EVIDENCE BASE UTILISED TO JUSTIFY A HYDROGEN BLEND GAS NETWORK SAFETY CASE

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ABSTRACT

Blending hydrogen with natural gas up to 20 % mol/mol has been identified as a key enabler of hydrogen deployment within the UK gas network. This work outlines the evidence base generated to form the basis of safety submitted to the Health and Safety Executive (HSE) to justify a demonstration of hydrogen blending on a live public gas network within the UK, supplying a hydrogen blend to 668 homes over the course of 10 months. An evidence base to demonstrate that gas users are not prejudiced by the addition of hydrogen is required by the Gas Safety (Management) Regulations [1] to allow hydrogen distribution above the 0.1 mol% limit specified within the regulations. The technical evidence generated to support the safety case presented to the HSE concerned the implications of introducing a hydrogen blend on appliance operation, materials, gas characteristics and operational procedures. The outputs of the technical evidence workstreams provided input data to a Quantitative Risk Assessment (QRA) of the GB gas distribution network. The QRA was developed in support of the safety case to allow a causal understanding of public risk to be understood, where harm due to gas usage was defined as risk to life caused either by carbon monoxide poisoning or as a result of fires/explosions. Public records were used to calibrate and validate the base risk model, to understand the dynamics of public risk due to natural gas usage. The experimental and analytical results of the technical workstreams were then used to derive risk model inputs relating to a hydrogen blend. This allowed a quantified comparison of risk to be understood to demonstrate parity of safety between natural gas and a hydrogen blend. This demonstration of risk parity is a condition precedent of allowing the distribution and utilisation of hydrogen blends within the GB gas network

1.0 INTRODUCTION

The work presented within formed the safety case submitted to the Health and Safety Executive (HSE) to justify the transportation and utilisation of a hydrogen blend up to 20 % mol/mol ('a blend') within a UK public gas network in the Winlaton area of Gateshead, Newcastle. The demonstration of hydrogen blending, and its supporting safety case, is part of the HyDeploy project [2]. A previous safety case [3] was successfully presented to the HSE by the HyDeploy project to facilitate the first trial of hydrogen blending in the UK, which was undertaken in a private gas network owned and operated by Keele University, UK. The evidence base presented to support the safety case for the public demonstration of hydrogen blending builds upon the previously established evidence for the Keele University trial.

To own and operate a gas network within the UK a safety case must be presented and accepted by the HSE [4] which complies with the gas quality specifications stipulated within Schedule 3 of the Gas Safety (Management) Regulations, 1996 (GS(M)R). Such stipulations require the content of hydrogen to remain less than 0.1 % mol/mol. The HSE is able to grant an exemption to requirements within GS(M)R if it can be satisfied that the health and safety of persons likely to be affected by the exemption will not be prejudiced in consequence of it. Therefore, evidence must be presented and accepted by the HSE to demonstrate that the proposed exemption is 'as safe as' normal gas qualities.

The work presented is the risk assessment methodology and supporting evidence that was developed to demonstrate the parity of risk between a 20 % mol/mol hydrogen blend and natural gas for the purpose of conducting a physical demonstration. This demonstration is to provide a hydrogen blend to 668 homes in Winlaton, Gateshead, as well as a minority of larger users. Such a demonstration will be the first transportation and utilisation of a hydrogen containing gas within a public UK gas network since the conversion from towns gas to natural gas was completed in the 1976 [5].

2.0 METHODOLOGY

2.1 Quantitative Risk Assessment

To allow a discrete comparison of risk between natural gas and a hydrogen blend to be computed, a Quantitative Risk Assessment (QRA) was developed. The QRA enabled the causal relationships to be understood between public risk and the characteristics of a gas conveyed within a gas network, both in relation to the network itself and downstream usage within buildings.

Risk was defined as the risk to life due to exposure to carbon monoxide (CO) or as a consequence of fires/explosions. A fault tree [6] was developed using 'AND', 'OR' and 'NOT' logic gates to enable the detailed relationships underpinning gas usage risk to be developed. The fault tree was developed to the necessary level of detail to allow identification of the gas-specific basic events that must combine with environmental, mitigative and human behavior basic events to trigger the chain of risk causality.

2.1.1 CO Fault Tree

Risk due to CO exposure relates to a combination of; high CO in the appliance flue gas; poor fluing or ventilation; and CO build up not prevented by a person. All three of these events are required to create the conditions necessary for CO exposure to represent a risk to life. It is this combination of three independent events that yields the relatively low risk of CO poisoning within domestic settings due to natural gas usage. As CO risk relates to poor appliance behaviour, this leg of the QRA was subcategorized by appliance type within a domestic setting. This allowed any appliance-specific considerations to be taken account such as safety devices that are unique to certain appliances. The CO leg of the fault tree was subcategorized into; central heating boilers; space heaters; cooker hobs; cooker grills; and cooker ovens.

