a configurable limit is measured for more than a momentary pulse.

The combination of one (or more) physical excess flow valve in series with the instrumented valve in the meter will provide a high level of reliability in stopping the flow of gas for the largest releases. For the purpose of this assessment, it is assumed that both valves are set at ~20 m^3/h as this is the maximum flowrate envisaged to be required by a householder using standard appliances. 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.

Setting the flowrate at 20 m^3/h mitigates against the ‘large’ and ‘very large’ leaks as defined in this report. The EFVs will not provide protection against leaks within the normal operating range of flows that could be seen within the gas installation.

This assessment has assumed that there will be two EFVs installed at every meter point. One mechanical EFV upstream of the meter, after the ECV or in the service pipe, and one EFV within the smart meter installation.

According to the HSE failure rate guidance derived for Land Use Planning [49], excess flow valves have a failure rate of 1.3×10^{-2} per year if tested every year and an order of magnitude higher if tested every 10 years. Given that these valves could not reasonably be tested every year, the higher failure rate value, of 1.3×10^{-1}, is used. This is considered representative for the purposes of this assessment in determining whether hydrogen is feasible for use within a community trial. As in this case, the valves will be newly installed and recently tested.

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.

Figure 14 shows a cross-section of a mechanical EFV during normal operation, with gas flowing through it. As flow through the EFV increases, the pressure drop resulting from gas flowing around the plug increases, exerting an increasing force that is counterbalanced by the spring.

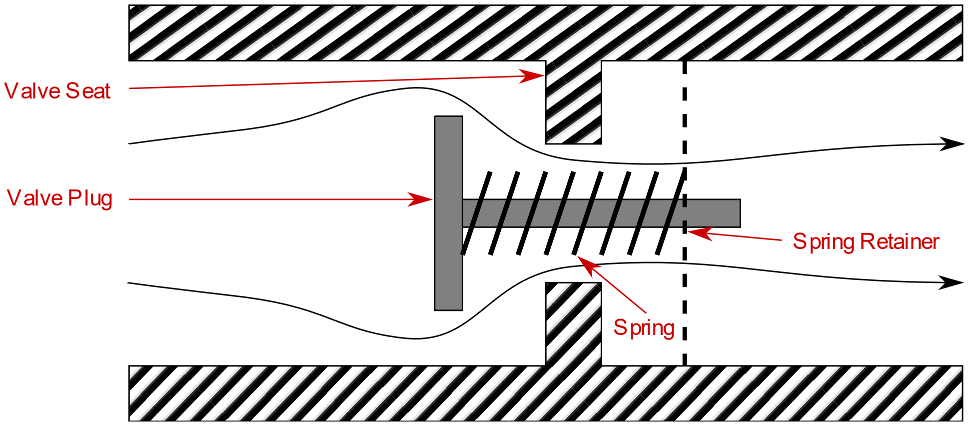

Figure 14: Excess flow valve – normal flow conditions

As the flow and hence the force acting on the spring increases, the plug is pushed towards the seat, and when the flow is above a critical value the valve will be closed as shown in Figure 15. Because the pressure differential acting on the valve plug face is the driving force to cause the EFV to close, it will provide protection against either a gradual or a sudden increase in flow.

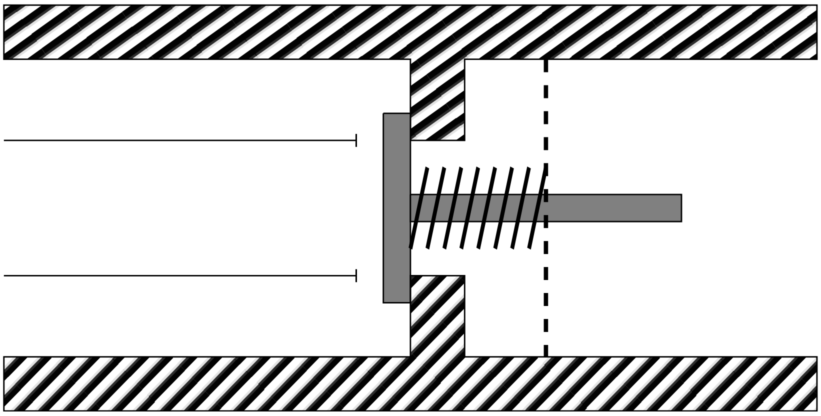

Figure 15: Excess flow valve – closed position

Excess flow valves such as these operate according to straightforward physical principles, with the pressure drop – flow relationship being fundamental fluid mechanics, and spring compression being well described by Hooke’s Law.

EFVs for domestic installations are available and in use as CE-marked fittings that directly screw into British standard gas meter emergency control valves. They are equipped with very small weep holes in their plugs. This allows these valves to slowly pressurise a gas-tight downstream system and so avoids the need for bypass systems or other arrangements to be provided. The weep hole is of such a small diameter (well below one millimetre) that no build-up of flammable atmosphere could feasibly occur from a system that is not gas tight.

A specification for the smart meter EFV has been developed as part of WP10 [50]. The algorithm that has been developed allows for configuration of the point at which the valve would operate to match the size of demand that could occur during normal operations, and includes a fast response if the flow through the valve were to exceed the meter overload flowrate, indicating a flow beyond the maximum rate that the meter is tested to accurately measure.

EFVs are reliable items of equipment that can respond very quickly to shut off the supply of gas when flow is too high – they are used in medium pressure natural gas supply to UK properties, in the USA (which has higher pressure systems than the UK), and are commonly used in German gas supplies. There is no reason to believe that an EFV appropriately sized for hydrogen would be any less reliable than one appropriately sized for natural gas. The combination of a conventional physical EFV with hardware and software monitoring in a specifically designed gas meter will result in a system with very good reliability.

8.2 Improved appliance safety features

A large proportion of injuries from gas incidents are associated with gas cooker operations, particularly due to leaving unlit gas flowing. This has been partially addressed where gas cookers in rented accommodation must now be equipped with flame failure devices, but significant numbers of cookers without FFDs remain in owner occupied properties.

With the replacement of appliances that would be required for conversion from natural gas to hydrogen, old appliances without FFDs in privately owned properties would potentially be replaced before they might without intervention. All new hydrogen appliances would be equipped with FFDs in accordance with the guidance set out in PAS44 44 [46].

Whilst this improvement can be described qualitatively, quantitative assessment would be subject to very high levels of uncertainty.

8.3 Ventilation

Ventilation is present to differing degrees in any property due to the need for fresh air to breathe and to avoid build-up of moisture. This has been considered within the construction of the QRA model as described in section 4.3:

- Highly Sealed – Very air-tight constructions normally associated with mechanical ventilation where this system is malfunctioning i.e. with no natural continuous ventilation. Note: these houses are to be excluded from any community trial. (QRA assumed frequency of 4%)
- Moderately Sealed – Houses similar in construction to that of the 'HyStreet' where Hy4Heat experiments where undertaken, with additional continuous ventilation present. (QRA assumed frequency of 37%)
- 'Leaky' – Houses built pre-1980s, with floorboards, chimneys etc. that are well ventilated enough to not require additional vents (QRA assumed frequency of 59%)

Additional ventilation could be added to properties through adding vents in rooms where hydrogen accumulation could occur. This would have particular benefit when placed at high levels. This is somewhat similar to the current requirements contained within Building Regulations (e.g. Approved Document J England) and various British Standards to ventilate various gas installations.

Addition of ventilation will inherently reduce the steady-state concentration of gas in air that would ultimately be reached due to a gas release. For a lean fuel-air mixture, this would reduce the flame speed of the gas mixture and hence reduce the peak explosive power output and increase the minimum ignition energy of the mixture and hence reduce the likelihood of ignition occurring.

Quantifying the effect that increased ventilation would achieve is challenging and would be accompanied with a degree of uncertainty. Additionally, choice of a suitable vent would be important to ensuring that building energy efficiency is not adversely affected. Further consideration should be given to the benefits and challenges associated with increased ventilation levels, particularly with a view to the initial occupied trials with hydrogen. Due to the difficulty of assigning a quantitative effect, this has not been tested within the QRA.

Experiments undertaken by DNV GL [47] [48] compared the movement and accumulation of hydrogen and methane released within rooms and 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.

The second phase of these experiments consisted of hydrogen gas releases using a variety of combinations of vent openings in the kitchen cupboards 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 10,000 mm^2 ceiling vent, ducted to the external wall, had the effect of reducing the maximum concentration of hydrogen seen within the kitchen. Tests were performed for a number of equivalent hole sizes, including 5.1 mm and 7.2 mm, with and without ceiling vents present. For the 7.2mm hole size, without a vent present, the maximum hydrogen concentration recorded was 32% at the high point of the kitchen. With the addition of a 10,000 mm^2 ceiling vent, the maximum concentration recorded was reduced to 17% at the high point of the kitchen. For the 5.1mm hole size, without a vent present, the maximum hydrogen concentration recorded was 22% at the high point of the kitchen. With the addition of a 10,000 mm^2 ceiling vent, the maximum concentration recorded was reduced to 8% at the high point of 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.

8.4 External or case-by-case-checked meter location

Gas meter installations can be mounted within domestic properties, or within meter housings externally. The meter installation, particularly the section between the emergency control valve (ECV) and the meter regulator, is the highest-pressure part of the gas installation and so is the part of the gas installation where the any leak would be the highest rate for a given hole size. Gas meters, and their associated regulators and pipework were the largest single cause of gas leaks within the FCO leakage reports.

Locating gas meters outside rather than inside properties would result in very significant reduction in the chance of any leak from the gas meter installation propagating inside. Additionally, whilst tracking of gas from any gas mains or service leak has not been considered within this QRA, it is expected that locating the meter installation outside would reduce the risk of any upstream leak tracking into the property.

Relocating of meters from an internal to an external installation should be approached cautiously, however. Other factors must be borne in mind as to why the meter was installed internally in the first place. These can be reasons such as installations in Victorian terrace houses on streets where there is no space for external meter boxes, flats where multiple external boxes would lead to confusion, or installations in areas where there is prevalence of thefts of copper piping. Because of this, locating meters externally should not be a mandatory requirement for any realistic hydrogen system.

This is discussed in detail with BS 6400-1:2016. Points within this comprehensive standard include deprecated locations where the meter could impede escape in case of fire as well as the need for protection against acts of vandalism.

As a result of this, meter location may be considered on a case-by-case basis as part of the engineering work required during any conversion and meters should be placed in accordance with best practice – either outside the property or within the property less than two metres from where the service pipe enters and in a suitably ventilated location.

There may conceivably be adverse effects related to locating the meter and ECV outside the property but as this is in line with current best practice, it is not expected that there would be a significant difference between whether natural gas or hydrogen was being conveyed.

8.5 Gas detection and alarms

Smoke alarms, carbon monoxide alarms, and heat alarms are now well established within domestic properties (the latter mainly in Scotland), so extending the alarming profile to include hydrogen detection does not seem unreasonable. No domestic detector is currently available, but sensors are available for integration within commercial and industrial gas proving systems.

Whilst odorization of gas performs very effectively to warn against gas releases, it does not provide warning while occupants are asleep or for the small proportion of people who are unable to smell the odorant. Audible alarms would help address this marginal proportion of events.

Conceptually, hydrogen detectors could be connected to automated valves either within a meter or as a standalone system in domestic situations to replicate the possible use for non-domestic systems. One view is that this could be an interesting area for follow on work; another view is that such technology could reduce the effectiveness of odorization that has been so well proven worldwide, especially if people began to rely upon it.

9 Results – base case

The risk results presented in this section are calculated by combining the output from the frequency assessment, which aims to estimate the frequency of a range of ignited events, with the consequence assessment, which estimates the level of harm associated with these ignited events. As structural damage dominates the potential for causing harm, the categories outlined in section 7.5 regarding extent of structural collapse, provide a basis for which to group ignited events which would lead to a comparable level of injury.

As outlined in section 3, this assessment only considers the risk from fires and explosions and, as such, the risk from CO poisoning has been excluded from these results. It is recognised that CO poisoning is a contributor to the current natural gas risk profile. As hydrogen does not produce CO as one of its combustion products, the risk from CO poisoning would be eliminated with use of hydrogen gas. The QRA does not take benefit of this fact as part of the comparative assessment.

9.1 Natural gas

9.1.1 *Frequency of fire/explosion event*

The assessment estimates a total of nine ignited events per year for the total GB population for the natural gas base case.

It is important to note that these results do not include any incidents which might be expected to arise from misuse of appliances, such as leaving a gas hob switched on and unlit, as described in section 3.5.1.

Comparison with recent natural gas data

This compares reasonably well (at least at the high level) with recent HSE GSMR data, which indicates the following total number of fires and/or explosions as reported by the HSE, originating from leaks downstream of the ECV (excluding incidents originating from appliances or house fires as these are not considered in this assessment).

Table 28: Summary of HSE GSMR incident data (data for incidents originating downstream of the ECV)

Year	**Fires and/or explosion incidents**	**Incidents with injuries**
2016/17	18	9
2017/18	13	8
2018/19	6	5
2019/20	9	5

9.1.2 *Risk results*

In order to estimate the level of risk associated with the natural gas case as predicted by the model used in this assessment, the combination of frequency of event and consequences of those events is required. Table 29 summarises the predicted number of injuries per year for GB population for the natural gas base case. It can be noted that the number of very large explosions predicted is greater than that observed in practice from historical incident reporting.

Table 29: Natural gas base case risk results

Type of event	**Predicted number of events per year (GB population)**	**Predicted number of individuals injured per event**	**Predicted number of individuals injured (per year GB)**
Kitchen explosion (5-7.5 vol%)	3.5	0.35	1.2
Kitchen explosion (7.5-14 vol%)	2.2	2	4.4
Kitchen explosion (14-15 vol%)[3]	0	0.35	0
Whole downstairs explosion (5-6.5 vol%, or 11-15 vol%)	1.5	0.9	1.4
Whole downstairs explosion (7-11 vol%)	1.8	5.5	10.1
Total	**9**	**n/a**	**17**

9.2 Hydrogen gas

9.2.1 Frequency of fire/explosion event

The assessment estimates a total of 39 ignited events per year for GB population for the hydrogen gas base case.

9.2.2 Risk results

In order to estimate the level of risk associated with the hydrogen gas base case as predicted by the model used in this assessment, the combination of frequency of event and consequences of those events is required. Table 30 summarises the predicted number of injuries per year for GB population for the hydrogen gas base case (This can be compared with Table 29 for natural gas).

Table 30: Hydrogen gas base case risk results

Type of event	**Predicted number of events per year (GB population)**	**Predicted number of individuals injured per event**	**Predicted number of individuals injured (per year GB)**
Kitchen explosion (5-14 vol%)	20.0	0.35	7.0
Kitchen explosion (14-23 vol%)	2.8	2.3	6.5
Kitchen explosion (>23 vol%)	2.8	7.4	20.4
Whole downstairs explosion (5-13 vol%)	11.4	0.9	10.2
Whole downstairs explosion (13-21 vol%)	0.4	5.5	2.4
Whole downstairs explosion (>21 vol%)	2.0	9.4	18.8
Total	**39**	**n/a**	**65**

The results show both a high predicted number of large natural gas and hydrogen incidents. The increased number of injuries per incident for hydrogen inevitably leads to an increased value for

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[3] This value is known to be unrealistically low, but it is important to not over-estimate the risk from methane.

annual injuries which is considerably larger than that predicted for natural gas. This is because of the more serious consequences predicted by the Warwick model for the higher concentration hydrogen explosions.

