Final Report

AHRI Report No. 8024

ASSESSMENT OF HYDROGEN ENRICHED NATURAL GAS

Final Report

Date Published – JANUARY 2021

Paul A Needley CEng, FIMechE, FEI
Dr Lukasz Peronski PhD, MSc Eng

ENERTEK INTERNATIONAL LTD
Kingston upon Hull
East Yorkshire
United Kingdom

Prepared for

AIR-CONDITIONING, HEATING AND REFRIGERATION INSTITUTE
2311 Wilson Boulevard, Suite 400, Arlington, Virginia 22201-3001

DISCLAIMER

CONTENTS

1 EXECUTIVE SUMMARY

1.1 Remit and Methodology

1.1.1 This study has been carried out by Enertek International Ltd on behalf of AHRI to appropriately validate whether American gas appliances remain safe if they are fuelled by hydrogen enriched natural gas. The project brief covers new, existing, and old (legacy) appliances.

1.1.2 The resulting conclusions and recommendations have emerged following extensive analysis of state-of-the-art information from international research projects, product details supplied by AHRI members, evaluation of theory, classification of products and risk analysis arising from FMEA's for each product type.

1.2 The Case for Hydrogen Enrichment

1.2.1 Hydrogen enrichment offers decarbonisation opportunities to the gas industry and improves its environmental competitiveness with other forms of fuel.

1.2.2 Governments worldwide are committed to reducing CO_2 emissions. Decarbonisation of electricity is progressing rapidly, and electrification of heat (via heat pumps) is being promoted in many areas. Hydrogen is the main vector available to the gas industry to remain CO_2 competitive. Blending hydrogen with natural gas can be introduced progressively, commensurate with the availability of hydrogen as production increases and 20% is deemed as being a suitable maximum without major changes to gas appliances. 100% hydrogen is a step change being considered by many countries for introduction in the future.

1.3 The Implications for Appliances Supplied With up to 20% Vol Hydrogen

1.3.1 The Wobbe number of Hydrogen is broadly similar to that of Natural Gas and consequently the heat flow through pipes is very similar. This means that subject to soundness of construction and materials, gas flow through existing pipework fittings and appliances is acceptable without modification.

1.3.2 Although hydrogen has a higher combustion temperature and flame speed, when mixed with natural gas the effect of the hydrogen is offset by the lower calorific value which results in a downrating of approximately 5% of heat input. This downrating appears to reduce the potential increase in combustion temperature to a similar level to methane without the 5% downrating and test results to date indicate that despite the theoretical increase in NOx, actual NOx emissions appear to be reduced (notwithstanding the 5% downrating).

1.3.3 Flame light-back is a potential concern, but research in this study indicates that the risk is largely limited to older, atmospheric combustion appliances. A calculator has been provided to enable manufacturers to determine the level of risk for their appliances.

1.3.4 Potential leakage of hydrogen from fittings and hydrogen embrittlement of steel are theoretical concerns, but further research is needed to quantify whether either of these are likely to be a realistic practical problem. Likewise, the long-term reliability of appliances operating with localised higher burner temperatures and potential corrosion from an increased amount of water vapour needs to be determined.

1.3.5 The change in gas properties could (at some point) have an effect on the certification status of appliances which have been certified for use with methane. It is important to determine the threshold of hydrogen blending which would invalidate the certification of existing appliances, especially legacy appliances, and whether further tests are required on new appliances.

1.4 Overall Conclusions and Recommendations

1.4.1 This project has assessed the uncertainties and safety implications of hydrogen-enriched natural gas to understand the potential impacts of hydrogen-enriched natural gas on factory (new) and currently installed (legacy) gas-fired products and components manufactured by AHRI Members to validate whether hydrogen-enriched fuel is safe or not.

1.4.2 The overall conclusion is that subject to conducting further research in the key areas defined in the report, theoretical indications and initial evidence suggests that current production appliances should operate safely when supplied with up to 20% hydrogen in the US gas main without significant risk, providing that no adjustments are made to the appliance to redress the downrating of approximately 5% due to the change in fuel characteristics.

1.4.3 No significant differences were found between each of the appliance types examined.

1.4.4 Older appliances are more at risk due to potential light-back problems, but it is likely to be legacy appliances rather than recent production models which may cause problems. However, old (legacy) appliances will be less efficient than newer ones, and rather than try and adapt them to remain safe with 20% hydrogen, it is likely that more CO_2 can be saved by replacing the appliance with a new one than by adding 20% Hydrogen to the fuel supply! This reality has been identified in other markets and a political campaign to subsidise the replacement of older appliances would be worthy of consideration.

1.4.5 The certification status of appliances should be considered to ensure that the change in gas supply does not invalidate certification (and therefore insurance cover for installations).

1.4.6 There are several research projects underway worldwide to investigate the performance and long-term effect of appliances operating on a 20% hydrogen admix, and there are further projects looking at greater percentages of hydrogen up to 100%. The US may choose to conduct an independent research programme to validate specific risks associated with US products and installations or could choose to join (and perhaps extend) existing research programmes to take advantage of the work already being carried out elsewhere.

2 PROJECT BRIEF

2.1 Project Objectives

2.1.1 To assess the uncertainties and safety implications of hydrogen-enriched natural gas by conducting a screening analysis and research to understand the potential impacts of hydrogen-enriched natural gas on factory (new) and currently installed (old) gas-fired products and components manufactured by AHRI Members.

2.1.2 To appropriately validate whether hydrogen-enriched fuel is safe or not.

2.2 Scope

2.2.1 Gas-fired products and essential components such as valves, pipes and corrugated stainless steel tubing (CSST) that connect the equipment to the supply line.

2.2.2 The equipment assessed includes:

- Furnaces
- Boilers
- Burners
- Control valves
- Venting products
- Water heaters
- Pool heaters

2.3 Terms of Reference

2.3.1 To review publicly available literature and technical publications.

2.3.2 To gather evidence from members.

2.3.3 To conduct limited interviews with key personnel where appropriate but with limited disclosure regarding the specification of the AHRI project.

3 INTRODUCTION

3.1 Background and History – Hydrogen Blending

3.1.1 The concept of hydrogen replacing natural gas in the mainstream gas main was first considered by the UK government in 2012. Other European countries took an interest around a similar time and many projects have since been commissioned to determine the feasibility of using hydrogen as a low carbon replacement for natural gas.

3.1.2 Hydrogen offers the opportunity to reduce the carbon intensity of the products of combustion by blending hydrogen with methane, or ultimately replacing methane to give zero emissions. (Providing that the hydrogen is produced with zero emissions).

3.1.3 Hydrogen also has other uses within the decarbonisation agenda both as an energy storage medium via power to gas, for use in industry, and for use in transport.

3.2 Types of Hydrogen Projects Currently Being Undertaken

3.2.1 Many projects have been undertaken and many others are underway with the objectives of identifying and investigating:

- The production of hydrogen.
- The transport and distribution of hydrogen.
- Blending hydrogen with methane.
- Pure hydrogen replacing methane.

3.2.2 In each case, the challenges can be grouped as:

- Safety issues and concerns.
- Technical challenges.
- Economic implications and business models.

3.2.3 These can be considered as applying in descending order of challenge or importance.

3.3 The Report Authors - Enertek International Ltd

3.3.1 Enertek International Ltd is an independent engineering consultancy specialising in gas appliance design, development, and certification. The company was incorporated in England in 1988, employs 27 staff and undertakes consultancy, contract product design, development and certification testing on behalf of manufacturers of gas appliances throughout the UK, Europe, the United States and Australia.

3.3.2 Enertek's quality system is UKAS Accredited to ISO/EN 17025, the international laboratory quality Standard and the company has a UKAS/ILAC accredited laboratory capable of testing most types of gas, oil or electrical domestic & commercial heating and catering equipment.

3.3.3 Enertek International are at the forefront of hydrogen appliance developments in the United Kingdom and are currently working on hydrogen appliance development for the UK government (The Department for Business, Energy, and Industrial Strategy).

3.3.4 Enertek International have carried out test work for a major European manufacturer to determine at what concentration of blended hydrogen current gas boilers become unstable, unsafe or unreliable. The result of this work is confidential, but the background IP and lessons learned will be of value to the proposed AHRI project.

3.3.5 Enertek are delighted to have been offered the opportunity to conduct AHRI project 8024 and hope that our experience and position in the industry repays the confidence trusted in the company by AHRI Members.

3.4 Project Methodology

3.4.1 This project has been divided into several sections to fully cover the project brief. The project starts with a review of current literature available in the public domain (Section 4). This section looks at international evidence of projects taking place and considers technical information as well as geographical locations and concludes with a review of published technical documents and research papers.

3.4.2 Section 5 delves into a theoretical assessment of the feasibility of using blended hydrogen in gas appliances. This focusses the above information in line with the brief and provides a set of rules to assist with understanding the likelihood of problems with current or pre-installed appliances.

3.4.3 Section 6 merges the physics and internationally researched challenges of hydrogen into a concise section relevant to the products manufactured by AHRI members. This section explores the threat of flame light-back in detail and includes some test results on typical burners to verify the theory with performance results.

3.4.4 Section 7 presents the scenario regarding hydrogen blended methane for each of the product categories contained in the brief. Manufacturers names have been omitted, and information generalised where necessary to protect individual organisations Intellectual property rights.

3.4.5 The scenario for each product category is further analysed in section 8 with a series of FMEA's to provide manufacturers of each product type with a template which can be used to assess any likely risks or challenges relating to their own products so that they can take any necessary action in advance of hydrogen blending being introduced.

3.4.6 Finally, overall conclusions and recommendations are presented in sections 9 and 10 in a format whereby AHRI and their members can make industry wide consensus decisions regarding the suitability of product on the US market being compatible with blended hydrogen at a range of different blend concentrations.

4 LITERATURE AND EVIDENCE REVIEW

4.1 International Interest in Hydrogen

4.1.1 Significant interest is being shown internationally regarding the potential use of hydrogen for decarbonising the gas supply.

4.1.2 Many of the studies and projects where reports are publicly available relate to the production and transmission of hydrogen. Significantly less information is available regarding the effect of hydrogen (or hydrogen blending) on appliances. A summary of the most important developments relating to the brief of this project are summarised below:

4.2 The United States

4.2.1 Interest and research into hydrogen in America has increased in recent years and currently covers many topics and different areas of interest. This looks set to continue (evidenced by the decision by AHRI to initiate this project).

4.2.2 *Advanced Power and Energy Program (University of California, Irvine)*

4.2.2.1 Professor Vince McDonell is leading a programme of research regarding hydrogen blending on appliances, specifically focussing on gas turbine engines, (which are known to be sensitive to admixtures) in addition to other appliances. Professor McDonell kindly contributed to this project and will be a very useful contact if follow up work is required.

4.2.2.2 The California Hydrogen Business Council provided a list of reports (from around the world) via Professor McDonell which demonstrated the depth of research and knowledge already known and available in the US.

4.3 The United Kingdom (GB)

4.3.1 *Government Policy*

4.3.1.1 In June 2019, the UK Government passed legislation to make Net Zero CO_2 by 2050 a legally binding target. Decarbonisation is therefore a key policy and hydrogen is seen as the only viable way to continue to operate a major national gas grid in the longer term.

4.3.1.2 In November 2020, the Prime Minister of the United Kingdom published a 'Ten Point Plan for a green industrial revolution' and Point 2 is 'Driving the growth of low carbon hydrogen'. **https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.** Points 1, 7, and 8 are also relevant to this study, 'Advancing Offshore Wind', 'Greener Buildings' and 'Investing in Carbon Capture, Usage and Storage (CCUS) respectively'.

4.3.1.3 Essentially, the PM's plan is to start blending hydrogen into the UK gas main from 2023, and at the same time have trials for 100% hydrogen heating of homes. Investment in excess wind power and CCUS to extract hydrogen from methane will produce the hydrogen to facilitate this.

4.3.1.4 Hence it is now the UK's policy to start injecting hydrogen into the gas grid as soon as it is technically feasible to do so.

4.3.1.5 Electrification of heat is deemed problematic given limited generation and distribution capacity coupled with other demands on electricity including the expected move towards electric vehicles, but heat pumps are to be promoted, especially for new build and off-grid homes.

4.3.1.6 The UK Government Department for Business, Energy, and Industrial Strategy (BEIS) is a major sponsor of projects relating to hydrogen.

4.3.2 *BEIS Hy4Heat*

4.3.2.1 Hy4Heat is a UK Government sponsored project which aims to establish whether it is 'technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances. This is specifically aimed at 100% hydrogen and involves many of the leading manufacturers and component suppliers in the UK and Europe.

4.3.2.2 Further information about the project and published newsletters can be ae accessed at https://www.hy4heat.info/ and specific details about the programme to develop hydrogen domestic appliances (Work package 4) are available at https://www.hy4heat.info/wp4 and commercial appliances (Work package 5) at https://www.hy4heat.info/wp5.

4.3.2.3 Enertek International Ltd are heavily involved in this project and would be pleased to provide AHRI members with updates or more details upon request.

4.3.2.4 This project commenced in 2018 and is due for completion in mid-2021, with the expected output being a range of EC Certified domestic and commercial appliances suitable for sale in the UK. Initially these appliances will be used to feed into other hydrogen projects including H100 and H21 (see below).

4.3.3 *HyDeploy*

4.3.3.1 HyDeploy is the UK's first practical project to demonstrate that hydrogen can be safely blended into the natural-gas distribution system without requiring any changes to appliances. The site chosen is Keele University campus which is located in the West Midlands.

4.3.3.2 The first part of the project was an extensive technical programme to establish the necessary detailed evidence base in support of an application to the Health & Safety Executive for Exemption to Schedule 3 of the Gas Safety (Management) Regulations (GS(M)R) to permit the injection of hydrogen at up to 20% volume for a ten-month trial.

4.3.3.3 The safety case included limited laboratory testing on a number of appliances to prove that the effects of the blended gas did not significantly change performance parameters and remained safe.

4.3.3.4 The appliance certification status for all appliances in the homes involved in the trial was deemed to be unaffected, because the blended gas to be used remains within the permitted Wobbe Number range for distribution in the UK gas main.

4.3.3.5 The second task was the construction of the electrolyser and grid entry unit, along with the necessary piping and valves to allow hydrogen to be mixed and injected into the Keele University gas-distribution network.

4.3.3.6 The third task is the trial itself, which started in late 2019 but was suspended due to the Covid 19 pandemic. The trial has resumed and by August 2020 was injecting around 15% hydrogen (progressively increasing to 20%). The trial is due to end in late February 2021 (when the H&S exemption expires) and results will be made public in due course following completion of the project report.

4.3.3.7 In parallel with the main project, major boiler manufacturers have supplied two identical boilers for testing. At least 8 boilers in total are on a marathon test rig, half of which are being fired on methane and the other half on blended methane / hydrogen up to 20%. At the end of a 12-month test period these boilers will be returned to the manufacturers for evaluation. The manufacturers will not be advised which one was operating on natural gas and which one was operating on blended gas until after the manufacturer has finished their assessment. The purpose of this is to determine whether the boilers operating on blended gas deteriorate faster than the ones on methane. This is perhaps the most important feedback from the project and will be of interest to all manufacturers if the results are made public by the manufacturers concerned.

4.3.3.8 Upon completion of the tests at Keele, further, larger scale trials are planned on public networks in the North East (Gateshead) and the North West of the UK.

4.3.3.9 The objective of HyDeploy is principally to develop the initial evidence base that hydrogen can be blended into a UK operational natural-gas network without disruption to customers and without prejudicing the safety of end users.

4.3.3.10 Further details about the project can be accessed at https://hydeploy.co.uk/

4.3.4 *H21 – Leeds Citygate (NGN)*

4.3.4.1 The H21 Leeds Citygate project was a study carried out in 2016 with the aim of determining the feasibility from both a technical and economic viewpoint of converting the existing natural gas network in Leeds (one of the largest UK cities) to 100% hydrogen. The proposal is to start converting Leeds to 100% hydrogen in 2028. This project is focussed on 'upstream' of the appliance and further details can be accessed at https://www.h21.green/projects/h21-leeds-city-gate/.