The basic fault tree structure for each of these appliance legs was identical, however segregation allowed appliance-specific inputs to be evaluated; for example, appliances operations per year. Of the independent events necessary for any potential fatality to occur, the only one which relates to the quality of gas supplied is the 'high CO in the appliance flue gas', as this relates to the dynamics of combustion. The dominate cause of high CO within an appliance's flue gas is due to appliance malfunction. Therefore, an understanding of how a hydrogen blend compares with natural gas regarding the generation of CO from malfunctioning appliances was identified as a key technical line of investigation.

2.1.2 Fire and Explosions Fault Tree

Risks due to fire and explosions ('F/E') were categorized into the following: appliance lightback; explosion due to release from the appliance; explosion within a confined space; external explosion. Once again, a series of independent events are necessary for such scenarios to be realised. These events are; flammable gas is released; the gas accumulates to a flammable concentration; an ignition source of sufficient magnitude is present; and a person is not there to prevent the explosion.

The fault trees for the four sub-branches of the F/E leg of the QRA were unique in their structure due to each scenario being a unique chain of events that could lead to an F/E event occurring. The gas quality specific basic events were however common to all, as they related to the fundamental gas characteristics and are therefore independent from the specific chain of events. The one exception to this related to the propensity for gas qualities to lead to lightback within appliances. The necessary gas characteristic investigations that required exploration therefore related to the impact of a hydrogen blend with respect to:

1. The propensity and magnitude of leakage
2. The accumulation behaviour of leaking gas
3. The ignition characteristics of a flammable cloud
4. The resultant impact of ignition upon building structures

Analytical and experimental investigations were undertaken to understand any differences in the above four considerations between a hydrogen blend and natural gas.

2.1.3 Scenario Development

The structure of the QRA was developed to be regionally agnostic. This allowed both model validation to be undertaken as well as the development of geographically specific models based on input specification. Following the development of the QRA structure, three scenarios were developed to enable a rigorous comparison of risk to be undertaken of the specific region under consideration, namely, Winlaton. The three scenarios developed are summarised in Table 1.

Table 1. QRA scenarios

QRA Scenario	Region	Fuel
1	Great Britain (GB)	Natural Gas
2	Winlaton	Natural Gas
3	Winlaton	Hydrogen Blend

The first scenario was developed to enable validation of the model to be undertaken using public data from independent and credible sources. This allowed the relevant inputs to be specified for the outturn results of the model to be compared to public data sources. Following validation of the logic structure a regionally specific QRA was developed (scenario 2), based on specific inputs relating to the Winlaton area. This allowed the baseline regional risk related to natural gas to be understood as a datum for comparison. The final scenario (scenario 3) was a modification to scenario 2 where the gas quality-specific inputs were modified to reflect a hydrogen blend. Comparison of the QRA results between scenario 2 and 3 allowed a direct risk comparison between the hydrogen blend and natural gas to be undertaken for the Winlaton area under consideration for the demonstration.

2.2 Gas Characteristics

Gas characteristics research was conducted to provide evidence to allow hydrogen blend specific inputs to be used with the F/E elements of the QRA as well as to provide evidence to allow natural gas operational procedures to be assessed for any potential changes. The focus of the gas characteristics assessments was on the constituent events necessary for fires/explosions to occur and damage buildings, which would lead to risk of fatality.

2.2.1 Leakage & Accumulation

Swain and Swain [7] showed that the leakage rate of gas is affected by whether the flow through the leakage path is laminar or turbulent. The volumetric flowrate is inversely proportional to the dynamic viscosity if the flow is laminar, and inversely proportional to the square root of the density if the flow is turbulent. The impact of introducing a hydrogen blend into natural gas supplies can be explored by comparing flow rates of the blend relative to flow rates of natural gas and the results are different depending on whether the flow is laminar or turbulent. For details of this analysis, see Gant *et al.* [8].

The accumulation behaviour of gas leaks in single and connected rooms was studied both experimentally and computationally. A wind tunnel test facility was used to conduct physical experiments at approximately 1:2 reduced scale (left hand side of Figure 1). A Computational Fluid Dynamics (CFD) model of the facility was developed and validated using results from these physical experiments (right hand side of Figure 1). A simpler stratified-layer model of gas accumulation in a single enclosure was also tested [9]. The CFD model provided useful insight into the flow behavior and additional confidence in the use of the simpler single-enclosure model. In the final stage of the work, the validated single-enclosure model was coupled with Monte-Carlo analysis to assess the impact of a hydrogen blend across a wide range of realistic conditions, i.e. a range of room sizes, gas release locations and sizes, gas pressures, ventilation opening sizes and locations, and wind speeds and directions.