Recent publications [55] [56] 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 often predicts overpressures above 1000 mbarg; in practice nearly all UK housing has failed below 200 mbarg and the most robust buildings by 600 mbarg.

10 Results – with additional risk reduction measures

As outlined in section 9, 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 natural gas system, with no additional control measures in place.

This following section discusses how the implementation of risk reduction measures can reduce the overall risk to a level that is comparable to natural gas.

10.1 Excess flow valves

As described in section 8.1, EFVs are devices which automatically respond to excessively high rates of flow by closing off the supply of gas. A further QRA model case termed “Hydrogen (+2EFVs)” assesses the impact of introducing two EFVs into the domestic gas system:

- One upstream of the meter installation[4]
- One located within the smart meter installation.

It is assumed that both of these EFVs are set at a flowrate of 20 m^3/hr. This value is based on the maximum flow of hydrogen gas that could be reasonably expected to be needed (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.

Referring back to the hole size categories, as described in section 5.2.4, this flowrate prevents leaks in both the ‘large’ and ‘very large’ hole size categories.

According to the HSE failure rate guidance derived for Land Use Planning, excess flow valves have a failure rate of 1.3×10^{-2} per year if tested every year and an order of magnitude higher if tested every 10 years. Given that these valves could not reasonably be tested every year, the higher failure rate value, of 1.3×10^{-1}, is used. This is considered representative for the purposes of this assessment in determining whether hydrogen is feasible for use within a community trial. As in this case, the valves will be newly installed and recently tested.

In the event of any future nationwide hydrogen roll-out, further work may be needed to determine whether there is a requirement for regular long-term maintenance strategies in order to ensure these valves are performing as expected.

It is assumed that the two EFVs are located in series with each other and that there are no common cause failures associated with the valves.

10.1.1 Frequency of fire/explosion event

The assessment estimates a total of 26 ignited events per year for the hydrogen gas case for total GB population with two EFVs.

10.1.2 Risk results

In order to estimate the level of risk associated with the hydrogen gas base case as predicted by the model used in this assessment, the combination of frequency of event and consequences of those events is required. Table 31 summarises the predicted number of injuries per year for total GB population for the hydrogen gas case with EFVs.

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[4] In practice, this could either be located between the meter and the ECV or upstream of the ECV in the service pipe or top tee. The further upstream the EFV is placed, the more protection it offers from potential uncontrolled leaks

Table 31: Hydrogen (+EFVs) gas risk results

Type of event	Predicted number of events per year (GB population)	Predicted number of individuals injured per event	Predicted number of individuals 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 EFVs 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.

11 Risk comparison (natural gas vs hydrogen)

Table 32 shows a comparison between the predicted number of injuries for natural gas case, hydrogen unmitigated case and the hydrogen gas case with two EFVs installed. The table illustrates total injuries per year estimated for each of the cases considered. The table below reports the total number of predicted injuries from all types of incidents and does not split out by number of injuries per event.

Table 32: Comparison of predicted number of injuries for the natural gas base case, hydrogen base case, and the hydrogen gas case with two EFVs installed*

	Indicative average annual number of injuries (HSE GSMR Data 2016-2020*)	**Natural gas – Predicted number of individuals injured (per year GB)**	**Hydrogen base case – predicted number of individuals injured (per year GB)**	**Hydrogen + 2EFVs – predicted number of individuals injured (per year GB)**
Total estimated no. of injuries per year:**	**12***	**17**	**65**	**16**

Note: These numbers should be considered in orders of magnitude rather than absolute values

**Value calculated from GSMR incident data (excluding appliance and house fire incidents) and HyDeploy analysis of injuries per incident (Section 1.4). Is used as a representative value for comparison with the QRA predictions and is indicative only.*

***It should be noted that the current predicted total number of injuries per year have not been adjusted against the total housing topology type to reflect the predicted risk for a typical two-up, two-down UK terraced house (as per the scope of this assessment).*

Care must be taken when interpreting the risk results produced from the QRA. Initial inspection shows that large numbers of injuries from fires and explosions are predicted for all three cases (natural gas, hydrogen, and hydrogen with EFVs). This 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 a result, the natural gas case overpredicts the number of injured people when compared to the HSE GSMR report data. This overprediction is also assumed to be apparent in the hydrogen gas case, given that the same consequence model is used for both gases, with more conservative assumptions associated with the hydrogen case.

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 the results are compared on a relative likelihood basis, rather than an absolute basis.

From the table above it can be seen that the overall predicted risk is greater for the hydrogen unmitigated case than natural gas case. However, the introduction of two EFVs reduces the overall hydrogen risk to a level comparable to the natural gas case.

12 Importance analysis

12.1 Purpose

In order to determine the overall importance of each of the variables modelled in the QRA, an importance analysis was undertaken. The Fussell-Vesely (F-V) importance value method was chosen as it is a standard approach for importance analysis in such safety models.

It indicates the relative importance of the model parameters to one another in terms of contribution to the overall risk of weighted injury[5]. Higher F-V importance values indicate a great contribution to the risk of weighted injury.

The top five contributors by F-V importance values are shown in the tables below. Any reduction in the frequency of occurrence of these top contributors would lead to the greatest reduction in overall risk of injury.

12.2 F-V Results – natural gas case and hydrogen base case

From Table 33 and Table 34 below it is shown that the highest contributor to the frequency of ignited events for both gases is the leak frequency associated with third party damage to pipework. This aligns with the third-party damage cause as the majority of leaks (with the potential to lead to an ignited event) recorded in the FCO survey fall into this category.

The next three contributors are also the same for both gases (although not in the exact same order, the F-V importance values are broadly the same for all three variables). These are gas leak from third party damage going undetected, medium air permeability and ignition probability (related to third party damage in the kitchen).

The frequency values within the natural gas and hydrogen models are the same for most variables, with the exception of ignition probability which differs between the two. Therefore, the importance values are broadly the same between the two models, highlighting this consistency.

Medium air permeability is of greater relative importance in the hydrogen model compared to the natural gas model. This is due to the higher concentrations that hydrogen will tend to accumulate compared to natural gas.

Low air permeability does not feature in the top contributors of any of the cases. Although the scenarios with low air permeability have the potential to lead to the worst consequences, the probability associated with having a low air permeability is very low. Therefore, the contribution to the risk is also low.

The third highest contributor for both gases is the gas leak from third party damage going undetected. This highlights the importance of odorisation as a key risk reduction measure.

The very large leak frequency (relating to third party damage) features as a top contributor in both models as these are the leaks which lead to the worst consequences and hence contribute significantly to the overall risk.

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[5] Within the QRA model, the severity of consequence associated with each type of ignited event has been weighted to allow for a comparison of risk to be undertaken within the model itself. The highest consequence event has a weighting of one, and the other events are weighted based on the comparative number of injuries associated with the event. See Appendix E for weighted consequence categories.

Table 33: Fussell-Vesely importance analysis for natural gas model

Event description	Fussell-Vesely importance
NG leak frequency (third party damage pipework) (all leak sizes)	0.8162
Ignition NG (third party, internal, kitchen only)	0.6936
Third party, gas not detected	0.661
Mid air permeability (5 $m^3/(h.m^2)$	0.6206
NG very large leak frequency (third party damage pipework)	0.4513

Table 34: Fussell-Vesely importance analysis for hydrogen gas base case model

Event description	Fussell-Vesely importance
H_2 leak frequency (third party damage pipework) (all leak sizes)	0.7747
Mid-air permeability (5 $m^3/(h.m^2)$	0.68
Third party, gas not detected	0.6416
Ignition hydrogen (third party, internal, kitchen only)	0.4963
H_2 very large leak frequency (third party damage pipework)	0.4816

12.3 F-V Results – hydrogen (with EFVs) case

Table 35 below shows the five top importance variables for the hydrogen case with two EFVs. Although the top contributor is still the pipework third party damage leak frequency, it is notable that gas detection has fallen in importance. This can be explained by the introduction of the EFVs as effective risk reduction measures for large and very large leaks, decreasing the reliance on odorization as the key line of protection against ignited events. The frequency of a medium leak caused by third party damage to pipework is in the top five contributors in this case. This is indicative of the EFVs being effective for only large and very large leaks. The medium leak category is therefore contributing a significant proportion of the relative overall frequency of ignited events. The overall frequency of ignited events is lower than for the hydrogen base case. However, the frequency of ignited events from medium leaks is unchanged, therefore, this is relatively a more important factor.

Table 35: Fussell-Vesely importance analysis for hydrogen gas case + 2EFVs

Event description	**Fussell-Vesely importance**
H_2 leak frequency (third party damage pipework) (all leak sizes)	0.7306
H_2 medium leak frequency (third party damage pipework)	0.5444
Mid-air permeability (5 $m^3/(h.m^2)$)	0.5329
Third party, gas not detected	0.5009
Ignition hydrogen (third party, internal, whole downstairs)	0.408

13 Discussion and recommendations

13.1 Discussion

Table 32 above has already shown a comparison between the real world indicative average annual number of 12 injuries (HSE GSMR Data 2016-2020) and the QRA model predictions of 17 injuries for the natural gas case, 65 for the hydrogen unmitigated case and 16 injuries for the hydrogen gas case with two EFVs installed. The QRA model predictions are also compared below to HyDeploy data. Both comparisons suggest the QRA model is likely to be overestimating injuries, but for reasons that should not affect its ability to compare natural gas to hydrogen.

HyDeploy analysed a number of fire/explosion incidents which occurred between 2005 and 2015 [51] and Table 36 below presents the data categorised by number of injuries per ignited event and the proximity of these injuries to the ignition source.

Table 36: Gas Incident Injury Levels from HyDeploy analysis of incidents occurring between 2005 and 2015 [51] (Based on assumptions)

Ignited events categorised by no. of injuries and proximity of injured persons from ignition source	**Number of incidents**	**Approximate no. of injuries based on assumptions**
Ignited events causing zero injuries	15	-
Ignited events causing one injury (total)	*33*	*33*
Ignited events where injury occurs at source	17	17
Ignited events where injury occurs at source enclosure	11	11
Ignited events where injury occurs at adjacent enclosure	1	1
Ignited events where location of injury is unknown	4	4
Ignited events between one to three injuries (assumed two per incident) (total)	*20*	*40*
Ignited events where injuries occur at source	6	12
Ignited events where injuries occur at source enclosure	7	14
Ignited events where injuries occur externally	1	2
Ignited events where injuries occur at source and adjacent enclosure	1	2
Ignited events where injuries occur at adjacent property	2	4
Ignited events where injuries occur at source and adjacent property	1	2
Ignited events where injuries occur at source and externally	1	2
Ignited events where location of injuries is unknown	1	2
Ignited events causing over three injuries (assumed 4.5 per incident) (total)	*6*	*27*
Ignited events where injuries occur at source	3	13.5
Ignited events where injuries occur at source and adjacent property	1	4.5
Source and external	2	9
Ignited events causing unknown number of injuries	6	-
Approximate total number of injuries based on assumptions		100

Note:

1. ‘Source’ refers to the source of the explosion. ‘Source enclosure’ refers to the room in which the explosion originated. ‘Adjacent enclosure’ refers to an adjacent room within the same property within in which the explosion originated. ‘External’ refers external to the property. ‘Adjacent property’ refers to the property adjacent to where the explosion originated
2. The HyDeploy analysis categorises incidents into either ‘1 injury’ per incident, ‘between 1-3 injuries’ per incident or ‘over 3 injuries’ per incident. In order to calculate an approximate total number of injuries an assumption has been made about each of these categories. For the ‘1 injury’ category, 1 injury per incident has been assumed. For the ‘between 1-3 injuries’ category, 2 injuries per incident has been assumed. For the ‘over 3 injuries’ category, 4.5 injuries per incident has been assumed.

The above table shows that a majority of injuries from this real-world dataset are associated with being inside the originating property (67%) and only 27% of injuries are associated with the largest incidents. Whilst not entirely equivalent, this QRA shows a different consequence distribution i.e. 38% of injuries are associated with being inside the originating property and 59% come from the largest explosions. Together these indicate that this QRA is overestimating the impact of large explosions on adjacent properties. There are several likely reasons for this:

- The consequences model assumes a brick-built terraced property, chosen to represent the potential worst-case consequences due to their proximity to other properties
- The consequences model benchmarked on terraced housing overpredicts damage
- Large leaks are more likely to be smelled and reported by people external to the property. This could also lead to lower consequence as people would evacuate
- In practice, not everybody receives injury even after major damage to a property. Generally, there are a number who are uninjured or only lightly injured

To understand the number of incidents which occur in a variety of property types, Table 37 presents the HyDeploy incidents categorised by property type according to their analysis[51].

Table 37: Gas Incidents by Property type (HyDeploy analysis of incidents occurring between 2005-2015 [51])

Property type	Number of incidents	Percentage
Bungalow	14	18%
Multi-occupancy	12	15%
Terrace	25	31%
Semi-detached	19	24%
Detached	6	8%
Unknown	4	5%
Total	**80**	**100%**

This table shows that only 31% of gas explosions occurred within properties categorised as terraced houses.

This proportion of incidents occurring in terrace houses is close to the general proportion of terrace houses in England – the English Housing Survey 2018 [52] reports 28.4% of properties as terrace houses. Semi-detached house proportions also closely match each other (with 25.4% in the English Housing Survey) while the bungalow and detached house proportions are further apart from each other.

These data sources show that the number of incidents occurring in terrace houses are as may be expected based on housing stock levels. This does not imply that incident consequences will be the same in all property types.

Other property types, which are not in as close proximity to adjacent properties (with the exception of houses in multiple occupation) may be less likely to result in damage to adjacent properties and so would be expected to result in lower injury numbers per incident. Quantifying the relative reduction in injury level for detached/semi-detached houses compared to terraced houses would require full consequence analysis, currently outside the scope of this assessment.

Based on historic incidents, it is noted that explosions within detached properties resulting in demolition of adjacent properties is rare. There may be severe glass loss in adjacent properties, but structural failure is historically rare. Experimental evidence from the H100 SGN FIB tests [54], showed that with hydrogen at stoichiometric concentration the overpressure measured at five metres beyond the constrained structure was unlikely to cause major destruction.

Another consequence of this choice of terraced housing as a benchmark is to overpredict within the QRA the importance of those very rare very large explosions, as said above these are predicted to cause about 59% of injuries; this is much higher than would be reflected in reality. In practice predicting the frequency of these incidents precisely is effectively impossible, especially as the historical data is complicated by leaks from steel service pipes inside the property, which are now being replaced when discovered.

Tuning the model to account for the difference between predictions and historical data would require application of further assumptions about how different property types respond to incidents, which would introduce potential for further uncertainty. Instead, it is possible to consider these consequences in a qualitative manner to support the quantitative assessment.

Due to the limitations of the model, the absolute injuries predicted should be treated cautiously but there is confidence that the relative risks of injury associated with natural gas and hydrogen are representative, and in particular that the model confirms the beneficial effects of excess flow valves.

13.2 Recommended risk reduction measures from QRA

From the results outlined above, 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 at every meter point:

- One upstream of the meter installation[6]
- One located within the smart meter installation[7]

13.3 Safe management of hydrogen

This section outlines a number of recommendations to manage the safe use hydrogen from the safety assessment conducted. Whilst the effect of these observations has not been quantified within the risk estimation outlined in this report, these factors should be taken into account when considering the holistic risk profile associated with conveyance of hydrogen gas compared to natural gas.