4.3.5 *H21 – Further Phases*

4.3.5.1 Following the success of the original H21 project, several follow up projects have commenced and are ongoing under the H21 banner (Phase 2), all aimed at proving the feasibility of network conversion to 100% hydrogen.

4.3.5.2 Phase 2 includes testing appliances in purposely built houses at DNVGL's facility at SpadeAdam **https://www.dnvgl.com/oilgas/perspectives/heating-homes-with-hydrogen-proving-the-safety-case.html**

4.3.5.3 Leakage dispersion tests have already been completed and two hydrogen boilers were recently installed, with other hydrogen appliances to follow shortly.

4.3.5.4 Further information is available from https://www.h21.green/projects/.

4.3.6 *SGN - H100*

4.3.6.1 SGN's H100 project is to construct and demonstrate the UK's first network for 100% hydrogen. The project is built-up of a series of smaller projects that focus on each key aspect of hydrogen research. These will develop the evidence to enable SGN to progress towards the construction and physical operation of the UK's first 100% hydrogen network.

4.3.6.2 Workstream A is examining the technical and commercial feasibility of constructing a new, dedicated network capable of providing 100% hydrogen to approximately 300 homes and businesses. Workstream B is the Feasibility and Front-End Engineering Design studies. These are identifying and evidencing the potential regulatory, technical, and physical issues that need to be overcome in preparation for construction and operation of the network. Workstream C is to build and install the network to 300 homes in Fife, with installation of appliances for demonstration commencing in late 2021. The project has a five-year operational phase following completion of the installations.

4.3.6.3 Assuming that this is successful, there are plans for larger networks to follow.

4.3.6.4 Further details are available at https://www.sgn.co.uk/H100Fife.

4.4 Germany

4.4.1 Within the last few weeks, the German Government have adopted a new hydrogen strategy and devoted 9 Billion Euros (10.5 Billion USD) for investment in making hydrogen a marketable fuel. This is to be divided with 7B € for promoting hydrogen technologies within Germany and 2B € designated for international partnerships.

4.4.2 The strategy states that hydrogen will be used in the steel and chemical industries, for heating, and in the transport sector.

4.4.3 Germany has declared that only hydrogen produced from renewable energies ('green' hydrogen) is sustainable in the long term.

4.4.4 The government intends to establish a hydrogen coordination centre to support Ministries and their hydrogen council, and to monitor progress in an annual report. Every third year, a more extensive report will re-evaluate the strategy and the action plan. In addition, a working group will be set up to ensure smooth cooperation between the federal level and Germany's states.

4.4.5 At this stage it is not clear whether distributed gas will be blended or ultimately 100%, nor is it clear how much resource will be spent on hydrogen for heating, but various studies and projects have already taken place in Germany, and Germany is playing a major part in the ThyGa project (see section 4.11)

4.4.6 Germany is strong on support for fuel cell heating systems and support will be continued and possibly expanded to boost the use of hydrogen in the heating sector.

4.5 Australia

4.5.1 A Government paper states aims for decarbonising include heating. The different States' approaches are reported with all States embracing hydrogen regarding production and distribution, but only South Australia is intending to undertake work with boilers.

4.5.2 The Government report states that Australian Gas Infrastructure Group (AGIG) are investing $11.4M in a demonstration hydrogen park project and injection into local gas. Initially 5% hydrogen mix but looking at going to 10% soon.

4.5.3 There are currently 23 hydrogen specific demonstration projects and research facilities in Australia, (mainly around the South East Coast), but these cover all aspects of hydrogen, nonetheless blending into the gas grid and eventual use of 100% hydrogen is a stated objective.

4.6 Canada

4.6.1 Natural Resources Canada released their **Hydrogen Strategy for Canada** on 17th December 2020.

4.6.2 Titled 'Seizing the Opportunities for Hydrogen – A call to Action', the 104-page document covers all aspects of hydrogen and states Canada's opportunities to produce, use and even export hydrogen.

4.6.3 The section most relevant to this report (pages 60 – 63) demonstrates a good awareness of worldwide developments regarding hydrogen for heating, and states aspirations for Canada starting with 5% hydrogen blending and increasing progressively, with 100% hydrogen for some regions of Canada.

4.6.4 The article concludes that blending at a low level is technically feasible today and by 2050 hydrogen could account for 86% of the gas supply by volume.

4.7 **Belgium**

4.7.1.1 Belgium organisations (including Marcogaz who are based there) are active in hydrogen projects, but no information has been located specifically relating to any trials in Belgium.

4.8 **Italy**

4.8.1.1 SNAM (a distribution company) is to test a 10% mix in southern Italy and is currently running a 5% mix test area near Salerno.

4.9 **Japan**

4.9.1.1 Although interested in hydrogen for vehicles and fuel cells, we are not aware of any other interest in using hydrogen for heating (apart from fuel cells).

4.10 **South Korea**

4.10.1.1 South Korea has a clear policy directed towards hydrogen but aimed at vehicles and fuel cells only for heating. There is no mention of boilers or hydrogen admixtures.

4.11 **The Netherlands**

4.11.1.1 *The TKI New Gas Programme*

4.11.1.2 This is the Dutch government programme to stimulate innovative applications of gas. In 2018 the 'Hydrogen Roadmap' was published, which describes where and how sustainable hydrogen can be embedded into the Dutch energy and raw materials system. In July 2019, a preliminary study into the Dutch market for hydrogen was published.

4.11.1.3 The Northern provinces in the Netherlands are particularly active in hydrogen. The HYDROGREENN network (HYDROGen Regional Energy Economy Network Northern Netherlands) is project manager of the Hydrogen Neighbourhood in Hoogeveen for house heating and production facilities.

4.11.1.4 Currently, several pilot projects are running where hydrogen is used for heating and cooking.

4.11.1.5 In June 2019 the first hydrogen-only boilers were installed in Rozenburg, Rotterdam, as part of a pilot. Partners in the pilot are Gasterra, Bekaert Heating, Remeha, DNV GL, Stedin (grid operator), and City of Rotterdam.

4.11.1.6 Similar hydrogen pilots are running or are being considered in Ameland, Hoogeveen, and Goeree-Overvlakkee

4.12 European Research Project - ThyGa

4.12.1.1 The European Commission has decided to fund a new 'THyGA' project (Testing Hydrogen Admixtures for Gas Appliances). This project sets out to develop and communicate a detailed understanding of the impact of blends of natural gas and hydrogen on end use applications, specifically in the European domestic and commercial sector.

4.12.1.2 The project objectives are stated as 'THyGA aims at closing knowledge gaps regarding H2NG blends, to identify and recommend appropriate codes and Standards that should be modified or adapted to answer the needs for new and existing appliances'

4.12.1.3 The project focusses on European domestic and commercial end-users (heating, hot water, and cooking appliances) and will cover both technical and regulatory aspects including safety, combustion, chemistry, and materials. Hence there is a significant overlap with the brief of this project, albeit in Europe instead of the US.

4.12.1.4 There are nine partner companies involved in the project (mainly utilities and research associations) from six European Countries (not including the UK). Although the UK is currently outside this project, this could change and Enertek International are hoping to have some involvement as the project gathers pace.

4.12.1.5 The project includes testing up to 100 appliances to determine the practical effect of hydrogen admixtures. This will be done by laboratories in Denmark, France and Germany.

4.12.1.6 THyGA have recently published two reports relevant to this project, one regarding combustion and the other one regarding materials science (and in particular hydrogen embrittlement). Both reports were accompanied with Webinars (Enertek International took part in both). A summary of the relevant part of the materials report is provided in section 4.12.6, and a summary of the combustion report is covered in section 4.12.7.

4.12.1.7 Further details and all accessible material (including the reports in full) can be reached via **https://thyga-project.eu/#**

4.13 Technical Documents and Research Papers

4.13.1.1 Several documents have been found relevant to appliances. These are listed in the bibliography at the end of the report and referred to where appropriate in the following sections.

4.13.2 Marcogaz Technical Association Bulletin 23/10/17 – Impact of Hydrogen in Natural Gas on End-Use Applications

4.13.2.1 Marcogaz (The technical association of the European natural gas industry) conclude that it is generally agreed that mixtures of natural gas with up to 10% by volume of hydrogen can be injected and conveyed without significant integrity problems in traditional natural gas grids, apart from a few applications. Key points in this document are summarised below.

4.13.2.2 Many natural gas applications can use mixtures of hydrogen and natural gas without significant problems. As an example, modern European domestic appliances are certified as complying with the European Gas Appliance Regulation (GAR). Part of this process involves using a test gas with 23 % hydrogen (gas G222, as defined in EN 437) and several pilot projects in Europe focusing on residential/commercial utilization have demonstrated that safe operation of these types of appliances is feasible with up to 20% of hydrogen in natural gas.

4.13.2.3 Some stakeholders, however, have concerns regarding the utilization of hydrogen/natural gas mixtures and this paper addresses these concerns, pointing out available solutions and highlighting opportunities which may arise due to the blending of hydrogen and natural gas.

4.13.2.4 The Marcogaz paper includes a useful graph (Figure 1) showing the relative properties of hydrogen blends from 0 to 100% which demonstrates that whilst Calorific Value and Relative Density differ greatly between the two gasses, the Wobbe number is relatively constant.

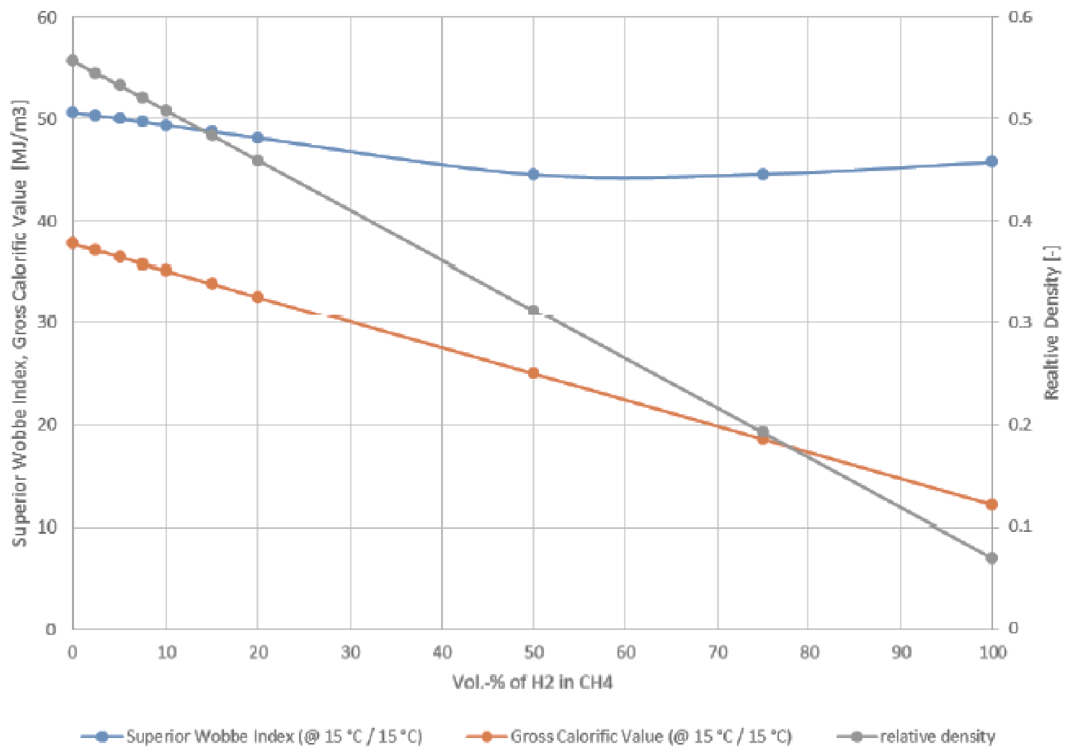

Figure 1 Impact of H_2 concentration in CH_4/H_2 mixtures on some gas quality properties

4.13.3 **Marcogaz Briefing to the 33rd Madrid Forum, 23/24 October 2019**

4.13.3.1 A key conclusion announced by Marcogaz at the Madrid forum was 'Major elements of the existing NG infrastructure and residential gas appliances are expected to accept 20% volume H_2 without major modification, and higher concentrations above 20% volume H_2 could be reached through R&D and using further measures or replacements

4.13.3.2 Also, presented was a summary showing the state of readiness for hydrogen (Figure 2)

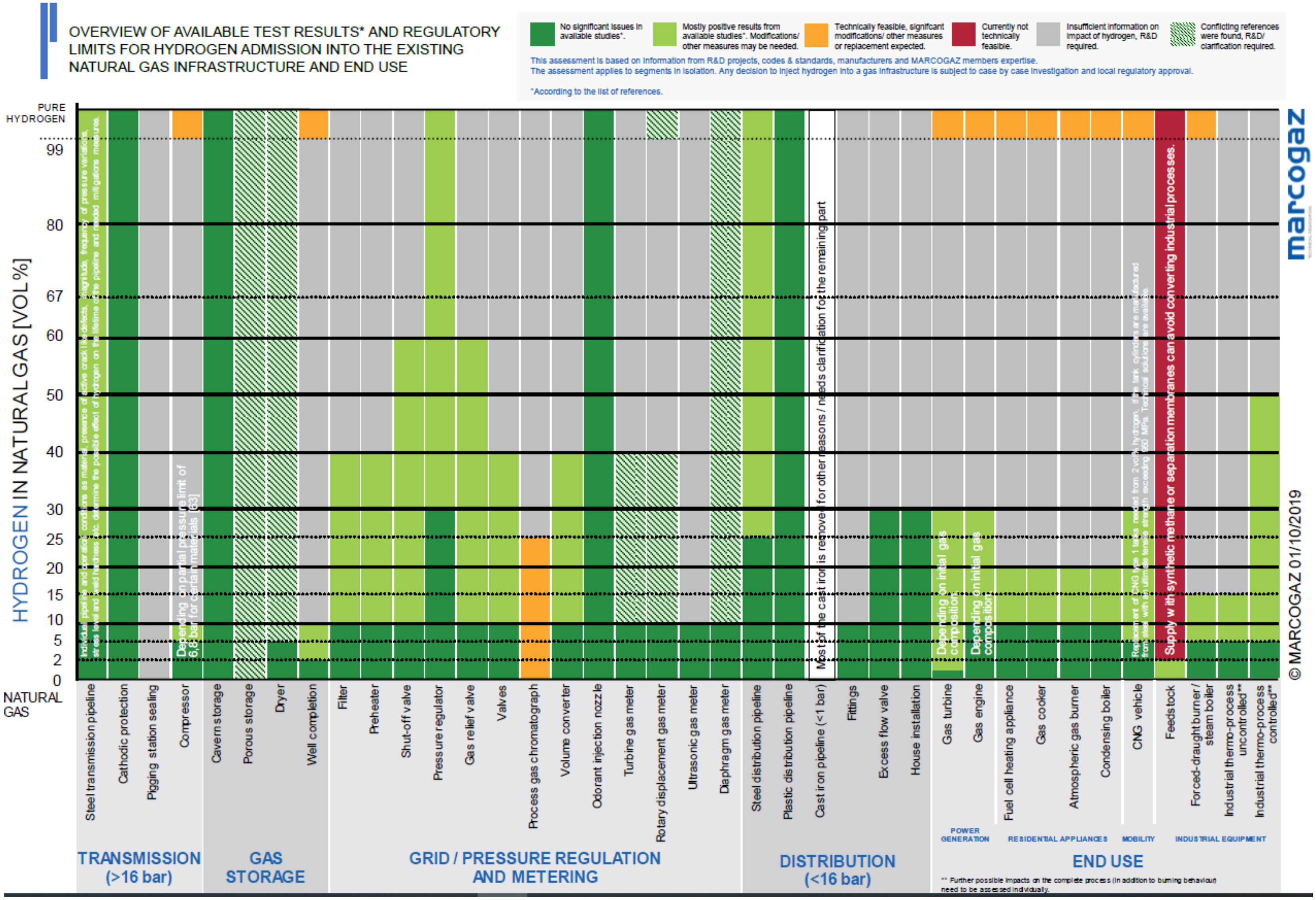

Figure 2 Overview of available test results and regulatory limits for hydrogen admission into the existing natural gas infrastructure and end use

4.13.3.3 **Marcogaz Conclusions for Natural Gas Infrastructure and Residential Appliances** (Based on the studies listed in the report's references):

- Major elements of the gas transmission, storage and distribution infrastructure and residential gas appliances are expected to be able to accept 10% volume H_2 without modification.
- Some networks and residential appliances are already being operated with 20 % volume of H_2.
- Major elements of the infrastructure and residential appliances are expected to be able to accept 20% volume H_2 with modification.
- Higher concentrations (above 20% volume H_2) can be reached through R&D by further measures or replacement.