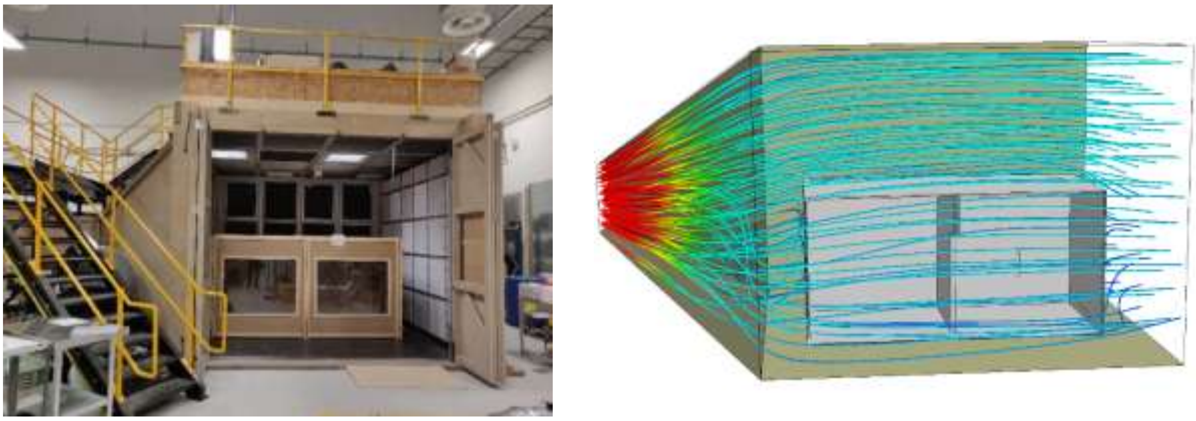

Figure 1. Gas leakage and accumulation test facility

2.2.2 Ignition Sensitivity

Ignition sensitivity was evaluated through literature review and desk-top analysis, where the two flammable characteristics assessed were; the flammable range; and the minimum ignition energy (MIE). Pure hydrogen is known is have a greater flammable range and lower minimum ignition energy than methane [10]. To assess whether the change in flammable range was material or not for a hydrogen blend, Le Chatelier’s Principle was applied, assuming binary mixtures of hydrogen and methane, where the hydrogen fraction was either 0 % mol/mol (pure methane) or 20 % mol/mol.

An assessment of the MIE was undertaken to understand if any marginal sources of ignition would likely be present between the MIE of methane and that of a hydrogen blend. Theoretical analysis based on quenching distances was used as the basis of assessment. It is noteworthy that methane and methane containing up to 25 % vol/vol hydrogen are both Group IIA gases and are treated identically from the perspective of ATEX ratings [11] for electrical equipment within flammable zones.

2.2.3 Explosion Severity

Explosion severity was the final stage of assessment undertaken. An analytical exercise was conducted to predict the difference in overpressures that would be observed due to the gas quality changes. The modelling focused on three widely used explosion severity models [12, 13, 14] to allow exploration of different conditions such as equivalence ratio, obstruction, enclosure volume and vent sizing.

To support the analytical research physical experimentation was undertaken informed by the leakage and accumulation research to derive the experimental conditions. This enabled continuity to be maintained within the overall comparative analysis. A dedicated facility was constructed which enabled gas to be released at a set pressure within a confined space to a pre-determined concentration, where ignition could be initiated from the back or center of the room. One end of the facility was constructed such that the vent characteristics could be adjusted, as well as partitions and obstacles installed within the facility to promote turbulent flame dynamics. The facility is shown in Figure 2.

Figure 2. Explosion severity test facility

A series of nearly 60 tests were conducted where the characteristics of the flammable conditions as well as the physical configuration of the facility were varied. This allowed a detailed understanding of the difference in explosion severity to be evaluated between methane and a hydrogen blend.

2.3 Appliance Behaviour

The study of appliance behaviour was critical to understanding the relative implications of a hydrogen blend. The impact of a hydrogen blend was studied in relation to the two following variables:

1. Appliance design – This allowed an analysis to be completed that was reflective of the full domestic appliance population across the UK

2. Appliance condition – This allowed an analysis to be completed that was reflective of all possible appliance conditions (from well operating to malfunctioning)

By defining a matrix of appliance/condition combinations an understanding of appliance behaviour could be generated which was representative of the UK appliance population and all appliance conditions within that population.

2.3.1 Appliance Design

To explore domestic appliance design variation, certification and design standards were reviewed as well as undertaking extensive manufacturer engagement. Standards dated back to the introduction of the first natural gas standards in 1976 were reviewed and a sample set of 13 appliances was developed that was reflective of the full UK appliance population dating from present day back to 1976. The appliances were selected based on burner designs. This is because the impact of a hydrogen blend as it relates to CO production is a function of the quality of combustion achieved, therefore the distinguishing component within appliances that could impact this process is the burner design. The performance of other components such as the heat exchanger, gas valve, air fan etc were deemed independent of gas quality and therefore variation across different designs was not deemed necessary. It is noteworthy that natural gas appliances between 1976 – 1993 required lightback testing [15] with test gas G22 to obtain their certification. G22 is a binary mixture of methane and hydrogen with a hydrogen content of 35% mol/mol. Following the introduction of the Gas Appliance Directive (GAD) [16] (superseded by the Gas Appliance Regulation 2016/426 in 2018 [17]) this certification testing changed to test gas G222 [18], which contains 23 % mol/mol. Therefore, all UK domestic natural gas appliances have had some form of hydrogen testing as part of their certification for sale.