13.3.1 External (or case by case checked) meter location

Currently, houses in Great Britain that are connected to the gas distribution network, have a meter installation located either internal or external to the property. Meter installations are known to be a common source of leaks within the domestic environment. Additionally, the piping connecting the ECV to the regulator just upstream of the meter, operates at a higher pressure than the rest of the

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[6] In practice, this could either be located between the meter and the ECV or upstream of the ECV in the service pipe or top tee. The further upstream the EFV is placed, the more protection it offers from potential uncontrolled leaks

[7] A specification for the smart meter EFV is currently being developed as part of Hy4Heat WP10

system downstream of the meter installation. Therefore, this is the part of the domestic gas system where the leak rate would be highest for a given hole size.

Locating meters externally reduces the likelihood of accumulation of flammable gas inside the property compared to meters located internally. This could be expected to lead to a reduction in risk as the potential for a hazardous situation to develop has been reduced.

The impact of meter location has not been quantitatively assessed in this study due to a lack of supporting data. However, from the FCO data recorded [6], it is known that around 30% of leaks originate from the meter installation. Whilst 99% of these leaks are tiny, it follows that due to the sheer number of leaks associated with the meter installation, there is a potential for larger leaks to develop if left unnoticed.

Therefore, meter location should be considered on a case-by-case basis as part of the engineering work required during any conversion. All meters shall be replaced with new hydrogen gas meters and shall be installed outside of the property. 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 and in a suitably ventilated location. For the purposes of a community trial, an under stairs cupboard should not be considered a 'suitably ventilated location'

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. This is to minimise the risk of householder tampering.

13.3.2 Ventilation

The QRA has considered three different levels of ventilation in domestic dwellings, the frequency distribution of which is based upon BRE data [22] (described in Section 4.3):

- Highly Sealed – Very air-tight constructions normally associated with mechanical ventilation where this system is malfunctioning i.e. with no natural continuous ventilation. Note: these houses are to be excluded from any community trial. (QRA assumed frequency of 4%)
- Moderately Sealed – Houses similar in construction to that of the 'HyStreet' where Hy4Heat experiments where undertaken, with additional continuous ventilation present. (QRA assumed frequency of 37%)
- 'Leaky' – Houses built pre-1980s, with floorboards, chimneys etc. that are well ventilated enough to not require additional vents (QRA assumed frequency of 59%)

Given the role that ventilation takes in preventing against build-up of flammable atmosphere, it is considered appropriate to ensure that all properties involved in a community trial have ventilation levels that are, as a minimum, equivalent to the 'moderately sealed' house.

To understand the size of the vents that would be required in such houses, it is important to note that the leaks of concern are medium-sized leaks (those in the range 3 mm – 7 mm), which EFVs do not provide protection against.

Tests performed at the 'HyStreet' houses, at DNV GL Spadeadam [47], indicated that a vent area of 10,000 mm^2 located at ceiling height was effective at reducing hydrogen concentrations for medium-sized leaks[8].

It is recommended that rooms with gas appliances installed (e.g. boilers, hobs) or containing extensive pipe work should have vents with equivalent area of 10,000 mm^2, located as close to the ceiling level as possible and no more than 500 mm below ceiling level.

To give confidence that this vent area is not unreasonable from a practical perspective, it is noted that the minimum equivalent area of background ventilators for single-storey dwellings required by the 2021 legislative draft of English and Welsh Building Regulations Approved Document F [58] is 10,000 mm^2.Scottish Regulations require slightly larger areas. However, it should be noted that these regulations were not introduced with the intention of controlling the build-up of flammable gas.

If the property currently relies substantially upon purge ventilation using a local mechanical fan (as is common in bathrooms and kitchens), then the louvres on this fan (if fitted) shall be fitted with a stop to ensure a minimum of 10,000 mm^2 of ventilation at all times. The continuous ventilation fitted alongside such fans is often inadequate for this purpose.

No additional ventilation is suggested in two-storey property hallways containing pipework. Such zones are considered inherently well ventilated.

Particular care should also be taken with regard to the compliance of undercutting of internal doors in accordance with the 2021 draft of Building Regulations Approved Document F [58].

Experiments undertaken by DNV GL [47] showed that the addition of cupboard vents reduce the concentration of hydrogen recorded 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, venting in any void should now be made mandatory in accordance with Building Regulations ADJ or regional equivalent (i.e. exemption should not be granted to manufacturers for hydrogen appliances).

Experiments were also undertaken in the basement of the property, in which air bricks were added to create additional ventilation. These tests showed less conclusive results, with some smaller vent tests recording an increase in the maximum hydrogen concentration compared to tests with no vents. 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.

13.3.3 Odorant

The model assumes that the same odorant is used for hydrogen as is currently used for natural gas. Therefore, it is important that this is implemented as a risk reduction measure in any community trial.

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[8] Tests were performed for equivalent hole sizes of 5.1mm and 7.2mm with and without ceiling vents present. For the 7.2mm hole size, without a vent present, the maximum hydrogen concentration recorded was 32% at the high point of the kitchen. With the addition of a 10,000mm^2 ceiling vent, the maximum concentration recorded was 17% at the high point of the kitchen. For the 5.1mm hole size, without a vent present, the maximum hydrogen concentration recorded was 22% at the high point of the kitchen. With the addition of a 10,000mm^2 ceiling vent, the maximum concentration recorded was 8% at the high point of the kitchen.

13.3.4 Appliance safety

Uncontrolled gas releases arising from appliances which are faulty or incorrectly operated are not directly considered within the QRA.

In the event of any future conversion to a hydrogen gas system, appliances would need to be replaced with those suitable for use with hydrogen gas. Such appliances will be newly developed, and so it is envisaged that all of these appliances will contain FFDs.

As discussed previously (sections 3.5.1, 8.2), there are currently a significant number of ageing appliances in use within the GB housing stock. Replacement of these appliances would effectively be an enforced modernisation for those properties containing old appliances without FFD.

This can reasonably be expected to contribute a significant risk reduction by reducing the potential for incidents arising from appliances that are left on and unlit.

13.3.5 Gas detection and alarms

Whilst odorization of gas performs very effectively to warn against gas releases, it does not provide warning for the small proportion of people who are unable to smell the odorant. Audible alarms would help address this and should be available to those consumers who are unable to smell.

13.3.6 Polyethylene (PE) service pipes

This assessment focuses on leaks downstream of the ECV and excludes leaks which arise from damage to service pipes. However, it is noted that damage to service pipes is a common cause of incidents as reported under GSMR.

In the event of any community trial, work will need to be undertaken to replace meter installations. Whilst undertaking this work, it would be prudent to also replace any existing steel service pipes with more robust PE pipe. Whilst not eliminating the risk entirely, this would be expected to reduce the likelihood of a leak arising from a service pipe.

13.3.7 CO poisoning

The QRA detailed in this report does not consider the risk arising from carbon monoxide (CO) poisoning due to incomplete combustion of fuel within household appliances. This has been excluded from the QRA, so that a direct comparison of the risk associated with fire and explosion effects can be made between the two gases.

The number of fatalities associated with CO poisoning has been falling significantly in recent years and the latest natural gas CO fatality was in 2015. Injuries are higher and currently, there are around 200 injuries per year associated with carbon monoxide poisoning in Great Britain [43]. These injuries are due to CO poisoning from a range of causes, including faulty natural gas appliances, LPG appliances and house fires.

The absence of carbon within hydrogen gas would effectively eliminate the risk of CO poisoning from malfunctioning natural gas appliances in the event of any future conversion to a hydrogen gas system.

Although the QRA does not take account of this effect, it is important to note that, in practice, this would translate to a reduction in this part of the current risk associated with domestic gas conveyance.

It is important to note that the risk of CO poisoning due to causes other than the distribution of natural gas, such as, house fires or liquified petroleum gas (LPG) appliances would not be reduced.

13.3.8 Noise

Unfortunately, even very small hydrogen ignitions can be disproportionately noisy, this may need to be addressed in consumer literature at an appropriate time.

14 Summary of Recommendations

The following risk reduction measures are recommended to 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 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
- EFV to limit the flow rate to 20m^3/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
  b. Immediately after the ECV
- Hydrogen gas meter containing an integrated EFV to limit the flow rate to <20m^3/hr or set at a lower value that is related and proportionate to the maximum usage of appliances installed within the individual property
- 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 mm2, 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.
     - Whilst the QRA results do incorporate a small proportion of houses with ventilation levels equivalent to less than this 10,000 mm^2, a conservative approach has been taken with respect to this recommendation.
     - 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 should not be used. The use of stops to ensure provision of at least 10,000 mm^2 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 the ECV):

  a. 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.

  b. A tightness test shall be undertaken to current natural gas standards prior to conversion to hydrogen 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.

  c. 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^3/hr (expected to be exclusively non-domestic), then a conventional interlock automatic isolation valve (AIV) 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

- Hydrogen detection alarms should be installed where residents are unable to smell the gas odorant or request such a device

- The same odorant with the same effectiveness is to be added to hydrogen as is currently used for natural gas (Odorant NB)

- 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 (e.g. the potential for flames to be less visible)

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

Of these risk reduction measures; the risk reduction impact of the excess flow valves has been quantitatively assessed, using the QRA model, as described in this report. The remaining measures have been discussed qualitatively in sections 8 and 13.3, and are informed by experimental data, engineering judgement and literature review.

The excess flow valves only provide protection against large leaks. To manage the risk associated with the full range of leak sizes, this holistic package is recommended to provide the appropriate level of risk reduction, based on engineering judgement and best practice as outlined in section 13.3.

14.1 Wider safety management

The following sections detail recommended good practice for wider safety management within any community trial.

14.1.1 Competence and training

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

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

14.1.2 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, safety case and 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.

These measures are considered to be an appropriate starting point for defining the safety requirements for wider network conversion. Beyond early community trials, further work is recommended to develop safety measures specific to premise types currently outside the scope of this assessment.

15 Open items

This section details a number of open items and recommendations for further work.

No.	Item	Discussion
1.	Ignition probability model assumption of maximum steady-state concentration and contact factor of one	The intent of the Hy4Heat QRA (and its supporting evidence/modelling reports e.g. the Gas Dispersion Modelling Report [19] and Consequence Modelling Report [5]) is to provide a safety assessment which strikes a balance between complexity (and therefore effort to develop models) and usability, aiming to use relatively simple but robust models where practicable, whilst recognising their limitations and explicitly discussing the effect of these limitations on the end output. The ignition model approach is aligned with the approach used for dispersion modelling within the Gas Dispersion Modelling Report [19] and the Consequence Modelling Report [5]. Although there are differences between the physical properties of natural gas and hydrogen which result in differences in the way dispersion occurs, it is difficult to directly link the effect of these to changes in ignition probability. This is primarily due to: • the greatly increased complexity of quantifying the effect of concentration-dependency (and therefore, by extension, time-dependency) on ignition probabilities; • the lack of robust and statistically significant supporting data which would support the development of the above; and • the variability in the three-dimensional location of both ignition sources within the home and the potential leak locations; These factors would all contribute to a rapid increase in uncertainty in the model if they were to be developed in this QRA report. Increase in model granularity and detail (and the associated real *and* perceived benefits) must be balanced with inherent disbenefits arising from estimating values which are largely or wholly reliant on engineering judgement. Considered at a high level, ease of ignition (and therefore ignition probability for a specific scenario) increases the closer a flammable gas mixture gets to the concentration that represents an ideal equivalence ratio for its ignition. Moving away from that ideal equivalence ratio results in the mixture becoming either too fuel-lean or too fuel-rich. This means that adjusting ignition probabilities for exact concentrations would have the effect of both increasing and decreasing probabilities, depending on the exact scenario being considered. The net impact on the overall likelihood is unknown but its significance is anticipated to be relatively minor in the context of the results of the *comparative* QRA being performed. See open item 5 for further discussion of the effect of gas concentration on ignition energy. The use of maximum steady state concentrations for the consequence modelling means that the worst-case consequences are derived when modelling deflagration effects. If ignition were to occur prior to a gas leak reaching its maximum steady state, it is plausible that hydrogen may have accumulated faster than natural gas when comparing identical scenarios. However, the effects of this potential non-conservatism (from a comparative likelihood perspective) are likely to be minimal given that hydrogen is likely to ignite earlier than natural gas (due to its significantly lower MIE) and due to the significantly reduced physical consequence (and therefore reduced number of injuries/fatalities).

No.	Item	Discussion
		As described above, the three-dimensional variability of where ignition might occur within the home is not considered in detail when deriving ignition probabilities. However, it is taken into account within the Consequence Modelling Report [5, section 2.3] when considering the effect of ignition location on explosion consequence due to its impact on parameters such as explosion overpressure, extent of glass throw, and similar. It is considered that the current model (and accompanying discussion) is appropriate for the goal of comparing the safety of natural gas and hydrogen for the purpose of moving to community trials. The exhaustive screening exercise followed by targeted quantifying of key ignition contributors (see open item 4) means that, whilst the model does not capture all real-life considerations and phenomena, it provides an appropriate basis for a *comparative* QRA. The development of these model refinements within the current Hy4Heat QRA report was judged to be disproportionate relative to the benefits gained and the contribution towards achieving the end goal of the Hy4Heat.
2.	No cross-referencing of hydrogen ignition model with historic data (domestic and industrial)	The current hydrogen ignition probability model has necessarily relied upon engineering judgement more heavily than the one for methane. This is due to the lack of historic data from a domestic environment which could be used to validate the model, as roll-out of hydrogen in the home is a novel proposal. There exists historic hydrogen fire and explosion data from industrial applications from e.g. steam methane reforming, coal gasification, electrolysis, etc, to manufacture hydrogen; use of hydrogen as a fuel in the aerospace industry; and the generation of hydrogen during some accident conditions in nuclear power stations, to name a few. However, a common aspect to all these applications is the very different environment in which hydrogen is handled. For the reasons described in section 5.1, this data is not directly applicable to the QRA model. In future, data collected from the proposed hydrogen community trials (and eventual wider roll-out, if implemented) could be collected and used to update and refine the QRA model in an iterative manner to achieve continuous improvement in the model. There are very considerable quantities of reputable data on the comparative fires and explosions arising from natural gas and town gas (50 %H_2 v/v). Natural gas has flammable limits 5-15% , town gas 4-44% and hydrogen 5-74%. The stoichiometric mixtures for natural gas, town gas and hydrogen are 10%, 20-22% and 29% respectively. The flame speed of town gas also lays roughly slightly less halfway between nat gas and hydrogen. 13 million homes and 44 million appliances were converted from town gas to natural gas with no change in injury or fire/explosion rates from 1968 to 1977; this data offers real potential to shed further light on the risks potentially arising from any large scale re-purposing of the gas grid to hydrogen.
3.	Perceived discrepancy between historic natural gas incident data and QRA natural gas ignition model numbers	Analysis of gas industry reported incident data obtained from the HSE shows that over the period 2012-2016 there were on average 52.2 fires and explosions per year in Great Britain associated with natural gas [1]. No details are available regarding the pre-existing atmosphere in those incidents. As described in the Gas Escape Frequency and Magnitude Assessment [6], the GSMR mandates that gas in building (GIB) incidents are recorded whenever they occur, measuring (where practicable) the concentration of gas in the home. Over the