4.13.3.4 **Marcogaz Conclusions for Industrial Processes** (Based on the studies listed in the report's references)**:**

- Many industrial processes (except feedstock) are expected to be able to accept 5% volume H_2 without modification.
- Current power plant gas turbines, industries using natural gas feedstock and CNG steel tanks are assessed to be sensitive to even small quantities of hydrogen and need further R&D/mitigation measures when planning to convey higher hydrogen concentrations.
- Thermal processing equipment (such as furnaces and burners) are expected to be able to accept 15% volume H_2 with modifications.
- Higher concentrations (above 15% volume H_2) can be tolerated through R&D, further measures, or replacement.

4.13.3.5 Marcogaz also consider the impact of hydrogen blending upon NOx emissions and conclude that whist in principle, hydrogen in natural gas can lead to higher NOx emissions due to higher local temperatures in the combustion zone, test results show that NOx formation is dependent on the specific process / application, and studies show that even significant concentrations of hydrogen in natural gas can be handled without dramatic increases in NOx emissions if appropriate measurement and control technologies are used to control the process.

4.13.3.6 A further conclusion from Marcogaz is that research demonstrated that many residential and commercial gas appliances can be adapted to handle up to 30% volume of hydrogen in natural gas without safety concerns, and in industrial thermal applications up to 50 % of hydrogen in natural gas could be handled without negative impact on efficiency, product quality and pollutant emissions if proper measurements and control technologies are applied.

4.13.3.7 Finally, Marogaz conclude that gas turbines and gas engines are probably the most sensitive end-use applications with regards to hydrogen admixture into natural gas. Manufacturers and researchers are currently investigating new technologies to address this issue

4.13.4 **Hydrogen-Enriched Natural Gas as a Domestic Fuel: An Analysis Based on Flash-Back and Blow-Off Limits for Domestic Natural Gas Appliances Within the UK** – Daniel R Jones & Charles W Dunnill (Sustainable Energy and Fuels, Issue 4 2018):

4.13.4.1 A conclusion from Jones/Dunnil's study is that hydrogen has emerged as a foremost candidate to offset and eventually replace the use of traditional gaseous fossil fuels.

4.13.4.2 They state that European trials have already been conducted to investigate the practical implementation of hydrogen-enriched natural gas (HENG) within a mains gas supply. In this work, the limitations of such a strategy are evaluated based on a novel meta-analysis of experimental studies within the literature, with a focus on the constraints imposed by the phenomena of flash-back (light-back) and blow-off. Through consideration of the Wobbe Index, they discuss the relationship between volume hydrogen percentage and annual carbon dioxide output, as well as the predicted effect of hydrogen-enrichment on fuel costs.

4.13.4.3 It is further shown that in addition to suppressing both blow-off and yellow-tipping, hydrogen-enrichment of natural gas does not significantly increase the risk of flash-back on ignition for realistic burner setups, while flash-back at extinction is avoided for circular port diameters of less than 3.5 mm unless the proportion of hydrogen exceeds 34.7 % by volume.

4.13.4.4 They propose that up to 30% by volume of the natural gas supply may be replaced in the UK with guaranteed safety and reliability for the domestic end-user, without any modification of the appliance infrastructure.

4.13.5 **Impact of hydrogen mixture on installed Gas appliances** – Petra Nitsche-Kowsky, Werner Wessing – E.ON Ruhrgas AG – Kuala Lumpar World Gas Conference 2012

4.13.5.1 This is a comprehensive assessment of the possibilities of blending hydrogen with methane to find acceptable limits and has been used in places to supplement and verify some of the work carried out in this report.

4.13.5.2 The project was carried out in Germany, well in advance of the current impetus for hydrogen but the science has not changed since 2012 even though the landscape has.

4.13.5.3 This is the earliest evidence we have found regarding the principle of hydrogen blending and more recent projects have built on the evidence in their report.

4.13.6 **THyGA Report 24 June 2020: Non-combustion related impact of hydrogen admixture - Material Compatibility** - Lisa Blanchard & Laurent Briottet, CEA, Grenoble, France

4.13.6.1 On 26 October 2020, THyGA held a webinar to present and discuss their report. Over 210 persons or organisations attended the session, which shows the significance of this work to the European Industry. All information is available by following the links at the end of this section.

4.13.6.2 The report (a desk-based exercise and literature review) considers the susceptibility of metallic materials used in gas appliances towards hydrogen embrittlement and includes carbon steels, stainless steels, copper, brass, and aluminium alloys. It also considers mechanical loading (stress), temperature, and hydrogen pressure conditions.

4.13.6.3 The report comments that experience has shown low alloy steels to be more susceptible to hydrogen embrittlement than stainless steels, and that austenitic stainless steels are less susceptible than ferritic stainless steels. However, the operating conditions in the natural gas distribution network within buildings are deemed much less severe than those analysed.

4.13.6.4 The main conclusions from the report can be summarised as:

- A mixture of natural gas and up to 50% hydrogen should not be problematic for any of the metallic materials employed in domestic and commercial installations, unless high mechanical stress or strain concentrations are present.
- An investigation on chemical compatibility has shown that polymer materials, and specifically polyethylene, are not subjected to deterioration after long term exposure in dihydrogen. (H_2 molecule).
- Hydrogen permeability through each material was considered but deemed to be insignificant regarding the scope of the report.
- Due to physical properties of hydrogen, it leaks 2.5 times faster than methane.

4.13.6.5 Finally, the report stated that the tightness of the gas distribution network (within buildings) and appliance components will be investigated during the experimental phase of the THyGA project.

4.13.6.6 For further reading, the comprehensive report is available for downloading from https://thyga-project.eu/deliverable-d2-4-non-combustion-related-impact-of-hydrogen-admixture-material-compatibility/ and the webinar, slides and question and answer session from https://thyga-project.eu/webinar-materials-science-impacts-of-hydrogen-blends/

4.13.7 **THyGA Report 27 June 2020: Impact of Hydrogen Admixture on Combustion Processes – Part I: Theory** - Jörg Leicher, Johannes Schaffert, Stéphane Carpentier, Rolf Albus, Klaus Görner, (GWI, Essen, Germany & ENGIE, CRIGEN Lab, France.

4.13.7.1 On 30 October 2020, THyGA held a webinar to present and discuss their report. Over 260 persons or organisations attended the session, which shows the significance of this work to the European Industry. All information referenced is available by following the links at the end of this section.

4.13.7.2 The report (a desk-based exercise and literature review) considers the Impact of hydrogen admixture on combustion processes.

4.13.7.3 Some of the information repeats what has already been presented in this report from Marcogaz, and other information has been used to supplement Enertek's theoretical assessment in the next section, hence, to avoid repetition in this section the documentation will be limited to the conclusions of the report.

4.13.7.4 The main conclusions from the report can be summarised as:

- Using hydrogen blended methane can affect combustion processes in gas appliances in terms of performance and safety due to the different physical and chemical properties of hydrogen and methane.
- Any consequences will become more significant as the percentage of hydrogen is increased.
- The combustion hardware and technology affect the degree of change when blended gas is supplied. (Pre-mix/ atmospheric and any combustion controls).
- Hydrogen requires less oxygen for combustion than methane, (figure 5, section 5.33) so in an appliance without combustion control, the mix becomes leaner and compensates for the potential effects on flame temperature, flame speed, and NOx.
- In an appliance with a combustion control which keeps a constant excess air level, temperatures will increase as will flame speed and NOx emissions.
- From a safety viewpoint, carbon monoxide levels should not increase with an admixture unless excess air causes flame instability.
- From a safety viewpoint the maximum explosion pressure of hydrogen is slightly lower than methane, but the deflagration index is slightly higher.

4.13.7.5 Finally, the report identified some open items which cannot be fully addressed without test work which is a future work package of the project. These include flame colour, and flame ionisation.

4.13.7.6 For further reading, the comprehensive report is available for downloading from https://thyga-project.eu/deliverable-d2-2-impact-of-hydrogen-admixture-on-combustion-processes-part-i-theory/ and the webinar, slides and question and answer session from https://thyga-project.eu/webinar-impact-of-hydrogen-admixture-on-residential-and-commercial-combustion-processes-insights-from-combustion-science/.

5 THEORETICAL EVALUATION OF HYDROGEN ENRICHED METHANE

5.1 Outline

5.1.1 This section of the report aims to investigate and identify physical properties of natural gas fuel-air mixtures as well as hydrogen enriched natural gas fuel-air mixtures which are important for the safe and stable operation of burners in gas fired appliances. It also considers the impact of the physical properties of the gas on the operation of the burners and the heating appliances in which they operate.

5.2 Terminology and Definitions

5.2.1 *Laminar Flame Speed*

5.2.1.1 Laminar flame speed is the speed of propagation of the flame front in a quiescent gas fuel-air mixture. It is known to vary with the composition of the fuel, the amount of the air present in the fuel-air mixture (typically expressed in terms of the Equivalence Ratio in this context) as well as the temperature and pressure of the fuel-air mixture.

5.2.1.2 It should be noted that in some cases, e.g., in large-scale burners in power stations, flame speed may be affected by turbulence and then the actual flame speed is different from the laminar flame speed.

5.2.1.3 If the velocity of the fuel-air mixture in the flame ports of a burner is lower than the flame speed, then the flame propagates into the burner (i.e., it lights-back) which is a safety risk and is not acceptable. The opposite extreme of the operation of a gas burner is that the velocity of the fuel-air mixture is higher than the flame speed to the point at which the flame front is lifted off the burner. Changing the composition of a gas fuel may cause one of these scenarios to occur in a burner.

5.2.2 *Heat Input*

5.2.2.1 Heat input is the rate at which the chemical energy supplied to a burner in the fuel is transformed by the burner to the thermal energy of the combustion products. Changing the composition of a gas fuel may change the heat input, i.e., the power of the burner.

5.2.3 *Excess Air Factor*

5.2.3.1 The excess air factor is the ratio of the amount of the air (either volume or mass) supplied for the combustion process, to the minimum (stoichiometric) amount of the air, required for the complete combustion of the unit amount of the fuel supplied for combustion. An excess air factor equal to 1 means the stoichiometric amount of air is supplied for combustion. An excess air factor above 1 means that the combustion is lean, i.e., that there is more air than the theoretical minimum required for the complete combustion. An excess air factor below 1 refers to rich combustion, i.e., with less air present than the theoretical minimum required for the complete combustion. This is incomplete combustion and produces dangerous levels of CO with fuel containing carbon.

5.2.4 *Equivalence Ratio*

5.2.4.1 Equivalence ratio is a measure of the fuel richness of a fuel-oxidant mixture (gas-air in this case). The equivalence ratio equal to 1 means the stoichiometric amount of air in the mixture. The equivalence ratio above 1 means that the mixture is rich, i.e., that there is less air in the mixture than the theoretical minimum required for the complete combustion. The equivalence ratio below 1 refers to a lean mixture, i.e., a mixture with more air present than the theoretical minimum required for the complete combustion.

5.2.5 *Adiabatic Flame Temperature*

5.2.5.1 Adiabatic flame temperature (at constant pressure) is the temperature of the products of the complete combustion if there is no energy loss to the outside environment.

5.2.5.2 Figure 3 (Source THyGA) shows the adiabatic flame temperatures for methane, hydrogen and a 50% mix. Note that the 50% mix is not halfway between the other two lines due to the different properties of the gases.

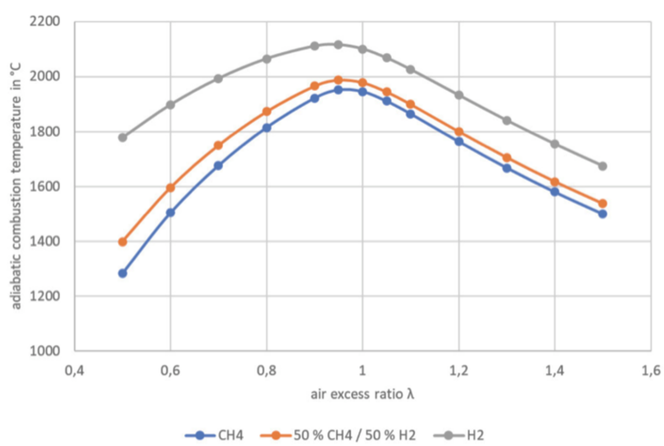

Figure 3 Adiabatic combustion temperatures of methane, hydrogen and a 50/50 blend.

5.2.6 *Burner ports*

5.2.6.1 Burner ports are the apertures in the direct vicinity of the flame through which the gas-air mix exits the burner and enters the combustion chamber

5.3 Gas Appliance Design Characteristics

5.3.1 *Design for Excess Air*

5.3.1.1 All domestic and commercial gas appliance combustion systems are designed to run with excess air (i.e. not at stoichiometric conditions). There are two main reasons:

- To allow for variations in the quality of the gas supply (and to a lesser degree air supply – warmer air in summer is less dense than cold winter air)
- To allow for incomplete mixing of gas and air within the combustion system.

5.3.1.2 With methane, the level of excess air is normally measured by the CO_2 content in the products of combustion. For example, a 9.5% CO_2 reading in the flue gas of a methane appliance (Stoichiometric = 11.73% CO_2) is an excess air level of approximately 21% excess air.

5.3.1.3 Atmospheric burners run at much higher levels of excess air because the mixing of gas and air is far more difficult to balance across the burner. A 7.5% CO_2 level gives an excess air level of approximately 50%.

5.3.1.4 Excess air is heated by the combustion process but provides no additional chemical energy, hence heating more air than necessary reduces the temperature of the combustion products and consequently reduces the appliance efficiency.

5.3.1.5 However, excess air also cools the flame which usually infers lower NO_x levels.

5.3.2 *Gas Supply Tolerances*

5.3.2.1 Unlike the US where propane air tests represent a combustion challenge, In Europe, natural gas appliances are subjected to ‘limit gas’ tests during the certification process.

5.3.2.2 There are typically three limit gases used. Reference gas is pure methane (known as G20) and limit gases are:

- G21 – Combustion limit gas G21 incorporates 13% propane blended with 87% methane. This has a higher calorific value and needs more oxygen for complete combustion and thereby ‘eats into’ the safety margin provided by the excess air.
- G222 – Light-back limit gas incorporates 23% hydrogen blended with 67% methane. This has a higher flame speed and tests the propensity of the burner to light-back during operation. A light-back situation is considered dangerous and would fail a certification test (high CO is a result of light-back on an atmospheric burner).
- Interestingly before European Standards, the old British Standards used G22 which was approximately 35% hydrogen and 65% methane with an even higher flame speed.

- G23 – Lift limit gas with 7.5% Nitrogen blended with 92.5% methane to test for flame lift off, instability and even extinction due to a lower flame speed.