2.3.2 Appliance Condition

Appliance condition variation relates to the impact of CO production along a continuum from well operating through to malfunctioning. To explore the impact of this variation six fault modes were identified which could impact upon appliance performance, they were; poor maintenance; incorrect set-up; malfunction; maloperation; ad hoc repairs; and flue installation. These fault modes were reviewed by appliance manufacturers as being representative of all fault modes.

The impact of gas quality upon CO production ultimately relates to any impacts upon the stoichiometric ratio of combustion. Excessive production of CO primarily relates to a lack of oxygen availability and the effective reduction in air/fuel ratio achieved within the burner. This ratio can be influenced by fault modes, e.g., an incorrectly set up appliance or blocked air inlet. CO production is not the fault itself but the impact the fault has on the air/fuel ratio within the burner. Therefore, all fault modes could be explored by proxy by manually manipulating the air/fuel ratio within the burner to promote CO production. This process was undertaken with 100 % mol/mol methane and then repeated with a binary mixture of methane plus 20% mol/mol hydrogen to allow a direct comparison of appliance malfunction to be made between the two gases.

The risk implications of CO exposure due to poorly operating appliances was explored by combining the 'perfectly-mixed' room model for pollutants [19] with the accepted model of CO build up within a body developed by Coburn, Forster and Kane [20,21]. The appliance performance test results were combined with Monte-Carlo analysis of the combined model to allow real world variability in physical considerations such as room sizes to be accounted for in the assessment.

2.3.3 Appliance Testing

Appliance testing was undertaken to understand the implications of introducing a hydrogen blend both on the performance and safety of UK appliances. A summary the testing undertaken is given in Table 2.

Table 2. Appliance testing summary

Testing	Appliances Tested
Internal component temperatures	Ovens, heaters and boilers
Delayed ignition	Boilers, fires and ovens
Safety device functionality e.g. oxygen depletion sensors and flame detection devices	Fires and boilers
Flame chilling effects	Hobs, fires and boilers
Air inlet blockage (linting)	Boilers and fires
Burner damage impact	Heaters
Incorrect appliance set up e.g. excessive gas fire decorate coals	Fires
Commissioning adjustments	Boilers
Combustion efficiency	Boilers and fires
Flue gas emissions (including NO_x)	All appliances
Lightback testing	Boilers, fires and hobs
Low/high gas supply pressures	All appliances
Fault mode testing	Boilers

2.4 Materials

The materials research was focused on understanding if any detrimental impact upon mechanical properties of common gas network assets and components would be expected due to the hydrogen blend. This involved soaking a selection of metal 'coupons', both ferrous and non-ferrous, in a chamber filled with 8 bar pure hydrogen for up to 5 weeks. The materials selected for the experimentation were based on an asset survey of network components and assets as well as being representative of downstream appliances and installations. The soaking conditions were chosen to provide a conservative assessment of the demonstration conditions, given that that the experimental partial pressure was 13 times the maximum demonstration partial pressure. An example of a soaking chamber is given in Figure 3.

Figure 3. Materials soaking chamber

Following this soaking phase, the materials were extracted and mechanically tested. This involved both tensile and hardness testing. Following the tensile testing SEM micrographs were taken to analyse the fracture surface. This observational evidence could then be combined with the mechanical test results to understand if any impacts due to exposure to hydrogen could be decerned. Ultimately the integrity of materials as they relate to exposure to hydrogen relates to expected frequency of leaks to occur due to mechanical failure. Therefore, the materials assessments informed the elements of the QRA where gas leaks form part of the risk chains.

2.5 Procedures

Procedures are critical to ensure the safe operation of both the gas network (upstream of the emergency control valve) and activities undertaken within homes (downstream of the emergency control valve). The output of the gas characteristics, appliances and materials research streams were used to inform a review process of all procedures that could be utilised within the proposed demonstration. This review process involved evaluating the available technical evidence and reaching a determination of whether the procedures that govern both network and appliance related work activities required alteration to accommodate a hydrogen blend.

3.0 RESULTS

3.1 Procedures

3.1.1 Network (Upstream) Procedures

The vast majority of network procedures were found to be suitable and appropriate for use with a hydrogen blend network [22]. A two-detector solution using currently available gas detection equipment was employed, albeit with a minor recalibration by the manufacturer, in combination with the current action levels for emergency response. Direct purging was the only procedure that required modification to accommodate a hydrogen blend, where the minimum purge velocity had to increase to ensure the same Froude number was achieved. However, this change was found to be below the operating velocity of the associated machinery used to perform the activity, therefore did not make any practical difference to the activity.