No.	Item	Discussion
		same period as the fires and explosions described above, there were 297 GSMR GIB 'reportable' incidents. These are incidents where an atmosphere with greater than 20% of the lower explosive limit (LEL) of natural gas was reported in the property. This compares to approximately 12,000 events per year where any level of GIB was reported [1]. It was therefore concluded that the number of occasions where the atmosphere in a building in Great Britain exceeded the LEL of natural gas per annum between 2012 and 2016 must be: • greater than 52.2 (because a flammable/explosive atmosphere is necessary for a fire/explosion event to take place); and • fewer than 349.2 (297+52.2, i.e. the sum of the reportable GIB incidents (where an explosive atmosphere may have existed, but there was no fire/explosion) and fire/explosion incidents). In the absence of any further information being feasibly obtainable, the median of these limits, 200.7, served as an initial estimate of the number of occasions per annum in Great Britain where a flammable atmosphere occurs. Therefore, the overall likelihood of ignition of natural gas had to be: • higher than 0.15 (52.2 / 349.2 = 15% = 0.15) – *and* • lower than 1.00 (349.2 / 349.2 = 100% = 1.00) with the average (flammable atmospheres existing halfway between 52.2 and 349.2 times per year) being 0.26. This was consistent with the industry accepted value of 0.25 i.e. ignition occurring in one of every four GIB events. When contrasted with the natural gas ignition model provided in this report (proposing overall ignition likelihoods of approximately 0.1 for natural gas), there is an apparent discrepancy. However, this is explained by looking at the basis of the data in more detail. The value of 0.25 is the overall likelihood ignition of past events when including the totality of all the event nodes in a potential explosion scenario i.e. human behaviour such as opening windows, detection of gas, etc. The ignition model in this report proposes approximately 0.1 as the natural gas ignition probability specifically for the ignition event node within the overall QRA event trees i.e. ignition independent of human actions and other event nodes. As a result, these two values are actually for two separate parameters, and therefore it is normal for them to not match. Nevertheless, it is acknowledged that the actual ignition probability for both gases is likely to be somewhat higher for concentrations close to stoichiometric. As discussed under open item #1, an area of further refinement for the model is the development of ignition probabilities as a function of flammable gas concentration. This would potentially also allow closer alignment of the model results with real life past data for natural gas, whilst bearing in mind the discussion above describing why for natural gas this data should not be calibrated against the fraction of GIB events resulting in fire/explosion. The GIB data also is often opaque on the precise source of the leak e.g. appliance, or service pipe within or exterior to the property.

No.	Item	Discussion
4.	Low granularity of quantitative ignition model and exclusion of certain known ignition sources	It is important to note that screening out from further assessment in the QRA did not always mean that the source was judged to not be credible / reasonably foreseeable as a hazard. This was a particularly important point when considering the screening out of hazards which have, in the past, been shown to have led to natural gas incidents and accidents. Instead, the QRA was focused on the key ignition likelihood contributors which are generally those hazards which pose a moderate or high risk, and/or posed a significant difference when comparing natural gas to hydrogen, ideally quantifiable with a reasonable minimum level of certainty. There are many relatively weak ignition sources which contribute a very small (but non-zero) risk which were too difficult to model in an appropriate way. Estimating such low probabilities is difficult from numerous perspectives, and it was important that the assessment did not 'over-reach' by assigning and using numbers which are very uncertain but strongly influence the end outcome of the model (even if accompanying sensitivity analysis were provided). The effect of this was further mitigated by ensuring the ignition analysis captured all ignition sources where there may be a significant difference between natural gas and hydrogen i.e. where differences between the behaviour of the two gases are most likely). It is therefore important to note that the ignition probabilities developed within this report are judged to be appropriate for a comparative QRA, but <u>not</u> for an absolute hydrogen or natural gas QRA. Two potential areas of further work have been identified: • Applying Bayesian statistics to appropriately estimate the risk contributions of these low frequency events and build an ignition model which more closely reflects real life • Applying a detailed human behaviour model with the help of human factors specialists to better model human influenced aspects of the fault trees and event trees, including empirical experiments to do with task analysis (related not just to ignition but also some of the other event nodes within the overall event trees) The potential benefits of these two areas of further work should be contrasted with the accompanying effort required.
5.	Ignition treated as probabilistic (rather than threshold) phenomenon	As discussed in section 5.3.1 and illustrated in Figure 6, most data on methane and hydrogen MIEs is represented as a single data point (and therefore energy). As the name implies, this is the *minimum* energy that an ignition source needs to provide the gas before ignition can theoretically occur and is usually at (or near) a stoichiometric concentration. In practice, the actual ignition energy of a gas in a scenario is likely to be higher than the MIE, and is sensitive to a range of parameters, the main one being concentration in air. However, even MIE is increasingly no longer seen as a single threshold value (even under the ideal conditions used to measure MIE), but rather a statistical event. This is underpinned by literature such as that found in the aerospace industry, best summarised by the following excerpt from a paper [45] by the California Institute of Technology and the aerospace company Boeing: *"This view of the ignition, where the MIE is considered to be a single threshold value defined so that ignition always occurs when the ignition source is above that energy level, is the traditional viewpoint in combustion science and extensive tabulations of this kind of MIE data are available. However, in the aviation safety industry, a different*

No.	Item	Discussion
		approach to ignition characterization is being used that is more consistent with experimental observations and statistical treatment of engineering test data." Research conducted at Loughborough University [44, Chapter 4] provides some further information for comparing methane and hydrogen ignition probabilities. Arguably the most interesting data comes from tables 4.6 to 4.12. The experimental ignition probability tables show that sparks of energy up to 2 mJ (i.e. an energy already *significantly* higher than ~0.29 mJ methane MIE) did not ignite the methane in all cases (particularly for gas concentrations that were far from the stoichiometric concentration), and only ~50% of the time even for the stoichiometric concentration. Similarly, sparks of an energy level significantly above (0.5 mJ-4 mJ) that of the ~0.02 mJ hydrogen MIE were still often unable to ignite the hydrogen mixture at stoichiometric concentrations. For the reasons briefly outlined in the above discussion, ignition within this report has been treated as a probabilistic event, aiming to coarsely address the variability in actual ignition success and the low control of ignition sources in a domestic environment. A significant opportunity for improvement of the ignition model developed in this report would be the development of detailed probability distributions for each ignition source considered, graded by gas concentration and underpinned by a more extensive literature review.
6.	Evidence for hydrogen being comparable to natural gas with regards to material degradation in a domestic setting (i.e. low pressure, copper piping)	A key assumption of this assessment is that hydrogen would not cause accelerated material degradation compared to natural gas in a domestic setting. And, therefore, there is no change in the likelihood of an initiating leak between the two gases. This is considered a reasonable assumption based on theory. However, there is limited published evidence regarding the use of hydrogen in low pressure networks to reference. Note that HyDeploy have undertaken experiments to prove this effect, however, Hy4Heat have not had access to these. At low pressures, evidence from town gas (both historical and current in Hong Kong and Singapore) and the hydrogen industry would indicate this risk to be very low. This area is still undergoing discussion within the industry with further research on the topic being necessary. Operators will need to specifically consider which materials will be utilised in their individual trials and make a case on this specific basis. Cast iron should not be considered for use with hydrogen. However, the presence of cast iron within domestic properties is very rare. The hyh4heat annex specifies that the pipework inspection survey undertaken as part of any community trial should remove any cast iron components.
7.	Probability of gas detection	Within the QRA, a number of assumptions are made regarding the probability of detection of different types of leaks by different population groups (householder, passer-by, neighbour). These assumptions are based on engineering judgement, rather than concrete data analysis. Given the low number of incidents, the available data is insufficient to evaluate a specific probability for each type of detection.

No.	Item	Discussion
		It is acknowledged that the assumed probability associated with gas detection of large leaks by neighbours could be considered high. However, it is known that odorisation does result in the reporting /identification and repair of almost 100% of gas leaks; the sum of detection by the householder and neighbour should reflect this. It is possible that the assumed probability of detection and action taken by householders themselves in response to large leaks is not high enough (particularly as most often these leaks are due to damage created by a person) but it is the combination of the two types of detection which is important. There is anecdotal evidence from GDNOs of visitors, postmen, carers etc. who raise the alarm (or persuade the householder to raise the alarm) and in this context suggest a continuum between residents and neighbours, the contribution of which has not been able to be fully reflected within the QRA. It is recommended that further data collection and analysis be carried out to investigate the probability that a gas leak is detected in time to prevent an incident. This should provide a higher level of confidence in the values to be used here. Given the nature and rarity of gas incidents, any data collection undertaken would need to be an extensive exercise. Data collection and incident reporting (e.g. by GDNOs) may need to be improved to provide more confidence for future use in order to reduce the uncertainty inherent in the current evaluation. The current data collection regime may not be sufficient or appropriate to use as a basis for future risk assessments.
8.	Behavioural Response Assumptions	Within the QRA an assumption is made regarding behavioural response to gas leaks, in particular that 95% of the time extra ventilation is provided. It is important to note that this assumption is based on engineering judgement. There are about 420,000 gas leaks per year involving the leakage of natural gas from a hole in a pipe or failed joint. About 3% (FCO data) are of a size large enough to create a significant risk. This will include both very large and intermediate leaks (as defined above), equating to about 12,600 such leaks per year, leading to about 30 fires and explosions per year. This means only 0.23% of leaks are not correctly addressed before an explosion occurs (i.e. a window and door are opened and the gas turned off). In practice about 10 of these 30 are totally unexpected e.g. occurring as secondary incidents from house fires so even this number of 0.23% is cautious, and a high percentage of the remainder are full bore leaks [6] It is recommended that further data collection and analysis be carried out to investigate the likelihood that people respond in this manner when confronted with a gas leak and, hence, provide a higher level of confidence in the values to be used here. It should be noted that this 0.23% does not directly relate to a single contributor described within the QRA. The 99.77% encompasses scenarios where users took action before reaching a flammable atmosphere and also scenarios where a flammable atmosphere was reached but an ignition did not occur (this implies some action was taken at some point after flammable atmosphere was reached). The QRA has a probability associated with people responding to the smell of gas in time to prevent a flammable atmosphere (i.e. by opening windows or closing ECV) and then a probability associated with ignition given a flammable atmosphere is present. Therefore, it is not possible to directly compare this in a quantitative manner to the QRA. Instead, the following discusses the qualitative judgement which supports the numerical assumptions made in the assessment. Out of each 100 reported gas leaks about 95 reports are made by the person directly involved with the leak (e.g. the householder or 3rd party creator of damage) and 5 are from neighbours, passers-by etc who smell gas. This is supported by

No.	Item	Discussion
		the large number of contract call outs from GDNO's to locksmiths to gain entry to empty or non-responsive property after a PRE from a concerned passer-by. Only a very small number (i.e. the 0.23% detailed above) are left without a response being made. The relative straightforward response required to detection of a gas leak, and the public perception of danger that is associated with a gas leak explains why this level of reliability can be higher than might more commonly be used in high hazard installations. The situation is very different to that on a chemical process plant, where the scale and complexity of the plant can make leak identification a challenge. In the case of a domestic leak, there is only one flammable gas, its smell is well known, the action to take is simple and understandable. All of the evidence supports the theory that at low pressures (<75 mbarg) and certainly below 20 mbarg leaks are independent of the gas being conveyed. As hydrogen will be odorised identically to natural gas it will be expected that leaks will be created and reported in an identical fashion. Given the nature and rarity of gas incidents, any data collection undertaken would need to be an extensive exercise. As above, data collection and incident reporting (e.g. by GDNOs) may need to be improved to provide more confidence for future use in order to reduce the uncertainty inherent in the current evaluation. The current data collection regime may not be sufficient or appropriate to use as a basis for future risk assessments.
9.	Time taken to hazardous concentrations	The QRA assumes that there is no significant difference in the time available to respond to a gas leak for either methane or hydrogen. This is based largely on engineering judgement as set out in section 6.2.3. Gas leaks are essentially from two sources: 1) Caused by 3rd parties. These are of random size and currently can produce leaks up to about 20m3/h of natural gas if the leak is full bore, depending upon the meter type, the length of the service pipe and the pressure in the main. If a small or medium leak, the damage may not be immediately obvious, but (certainly after fitting of an excess flow valve) the gas concentration will rise fairly slowly over the period of tens of minutes to an hour. The likelihood of ignition will be dependent upon the occupancy after creation of the leak. High occupancy will increase the chance of detection by smell but also increase the likelihood of ignition. If the property is empty the likelihood of ignition is probably low, but this will depend upon whether the central heating has been left on. If the property is empty for some time, there is an increased likelihood of the gas not igniting and being smelt by a neighbour or other visitor to the vicinity of the property. 2)Spontaneous by corrosion or other means. These are nearly always very small leaks that become progressively worse with time; those extremely few large events are always one-off. Again, the likelihood of ignition will be dependent upon the occupancy after creation of the leak, but (as said before) the leak will usually start off very small. High occupancy will increase the chance of detection by smell but also increase the likelihood of ignition. If the property is empty the likelihood of ignition is probably low, but this will depend upon whether the central heating has been left on. If the property is empty for some time,

No.	Item	Discussion
		there is an increased likelihood of the gas not igniting and being smelt by a neighbour or other visitor to the vicinity of the property. It can be seen that the likelihood of a leak followed by ignition is dependent upon not only the size of the leak, but rate of local ventilation and time. A limitation of the QRA model is that the time-dependency of these incidents has been discounted and a steady-state assessment has been undertaken. Time-dependency adds a further layer of uncertainty and there is insufficient data available to derive relevant assumptions surrounding the time element of how these incidents take place. This time-dependency has been qualitatively assessed, as outlined in section 6 and within the ignition assessment (5.3.3). There is insufficient data to unravel these issues which only occur roughly 20-30 times per year i.e. 1 fire per million homes per year. It is the rarity of these events in a domestic environment that make them difficult to understand, especially as a high proportion (perhaps 1/3rd) are malign or criminally negligent. The final complication is that the QRA itself does not reflect some of the incidents that arise. For example, flammable gas explosions during whole house fires (about 1 injury incident per year) and boiler explosions (about 1 injury incident per year). Gas release from unlit hobs due to absence of flame supervision devices (about 5 injury incident per year) are also excluded. There will always be a level of uncertainty inherent in the data and the approach taken to inform a risk assessment; it is because of this, that this QRA is essentially designed to be quantitatively comparative. The intent of this assessment is not to address the uncertainty but to highlight and reflect its implications on the comparative assessment and evaluate its significance and influence on the conclusion of these results
10.	Potential for detonation	Further work should be carried out on ignition in cupboards, adjacent rooms etc. to improve understanding of flame acceleration affected by congestion and confinement. And to investigate the potential for detonation arising from these types of ignitions.
11.	Consequences arising from detonation	Further work should be carried out to address the lack of understanding of the external consequences of detonation.

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Appendices

Appendix A – Current incident data

The below table is a list of the incidents which caused injury in the past four years (Apr-16 to Mar-20) as recorded by the HSE under the GSMR. There is a total of 62 incidents i.e. about 15 per year.

The summary cause column outlines the likely causes of the incidents given the information available. It gives an understanding that the largest cause of injuries is hobs (almost certainly exclusively without flame failure devices) followed by third party damage to pipework.

Also included are the levels of protection which should be helpful at addressing these risks. These include excess flow valves, external meters, and new hydrogen appliances. On some occasions where the leak may be modest in size, and the effectiveness of the EFV is in doubt a question mark has been added. In a few instances (about two incidents per year) it is not obvious that any level of protection can prevent the incident. These are likely to be small or modest in size (as by definition they have not tripped the EFV).