5.3.2.3 The following diagram (Figure 4) is useful in demonstrating the effect of variations in the gas quality upon excess air levels (source E.ON Ruhrgas) based on a methane burner set at 100% load with an air factor of 1.2 then operated with different gases

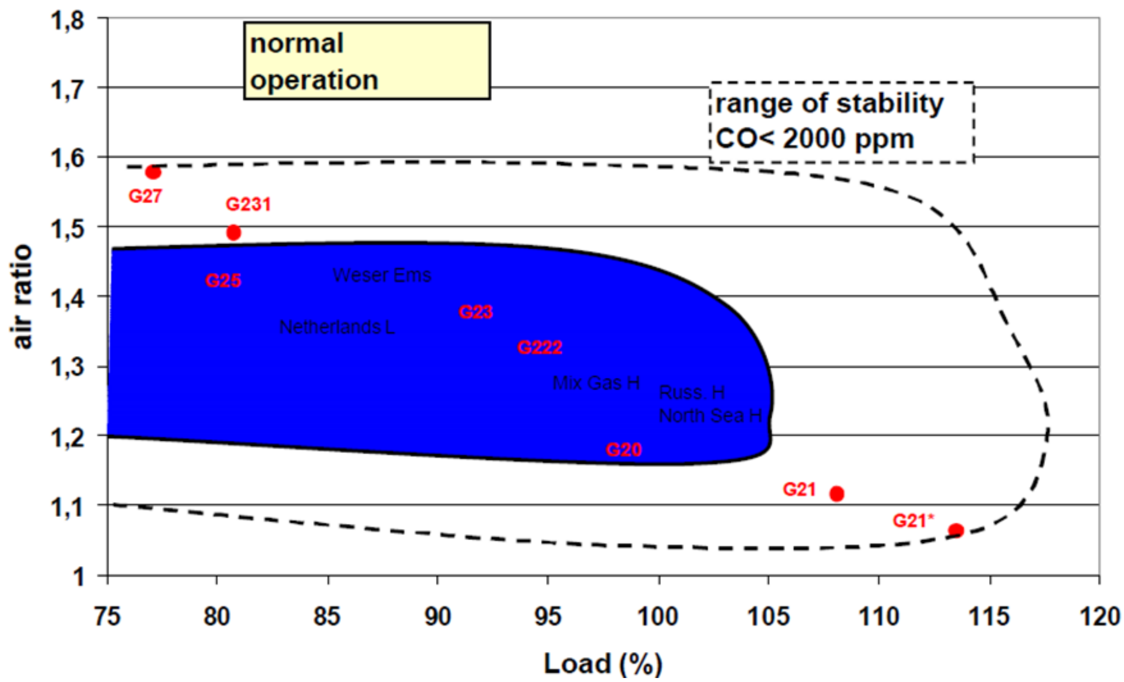

Figure 4 Air ratio for corresponding load percentage

5.3.3 *Implications for Hydrogen Blending*

5.3.3.1 The presence of limit gas tests means that all CE Marked (approved) gas appliances marketed in Europe (since at least the mid 1990's) have been tested for safe ignition, cross lighting and stability with 23% hydrogen blending. This cannot be said for American appliances hence there is a potential disadvantage for American manufacturers compared to their European equivalents.

5.3.3.2 Note that 'older' UK products tested to the old British Standards (NGC - 35% Hydrogen) are likely to be even more robust when tested with a hydrogen blend.

5.3.3.3 It could be inferred that this means a blend of 20% hydrogen could safely be added, but it is not that simple. Although tested on G222 for ignition, cross lighting, and stability there are no other tests with G222, hence burner or component temperatures are not measured, nor is thermal efficiency or heat input.

5.3.3.4 The reference gas G20 has a Wobbe number of 50.72 MJ/m^3 and tolerances allowed in the gas distribution network (UK) are between 47.2 MJ/m^3 to 51.4 MJ/m^3. Test Gas G222, with 77% methane and 23% hydrogen has a Wobbe Number of 47.8 MJ/m^3 and is therefore within the acceptable limits. This may vary for other European countries but the purpose of G222 is that it represents the limit (or just inside the limit) of what is allowed. Consequently, appliances certified for natural gas 'Group H' are deemed to be suitable for operation at this limit without modification.

5.3.3.5 If hydrogen blending causes the Wobbe number to fall below the limits, appliance certification would be deemed invalid, hence for practical purposes in Europe, 23% hydrogen is the maximum permissible without addressing certification. (Refer to Figure 1, section 4.12)

5.3.3.6 Although legally considered compliant, the European gas industry is considering introducing additional requirements and revising Standards should 20% blending become the norm, and one possibility is that G22 (35% hydrogen) may be re-instated as a limit gas.

5.3.3.7 As mentioned previously, hydrogen requires less air for combustion than methane, as shown in Figure 5 (Source: THyGA). The graph shows values for both gross and net calorific values.

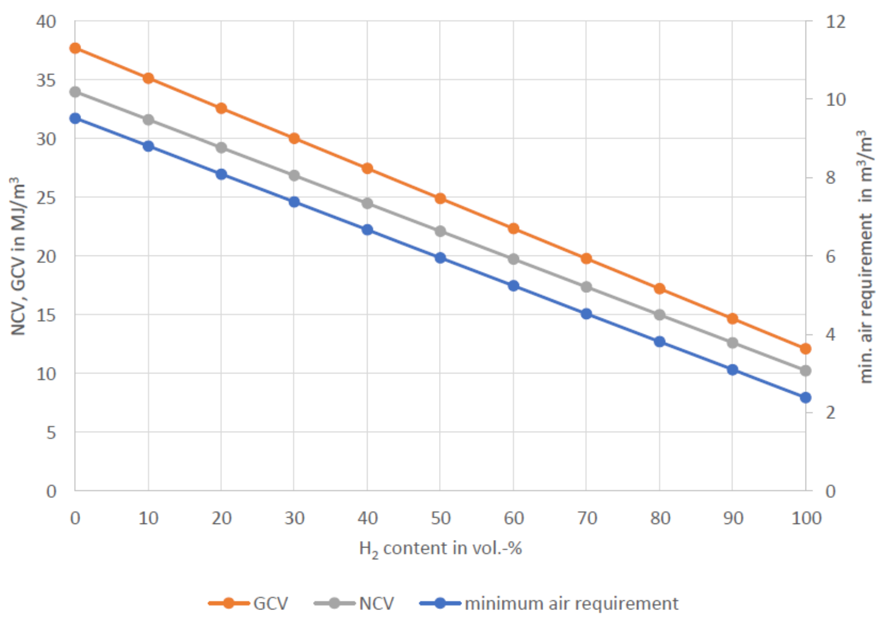

Figure 5 Impact of hydrogen content on minimum air requirement, net and gross calorific values @ 15°C

5.3.3.8 This means that for an appliance with unchanged airflow, the application of hydrogen to methane will result in a higher excess air level.

5.4 Consideration of a Hydrogen Enriched Combustion Model

5.4.1.1 Analysis of any of the afore-mentioned properties in isolation cannot predict the likely operation of gas burners and gas fired appliances with hydrogen enriched natural gas. All variables must be assessed together to provide an overall estimation of whether an appliance is likely to be suitable for any blend of hydrogen in methane.

5.4.1.2 As stated in section 5.2.1.3, if the velocity of the fuel-air mixture in the flame ports of a burner is lower than the flame speed, the flame will propagate into the burner (i.e., it lights-back) which is considered to be a safety risk and is not allowed. The opposite extreme of the operation of a gas burner is that the velocity of the fuel-air mixture is higher than the flame speed to the point at which the flame front is lifted off the burner. Changing the composition of a gas fuel may potentially cause one of these scenarios to occur in a burner.

5.4.1.3 The following analysis of each characteristic defined above is used to define a model for determining how hydrogen blending may affect burner or appliance performance.

5.4.2 *Laminar Flame Speed*

5.4.2.1 The laminar flame speed was calculated by means of pre-PDF polynomials within the Ansys Fluent Software for three concentration levels of hydrogen in the fuel: 0%H_2 (pure methane), 20% H_2 and 100% H_2 (pure hydrogen). Experimental values for hydrogen enriched natural gas blends were also obtained from the literature review for comparison purposes. The obtained values are presented in Figure 1 & Figure 2 as a function of the equivalence ratio.

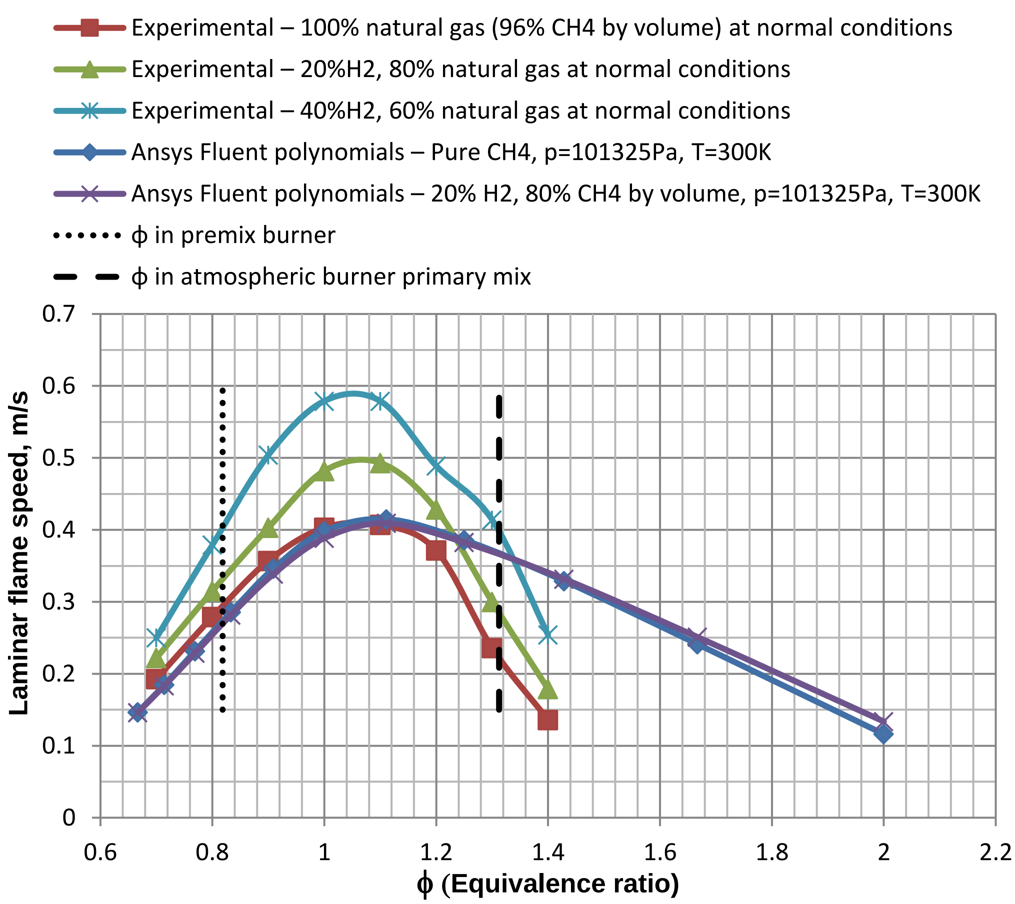

Figure 6 Laminar flame speed; calculated by means of the so-called pre-PDF polynomials within the Ansys Fluent Software, as well as experimental, see 5.4.2.1

5.4.2.2 It can be seen in Figure 6 that for pure CH_4 the Ansys Fluent polynomial calculations are relatively close to the experimental data up to about 1.1 equivalence ratio. Above this value of the equivalence ratio the calculated laminar flame speed diverges from the experimental results. There is also a discrepancy observed between the calculations and the experiments for the 20% hydrogen blend with methane namely, the calculation predicted very little difference in the laminar flame speed between pure methane and 20% hydrogen enriched blend. However, the experimental data indicated a distinct increase of up to about 0.1 m/s (about 25%) in the laminar flame speed for the 20% hydrogen enrichment. This highlights the potential risk of light-back which may occur in natural gas burners when supplied with a hydrogen enriched natural gas.

5.4.2.3 The experimental data shows that for higher concentrations of hydrogen the increase in the laminar flame speed becomes more dramatic. For pure hydrogen at the stoichiometric (equal to 1 equivalence ratio), the laminar flame speed reaches about 2.3 m/s (See Figure 7), which is nearly 6 times greater than that of natural gas.

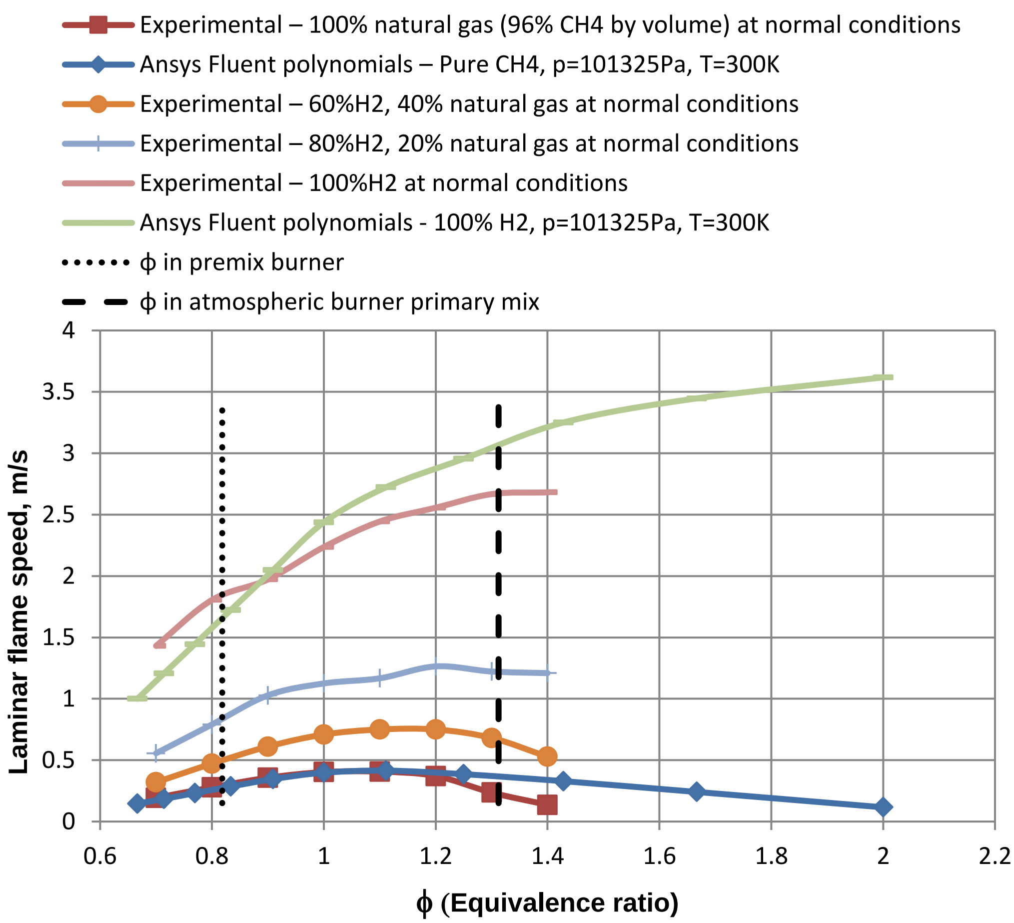

Figure 7 Laminar flame speed; calculated by means of the so-called pre-PDF polynomials within the Ansys Fluent 19.2 Software, as well as experimental.

5.4.3 *Heat Input*

5.4.3.1 The aim of the calculations described in this section is to estimate the likely impact of the hydrogen enrichment of natural gas on the heat inputs of gas fired appliances.

5.4.3.2 The flow rate of the gas fuel in gas fired appliances is typically controlled by the following factors: the gas supply pressure, the air pressure at the air-fuel mixing point and the gas flow restrictor (referred to as a nozzle, orifice, or injector). It is assumed in this section that the above factors would not change after adding hydrogen to the natural gas. Since manufacturers would probably prefer not to alter their designs, this is considered to be a reasonable assumption. Therefore, calculations of the flow rate of the gas fuel through a nozzle are expected to be representative of the impact of hydrogen enrichment of natural gas on the heat inputs of existing natural gas fired appliances, provided the supply pressure of the gas fuel remains unchanged.

5.4.3.3 In the calculations described in this section, flow rates of pure methane, pure hydrogen and 20% hydrogen 80% methane, through a nozzle, are predicted for a constant pressure loss across the nozzle and then converted to the corresponding heat inputs. The predictions are performed by means of two methods, namely the orifice formula, as well as the CFD simulation. The former is shown in Figure 8 and the latter in Figure 9.