3.1.2 Appliance Related (Downstream) Procedures

All domestic natural gas procedures that underpin Gas Safe competencies were found to be suitable to accommodate the characteristics of a hydrogen blend [23]. This review was peer reviewed by the standard setting bodies and was formulated into formal industry guidance [24].

3.2 Gas Characteristics

3.2.1 Leakage & Accumulation

The evaluation of volumetric leak rates for laminar and turbulent flows found a negligible change in expected flowrate for laminar flow conditions (since the dynamic viscosity of the blend was found to be 99% that of natural gas) and an increase of up to 10 % vol/vol for turbulent flow conditions (due to the 18% reduction in gas density following blending). The effect of this increase in volumetric flow rate under turbulent leak conditions on the gas accumulation behavior was examined in the Monte-Carlo analysis shown in Figure 4. Each point in the figure shows the predicted steady-state gas concentration within the stratified layer in an enclosure following a gas leak. The colour of the dot indicates the pressure difference across the enclosure due to the wind. Several thousand simulations were performed to cover a range of realistic conditions.

The Monte-Carlo analysis showed that there was very little difference in gas accumulation behavior between the blend and methane [25]. The average concentration for the blend was 0.5% v/v lower than for methane, with a standard deviation of 1.2 % v/v. The difference in the layer depth for the two gases was on average equal to 0.02% of the room height, with a standard deviation of 0.40%. For a standard room height of 2.3 m, this equates to a difference in layer height of 0.5 mm, with a standard deviation of 9 mm. Therefore, the gas accumulation behaviour of a 20 % mol/mol hydrogen blend was found to be practically identical to natural gas for the same physical leak conditions (aperture size and gas pressure) for both laminar and turbulent flow regimes, and across a wide range of real world conditions.

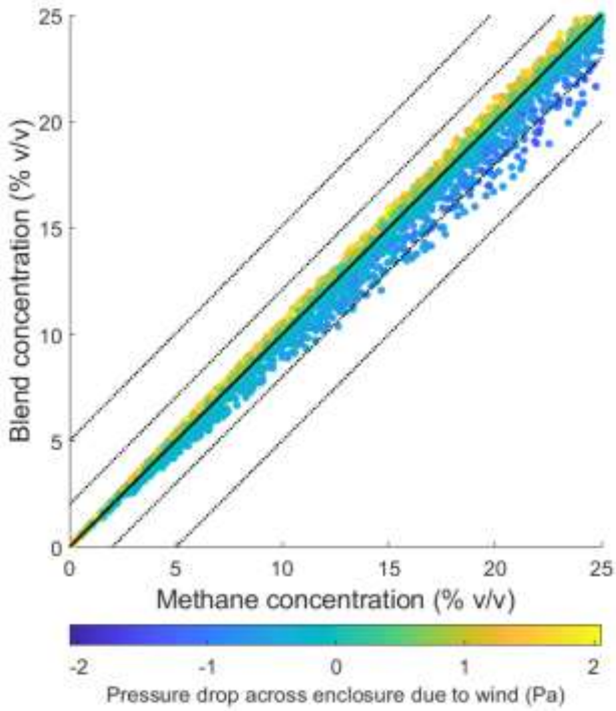

Figure 4. Accumulated gas concentration comparison

3.2.2 Ignition Sensitivity

The flammable ranges of methane and hydrogen are 5 – 15 and 4 - 74 % vol/vol respectively. The resulting range for a 20 % mol/mol blend is 4.8 – 18.8 % vol/vol. Therefore, a hydrogen blend does present a slighter wider flammable range compared to methane. The MIE of methane and a blend were found to be 0.24 mJ and 0.16 mJ respectively. Although the blend represented a slightly lower MIE, no credible ignition source would be expected to operate between 0.16 – 0.24 mJ, as nearly all real-world ignition sources [26] (electrical circuits, open flames, static etc) have energies at least an order of magnitude greater than the MIE of either methane or a hydrogen blend. The ignition sensitivity of the blend was therefore found to be very similar to methane.

3.2.3 Explosion Severity

The analytical and experimental research identified an increase in expected overpressure of ca. 25% as a consequence of introducing a hydrogen blend. However, the impulse of the pressure waves was found to be very similar between the two gases [27]. Harris [28] would indicate that impulse is the more appropriate metric to evaluate building damage from internal explosions, however for conservatism the overpressure results were taken forward as the basis of input into the QRA.

3.3 Appliances

3.3.1 Fault Mode Testing

The fault mode analysis observed a material reduction in CO production due to the introduction of hydrogen blends [31]. The results are shown in Figure 5 below.