Key	
Text Colour	**Description**
Red text	Incident due to natural gas escape from pipework or meter installation
Green text	Incidents not due to natural gas escape from network
Orange text	Incidents caused by lack of FFD
Blue text	Incident caused by independent contractor
Black text	Miscellaneous incident cause

Date	**Location**	**Incident**	**Summary cause**	**Suggested level of protection**
21/12/16	Downstream	Explosion after damage by power tool – disconnected 2017/12633	Third party	None
27/05/16	Downstream	Explosion traced to hole in pipe work under boiler – 2016/253672	Third party	None
16/01/17	Downstream	Tampering of gas installation caused explosion – 2017/62259	Third party	EFV
05/10/17	Downstream	Explosion after pipe damage – isolated – 2017/386870	Third party	EFV
19/02/18	Downstream	Damaged internal pipework – explosion, service capped – 2018/86170	Third party	EFV ?
25/01/2019	Downstream	Small explosion as a result of gas leak from internal pipework – 2019/59392	Corrosion	None

Date	Location	Incident	Summary cause	Suggested level of protection
23/03/2019	Downstream	Explosion in property traced to internal meter cupboard – 2019/174942	Third party ?	Ext meters
01/04/16	Downstream	Explosion in kitchen – interference on copper outlet – 2016/173485	Third party	EFV
02/04/16	Downstream	Explosion possibly due to third party interference – 2016/292400	Third party	EFV
18/10/17	Downstream	ECV left open, pipework left uncapped, explosion – 2017/415038	Third party	EFV
22/12/17	Downstream	Gas explosion – deliberate damage to service – 2018/32489	Third party	EFV
15/03/18	Downstream	Gas explosion – third party interference – 2018/119626	Third party	EFV
04/07/17	Downstream	House fire caused by hole in cooker flex – disconnected – 2017/300500	Corrosion	None
13/03/2019	Downstream	Explosion from open end copper pipe found in property – capped – 2019/100272	Third Party	EFV
27/12/2018	Downstream	Single fatality – explosion likely cause was leakage on internal pipework – 2019/107059	Corrosion	None
11/12/17	Downstream	Internal pipe joint failure, gas explosion – house collapsed, two persons injured, one killed – 201853857	Corrosion	EFV ?
23/03/2019	Service Failure	Explosion in area of gas installation in the flat – 2019/133034	Third party ?	Ext meters
18/04/2019	Downstream	Explosion whilst removing a gas meter causing burns to IP – secured – 2019/161150	Third party	Ext meters
16/12/2019	Downstream	Explosion in property caused by damaged internal pipe ignited by cigarette lighter – 2020/6150	Third party	None
16/12/2019	Downstream	Explosion caused by leaking gas from open ended flexible cooker hose – isolated – 2020/53041	Third party ?	EFV ?
12/10/16	Downstream	Ignition whilst relocating gas meter – capped – 2016/444075	Third party	Ext meters
05/03/17	Downstream	Failure of rubber hose on gas cooker – 2017/122386	Corrosion	None
20/12/16	Downstream	Gas ignited by SGN op soldering in utility room – 2017/15735	Third party	None
02/05/16	Downstream	Source located in kitchen – cause undetermined - 2016/219314	??	None

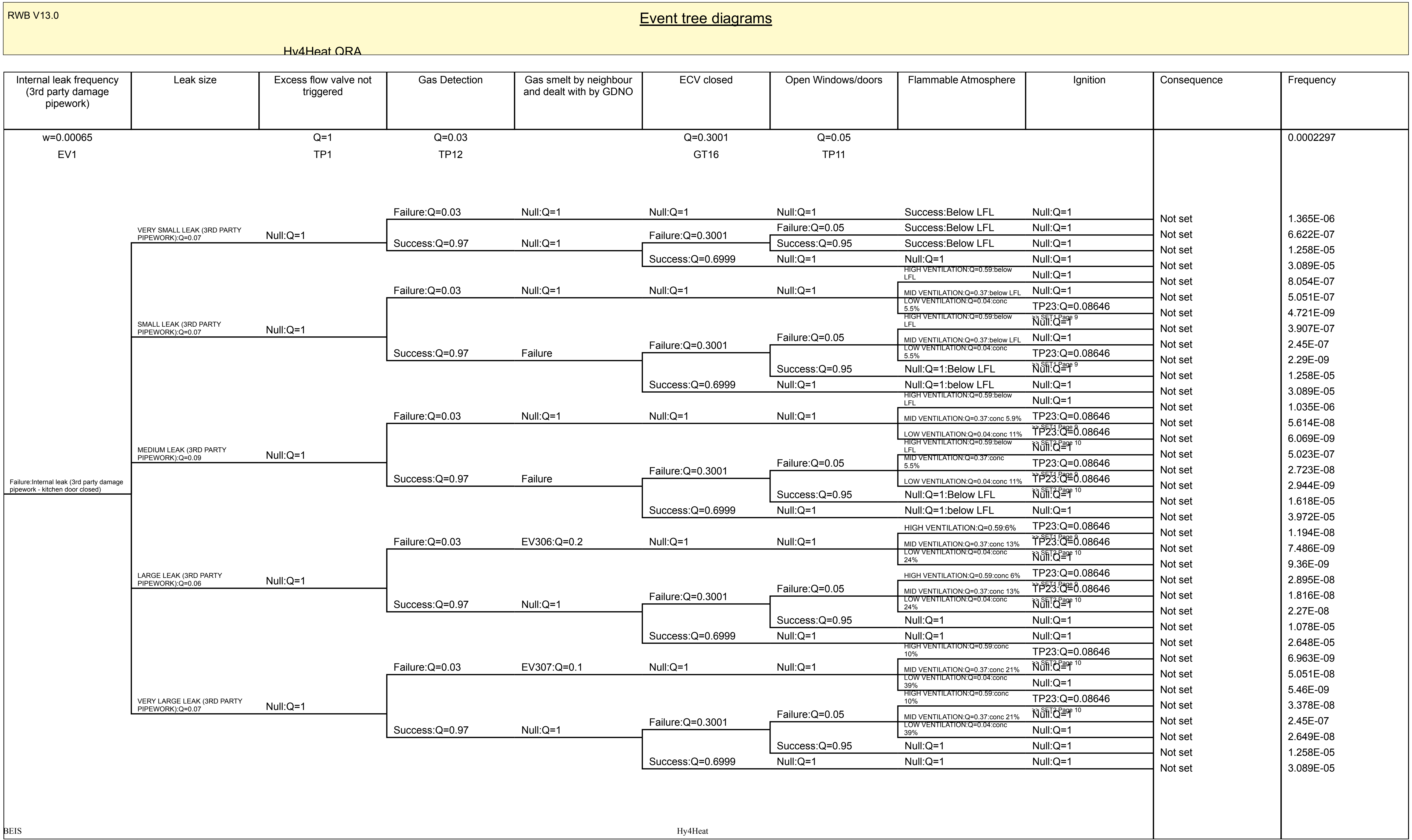
Date	Location	Incident	Summary cause	Suggested level of protection
11/06/2018	Downstream	Explosion – isolated, but not due to gas – 2018/226040	NA	
14/01/2019	Downstream	Explosion in property but not caused by a release from the network – 2019/39386	NA	
23/12/2019	Downstream	Explosion in property – Root cause undetermined but no network escape – 2020/31857	NA	
18/09/16	Downstream	Possible cause was fire from oxygen tanks in lounge – 2016/390208	NA	
07/01/18	Downstream	House fire – gas hob and cooker left on – service capped – 2018/18434	House fire	EFV
10/02/17	Downstream	House fire – disconnected – 2017/277045	House fire	EFV
19/04/17	Downstream	House fire – gas leak unconfirmed – isolated – 2017/194693	House fire	EFV
09/07/17	Downstream	House fire causing ignition of gas – disconnected – 2017/301302	House fire	EFV
30/06/16	Downstream	Small undetermined explosion from cooker hob - 2016/298932	Hob	New H_2 appliances
18/08/16	Downstream	Cooker rings left on unlit causing small explosion - 2016/379300	Hob	New H_2 appliances
03/11/16	Downstream	Cooker hob gas tap failed to light - Explosion - 2016/469799	Hob	New H_2 appliances
09/11/16	Downstream	Explosion - Gas rings possibly left on long time - 2016/466873	Hob	New H_2 appliances
02/02/18	Downstream	Gas cooker explosion - Capped - 2018/72425	Hob	New H_2 appliances
12/03/18	Downstream	Explosion - Likely due to gas hob - No leakage found - 2018/130521	Hob	New H_2 appliances
13/05/2018	Downstream	Gas hob turned but not lit, leading to explosion - Capped - 2018/180432	Hob	New H_2 appliances
12/09/2018	Downstream	Gas cooker left on; light sparked causing explosion - Disconnected - 2018/311561	Hob	New H_2 appliances
26/09/16	Downstream	Cooker controls left in on position causing ignition - 2016/396047	Hob	New H_2 appliances
09/01/17	Downstream	Cooker control tap left in on position unlit - 2017/54123	Hob	New H_2 appliances
05/01/18	Downstream	Unlit cooker hob leaking gas - Ignited, capped - 2018/225886	Hob	New H_2 appliances

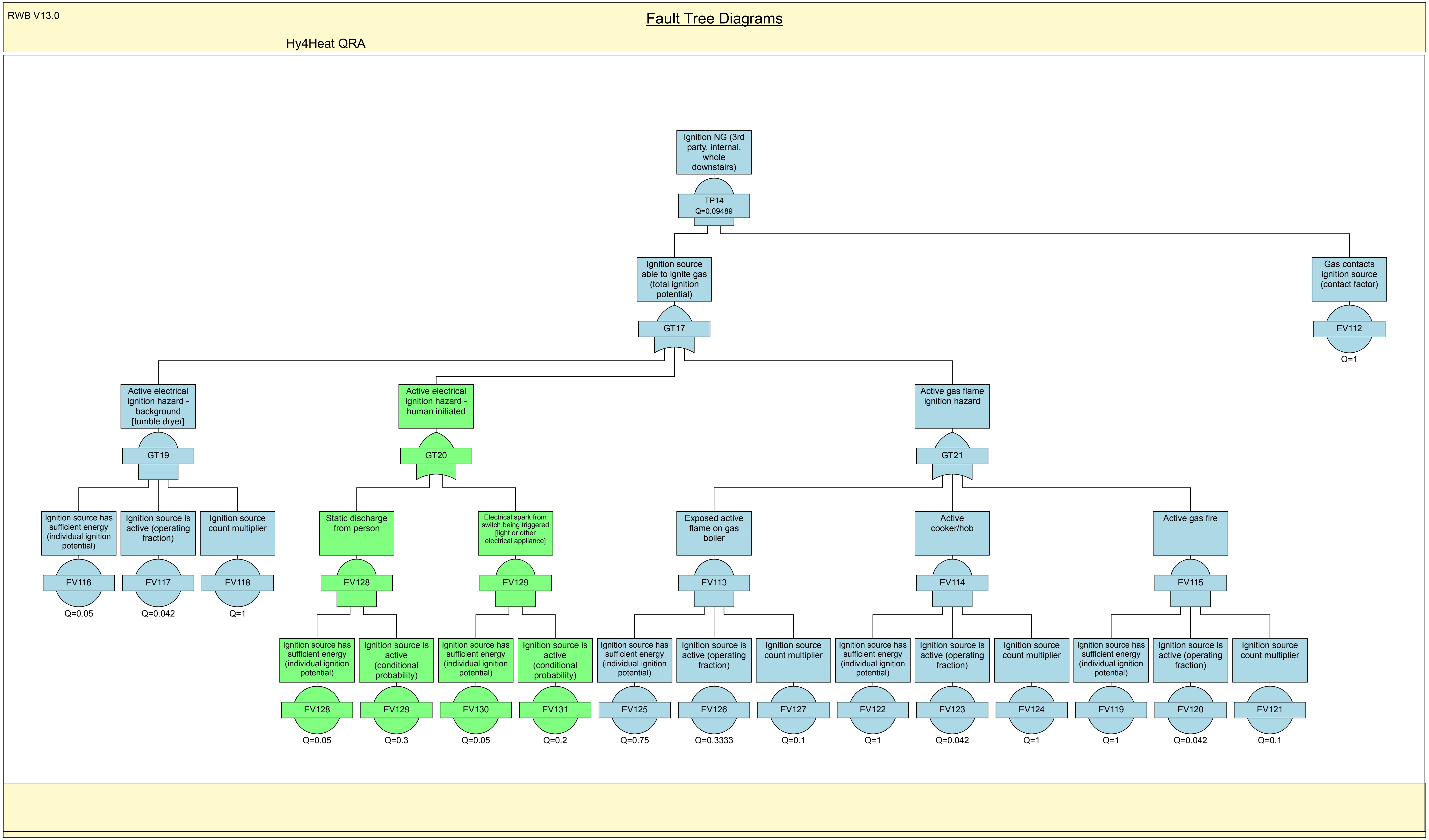
Date	**Location**	**Incident**	**Summary cause**	**Suggested level of protection**
04/02/18	Downstream	Investigation ongoing, possible issue with cooker hob - Capped - 2018/55911	Hob	New H_2 appliances
10/03/17	Downstream	Explosion in kitchen traced to cooker hob - 2017/120028	Hob	New H_2 appliances
28/12/2018	Downstream	Gas cooker ring in kitchen left in on position causing explosion - 2019/27149	Hob	New H_2 appliances
26/04/2019	Downstream	Occupant attempted to light cigarette from gas hob causing explosion - 2019/161069	Hob	New H_2 appliances
03/10/2018	Downstream	Gas cooker hob left on unlit c ausing exlosion in kitchen - Isolated - 2018/353084	Hob	New H_2 appliances
30/09/16	Downstream	Explosion caused by four unlit hob rings - 2016/396058	Hob	New H_2 appliances
22/07/2019	Downstream	Explosion caused by failure of occupant to light gas cooker & grill - 2019/234527	Hob	New H_2 appliances
31/07/2019	Downstream	Explosion following cooker left on unlit - Disconnected - 2019/226985	Hob	New H_2 appliances
23/09/2019	Downstream	All controls on cooker left in on position resulting in explosion - 2019/286758	Hob	New H_2 appliances
25/11/2019	Downstream	Explosion at property due to gas cooker left on unlit – isolated – 2019/378604	Hob	New H_2 appliances
02/12/2019	Downstream	Minor explosion with source traced to faulty gas fire – 2019/359644	Hob	New H_2 appliances
03/12/2019	Downstream	Gas hob left on unlit resulting in explosion – meter outlet capped – 2019/375452	Hob	New H_2 appliances
08/02/17	Downstream	Explosion from gas fire – disconnected – 2017/95472	Gas fire	New H_2 appliances
28/02/17	Downstream	Boiler fire – supply capped – 2017/127951	Boiler	New H_2 appliances
04/07/17	Downstream	Boiler explosion – replaced – 2017/301227	Boiler	New H_2 appliances
19/10/2018	Downstream	Explosion occurred when contractor was working on boiler – sealing disc fitted – 2018/353110	Third party	None
26/10/16	Downstream	Explosion at gas boiler in communal room – 2017/64827	Boiler	Commercial install
30/05/17	Downstream	Gas explosion – disconnected – 2017/236706	Unknown	-
18/02/18	Downstream	Kitchen explosion – cause unknown due to unsafe property – 2018/98469	Unknown	-

Date	**Location**	**Incident**	**Summary cause**	**Suggested level of protection**
17/04/2019	Downstream	Damage by reciprocating saw causing burns to face of IP – made safe – 20119/161123	Misc	Ext meter
19/09/2019	Downstream	Two-part tee disconnected from main whilst excavating – repair clamp fitted – 2019341195	Misc	-
26/11/2019	Downstream	Fire in car port melted section of external pipework – isolated – 2020/21720	Misc	None
10/12/2019	Downstream	Commercial gas fryer came loose and caused ignition – turned off at ECV – 2020/63	Unknown	Commercial install

Appendix B – Event Tree and Fault Tree

An example event tree and fault tree are shown below, taken from the natural gas model.