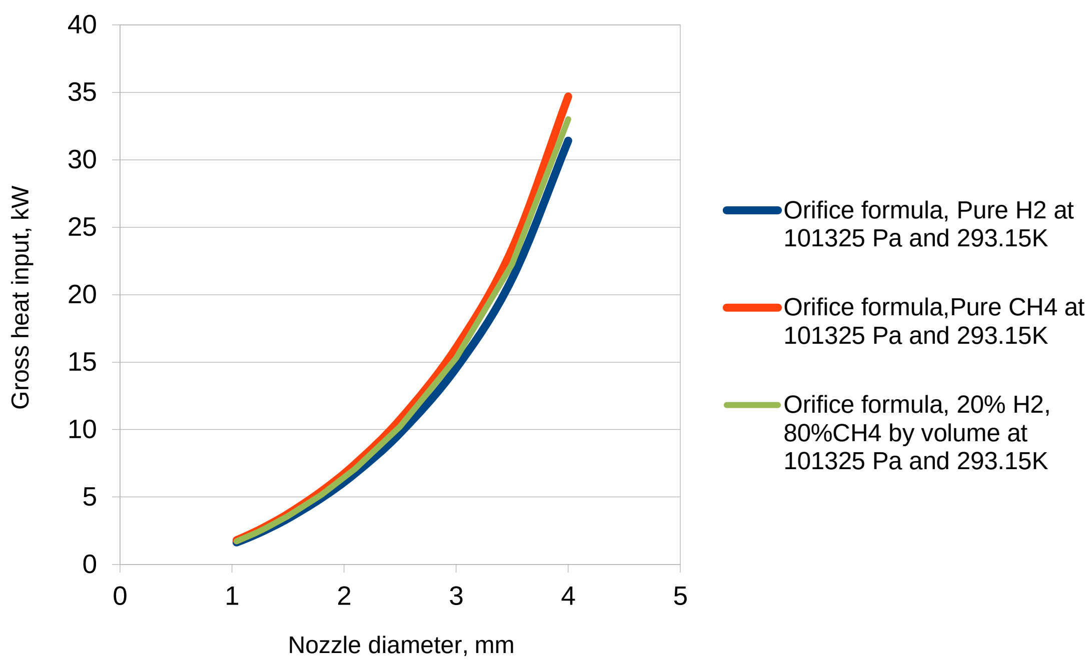

Figure 8 Gross heat input as a function of the gas nozzle/injector diameter at constant 2000 Pa (0.29PSI) Pressure loss across the nozzle, for pure hydrogen, pure methane and 20% hydrogen blend with methane, calculated by means of an orifice formula.

5.4.3.4 The heat input is reduced with the hydrogen enrichment of methane and this reduction is greater for higher concentrations of hydrogen in the mixture.

5.4.3.5 This difference in the heat input between pure methane and 20% hydrogen 80% methane predicted by means of the orifice formula, is equal to about 4.9% for the entire range of the nozzle diameters considered.

5.4.3.6 The same difference, predicted by means of the CFD simulations, ranges from about 4.7% to about 6.5%.

5.4.3.7 Considering the distinctively lower mass density of hydrogen compared with methane (nearly 8 times lower at room temperature and pressure), the difference in heat input is considered to be relatively low and this is attributed to the higher calorific value of hydrogen per unit mass.

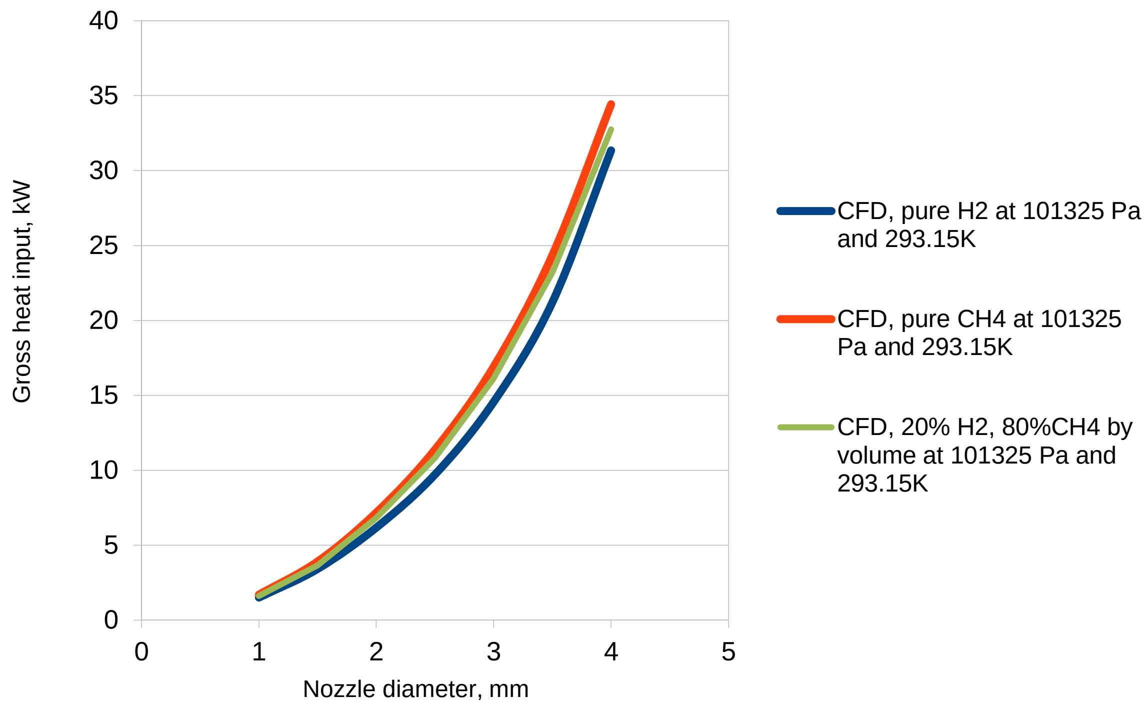

Figure 9 Gross heat input as a function of the gas nozzle/injector diameter at constant 2000 Pa (0.29PSI) pressure loss across the nozzle, for pure hydrogen, pure methane and 20% hydrogen blend with methane, predicted by means of the Ansys Fluent 19.2 CFD software

5.5 Mass and Energy Balance Calculations

5.5.1 Enriching natural gas with hydrogen will influence, to some extent, the composition of the combustion products. Therefore, the combustion related mass and energy balance calculations were performed to produce predictions on how the operation of natural gas fired appliances would be affected. These predictions are presented in Table 1 and described in more detail in the following sections.

Table 1 Mass and energy balance calculation results

Burner Type	Premix Burner System		Atmospheric Burner System	
Gas	Typical/mean values with natural gas fuel	Values predicted for natural gas fuel replaced with the 20% hydrogen 80% methane mix	Typical/mean values with natural gas fuel	Values predicted for natural gas fuel replaced with 20% hydrogen 80% methane mix
CO_2 concentration (by volume) in the flue gas	9.4%	8.26%	7.4%	6.5%
Overall excess air factor, λ	1.22	1.31	1.52	1.63
Excess air factor in the primary fuel-air mixture (with 50% primary aeration assumed)	Primary aeration not applicable	Primary aeration not applicable	0.76	0.82
Adiabatic flame temperature (at constant pressure)	1748°C (3178°F)	1672°C (3042°F)	1476°C (2689°F)	1411°C (2572°F)

5.5.2 *Excess Air Factor*

5.5.2.1 The flow rates of the combustion air are not expected to change noticeably in heating appliances with the natural gas fuel replaced with the hydrogen enriched natural gas, provided the appliance components and the gas supply pressures are unaltered. Further, it was assumed, in accordance with the findings of section 5.4.3, that by replacing the natural gas (methane) with 20% hydrogen 80% methane mix (by volume), the gross heat input will be reduced by 5%. Based on these the excess air factors were calculated for typical premix as well as atmospheric burners and they are shown in Table 1

5.5.2.2 It can be seen that the excess air factor is predicted to increase with the natural gas fuel replaced with the 20% hydrogen 80% methane mix.

5.5.3 *Adiabatic Flame Temperature*

5.5.3.1 It is predicted that enriching the natural gas with 20% hydrogen will reduce the adiabatic flame temperature. The expected implications are described in the following paragraphs.

5.5.3.2 However, if the combustion systems are adjusted to obtain the excess air factors unchanged, compared to the original fuel, then the adiabatic flame temperatures will be higher than these with the original fuel. **It is therefore important that appliances are not adjusted** otherwise design temperatures may be exceeded. Any appliances with automatic controls to maintain a predefined excess air ratio may not be suitable for hydrogen admixtures unless tested to ensure that temperatures stay within acceptable limits.

5.5.4 *Thermal Radiation of The Flame*

5.5.4.1 As a general rule, hydrogen flames are known to emit less thermal radiation compared to methane flames (in an appliance scale size of a flame). In addition, the reduced flame temperature in an unaltered appliance with the hydrogen enriched natural gas, see section 5.5.3, will also contribute to the reduced radiant energy from the flame and from the combustion products.

5.5.5 *Temperatures of The Heat Exchanger Walls*

5.5.5.1 The temperatures of the heat exchanger walls of an unaltered appliance with the hydrogen enriched natural gas, are expected to be lower compared with natural gas fuel. This is due to the predicted reduced adiabatic flame temperature with the hydrogen enriched natural gas in an unaltered appliance. However, due to the changed radiation properties of the flame (i.e. less energy radiated in the combustion chamber), local increases of wall temperatures downstream from the combustion chamber are also likely, although this is expected to be case specific, i.e. depend on the design of a particular heat exchanger.

5.5.6 *Thermal Efficiency of Gas Fired Heating Appliances*

5.5.6.1 There are two parameters which are predicted to change with the hydrogen enrichment of natural gas, and which are known to influence the thermal efficiencies of heating appliances namely, heat input and the adiabatic flame temperature. Reduced heat input is known to increase the efficiency. Reduced adiabatic flame temperature is known to reduce the thermal efficiency. Therefore, it is not certain how the enrichment of the natural gas with hydrogen will influence the thermal efficiency of gas fired appliances. In reality, for most appliances the efficiency change will be small, with the benefits of downrating offsetting the reduction in flame temperature. However, some adjustments of the efficiency level should be possible, if required, on new appliances by modifying the heat input and/or the excess air factor in the appliances.

5.5.6.2 There is more concern regarding heat exchanger designs whereby a high degree of heat transfer depends upon radiation, for example shell and tube boiler designs, but any loss of heat transfer in the primary pass will be offset by increased heat transfer in the secondary passes due to higher input temperatures from the primary pass. The overall effect is predicted to be very small with 20% blending.

5.5.7 *NO_X Emissions*

5.5.7.1 In appliances with low or no nitrogen content in the fuel, oxidization of the nitrogen from the air is known to be the main mechanism of NO_X formation in the combustion products. The intensity of this formation increases with increasing temperature of the flame. Therefore, the concentration of NO_X in the flue gas is expected to be reduced when the natural gas is replaced with the hydrogen enriched natural gas because of the reduced adiabatic flame temperature if unadjusted. However, if a combustion system is adjusted to obtain the excess air factors unchanged, compared to the original fuel, then the concentration of NO_X in the flue gas is expected to rise.

5.5.8 *Corrosion of the Components in Contact with the Flue Gas*

5.5.8.1 Nitrogen enrichment is expected to impact NO_X concentrations in the flue gas to some extent. This may affect the content of the nitric acid in the condensate. On the other hand, nitrogen enrichment reduces CO_2 concentration in the flue gas, which may affect the content of the carbonic acid in the condensate.

5.5.8.2 A chemical analysis of corrosion effects is outside the scope of this project but could be worthy of further research.

5.5.9 *Dewpoint Considerations*

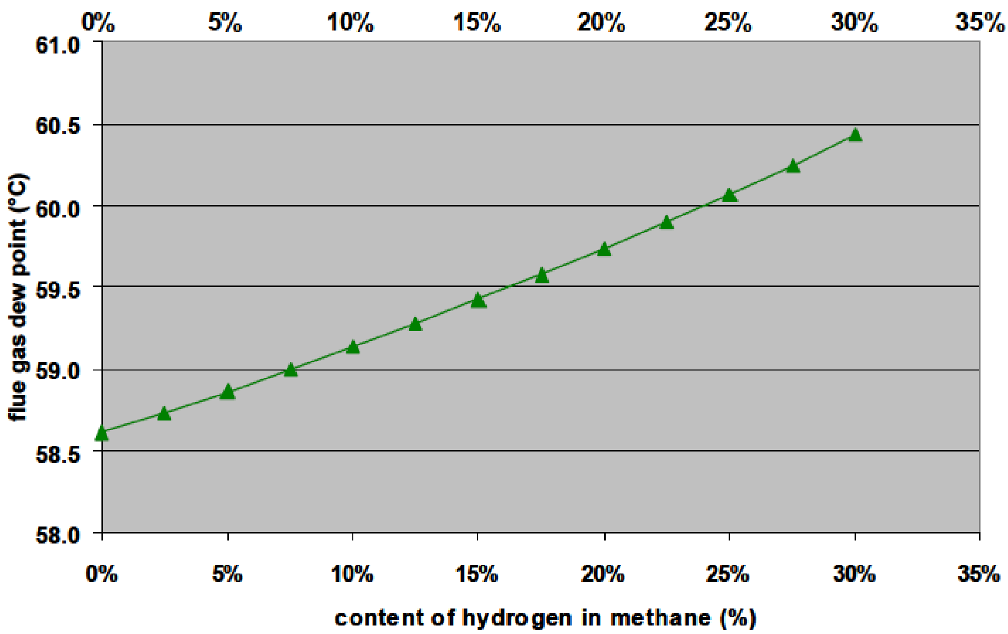

Figure 10 Dew point for hydrogen blended methane

5.5.9.1 As the percentage of hydrogen increases, the dewpoint increases, as does the volume of water vapour in the vent system.

5.5.9.2 At 20% blending, the dewpoint is approximately 1.3 degrees Centigrade (2°F) higher. This will marginally decrease efficiency on condensing appliances but could have an effect on the vent design category in borderline cases due to the additional condensate generated.

5.5.10 *Flame Detection*

5.5.10.1 Flame detection systems in residential and commercial gas appliances basically fall into two categories, heat sensing devices (thermocouples or thermopiles) and flame rectification, (ionisation) with the latter being prevalent on larger and more modern appliances.

5.5.10.2 Discussion regarding the flame temperature in the previous sections shows that there is not a significant difference. Therefore, it is unlikely to threaten the working tolerance of thermocouples or thermopiles over the range of hydrogen blending being considered.

5.5.10.3 Equally, flame ionisation is dependent upon ions in the carbon rectifying an electrical circuit. Although not specifically covered in the above sections, Enertek have practical experience of measuring the effect of increased percentages of hydrogen and from experience the flame signal does not become unstable until blends of 30% plus are achieved.

5.5.11 *Gas Soundness*

5.5.11.1 Hydrogen molecules are significantly smaller than methane molecules and are therefore more likely to leak from joints in the pipework, permeable materials, or any valve seats.

5.5.11.2 This is a challenge which is difficult to quantify by theory alone and is subject to test work to test the integrity of the pipework and controls with an appliance, and within the supply network.

5.5.11.3 In the draft hydrogen Standard being prepared in the UK (PAS 4444) soundness test are permitted either on air at 150 mbar or on hydrogen at 50mbar, the two conditions being deemed to be of equivalent stringency.

5.5.11.4 However, laboratory tests at Enertek have raised questions about the validity of this comparison and further research is needed.

5.5.12 *Safety*

5.5.12.1 Flammability limits for methane/air under standard temperature and pressure conditions are 5.3% to 15% with detonation possible between 5.7% and 14% by volume. The corresponding figures for hydrogen are much wider, 4.0% to 75% flammability and 18% to 59% for detonation.

5.5.12.2 Self-ignition temperatures are similar, 595°C for methane and 560°C for hydrogen, but the energy required to ignite hydrogen is much lower than for methane by a factor of up to ten.

5.5.12.3 The data above relates to pure hydrogen and pure methane, but it is clear to see that when mixed, the flammability and explosive limits will be higher than methane, dependent upon the degree of hydrogen blending.

5.5.12.4 Violent ignitions fall into two categories, deflagration (subsonic combustion) and detonation (supersonic combustion), the latter being more likely with hydrogen. A study into the conditions for, and effects of either are outside the scope of this report (and are deemed unlikely in an operational gas appliance installed and used in accordance with the manufacturer's instructions) but are worthy of further investigation in terms of the gas distribution system.