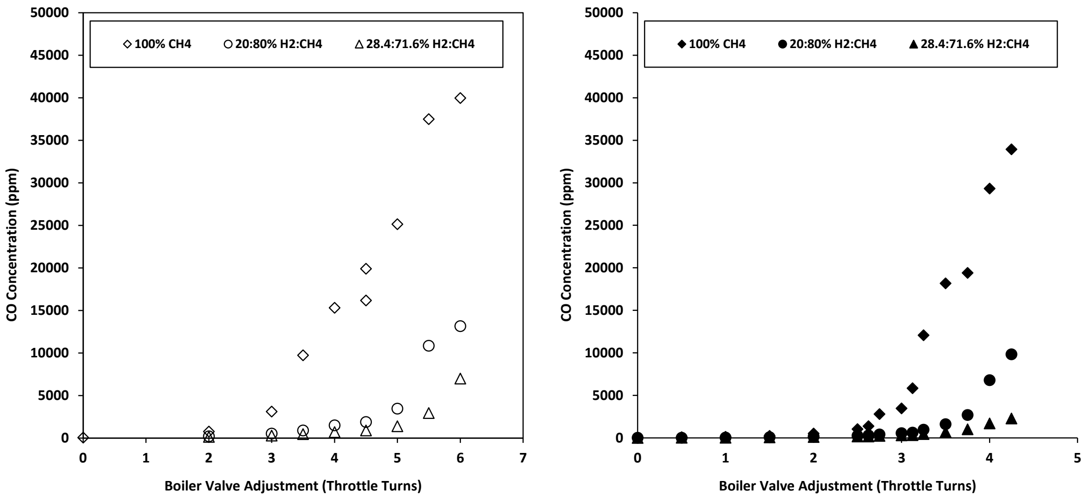

Figure 5. CO production during fault conditions (left – boiler A, right – boiler B)

On average CO production reduced by 70% as a consequence of the introducing a hydrogen blend. This was because of the lower theoretical air requirement of hydrogen compared to methane. Therefore, the introduction of a hydrogen blend to a natural gas valve with a given air/fuel ratio counteracts the reduced oxygen availability for combustion that results from the malfunctioning appliance. In many cases the malfunctioning appliances CO production reduced back to acceptable levels. Once these results were embodied within the CO exposure and uptake model, this significant reduction in CO production led to an almost elimination of expected risk to life due to CO exposure [32]. A conservative risk reduction factor of 50% was taken forward into the QRA.

3.3.2 Appliance Performance Testing

The appliance performance and safety testing outlined in Table 2 yielded no increase in operational risk as a consequence of introducing a hydrogen blend [33, 34]. Flue gas analysis results were in line with expectation i.e., reduced CO and carbon dioxide. A more surprising result was a consistent reduction in NO_x emissions. Upon investigation this was identified to be due to the increase in excess oxygen that results from introducing a hydrogen blend into a natural gas burner. This slightly cools the flame, in line with the reduction in Wobbe number of the fuel, which in turn reduces the production of thermal NOx. All other performance factors, such as combustion efficiencies, did not materially change with the introduction of hydrogen blend.

The results of the appliance testing were either; no change or; a positive impact on performance, due to the introduction of 20 % mol/mol hydrogen blend across all appliances and conditions. Due to the use of a UK wide representative appliance sample set, these results therefore demonstrate that all UK domestic appliances operate no less safely with a hydrogen blend relative to natural gas [35].

3.4 Materials

3.4.1 Mechanical Testing

Across all of the materials tested, which form common materials of construction within gas network, appliances and pipework (inclusive of steels, aluminum, brass, copper etc) no statistical difference in mechanical properties was observed between exposure to methane and exposure to a hydrogen blend at the test conditions [29, 30]. This evidence would therefore suggest that no wholesale reduction in material integrity would be expected to occur due to exposure with a hydrogen blend. Therefore, no additional leakage rates due to component failure would be expected during the demonstration.

3.4.2 Fracture Surface Micrographs

The fracture surface SEM micrographs found no obvious signs of hydrogen embrittlement. This aligned with the mechanical test results. An example of the SEM micrographs taken is shown in Figure 6.