RWB V13.0
Fault Tree Diagrams
Hy4Heat QRA
Ignition NG (3rd party, internal, whole downstairs)
TP14
Q=0.09489
Ignition source able to ignite gas (total ignition potential)
GT17
Gas contacts ignition source (contact factor)
EV112
Q=1
Active electrical ignition hazard - background [tumble dryer]
GT19
Active electrical ignition hazard - human initiated
GT20
Active gas flame ignition hazard
GT21
Ignition source has sufficient energy (individual ignition potential)
EV116
Q=0.05
Ignition source is active (operating fraction)
EV117
Q=0.042
Ignition source count multiplier
EV118
Q=1
Static discharge from person
EV128
Electrical spark from switch being triggered [light or other electrical appliance]
EV129
Exposed active flame on gas boiler
EV113
Active cooker/hob
EV114
Active gas fire
EV115
Ignition source has sufficient energy (individual ignition potential)
EV128
Q=0.05
Ignition source is active (conditional probability)
EV129
Q=0.3
Ignition source has sufficient energy (individual ignition potential)
EV130
Q=0.05
Ignition source is active (conditional probability)
EV131
Q=0.2
Ignition source has sufficient energy (individual ignition potential)
EV125
Q=0.75
Ignition source is active (operating fraction)
EV126
Q=0.3333
Ignition source count multiplier
EV127
Q=0.1
Ignition source has sufficient energy (individual ignition potential)
EV122
Q=1
Ignition source is active (operating fraction)
EV123
Q=0.042
Ignition source count multiplier
EV124
Q=1
Ignition source has sufficient energy (individual ignition potential)
EV119
Q=1
Ignition source is active (operating fraction)
EV120
Q=0.042
Ignition source count multiplier
EV121
Q=0.1

Appendix C – Malicious intent note

File Note

ARUP

Prepared by	Joseph Tam; Richard Bond Richard Bond	Date	2021-05-01T00:00:00
Subject	Malicious use of natural gas in the home environment		

C.1 Introduction

The objectives of this note are to define 'malicious intent' in the context of the misuse of natural gas in the residential environment with reference to the Health and Safety Executive's RIDDOR dataset and to briefly examine the potential implications for possible future hydrogen supply to residences.

C.2 Malicious intent

Based on our experience[9] of assessing physical malicious threats and risks, 'malicious intent' is usually defined as the: 'deliberate intent to cause harm, disruption, damage or interference'. Malicious actions can take many forms, however, common threats and other malicious activities, e.g. nuisance and disorder, that affect the built environment and its users are categorised as shown in Table 38.

Table 38: Typology of malicious threats, nuisance and disorder

Category	**Sub-category**	**Examples**
Crime	Petty crime	Pickpocketing, graffiti, theft of property
	Violent crime	Assault, criminal damage, arson
	Hate crime	Racially or religious motivated physical or verbal attacks on people or property
	Organised crime	Contraband smuggling, siphoning
	Sabotage	Intentional damage to critical operational equipment
Nuisance	Nuisance – people	Unwanted attention, stalking, harassment, anti-social behaviour
	Nuisance – property	Vagrancy, urban exploring
Civil Unrest/ Public Disorder	Industrial action	Work stoppages, picketing
	Protests and demonstrations	Rallies, marches, disruptive sit-in/occupations
	Rioting	Intentional damage to property, vehicles

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[9] This note has been produced by Arup's Protective Intelligence team, which identifies, assesses and prioritises physical malicious threats and risks to people, property and operations

Category	Sub-category	Examples
Terrorism	N/A	Politically motivated bombings, shootings or vehicle attacks

From our initial research and review of the RIDDOR data set, it is evident that the current natural gas supply in the residential environment is subject to malicious interference. The drivers for this activity are most likely to be primarily criminal or nuisance in nature (e.g. sabotage or nuisance – property as per Table 38) or stem from a personal grievance or negative personal circumstance.

C.3 Malicious use of gas supply in the home environment

C.3.1 RIDDOR dataset analysis

We have conducted a high-level analysis of the RIDDOR dataset, which contains fire, explosions and gas leaks in the residential environment in the UK that were recorded between April 2012 and March 2019. The dataset identifies some evidence of malicious damage or interference in the gas supply that has led to either a fire, explosion or gas leak. Our initial findings based on an analysis of the dataset is as follows:

- Between April 2012 and March 2019, there were 28 incidents assessed as 'malicious' in nature or that involve 'criminal intent'. Fifteen incidents reportedly originated at the cooker. This suggests that household appliances in residential homes are generally the target for someone intent on maliciously interfering with their gas supply. However, as reported in the dataset, some of these incidents were caused by 'user errors' and 'unknown', which could also imply a non-malicious intent such as leaving a gas cooker on by mistake
- There are 22 incidents that were reportedly caused by 'malicious damage' and 'unauthorised technicians'. These incidents indicate that past common methods of malicious intent have involved tampering, sabotage or third party interference in the gas supply either at the incoming supply (utility pipes) or gas meters inside the home. However, there are also other incidents recorded with other causes that include 'faulty electrics' and 'equipment failure', which may also be due to malicious tampering of equipment or unauthorised installation of third party equipment, e.g. to facilitate meter tampering
- The dataset recorded several incidents with the cause of 'arson'. However, we note that there are also incidents that were caused by 'fire'. It could be reasonably assumed that the incidents caused by arson were malicious in nature and those caused by fire were not. However, given the limited information on the detail of each incident it is not possible to confirm which events were malicious and which were accidental. Generally, there is a challenge in distinguishing between past incidents of malicious interference and non-malicious accidents. Furthermore, the dataset has approximately 342 incidents recorded between April 2012 and March 2019 with either 'unknown' or incomplete information with respect to their causes. Identifying the nature of the cause for each incident will be critical in determining the proportion of total malicious incidents in this dataset. The information gaps and lack of clarity in the criteria used to record each incident leads us to question the reliability and accuracy of the data
- Furthermore, there is an inherent limitation with this dataset. The past incidents recorded and documented includes only incidents that have resulted either in a fire, explosion or gas leak. Therefore, other incidents that have involved malicious intent but that did not result in a fire, explosion or gas leak – typically referred to as 'near misses' – were not recorded giving an incomplete picture of malicious use, interference and misuse of natural gas supply in the residential environment
- Finally, we attempted to conduct a year-by-year analysis of malicious incidents in the dataset to identify any trends over time. However, our finding was that the dataset was too small to

facilitate this analysis and we could draw no conclusion on whether the trend of malicious interference in gas supplies was increasing/decreasing or unchanged in the reporting period

C.3.2 Drivers of malicious use of gas supply

We have conducted a brief analysis of relevant open sources that offer insight into the likely drivers behind malicious interference with natural gas supplies in the residential environment. This is likely to be characterised by the following motives:

- Criminal attempts to profit financially from gas meter tampering or siphoning of gas. We understand that organised crime groups have been offering to tamper with gas supplies in residential environments because they can profit from some consumers' willingness to evade paying for their energy supply. These homeowners are likely to create the demand for criminal gangs that possess the knowledge and skills to tamper with gas supply equipment (e.g. meter cupboards or interconnected piping/wiring internally within a home). However, the supply of such a service by organised criminal groups is likely to be subject to change depending on the perceived profitability compared to other black market activities, e.g. metal theft, which they could carry out instead of meter tampering if considered more profitable/easier.
- To assuage negative personal circumstances, e.g. alleviate the effects of fuel poverty.
- Personal grievances against another resident either within the same dwelling or as a neighbour, e.g., deliberately cutting of gas supply in flats or apartments.
- Anti-social behaviour, e.g. youth gangs tampering with gas supply in a residence.
- Experimentation with gas supply out of curiosity.
- Attempt to evade payment for supply of gas, e.g. through meter tampering or siphoning, in the expectation they can shirk payment for their gas supply.
- To commit suicide through gas poisoning.
- A deliberate attempt to cause a fire or explosion in the targeted residence.

C.4 Potential implications for misuse of hydrogen

If the natural gas supply to commercial and residential consumers is replaced with hydrogen from 2050 as is proposed, we expect that some of the dynamics that drive current misuse of natural gas supply now are likely to remain relevant in 2050. For example, the desire to save on energy bills or find a source of heat for cooking or warmth in the winter through manipulation of energy supply is likely to be a driver of hydrogen supply misuse. Furthermore, if criminals can find ways of profiting from these desires or grievances and are technically able to tamper with the pipes, meters or appliances supplying or using hydrogen to homes, as is the case with natural gas today, attempts to tamper with the hydrogen supply is highly probable.

However, we note that if a hydrogen fuel supply to residential consumers is introduced from 2050, we understand that a built-in safeguard – flame failure devices – will be applied at the appliance end, which may reduce the ease with which the hydrogen fuel supply can be tampered with. Depending on the effectiveness of the flame failure device, this may in turn reduce the frequency of malicious activity, but only at the appliance end; the supply end (incoming pipes carrying hydrogen gas) will still be vulnerable to interference.

C.5 Conclusions and recommendations

- Given the RIDDOR dataset, it is very difficult – if not impossible – to gauge the true proportion of malicious incidents that involve a gas fire, explosion or leak. We judge that the picture is further distorted as malicious tampering of gas supplies that did not lead to a fire, explosion or gas leak in the home were not included in the dataset. For example, it is difficult to use the current dataset to conclude whether such ‘near misses’ incidents would lead to a fire or explosion if hydrogen replaces natural gas.

- Consideration should be given to building a more complete dataset that has clearly defined and consistent criteria/parameters for the recording of such incidents of malicious tampering of natural gas supply in the home with the help of industry stakeholders, e.g. using incident data provided by the police, fire brigade and industry revenue protection units that are tasked with dealing with energy theft. This dataset could then be used to establish a more accurate picture of the misuse of natural gas in the residential environment in the UK today. This in turn would inform subsequent feasibility studies of hydrogen supply to residential consumers.
- Consideration should be given to involving downstream energy industry stakeholders (e.g. revenue protection units of energy providers that have engineers responding to suspicious or near miss incidents) further to understand the trends in energy theft in the residential and commercial environment in the UK and what mitigations could be implemented in the future hydrogen supply to increase the difficulty and cost of tampering to make gas supply interference a more difficult task and less attractive target.

Appendix D – Sensitivity analysis

D.1 Ignition sensitivity

As described in section 5.3.2, the proposed hydrogen 'base' case ignition probability for weak electrical sources is 0.2 i.e. a four-fold increase from that of natural gas (0.05), based on the assumption that the ignition potential increases by *one* qualitative HSE RR226 strength category.

A sensitivity case is undertaken to assess the effect of increasing ignition probability associated with the hydrogen gas model. This is investigated because estimating ignition probabilities within a domestic environment for hydrogen is one of the highest uncertainty areas within the QRA model due to the lack of historical data and the complex nature of ignition (see open item #5 in section 15). It is therefore important to check that increasing the ignition probability further (as a sensitivity study) does not invalidate the conclusions of the QRA.

The hydrogen sensitivity case modelled makes the following changes with respect to the hydrogen base case:

- **ignition potential of weak electrical ignition hazards**: increased (0.2 → 0.5)
- **contact factors and source 'active' time**: no change
- **other parameters**: no change

This represents a ten-fold increase from that of natural gas (0.05), checking the effect of increasing the ignition potential by *two* qualitative HSE RR226 strength categories compared to natural gas. This was judged to be a sufficiently conservative sensitivity as 0.5 represents an ignition potential approximately half that of an open flame, which electrical sparks are unlikely to pose even to an easily ignitable gas like hydrogen. Nevertheless, the order of magnitude increase from natural gas (0.05) to the hydrogen sensitivity case (0.5) aligns with the approximate difference in MIE between the two gases, and can be considered a theoretical worst case for hydrogen. This allowed the quantifying of the effects of using an ignition model where the ignition strength is directly linked to the ratio of ignition source energy to gas MIE. See open item #5 in section 15 for further discussion.

Table 39: Ignition probabilities used in QRA model

Scenario	**Natural gas**	**Hydrogen (ignition base case)**	**Hydrogen (ignition sensitivity case)**
Ignition (third party – kitchen door open)	0.09	0.17	0.31
Ignition (corrosion/degradation – kitchen door open)	0.11	0.23	0.42
Ignition (third party – kitchen door closed)	0.09	0.15	0.27
Ignition (corrosion/degradation – kitchen door closed)	0.10	0.21	0.39

This increase in ignition probability logically leads to a predicted increase in frequency of ignited events and associated injuries. Table 40 outlines the results for the hydrogen ignition sensitivity case. This can be directly compared with Table 30.

Table 40: Hydrogen gas (no extra mitigation) ignition sensitivity case risk results

Type of event	Predicted number of events per year (GB population)	Predicted number of individuals injured per event	Predicted number of individuals injured (per year GB)
Kitchen explosion (5-14 vol%)	36	0.35	13
Kitchen explosion (15-23 vol%)	5	2.3	11
Kitchen explosion (24+ vol%)	5	7.4	35
Whole downstairs explosion (5-13 vol%)	20	0.9	18
Whole downstairs explosion (14-21 vol%)	1	5.5	4
Whole downstairs explosion (22+ vol%)	4	9.4	33
Total	**70**	**n/a**	**115**

It is also worthwhile to assess the impact of the excess flow valves when using this increased ignition probability. Table 41 outlines the risk results for hydrogen gas with the implementation of two EFVs at this increased ignition probability. This can be directly compared with Table 31.

The sensitivity results indicate that, with this worst-case hydrogen ignition probability, use with two EFVs does not show a disproportionate increase in risk compared to the natural gas case. Additionally, as described in Section 0, it is considered that this represents an overly conservative approach.

Table 41: Hydrogen gas (+2 EFVs) ignition sensitivity case

Type of event	Predicted number of events per year (GB population)	Predicted number of individuals injured per event	Predicted number of individuals injured (per year GB)
Kitchen explosion (5-14 vol%)	33	0.35	12
Kitchen explosion (15-23 vol%)	1	2.3	2
Kitchen explosion (24+ vol%)	<0.1	7.4	<1
Whole downstairs explosion (5-13 vol%)	12	0.9	11
Whole downstairs explosion (14-21 vol%)	1	5.5	4
Whole downstairs explosion (22+ vol%)	<0.1	9.4	<1
Total	**47**	**n/a**	**29**

D.2 Kitchen door open/closed

The base case assessment for both natural gas and hydrogen assumes that 50% of the time a leak occurs in the kitchen and is confined to that space and the remaining 50% the leak disperses though the ground floor of the property. For simplistic labelling, the former is referred to as ‘kitchen door closed’ and the latter as ‘kitchen door open’.