5.5.12.5 CO emissions are not deemed to be a threat with hydrogen admixtures because the addition of hydrogen reduces the oxygen needed for combustion and therefore increases the excess air factor (unless adjusted). Additional CO is only likely in the event of flame instability caused by excessive lift which is not anticipated on any of the gas appliances included in this study.

6 IMPLICATIONS OF HYDROGEN ENRICHMENT WITH RESPECT TO U.S. GAS APPLIANCES

6.1 Outline

6.1.1 Taking into account the literature review in section 4 and the theoretical investigation in section 5, Enertek International have created a working 'model' which can be used to identify the likelihood of any particular gas appliance performing safely and reliably with a blend of methane and hydrogen to a certain percentage.

6.1.2 It is clear from the previous sections that the effects of hydrogen blending are largely proportional to the percentage of hydrogen used.

6.1.3 Given the European experience with certification tests using G222 and the issues raised in this report, it would be ambitious to suggest that any concentration above 20% hydrogen should be considered.

6.2 Modelling Methodology Employed

6.2.1.1 The most evident and significant problem likely to prevent an appliance from successfully working on a blend of hydrogen and methane is flame light-back.

6.2.1.2 The flame speed characteristics for hydrogen blends have been calculated and verified from evidence gathered in the literature review and can therefore be considered to be known for any given blend of hydrogen / methane.

6.2.1.3 Light-back will occur if the flame speed through the burner ports is higher than the velocity of combustible gas through the flame ports.

6.2.1.4 Enertek have created a spreadsheet to enable determination of the velocity of combustible products through a burner for any given appliance by calculating the available port area and dividing it by the volume of combustible products based on the excess air level and heat input.

6.2.1.5 If the calculated velocity of combustible gas is lower than the flame speed for any given appliance and blend of gas the appliance can be declared at risk of being unfit for use in this situation.

6.2.1.6 This model will immediately identify products at risk of light-back with hydrogen blended methane. The model can then be used to calculate what needs to be changed (example burner port area) to prevent the likelihood of light-back.

6.2.1.7 This method will not be guaranteed because conditions can change in practice (for example burner port dimensions may increase when hot) and a reasonable safety margin (say 20% of flame speed for example) would need to be factored in to err on the safe side where appliances fall near to equilibrium speeds. On the other hand, there might be instances in which light-back is predicted and it does not occur in practice. This is because the calculation method is an approximation, which compares the predicted average flame speed with the predicted average fuel-air mix velocity. Therefore, this method identifies a risk of light-back and not the certainty of the light-back to occur, or not to occur.

6.2.1.8 This model has been created for premix and atmospheric burners subject to the correct input data, but this is more difficult to establish for atmospheric burners unless the exact amount of primary aeration is known.

6.2.1.9 The aspiration is that by assessing the data supplied by AHRI's members, the report will be able to assess whether any specific category of appliance is at greater risk of failure than other categories for any significant blend of hydrogen / methane.

6.3 Light-back calculations

6.3.1.1 The theoretical basis for the paper study light-back assessment is set in paragraph 5.2.1. The main principle is that light-back is not expected to occur at steady state burner operation if the average velocity of the fuel-air mix, flowing through the burner ports, is greater than the average flame speed.

6.3.1.2 The velocities of the fuel air-mixes flowing through the burner ports were calculated for a range of appliances in order to be compared with the corresponding flame speeds. This was performed for all appliances for which sufficient technical data was supplied by AHRI's members.

6.3.2 *Natural draft and induced draft appliances (partial premix)*

6.3.2.1 Seven different appliances were analysed in this category. Each of these appliances typically had a number of versions with different nominal heat inputs but the same type of combustion systems.

6.3.2.2 The burner systems in this category included systems with punched steel burners as well as systems with in-shot multi-hole and single hole firing burners.

6.3.2.3 For each appliance, the worst-case version (from the light-back point of view) and the worst-case steady state firing rate were selected for this analysis. Thus, for any multi-burner appliance a burner system configuration was selected for which the heat input per burner was lowest. Similarly, for any appliance in which the control allows for the reduced heat input per burner, the calculations were performed at the lowest heat input condition. Therefore, the calculated velocities of the fuel-air mix flowing through the burner ports are considered to be the lowest velocities occurring at the normal steady state operation of these burner systems.

It should be noted that the appliance (within the natural draft and induced draft appliance category) with the identified worst-case conditions (from the light-back point of view) was a fixed heat input appliance.

6.3.2.4 Since no primary aeration levels were known and only approximate CO_2 concentrations in the flue gas were known for the appliances under investigation, the calculations were performed either for certain assumed constant values of the primary aeration or for certain assumed constant CO_2 concentrations in the flue gas, see Figure 5 and Figure 6 respectively.

6.3.2.5 The calculated velocities of the fuel-air mix flowing through the burner ports, presented in Figure 10 and Figure 11 are the lowest from all the appliances and burner loading scenarios investigated in this section of the report. This implies that the presented figures are the worst-case scenarios from the light-back point of view at steady state normal operation of the burner systems.

6.3.2.6 In Figure 10 the calculation results with the assumed constant 50% primary aeration, are shown.

6.3.2.7 The blue line in Figure 11 is the calculated velocity of the fuel-air mix flowing through the burner ports with natural gas used as a fuel. The red line is the corresponding laminar flame speed. The green dashed line in Figure 11 is the calculated velocity of the fuel-air mix flowing through the burner ports with 20% hydrogen 80% methane (by volume) used as a fuel. The violet dashed line is the corresponding laminar flame speed.

6.3.2.8 All the CO_2 concentrations given in this section of the report (6.3) are the concentrations by volume in dry flue gas.

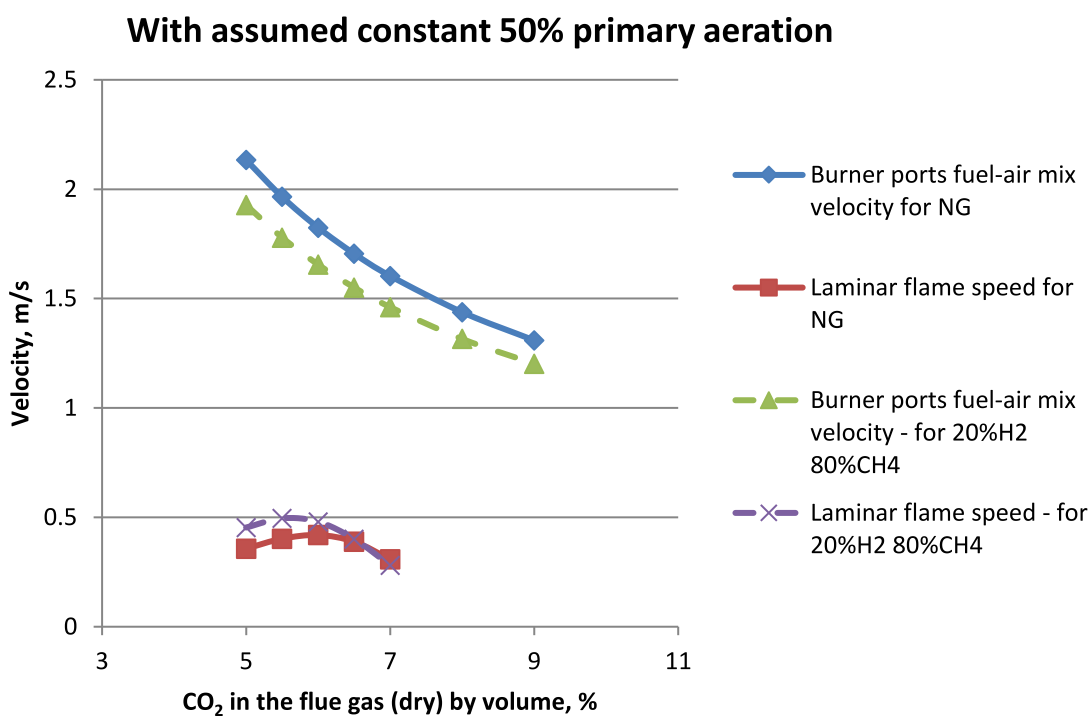

Figure 11 the velocity of the fuel-air mix flowing through the burner ports as well as the flame speed as functions of CO2 concentration in the flue gas, with the assumed 50% primary aeration.

6.3.2.9 In Figure 12, the calculated results with assumed constant CO_2 concentrations are shown. The blue line in Figure 12 the calculated velocity of the fuel-air mix flowing through the burner ports with the natural gas used as a fuel at 7.4% CO_2 concentration in the flue gas (by volume). The red line is the corresponding laminar flame speed. The green dashed line in Figure 11 is the calculated velocity of the fuel-air mix flowing through the burner ports with 20% hydrogen 80% methane (by volume) used as a fuel at 6.5% CO_2 concentration in the flue gas (by volume). The violet dashed line is the corresponding laminar flame speed. It should be noted that the lower CO_2 concentrations assumed for the hydrogen enriched methane, compared to the natural gas alone, are based on the CO_2 reduction predictions presented in Table 1, see section 5.5.

6.3.2.10 It can be seen in both Figure 11 and Figure 12 that for any CO_2 concentration considered (Figure 11) and for any primary aeration considered (Figure 12) the calculated burner port fuel-mix velocities are more than two or even three times greater than the laminar flame speed. This implies that no risk of light-back at normal steady state operation was identified by this calculation method.

6.3.2.11 It should be noted that the calculated burner port fuel-mix velocities are distinctively higher for the in-shot burners (not presented), compared to those presented in Figure 11 and Figure 12. This is most profound for the in-shot burners with a single firing hole per combustion chamber. However, the calculated Reynolds numbers for these burners indicate that the flow of the fuel-air mix may not be laminar. This implies that the actual flame speeds may be affected by the turbulence and therefore be greater than the calculated laminar flame speeds. Thus, the methods used in this section for the light-back calculations may not be adequate for the in-shot burners.

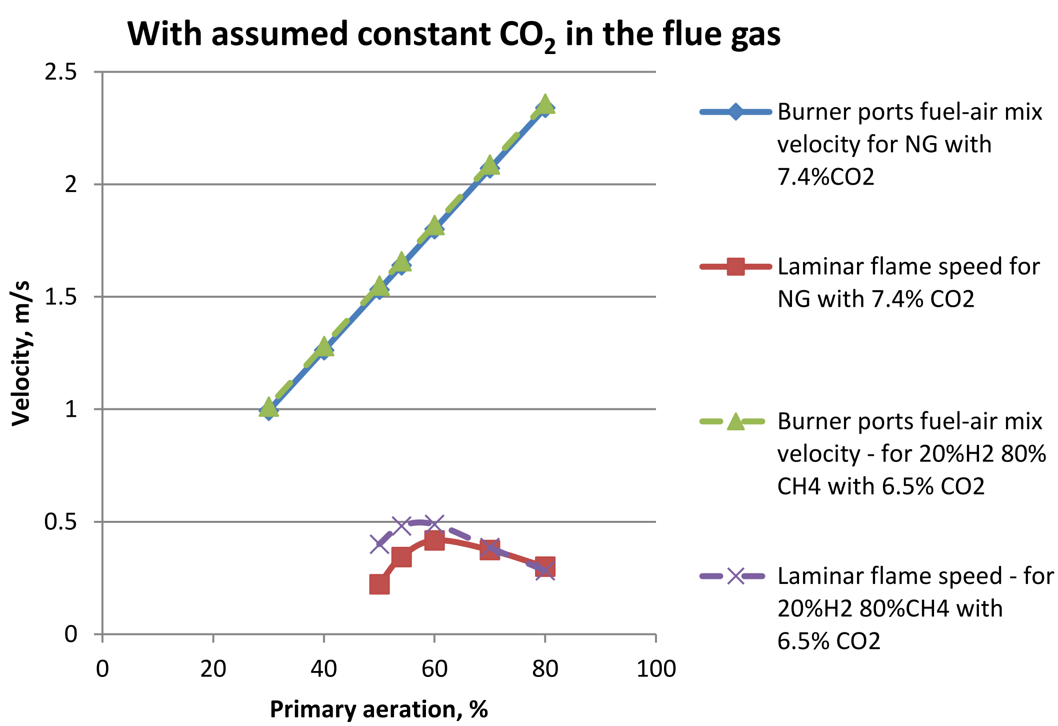

Figure 12 The velocity of the fuel-air mix flowing through the burner ports as well as the flame speed as functions of primary aeration, with the assumed constant CO2 concentrations in the flue gas.

6.3.3 *Forced draft (premix) appliances*

6.3.3.1 The majority of the premix related technical data supplied by the manufacturers for analysis was for appliances with steel fibre mesh burners. However, the calculation method used was deemed not to be appropriate for this type of burner. Light-back is not expected to occur with this type of burner due to the Davy Lamp principle where flames do not pass through a fine mesh, this may be due to quenching.

6.3.3.2 As the flame speed increases (due to the addition of hydrogen), the flame will sit lower on the burner and more heat will be transferred to the burner. The heat is conducted away from the flame and an element of 'quenching' takes place. This is affected by the material, thickness and port size, and a thermal balance is required to stabilise the flame. If the flame continues towards the burner, it will either light-back if the port size is large enough or be quenched before it can light-back if the port size (or mesh) is small.

6.3.3.3 However, there was technical data supplied on a single premix appliance with a punched steel burner. Therefore, the premix system light-back calculations were performed for this particular appliance and the results are presented in Figure 13. The calculations were performed for the lowest firing rate, i.e., the worst condition from the light-back point of view. In this case it was at the 10:1 turndown ratio.

6.3.3.4 The blue line in Figure 13 is the calculated velocity of the fuel-air mix flowing through the burner ports with natural gas used as a fuel. The red line is the corresponding laminar flame speed. The green dashed line in Figure 13 is the calculated velocity of the fuel-air mix flowing through the burner ports with 20% hydrogen 80% methane (by volume) used as a fuel. The violet dashed line is the corresponding laminar flame speed. The calculated burner port fuel-mix velocities are at least six times greater than the laminar flame speed in the considered range of the CO_2 concentrations in the flue gas. This implies that no risk of light-back at normal steady state operation was identified by this calculation method.

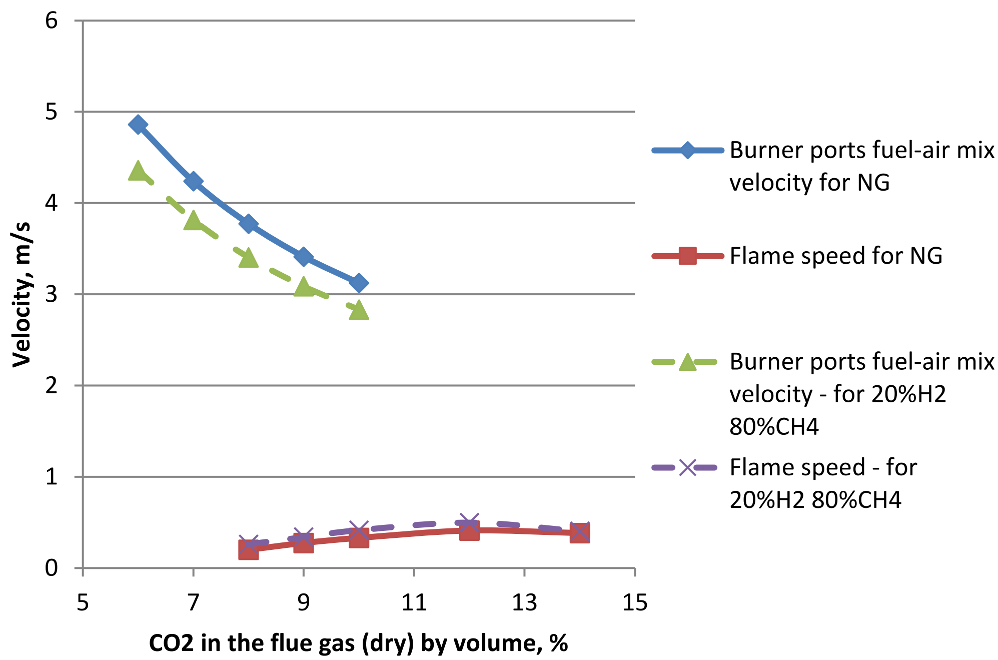

Figure 13 The velocity of the fuel-air mix flowing through the burner ports as well as the flame speed as functions of CO_2 concentration in the flue gas

6.4 Light-back performance Tests

6.4.1 One AHRI member could not supply burner drawings for evaluation in this exercise due to IP restrictions but gave us burner (and injector) samples so that we could measure the burner ports instead.