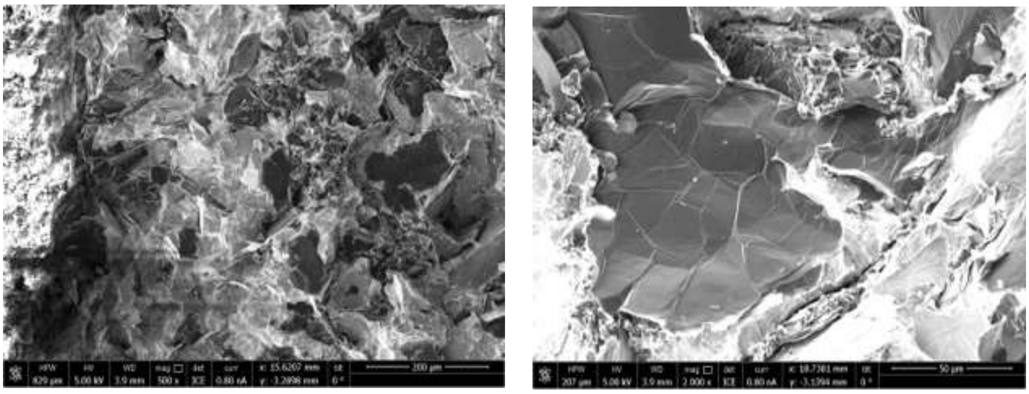

Figure 6. Fracture surface of cast iron specimen

3.5 Risk Assessment

Following the validation exercise of the QRA with GB data, a regional 'current' QRA was developed (scenario 2) using data collected on the demonstration area through local engagement, e.g. number of appliances per household by appliance type. This allowed the baseline level of risk with natural gas for the specific area under consideration to be computed. The pertinent experimental and analytical results (most notably from the appliance behaviour and gas characteristics research) were translated into the correct format for input into the QRA. A complete set of gas-quality specific inputs for a hydrogen blend was developed to allow the third QRA scenario to be developed [36]. This scenario represented the specific region of Winlaton being supplied with a hydrogen blend instead of natural gas. To contextualise the results of the three scenarios, they are compared to the broadly acceptable risk limit within the HSE's Tolerability of Risk Framework [37]. All three scenarios, as well as the HSE's broadly acceptable limit, are given in Figure 7.

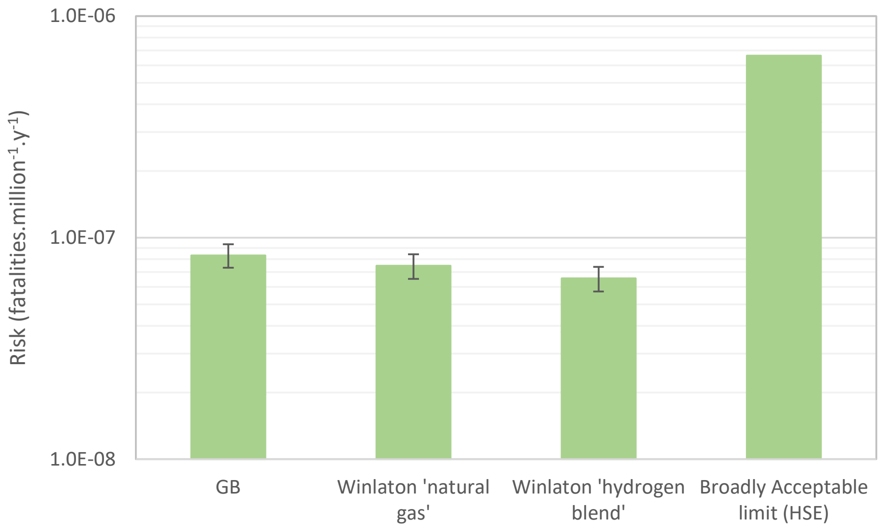

Figure 7. Individual risk associated with the conveyance of hydrogen blends

4.0 CONCLUSIONS

The overall risk assessment methodology enabled a comparison to be made between the risk profile of the Winlaton area supplied with natural gas and a 20 % mol/mol hydrogen blend. Through experimental and analytical research, combined with a validated QRA model, the risk assessment process demonstrated that individual risk within the demonstration area reduces as a consequence of blending hydrogen. The interpretation of research undertaken to enable hydrogen-blend QRA inputs to be developed employed a highly conservative approach, both with respect to CO and F/E fault tree inputs.

As a consequence of blending 20 % mol/mol hydrogen into the natural gas supply the individual risk profile within Winlaton was found to reduce by ca. 15%. The primary reason for the reduction in risk is as a consequence of the significant reduction in CO production within poorly operating appliances. The absolute risk of all three scenarios investigated (GB, Winlaton 'natural gas' and Winlaton 'hydrogen blend') were found to be an order of magnitude lower than the HSE's broadly acceptable limit of individual risk. This is reflective of the low risk to public safety within GB that results from gas usage.

5.0 ACKNOWLEDGEMENTS

Acknowledgement should be given to the HyDeploy consortium, consisting of; Cadent; Northern Gas Networks; Progressive Energy; Health and Safety Executive (HSE) Bespoke Research and Consulting; Keele University and ITM Power, as well as Dave Lander Consulting and Kiwa Gastec. Acknowledgement should also be given to the project funder, The Office for Gas and Electricity Markets (OFGEM) who sanctioned funding for the project under the Network Innovation Competition.

6.0 REFERENCES

1. Gas Safety (Management) Regulations. UK Statutory Instruments 1996, No. 551.
2. National Grid, HyDeploy NIC Submission, 2017, The Office of Gas and Electricity Markets.
3. Isaac, T., HyDeploy: The UK's First Hydrogen Blending Deployment Project, *Clean Energy*, 3, No. 2, 2019, pp. 114–125.
4. Regulation 3.1.a, Gas Safety (Management) Regulations. UK Statutory Instruments 1996, No. 551.
5. Williams, T.I., A History of the British Gas Industry, 1981, Oxford University Press, UK.
6. Ericson, C.A., Fault Tree Analysis Primer, 2011, CreateSpace Publishing Platform, UK.
7. Swain, M.R. and Swain, M.N., A comparison of H_2, CH_4 and C_3H_8 fuel leakage in residential settings, *Int. J. Hydrogen Energy*, 1992, 17(10), 807-815.