As this assumption is not based on evidence it is prudent to determine the sensitivity of the assessment to this assumption. Therefore, sensitivity cases were undertaken for each gas, firstly assuming that 100% of leaks occurred with the kitchen door open and secondly assuming that 100% of leaks occurred with the kitchen door closed. These are compared with the base case results for each gas to assess the sensitivity of this variable.

D.2.1 Natural gas results

Table 42 illustrates the natural gas results for the ‘kitchen door open’ and ‘kitchen door closed’ sensitivity cases compared to the base case assessment. It can be said that for the ‘kitchen door closed’ case, slightly more ignited events are predicted but the predicted number of injuries is less. This is due to the proportion of smaller leaks which in the base case when dispersed across the ground floor of a property would not lead to a flammable atmosphere. These small leaks when confined to the kitchen could develop a flammable atmosphere and go on to be ignited, hence the overall increase in ignited events.

The ‘kitchen door open’ case predicts the opposite – less ignited events but more injuries associated with these. The number of ignited events is lower as those small leaks which lead to a flammable atmosphere when confined to a kitchen would not reach a flammable atmosphere when dispersed into the larger ground floor area. The increase in injuries is due to the conservatism within the model assuming that leaks develop to steady state before ignition. Therefore, the medium and large leaks which develop to concentrations above 7%, are also assumed to have a large volume of gas present, resulting in more injuries. As opposed to the base case in which 50% of these leaks would be confined to a kitchen and have a lower volume of gas present at steady state, leading to fewer injuries.

Table 42: Natural gas sensitivity results comparison

Type of event	**Predicted number of events per year (GB population)** **base Case**	**Predicted number of individuals injured (per year GB)** **base Case**	**Predicted no. of events per year (GB population)** **kitchen door closed**	**Predicted number of individuals injured (per year GB)** **kitchen door closed**	**Predicted no. of events per year (GB population)** **kitchen door open**	**Predicted number of individuals injured (per year GB)** **kitchen door open**
Kitchen explosion (5-7.5 vol%)	3.5	1.2	6.9	2.4	0	0
Kitchen explosion (8-14 vol%)	2.2	4.4	4.3	8.7	0	0
Kitchen explosion (14-15 vol%)[10]	0	0	0	0	0	0
Whole downstairs explosion (5-6.5 vol%)	1.5	1.4	0	0	3.0	2.7

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[10] The assessment has considered the effect of going above the upper flammable limit on the expected consequences (refer to consequence modelling report [5])

Type of event	**Predicted number of events per year (GB population)** **base Case**	**Predicted number of individuals injured (per year GB)** **base Case**	**Predicted no. of events per year (GB population)** **kitchen door closed**	**Predicted number of individuals injured (per year GB)** **kitchen door closed**	**Predicted no. of events per year (GB population)** **kitchen door open**	**Predicted number of individuals injured (per year GB)** **kitchen door open**
Whole downstairs explosion (7+ vol%)[11]	1.8	10.1	0	0	3.6	19.9
Total	**9**	**17**	**11**	**11**	**7**	**23**

D.2.2 Hydrogen gas results

Table 43 illustrates the hydrogen gas results for the ‘kitchen door open’ and ‘kitchen door closed’ sensitivity cases compared to the base case assessment. Similarly, to the natural gas assessment, it can be said that for the ‘kitchen door closed’ case, slightly more ignited events are predicted but the predicted number of injuries is less. This is due to the proportion of smaller leaks which in the base case when dispersed across the ground floor of a property would not lead to a flammable atmosphere. These small leaks when confined to the kitchen could develop a flammable atmosphere and go on to be ignited, hence the overall increase in ignited events.

The ‘kitchen door open’ case predicts the opposite – less ignited events but more injuries associated with these. The number of ignited events is lower as those small leaks which lead to a flammable atmosphere when confined to a kitchen would not reach a flammable atmosphere when dispersed into the larger ground floor area. The increase in injuries is due to the conservatism within the model assuming that leaks develop to steady state before ignition. Therefore, the medium and large leaks which develop to concentrations above 14%, are also assumed to have a large volume of gas present, resulting in more injuries. As opposed to the base case in which 50% of these leaks would be confined to a kitchen and have a lower volume of gas present at steady state, leading to fewer injuries.

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[11] The assessment has considered the effect of going above the upper flammable limit on the expected consequences (refer to consequence modelling report [5])

Table 43: Hydrogen gas sensitivity results comparison

Type of event	**Predicted number of events per year (GB population)** **base case**	**Predicted number of individuals injured (per year GB)** **base case**	**Predicted number of events per year (GB population)** **kitchen door closed**	**Predicted number of individuals injured (per year GB)** **kitchen door closed**	**Predicted number of events per year (GB population)** **kitchen door open**	**Predicted number of individuals injured (per year GB)** **kitchen door open**
Kitchen explosion (5-14 vol%)	20.0	7.0	39.6	13.9	0	0
Kitchen explosion (15-23 vol%)	2.8	6.5	5.6	12.9	0	0
Kitchen explosion (24+ vol%)	2.8	20.4	5.5	40.3	0	0
Whole downstairs explosion (5-13 vol%)	11.4	10.2	0	0	22.5	20.2
Whole downstairs explosion (14-21 vol%)	0.4	2.4	0	0	0.9	4.8
Whole downstairs explosion (22+ vol%)	2.0	18.8	0	0	4.0	37.1
Total	**39**	**65**	**51**	**67**	**27**	**62**

D.2.3 Hydrogen gas case (with two EFVs)

Table 44 illustrates the results for the hydrogen gas case with two EFVs for the ‘kitchen door open’ and ‘kitchen door closed’ sensitivity cases compared to the base case assessment. Similarly, to the two previous cases, the ‘kitchen door closed’ case predicts more ignited events and the ‘kitchen door open’ case predicts fewer ignited events as compared to the base case. However, the predicted number of injuries is comparable across all three cases. This is because the ignited events and associated injuries are dominated by the smaller events in this case (due to the effectiveness of the EFVs at preventing the large and very large leaks).

Table 44: Hydrogen gas case with two EFVs sensitivity results comparison

Type of event	**Predicted number of events per year (GB population)** **base case**	**Predicted number of individuals injured (per year GB)** **base case**	**Predicted number of events per year (GB population)** **kitchen door closed**	**Predicted number of individuals injured (per year GB)** **kitchen door closed**	**Predicted number of events per year (GB population)** **kitchen door open'**	**Predicted number of individuals injured (per year GB)** **kitchen door open**
Kitchen explosion (5-14 vol%)	18.5	6.5	36.6	12.8	0	0
Kitchen explosion (15-23 vol%)	0.4	1.0	0.8	1.9	0	0
Kitchen explosion (24+ vol%)	0.05	0.3	0.1	0.7	0	0
Whole downstairs explosion (5-13 vol%)	6.5	5.8	0	0	12.8	11.5
Whole downstairs explosion (14-21 vol%)	0.4	2.4	0	0	0.9	4.8
Whole downstairs explosion (22+ vol%)	0.03	0.3	0	0	0.1	0.6
Total	**26**	**16**	**38**	**16**	**14**	**17**

Appendix E – Weighted consequence categories

Explosion scenario	Number of injuries predicted per event	Weighted injury index
Hydrogen gas, ‘kitchen door open’, ≥22 vol%	9.4	1
Hydrogen gas, ‘kitchen door closed’, ≥24 vol%	7.4	0.79
Natural gas, ‘kitchen door open’, ≥7 vol% Hydrogen gas, ‘kitchen door open’ 14 vol%-21 vol%	5.5	0.59
Hydrogen gas, ‘kitchen door closed’, 15 vol%-23 vol%	2.3	0.24
Natural gas, ‘kitchen door closed’, 8 vol%-14 vol%	2	0.21
Natural gas, , ‘kitchen door open’, 5 vol%-13vol% Hydrogen gas, ‘kitchen door open’	0.9	0.10
Natural gas	0.35	0.04

Appendix F – Materials of construction of gas systems downstream of the ECV

The current state of knowledge is best expressed in the following extracts from IGEM H1.

SECTION 6 : EFFECT ON MATERIALS

6.1 BACKGROUND

Extensive literature exists for the use of low to medium carbon, carbon-manganese steels and austenitic stainless steels in hydrogen containing networks. Much of this work pertains to high pressure systems; however this is of limited use when considering the materials used within low pressure (circa 25 mbar) domestic or light industrial systems. The materials currently used in the low pressure domestic and light industrial systems are radically different to those used in high pressure hydrogen industrial and automotive systems.

An extensive review has been conducted of the components and the materials used in domestic and light industrial systems. This has revealed the use of a wide variety of metals, polymers and elastomers. The metallic materials used range from low carbon steels, cast irons, copper, brass, stainless steels, various aluminium alloys and soldered joints. There may also be some lead pipes in older Victorian properties that are still in service. Polyethylene is used extensively for pipework in the distribution network upstream of the meter and polymers and elastomers are used extensively for components and seals in meters, valves and governors.

6.2 METALS

The mechanism for the permeation of hydrogen into metals is complex, but involves a number of stages:

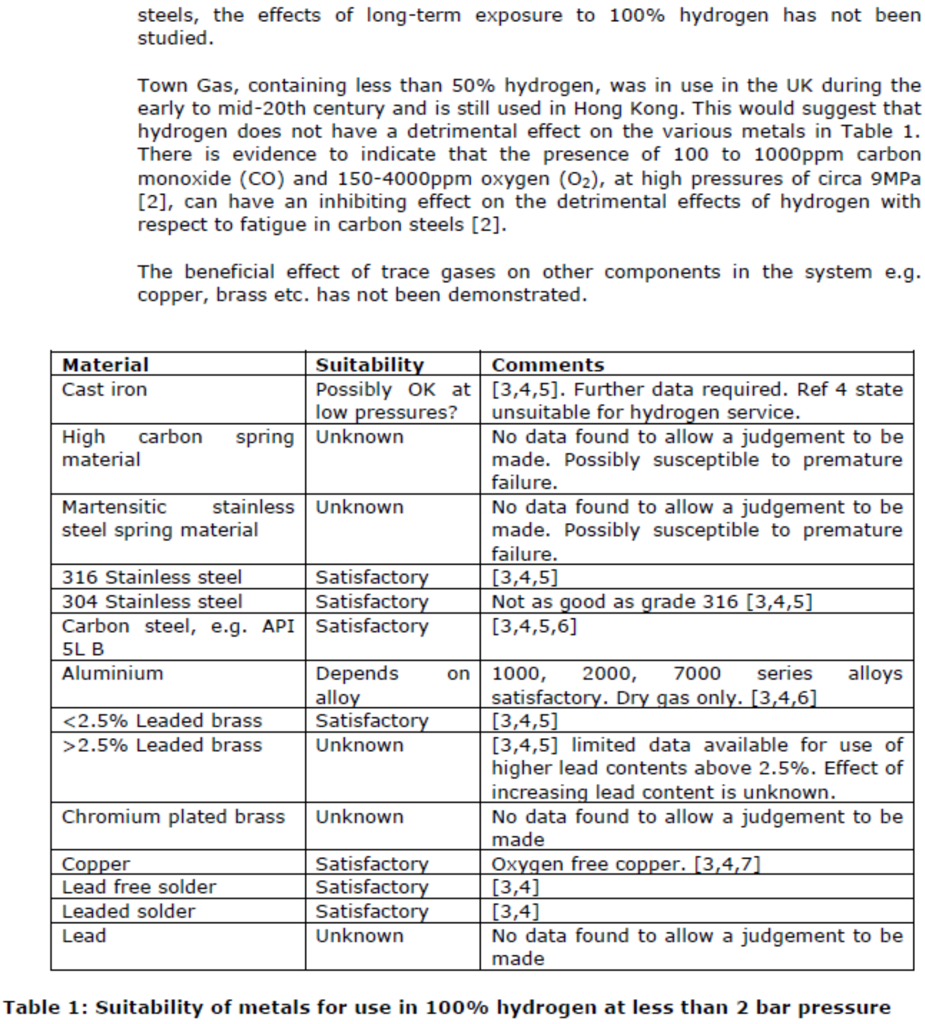
1. Adsorption onto the metal surface
2. Dissociation from molecular hydrogen to highly reactive atomic hydrogen
3. Atomic hydrogen diffusion towards low pressure/concentration region
4. On arrival at the external metal surface, hydrogen atoms recombine and hydrogen gas is released.

Although the mechanism of desorption and permeation of hydrogen in metals is independent of pressure, the effects of hydrogen on the material properties may be affected by the pressure of the system.

If the hydrogen pressure is sufficiently high, gaseous atomic hydrogen will enter the solid metal matrix, to produce secondary physicochemical effects such as material embrittlement or loss of ductility. This is often due to accumulation of atomic hydrogen, or recombined molecular hydrogen at lattice defects, which exist in all metals or at internal inclusions (impurities) within the metal. Metallic materials are prone to embrittlement or loss of ductility, provided that the hydrogen partial pressure is sufficiently high enough to promote these mechanisms. The ability of hydrogen to degrade the material is dependent on several factors including operating pressure, temperature, hydrogen concentration, contaminants, material, microstructure, the nature of a crack front, plastic strain and residual stresses within the material.

For metallic materials, the embrittlement effects are a small change in tensile strength, reduction in ductility (leading to brittle behaviour) and a reduction in fatigue life [1].

A review of the metallic components likely to be used within a domestic or light industrial gas system was conducted and the materials are listed in Table 1 along with the likely effect of exposure to hydrogen at a working pressure of up to 2 bar. For most materials, other than low carbon steels and austenitic stainless



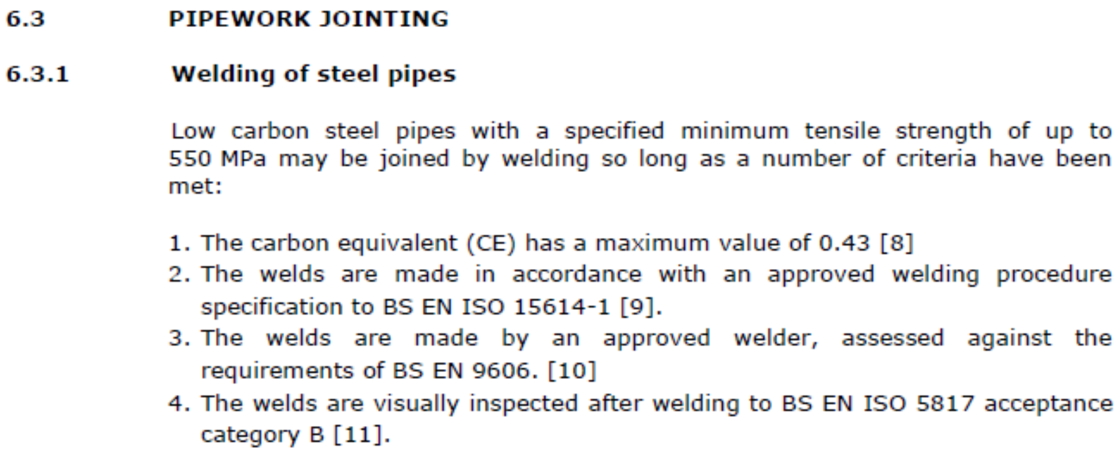
steels, the effects of long-term exposure to 100% hydrogen has not been studied.