6.4.2 Although not strictly within the scope of the project, we decided to use this burner to cross check our mathematical predictions that light-back would not occur by undertaking a short programme of test work to verify this theory.

6.4.3 A burner was set up in free air for a bench test with the correct injector and manifold pressure to represent normal operation and the burner was supplied with natural gas.

6.4.4 A lighted gas match was used as the ignition source to simulate a pilot. As expected, no light-back occurred despite repeated attempts with the burner both hot and cold.

6.4.5 The burner was then allowed to cool and then the tests were repeated with European Test Gas G222 (which we keep in stock). G222 as mentioned earlier in this report is the European light-back limit test gas and comprises 23% hydrogen and 77% methane by volume. By co-incidence this is typical of a 20% admix with an extra 3% thrown in for worst case tolerance.

6.4.6 Again, the lighted gas match was used as an ignition source and I am pleased to report that despite several attempts, hot and cold, high and low rates, the burner did not light-back.

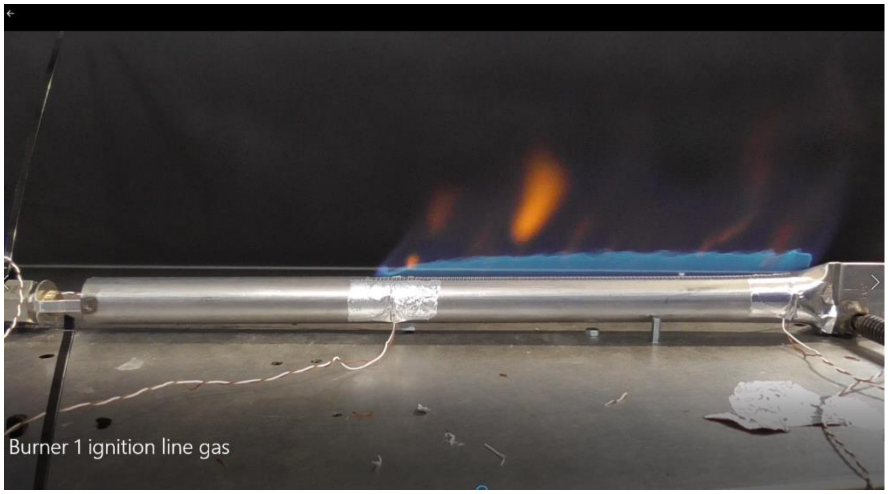

Figure 14 Burner operating on line natural gas

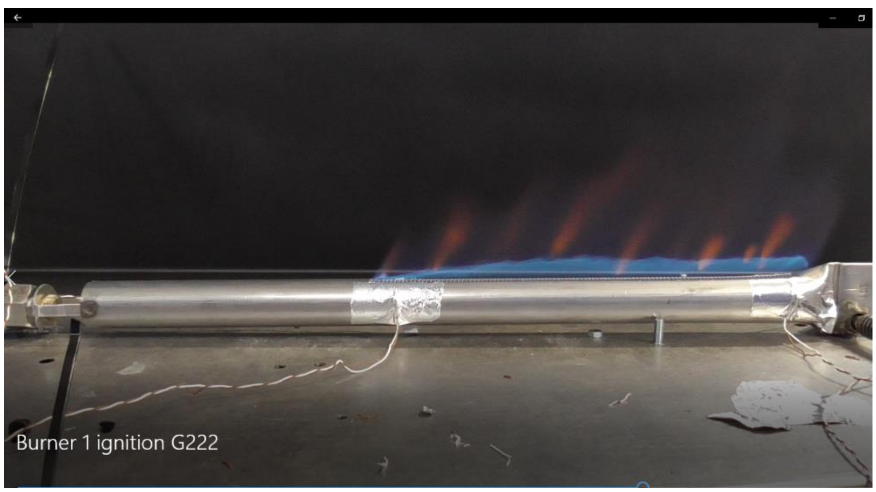

Figure 15 Burner operating on G222 under identical conditions

6.4.7 Finally, we wanted to check whether, in the event of light-back the flame would clear itself.

6.4.8 To do this test it was necessary to prove that when lit at the injector with line gas, the flame would revert through the burner (clear itself of light-back). We would then repeat the exercise with G222 and see whether it clear itself.

6.4.9 Unfortunately, the flame did not clear itself using line gas (methane) so this test could not be continued.

6.4.10 Note that all test work was undertaken on a single burner in free air. Although the result is comparative and indicative of the outcome as tested, the results could be different when tested in a fully operational appliance.

6.5 Temperature Performance Tests

6.5.1 One concern highlighted by the FMEA (Section 8) and appliance analysis is that with a hydrogen admix, the flame could sit lower on the burner and cause a temperature rise in the burner.

6.5.2 The test set up described above gave us a platform to undertake this test.

6.5.3 The burner was initially fired on line gas and allowed to reach thermal equilibrium with four thermocouples attached to various parts of the burner. The test gas was then changed to G222 and the burner operated until thermal equilibrium was restored.

6.5.4 The results demonstrated a significant increase in burner temperature as shown:

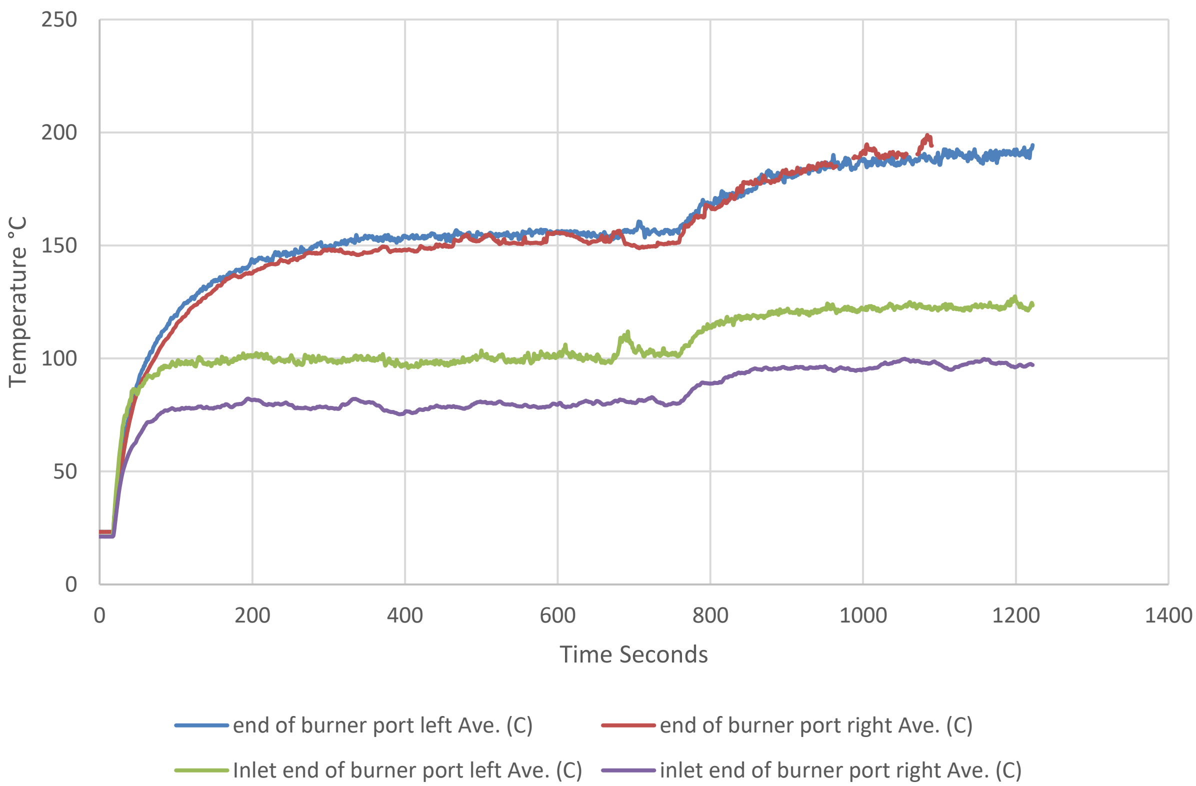

Figure 14 Changing from line gas to G222

6.5.5 The above changeover was recorded and the change in flame temperature can clearly be seen, although the change is over several seconds as the gas supply line is purged of natural gas.

6.5.6 The position of the thermocouples can be seen in Figure 13 and Figure .

6.5.7 These test results indicate that the flame-strip will run hotter with blended hydrogen so it is important that the material used can withstand this increase in temperature.

6.5.8 A rise of approximately 40°C (72°F) may not be enough to stress stainless steel except in marginal cases, but longevity should be tested for each appliance type. (Pre-mix may not be subject to the same temperature changes due to forced draught and higher excess air)

6.5.9 For new appliances, changes to the configuration of flame ports may alleviate the potential temperature rise, but for legacy appliances, especially ones with relatively large flame ports (similar to the model tested) the temperature rise on atmospheric burners may be inevitable.

7 PRODUCT EVALUATIONS

7.1 Methodology

7.1.1 The following sections describe the concerns and possible effect of hydrogen enriched natural gas on both new and existing (legacy) appliances. These comments are intended to draw attention to the critical areas of potential concern so that each manufacturer can use this section as a checklist for their own products.

7.1.2 These comments are primarily based upon Enertek's experience of designing, developing, testing, and acquiring certification for gas appliances across all three existing gas families (town gas, natural gas, liquid petroleum) plus hydrogen - both blended and 100%.

7.1.3 The comments also correspond with the academic knowledge, literature review and theory explored in earlier sections of this report.

7.1.4 It should be noted that as a desk-based study, practical assessment and quantification of these risks is difficult, but the FMEA's in section 8 provide further insight and risk assessments for future practical evaluation.

7.2 All Appliances – The following comments apply to all types of gas appliance

7.2.1 *Potential Leakage from Components & Joints*

7.2.1.1 As hydrogen is the smallest molecule, it has a greater tendency to leak through smaller openings. It has been experienced that both screw and flange joints are more susceptible to leaks when applied to hydrogen gas lines.

7.2.1.2 There is also potential for seals and jointing compounds to fail through reaction with either hydrochloric condensate waste, higher temperatures, or hydrogen gas directly.

7.2.2 *Unit Setup (Product Installation)*

7.2.2.1 Seals, jointing pastes, and fittings will need to be assessed for appropriateness for blended hydrogen lines. Where possible it would be recommended that welding joints are used, although service and disassembly would need to be considered when being designing connections.

7.2.2.2 Gas pipes within the building, (especially threaded steel pipes) would have to be pressure tested and inspected for suitability.

7.2.2.3 When checking an installation, a hydrogen gas detection unit may need to be used across the line to determine if there are any specific hydrogen leaks. It is possible that the hydrogen could leak from the line whilst still holding the natural gas.

7.2.3 *Installer Adjustments*

7.2.3.1 With hydrogen blending at up to 20% it is not anticipated or recommended that any adjustments would be made to the appliance at the time of supplying the new fuel and a 5% downrating would be accepted. (If it was intended to maintain the current heat input on production appliances, gas injectors for burners and pilot flames may need to be redeveloped).

7.2.3.2 The 5% downrating (with 20% blending) is useful in offsetting potential temperature increases which would occur if the appliance was adjusted to restore 100% of rating.

7.2.3.3 Adjusting the appliance to compensate for the downrating may invalidate the certification which is based on methane. If used with methane, the adjusted appliance will be over-rated.

7.2.3.4 A further complication is that the installer would have no means of accurately measuring the blend of hydrogen at the time of making the adjustment, the setting would be unknown.

7.2.3.5 However, although no heat input adjustments are recommended, (see above) as the hydrogen blending percentage increases, on some appliances (especially legacy appliances) pilot burners may need to be mechanically adjusted to accommodate a new flame shape and ensure that it creates reliable ignition across the burners. Some methods of flame proving may need an adjustment in their position to better contact the new flame characteristics.

7.2.4 *Operation*

7.2.4.1 Changing the fuel type will have an impact on combustion performance, however there are other anticipated challenges that will also affect combustion such as the changes in flame shape, available aeration, and increased vent updraft. NOx produced also has potential to change with the blended gas.

7.2.4.2 Any increase in combustion products temperature could lead to higher ambient temperatures for components and materials, which could potentially exceed the designed limit temperatures or safe contact temperatures for user controls and / or durability issues.

7.2.4.3 Due to changes in the flame characteristics, such as positioning and temperature, coupled with the expected downrating of approximately 5% (at 20% hydrogen). It is expected that the thermal efficiency is likely to be affected. However, not significantly as the various effects compensate for each other as explained earlier in the report.

7.2.4.4 As the hydrogen percentage increases, appliances that use pilot flames could potentially begin to have ignition issues due to pilot flame positioning and a change in flame shape/direction and vent updraft. No discernible issues are expected with hydrogen blends up to 20-25%.

7.2.4.5 As the hydrogen percentage increases (especially over 20%), flame proving methods that detect ions may begin to sense a lower ionisation current. If the appliance is using ionisation readings to determine when to shut the appliance off as a safety measure, this could affect cut off points and the appliance could deactivate pre-emptively.

7.2.5 *Combustion By-products*

7.2.5.1 With blended hydrogen being consumed, there will be an increase in condensate production and the disposal system will need to be assessed for suitability. There will also be an increase in hydrochloric condensate waste which could be incompatible with existing disposal line materials.

7.2.5.2 Pure hydrogen combustion produces approximately 40% more water vapour than methane, so a 20% blend is likely to produce approximately 8% more condensate, but this can vary depending upon conditions and the dewpoint so in practice the additional condensate may be up to 20%.

7.2.5.3 For condensing appliances in cold weather, it could become more frequent for condensate pipes to become blocked by frozen condensate due to the increased flow of condensate waste. Up to 20% extra condensate should be allowed for. This is unlikely to cause a problem with pipe sizing as they are usually significantly oversized by default.

7.2.5.4 With a hotter flame temperature, the products of combustion will have a higher vapour content which will enable the appliance to improve heat throughout the heat exchanger and vent. The marginally higher dewpoint (approximately 2°F) will cause condensation to occur at a slightly higher temperature than with methane.

7.2.6 *Vent Considerations*

7.2.6.1 For any given heat input, with an increase in the temperature of the combustion products it is expected that there will be more updraft generated in atmospheric appliances, which could further contribute to flame lift from on the burner.

7.2.6.2 Both higher flame temperatures and higher water vapour content are likely to contribute to higher vent temperatures throughout the combustion system. This will likely result in higher vent surface temperatures and the safety of the ducts & surrounding areas may need to be assessed.

7.2.6.3 However, if the appliance is not adjusted, the 5% downrating should alleviate the above two points, indeed the combustion products volume is likely to reduce.

7.2.6.4 There will be a small increase in the dewpoint (of around 2°F) which could affect the vent category in borderline cases.

7.2.6.5 The increased amount of water vapour in the products of combustion may be visibly evident by a greater amount of pluming (or steam visibly exiting the vent). This may cause concern if fitted close to adjacent properties or public pathways.

7.3 Furnaces (Additional Comments)

7.3.1 *Potential Leakage from Components & Joints*

7.3.1.1 Long term durability of components could be affected by any increase in flame temperature and condensate. Any furnace heat exchanger welds that are situated above the burner could be subject to increased temperature and condensate and could be susceptible to leakage.