8. Gant, S., et al, Preliminary analysis of gas release and dispersion behaviour relevant to the use of hydrogen in the natural gas distribution network (Research Report 1169), HSE, 2021.
9. Lowesmith, B.J., An experimental programme to study gas build up in domestic properties following releases of methane/hydrogen mixtures, 2006, NATURALHY project R0002-WP2-R-0.
10. Gardiner, W.C., Gas-Phase Combustion Chemistry 2nd Edition, 1999, Springer, USA.
11. BS EN 60079-20-1:2010 Explosive atmospheres. Material characteristics for gas and vapour classification. Test methods and data, 2010, BSI.
12. Sinha, A. and Wen, J., A simple model for calculating peak pressure in vented explosions of hydrogen and hydrocarbons, *International Journal of Hydrogen Energy*, 2019, 44: 22719 – 22732.
13. NFPA 68, Explosion Protection by Deflagration Venting, NFPA, 2013 Edition.
14. Molkov, V., Dobashi, R., Suzuki, M. and Hirano, T., Modelling of vented hydrogen deflagrations and correlations for vent sizing, *J. of Loss Prev. in the Process Ind.*, 1999, 12: 147 – 156.
15. BS 4947:1984 Specification for test gases for gas appliances, 1984, BSI.
16. Gas Appliance Direction (GAD 2009/142/EC), 2009, BSI.
17. Gas Appliance Regulation (EU) 2016/426 (GAR), 2016, BSI.
18. BS EN 437:2018 Test gases. Test pressures. Appliance categories, 2018, BSI.
19. Perry, R.H. and Green, D.W., Perry's Chemical Engineers' Handbook, 2007, McGraw-Hill, UK.
20. Coburn, R.F., Forster, R.E. Kane, P.B., Considerations of the physiological variables that determine the blood carboxyhaemoglobin concentration in man. *J. Clin. Invest*. 1965, 44(11):1899-1910.
21. Peterson, J.E., and Stewart, R.D., Predicting the carboxyhaemoglobin levels resulting from carbon monoxide exposures. *J. Appl. Physiol*., 1975, 39(4):633-638.
22. Wagstaff, D., Review of Gas Industry Procedures in Support of HyDeploy2 Research Programme, HSE Bespoke Research and Consultancy, 2020.
23. Durber. A. and Hollinshead, M., Downstream Gas Standards Review, Blue Flame Associates, 2020
24. Gas Safe Register, Technical Bulletin 159: Natural gas standards when working on domestic installations being supplied with natural gas containing up to 20 vol% hydrogen, 2021.
25. Kelsey. A., Pocock, D., Stewart, J. and Gant, S., HyDeploy2: Gas Characteristics - Accumulation, HSE Bespoke Research and Consultancy, 2020.
26. Hooker, P. and Hoyes, J., HyDeploy Report 4: Gas Characteristics (Leakage, Dispersion and Flammability), Health & Safety Laboratory, 2018
27. Hooker, P. and Torrado, D., HyDeploy2 – Analysis of the explosion severity parameters for 20% Hydrogen/ 80% Methane deflagration in vented enclosures, HSE Bespoke Research and Consultancy, 2020.
28. Harris, J., Investigation & control of gas explosions in buildings & heating plants, British Gas, 1983.
29. Engelberg, D.L., Scenini, F., Zhou, Y., Duff, J. and Mukahiwa. K., HyDeploy2: Delivery of Materials Analysis and Testing, The University of Manchester, 2020.
30. Brown, M., Loo-Morrey, M. and Sanchez, C., HyDeploy2: Experimental results from the HyDeploy materials work package, HSE Bespoke Research and Consultancy, 2020.
31. Pursell, M., Goff, R. and Torrado, D., HyDeploy2: Appliance Testing Experimental Results, HSE Bespoke Research and Consultancy, 2020.
32. Lander, D.F., Modelling of exposure and poisoning by carbon monoxide and assessment of the effects of fuelling gas appliances with hydrogen-natural gas blends, Dave Lander Consulting, 2020.
33. McLaughlin, P. and Wilcox, S., HyDeploy: Gas Appliances Laboratory Testing Results, Kiwa Gastec, 2018.
34. McLaughlin, P., HyDeploy Supplementary Lab Testing, Kiwa Gastec, 2018.
35. Pursell, M., Wagstaff, D., Rattigan, O. and Hooker, P., HyDeploy2: Operation of Gas Appliances with Hydrogen Blended Gas, HSE Bespoke Research and Consultancy, 2020.
36. Lander, D.F, HyDeploy2 – Quantified Risk Assessment of the field trial of hydrogen injection into the NGN gas distribution system at Winlaton, Dave Lander Consulting, 2020.
37. HSE, Reducing Risks, Protecting People, ISBN 0 7176 2151 0 (2001) 4.