Town Gas, containing less than 50% hydrogen, was in use in the UK during the early to mid-20th century and is still used in Hong Kong. This would suggest that hydrogen does not have a detrimental effect on the various metals in Table 1. There is evidence to indicate that the presence of 100 to 1000ppm carbon monoxide (CO) and 150-4000ppm oxygen (O_2), at high pressures of circa 9MPa [2], can have an inhibiting effect on the detrimental effects of hydrogen with respect to fatigue in carbon steels [2].

The beneficial effect of trace gases on other components in the system e.g. copper, brass etc. has not been demonstrated.

Material	Suitability	Comments
Cast iron	Possibly OK at low pressures?	[3,4,5]. Further data required. Ref 4 state unsuitable for hydrogen service.
High carbon spring material	Unknown	No data found to allow a judgement to be made. Possibly susceptible to premature failure.
Martensitic stainless steel spring material	Unknown	No data found to allow a judgement to be made. Possibly susceptible to premature failure.
316 Stainless steel	Satisfactory	[3,4,5]
304 Stainless steel	Satisfactory	Not as good as grade 316 [3,4,5]
Carbon steel, e.g. API 5L B	Satisfactory	[3,4,5,6]
Aluminium	Depends on alloy	1000, 2000, 7000 series alloys satisfactory. Dry gas only. [3,4,6]
<2.5% Leaded brass	Satisfactory	[3,4,5]
>2.5% Leaded brass	Unknown	[3,4,5] limited data available for use of higher lead contents above 2.5%. Effect of increasing lead content is unknown.
Chromium plated brass	Unknown	No data found to allow a judgement to be made
Copper	Satisfactory	Oxygen free copper. [3,4,7]
Lead free solder	Satisfactory	[3,4]
Leaded solder	Satisfactory	[3,4]
Lead	Unknown	No data found to allow a judgement to be made

Table 1: Suitability of metals for use in 100% hydrogen at less than 2 bar pressure



6.3 PIPEWORK JOINTING

6.3.1 Welding of steel pipes

Low carbon steel pipes with a specified minimum tensile strength of up to 550 MPa may be joined by welding so long as a number of criteria have been met:

1. The carbon equivalent (CE) has a maximum value of 0.43 [8]
2. The welds are made in accordance with an approved welding procedure specification to BS EN ISO 15614-1 [9].
3. The welds are made by an approved welder, assessed against the requirements of BS EN 9606. [10]
4. The welds are visually inspected after welding to BS EN ISO 5817 acceptance category B [11].

5. The welds and Heat Affected Zones (HAZs) have a maximum hardness of 250HB [8].

Welding of pipe previously subjected to hydrogen service may be susceptible to hydrogen cracking and need special consideration, such as preheating (for example to 50 °C) and allowed to cool slowly. Welding should be conducted by:

- the TIG process, or
- MMA welding using low hydrogen electrodes in accordance with manufacturer's recommendations and BS EN 1011-2 [12].

Pipes shall be visually inspected for cracks after cooling to ambient temperature, ideally after 24 hours as hydrogen cracks may not occur immediately after welding. It is recommended that visual examination is supplemented by magnetic particle inspection (MPI) or dye penetrant inspection (DPI).

6.3.2 Soldered joints

Evidence indicates that soldered joints can be made for hydrogen service. Leaded and lead-free solders can be used so long as a satisfactory gas tight joint is correctly made and tested.

6.3.3 Threaded joints in steel

Threaded joints contain a theoretical leak path for hydrogen along the joint interface, which will need to be leak tested. Joints should not be over-tightened due to the risk of embrittlement, particularly for joints that have been subjected to previous hydrogen service.

6.3.4 Compression fittings

Compression fittings contain a theoretical leak path for hydrogen along the joint interface, which will need to be leak tested. Joints should not be over-tightened due to the risk of embrittlement, particularly for joints that have been subjected to previous hydrogen service.

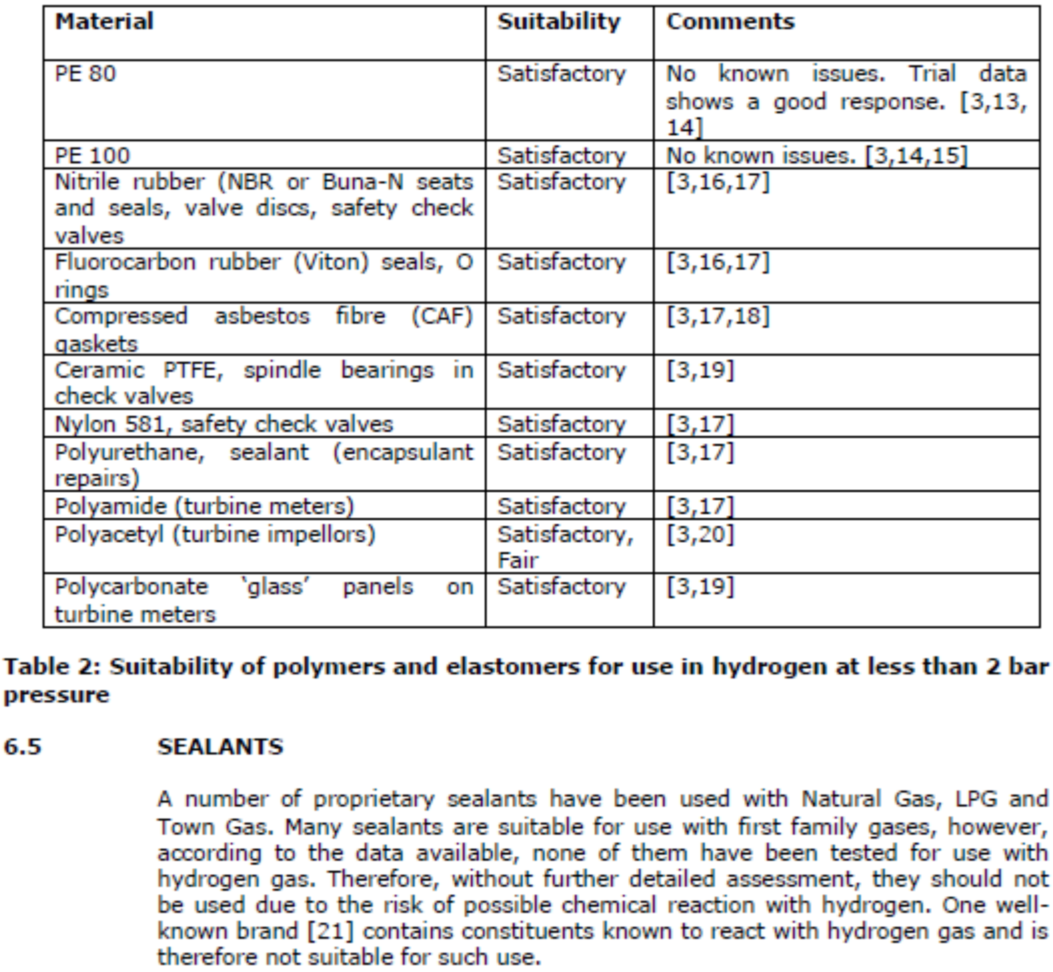
6.3.5 Press-fit joints

The use of press fit joints has not been demonstrated for hydrogen utilisation and the performance will depend on the choice of materials used in the fitting. Press-fit joints contain a theoretical leak path for hydrogen along the joint interface, which will need to be leak tested.

6.4 POLYMERS AND ELASTOMERS

Polymers and elastomers are primarily hydrocarbon compounds. Studies have been conducted into the effects of hydrogen on various compounds and their compatibility with hydrogen is given in Table 2. Generally, there will be a greater degree of hydrogen permeation through the polymers and elastomers when compared to Natural Gas. However, interaction of hydrogen with most polymers does not appear to be a problem.

Repair using squeeze-off and electrofusion techniques have been conducted on hydrogen exposed PE80 pipes and these processes appear to be tolerant to these conditions [3].



Material	Suitability	Comments
PE 80	Satisfactory	No known issues. Trial data shows a good response. [3,13, 14]
PE 100	Satisfactory	No known issues. [3,14,15]
Nitrile rubber (NBR or Buna-N seats and seals, valve discs, safety check valves	Satisfactory	[3,16,17]
Fluorocarbon rubber (Viton) seals, O rings	Satisfactory	[3,16,17]
Compressed asbestos fibre (CAF) gaskets	Satisfactory	[3,17,18]
Ceramic PTFE, spindle bearings in check valves	Satisfactory	[3,19]
Nylon 581, safety check valves	Satisfactory	[3,17]
Polyurethane, sealant (encapsulant repairs)	Satisfactory	[3,17]
Polyamide (turbine meters)	Satisfactory	[3,17]
Polyacetyl (turbine impellors)	Satisfactory, Fair	[3,20]
Polycarbonate 'glass' panels on turbine meters	Satisfactory	[3,19]

Table 2: Suitability of polymers and elastomers for use in hydrogen at less than 2 bar pressure

6.5 SEALANTS

A number of proprietary sealants have been used with Natural Gas, LPG and Town Gas. Many sealants are suitable for use with first family gases, however, according to the data available, none of them have been tested for use with hydrogen gas. Therefore, without further detailed assessment, they should not be used due to the risk of possible chemical reaction with hydrogen. One well-known brand [21] contains constituents known to react with hydrogen gas and is therefore not suitable for such use.

Interpretation of the above to hydrogen community trials

General pipework

Domestic and commercial pipework within property falling within the criteria for hydrogen community trial are extremely unlikely to contain materials of construction other than copper, brass, iron, aluminium and stainless steel. Some lead might be present prior to conversion but a visual inspection of pipework will be carried out and this will be removed.

It is just possible (although extremely rare) that high lead content brass might be present but any failure is very unlikely to be dramatic at 20mbarg. Several countries have limited the lead content of brass for over 20 years. Any new fittings will certainly be low in lead.

Cast iron fittings are unknown in a domestic situation and rare in commercial situations. Any cast iron components (e.g. old gas filters) should be removed or replaced.

It is theoretically possible there might be an interaction between regulator valve springs and hydrogen, but nearly all situations the valve spring is located in the air space above the regulator diaphragm. This zone is ventilated via the breather hole to fresh air. In community trials regulators will be replaced by known hydrogen complaint units.

Joints

Nearly all joints on existing domestic and commercial gas networks will be soldered, compression, flanged, washered or screwed. These are all sufficiently mechanically robust to prevent a large leak.

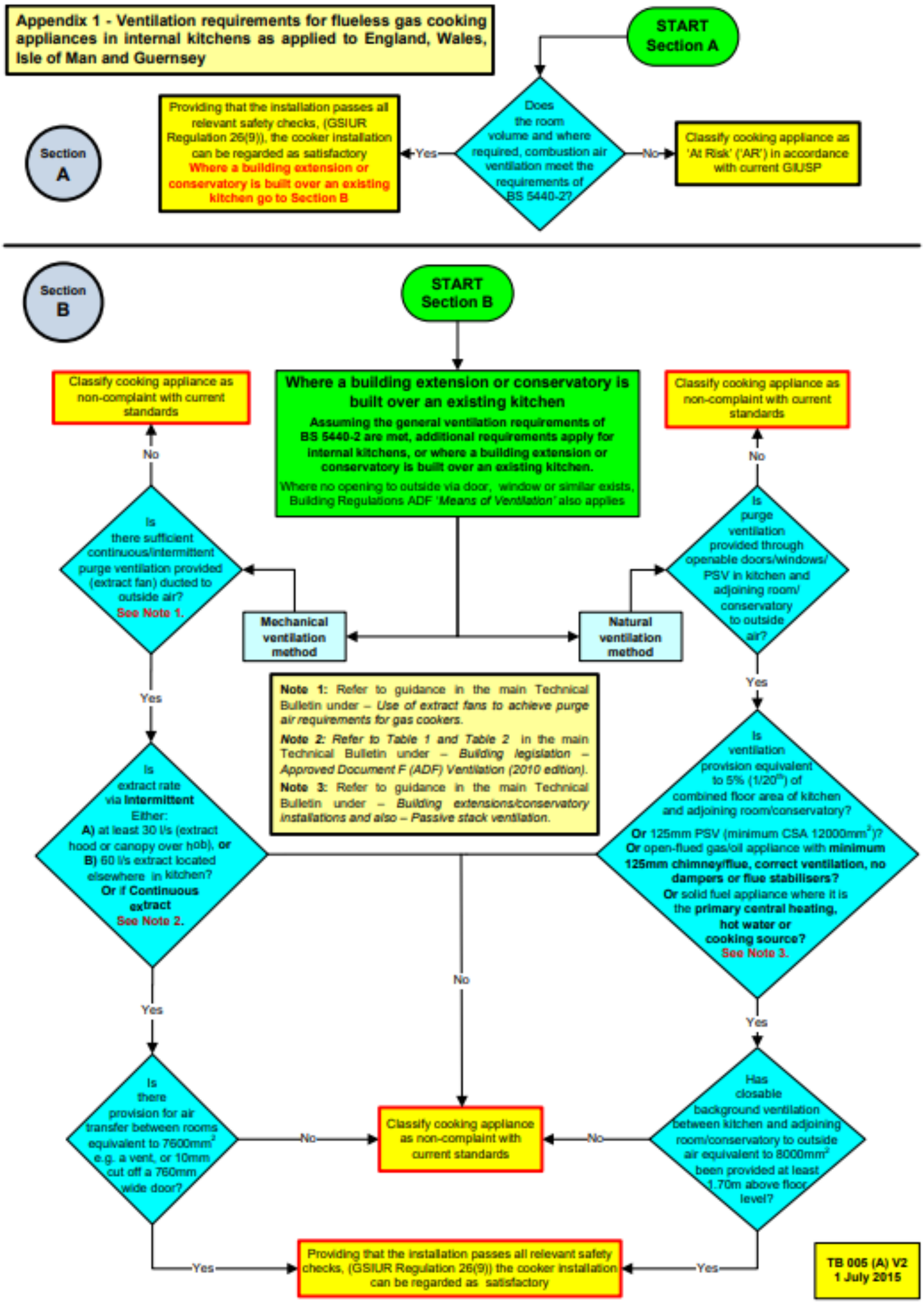
As is identified within the IGEM document some of the historical jointing compounds used may not be entirely suitable, but no realistic scenario can be envisaged whereby any ensuing leaks would any other than tiny and laminar. It is possible than hydrogen could dry out yarn similar to methane, but large parts of the UK use minimal fogging with mono-ethylene glycol and no downstream leaks occur. In summary any leak from the use of sub-optimal sealant will be small and occur over such an extended period that no significant risk is expected. If such leaks are detected an amelioration plan will need to be adopted.

Summary

Pipework systems downstream of the ECV and operating at 20mbarg will be unlikely to contain materials unsuitable for use with hydrogen. Such materials will be removed prior to re-purposing. In the even less likely event of these materials being incorrectly identified (missed) any leak is likely to grow slowly and cause absolutely minimal risk.

Appendix G – Example workflow

This appendix outlines an example of a typical workflow that an engineer may follow to comply with the recommendations as outlined in this document



Note 1: Refer to guidance in the main Technical Bulletin under – *Use of extract fans to achieve purge air requirements for gas cookers.*

Note 2: *Refer to Table 1 and Table 2* in the main Technical Bulletin under – *Building legislation – Approved Document F (ADF) Ventilation (2010 edition).*

Note 3: Refer to guidance in the main Technical Bulletin under – *Building extensions/conservatory installations and also – Passive stack ventilation.*

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