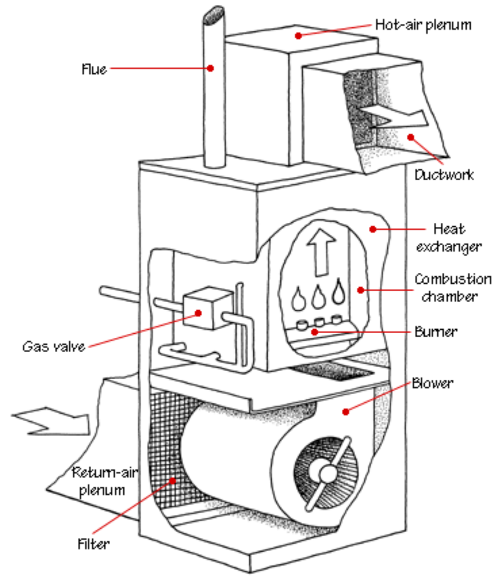

Figure 15 Furnaces

7.3.2 *Operation*

7.3.2.1 There is a potential that any increase in combustion products temperature could also lead to long term durability issues and subsequent cracking. Furnace heat exchangers that overheat frequently are known to sometimes prematurely fail and there is potential that an increase in combustion products temperature could also reduce heat exchanger durability, as could any exposure to unburnt hydrogen (Potential risk of hydrogen embrittlement).

7.3.2.2 Air conditioning units are sometimes installed downstream of the heat exchanger which may see a small increase in air temperature passing through them.

7.4 Boilers (Condensing and Non- Condensing)

7.4.1 *Operation*

7.4.1.1 Long term durability of components could be affected by any increase in flame temperature and condensate. Any welds inside the heat exchanger could be vulnerable long term, especially if the material is stainless steel and is exposed to unburnt hydrogen. (Potential risk of hydrogen embrittlement).

7.4.1.2 In industrial boilers (shell and tube design) there may be less radiation heat transfer in the combustion chamber due to the lower radiation emissivity from a hydrogen flame. This may result in higher back plate temperatures and more heat transfer in the secondary tubes. This could overstress different parts of the heat exchanger and lead to non-optimised performance or even premature failure.

7.5 **Burners**

7.5.1 *Appliance Installer Adjustments*

7.5.1.1 Where burners have been factory set using methane, the general comments in section 7.2 apply.

7.5.1.2 Where burners are commissioned on-site, the installer should commission the appliance as though the gas supply is 100% methane. This would be expected to facilitate the normal 5% downrating which offsets some of the potential problems with higher temperatures. However, Enertek have found no evidence to support this and commissioning on 20% blending should be investigated to determine whether the downrating is achieved or whether the appliance is over-rated under these circumstances.

7.5.1.3 If the commissioning engineer knows the hydrogen blend in the gas supply, there is a possibility that they may be able to adjust it to compensate for the downrating. This should be avoided, to prevent potential issues including exceeding the validity of the product's certification. As above, further research is needed in this area.

Figure 16 Burner

7.5.2 *Operation*

7.5.2.1 To maintain a reliable ignition performance at higher hydrogen blend percentages some burner-ignitor assemblies may need to be modified to ensure reliable ignition and longevity of components. This should not be needed unless the blend exceeds 25% hydrogen.

7.5.3 *Combustion By-products*

7.5.3.1 With an increase in temperature, appliance condensate production and deposition, atmospheric burners in particular may become more susceptible to corrosion which will affect the long-term durability and may lead to blocked burner ports, performance issues and potentially light-back.

7.5.3.2 Burner components are likely to be in contact with hydrogen molecules at elevated temperatures. Hydrogen embrittlement is a potential concern, depending upon the material specified. Hydrogen embrittlement is a durability failure mode.

7.6 **Control Valves**

7.6.1.1 *Potential Leakage through Valve Seats*

7.6.1.2 Shut off valves must be tested to ensure suitability for use as shut off valves. Due to the small molecular size of hydrogen, it is possible that the hydrogen element of the blended gas could seep through the valve seat. Potentially, (depending on the application) into the combustion chamber or atmosphere as unburnt hydrogen. Clearly this is undesirable.

7.6.1.3 Whilst this can be assessed for future production valves, legacy valves, especially those operating for a number of years could be subject to ageing of seals or mechanical wear. Appropriate pressure testing should be carried out when blended gas is used instead of methane.

7.6.2 *Operation*

7.6.2.1 Flow capacities will need to be assessed to ensure that the control valves can cope with the blended gas rate although due to similarities in Wobbe number, it is likely that flow rate will not be an issue.

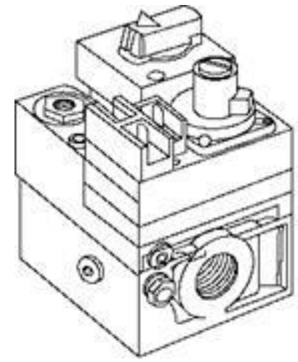

Figure 17 Control Valves

7.7 **Venting Products**

7.7.1 *Potential leakage*

7.7.2 The long-term durability of the sealing and jointing methods will need to be verified under both the new temperature conditions. Especially for designated condensing systems, with the extra hydrochloric condensate waste to ensure that the ducts do not begin to leak combustion products over time. The potential for hydrochloric acid formation is increased due to the greater presence of hydrogen molecules but in practice any change is likely to be minimal.

7.7.3 *Operation*

7.7.3.1 With blended hydrogen there will be an increase in condensate within the products of combustion. The vent system must be able to accommodate this.

7.7.3.2 Due to a potential increase in temperature of the combustion products, the temperature of the vent ducts may increase. It may need to be verified that the surface temperatures do not exceed the standard limit temperatures and do not exceed the design temperatures of the ducts. This is only likely to be an issue where plastic vent pipes are used.

Figure 18 Venting Products

7.7.4 *Combustion by-products*

7.7.4.1 In commercial / industrial condensing vent systems with separate condensate drains, the sizing of the condensate drain(s) will need revalidating to ensure that they are able to cope with the increase in condensate production. Where the vent drains back to the appliance, this will apply to the appliance drain rather than the vent.

7.8 Water Heaters (Condensing and non-condensing)

7.8.1 *Operation*

7.8.1.1 Many water heaters have a straight vent that is situated across the top of the burner, due to condensate build up on the inside of this vent. This can lead to condensate dripping back onto the burner causing hissing noises during operation, leakage outside of the water heater and long term performance issues due to burner corrosion. The extra moisture content in hydrogen blended gas could exacerbate this problem.

7.8.2 *Potential Leakage from Components & Joints*

7.8.2.1 Water storage tank welds that are situated above the burner may be subject to increased temperature/condensate. This means it would be susceptible to leakage and potentially hydrogen embrittlement, although unless this is made from high tensile steel and is exposed to unburnt hydrogen this is unlikely to be a problem.

7.8.3 *Combustion By-products*

7.8.3.1 Non-condensing water heaters do not have condensate disposal systems but upon cold start up, condensate is often deposited from the combustion chamber onto the burner or the base plate but evaporates as the heater temperature increases. With more condensate (from blended gas) to evaporate this will take longer and increases the risk of spillage from the base plate (overflow) or corrosion.

7.8.3.2 High efficiency water heaters (premix) may still need to be assessed to determine whether the appliance is able to vent all the vapour through combustion gas alone, or whether a condensate drain is present.

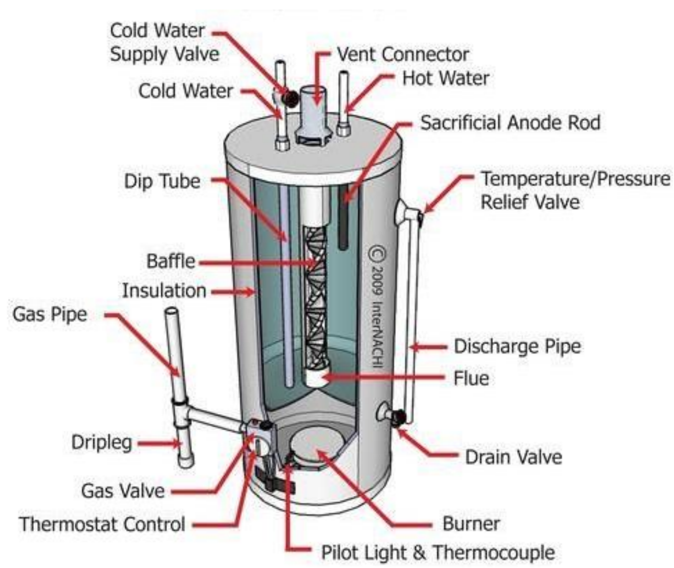

Figure 19 Gas Water Heater

7.9 Pool Heaters (Condensing and non-condensing)

7.9.1 The comments for water heaters in section 7.8 above apply equally for pool heaters, with the additional comments below.

7.9.2 *Potential Leakage from Components & Joints*

7.9.2.1 Where pool heaters are situated outdoors, hydrogen seepage through joints exterior to the building are of less concern due to their inability to build up in a contained area.

7.9.3 *Combustion By-products*

7.9.3.1 The additional water vapour could cause a nuisance if visible or if it 'pools' adjacent to the appliance on non-condensing models.

Figure 20 Pool Heater

7.10 Steel Pipe Fittings (Specifically Including Corrugated Stainless Steel Tubes)

7.10.1 *Operation*

7.10.1.1 With any blended hydrogen / methane gas, hydrogen molecules will be in contact with the tube walls. Hydrogen embrittlement is considered unlikely but is possible, even at room temperature in some materials.

7.10.1.2 Hydrogen embrittlement is more likely in high quality (tensile) steels than softer, mild steels. Although CSST is not particularly stressed in operation (at low gas pressures) its susceptibility to embrittlement will be affected by its manufacturing process.

7.10.1.3 It is recommended that specialist metallurgical advice is sought before commercially marketing CCST for use with hydrogen (unless this has already been undertaken during the design process).

7.10.1.4 Care should be taken not to over-stress the bends when installing the CSST, or any other pipework and situations should be avoided where CSST is subject to mechanical movement and stress during normal operation.

8 FMEA REGARDING HYDROGEN ENRICHMENT

8.1 FMEA (Failure Mode & Effects Analysis)

8.1.1 The information gathered during the product evaluation phase has been scrutinised using an accepted FMEA process, adapted to accommodate the concept of changing gas supplied from natural gas to natural gas blended with hydrogen. This FMEA process differs from a design FMEA (DFMEA) because the post assessment risk reduction techniques applied to a design FMEA cannot be used for appliances already installed or in current production.

8.1.2 The team involved in conducting the FMEA includes multi-disciplined Enertek International engineers who have not been involved in the project to date (to bring a level of independence to the FMEA exercises).

8.2 The FMEA Process

8.2.1 The process used for conducting the FMEA is described below:

1) Brainstorm the appliance design, construction, installation, and functionality to identify potential failure modes caused by the change from natural gas to natural gas blended with hydrogen.

2) List the potential failure modes relevant to the appliance type being considered.

3) List the potential effect (consequences) of each failure mode.

4) Document the reason (or potential cause) for the potential failure mode.

5) Determine how easy it would be to detect that the failure mode has occurred.

6) For each failure mode identified in step 2, score the severity of the consequences of the failure from 1 to 10. A threat to human life, accident or safety issue is scored 10.

7) For each failure mode identified in step 2, score the likelihood of the event occurring from 1 to 10 – Very likely to happen is scored 10.

8) For each failure mode identified in step 2, assign the chance of detection (1 to 10). Easy to detect gets a low score, very difficult to detect is scored 10.

9) Calculate the Risk Priority Number (RPN) = Severity x Occurrence x Detection) for each failure mode. The maximum score is 10 x 10 x 10 = 1000.

10) Sort the data in descending order based on the risk priority number.

11) Identify controls to monitor or protect against each risk.

12) Suggest action recommended to implement the controls.

13) Identify responsibility for implementing any recommended actions.

14) Provide an overall summary advising whether the perceived risk of blended hydrogen and methane is deemed acceptable for the appliance category concerned.

8.2.2 Note (A): The FMEA assessment applies to all blends of hydrogen / methane with the significance of the hydrogen becoming more prevalent (failure more likely) as the percentage of hydrogen increases. For the purposes of calculating the Risk Priority Number (RPN) and providing the conclusion, a percentage of 20% hydrogen, 80% methane was used.

8.2.3 Note (B): Enertek's normal FMEA process involves gathering several engineers around a table for the brainstorming part of the FMEA. Due to government restrictions in view of the Coronavirus pandemic this has not been possible hence input has been provided with social distancing measures in place and with remote working where necessary.

8.3 FMEA Results

8.3.1 A separate spreadsheet has been supplied with this report. The spreadsheet details all considered risks for each appliance category assessed and has been prepared with two working sheets (tabs) for each appliance.

8.3.2 The first 'tab' covers risks in a standard logical order and can be used for comparing with other FMEA's in the same order.

8.3.3 The second tab is identical to the first tab, except the data has been sorted in RPN order, the risks are listed in diminishing order. Note that the reference number (first column) is related to the reference number on the first tab, prior to sorting into RPN order.

8.3.4 A summary of the FMEA results for each category is provided on the following pages. The summary only includes risks scored above RPN = 200 except where lower risks can be included without an additional page break. Please refer to the spreadsheet to view all considered risks.

8.3.5 RPN = 200 was deemed to be an arbitrary point above which risks should be monitored or mitigated.

8.3.6 Note that in the 'responsibility for action' column, 'Government' appears quite regularly. This is a suggestion that government policy could be used to influence behaviour or reflects where government funding has been used elsewhere to support research into the issue identified.

7.1 FMEA – Furnaces

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET

ENERTEK PROJECT NUMBER E4357

APPLIANCE TYPE: PREMIX & ATMOSPHERIC COMBUSTION FURNACES (Condensing and Non-Condensing)

OBJECTIVE OF FMEA: To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.

DATE OF ISSUE:		COMPILIED BY:	Howard Ruston	PARTICIPANTS	HFR	PAN	LP	PW	**NOTES**: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.
ISSUE No:	1	APPROVED BY:	Paul Needley		DB	BM			

REF No.	PART OR PROCESS No.	PART/PROCESS FUNCTION	FAILURE MODE	EFFECT OF FAILURE	CAUSE(S) OF FAILURE	SEVERITY (1 - 10)	PROB-ABILITY (1 - 10)	DETECT-ABILITY (10 - 1)	RISK PRIORITY No. (RPN)	CONTROLS	SUGGESTED ACTION	RESPONSIBILITY FOR ACTION
5	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas from gas mixture.	Joints on existing appliances may require service activity.	10	6	8	480	R&D Tests (Appliances currently in production). Soundness check.	Testing to be performed on types of joints and seals to determine suitability for hydrogen. Appliance and gas joints should all be tested for tightness once conversion is compelted by a qualified gas engineer. Cast iron fittings should be avoided in gas lines.	Manufacturer. Gas engineer performing soundness checks during conversion.
6	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Exisiting component sealing seats may not be suitable for long-term hydrogen content use.	10	6	8	480	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures. Gas valves require life testing to prove that they are safe for purpose.	Gas engineer performing soundness checks.
12	Ignitor	Burner Ignition and Flame Proving	Appliance gets a false flame signal.	Gas flow through the burner when there is no flame. Damage to appliance if ignited.	If flame rectification is used, too much moisture can generate false readings.	10	3	10	300	R&D Tests (Appliances currently in production). -	Appliance to be tested to provve safe operation. Legacy appliances to be individually assessed.	Manufacturer. Government.
14	Burner	Combustion	Light back of fuel gas.	Burner failure. Flame failure. Loud bang upon ignition. Damage to appliance.	Insufficient gas pressure/ pressure drop or inappropriate burner. Flame ports too large	10	5	6	300	R&D Tests (Appliances currently in production).	Check burner suitability under different pressures. Legacy appliances to be individually assessed.	Manufacturer. Government.
1	General Components	Overall Assembly	Temperature of components exceeds design limits.	Component failure. Potential damage to safety devices. Potential leak of hydrogen gas.	Higher combustion temperatures.	9	4	8	288	R&D Tests (Appliances currently in production).	Check component temperatures against new ambient temperature of components. Legacy appliances to be individually assessed.	Manufacturer. Government.

16	Burner	Combustion	Higher Nox levels.	Higher Nox levels against standards.	Higher combustion temperatures.	7	5	8	280	R&D Tests (Appliances currently in production). -	To be assessed by R&D testing of appliance. Legacy appliances to be individually assessed.	Manufacturer. Government.
23	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back. Excess primary air.	If current burner not suitable for hydrogen, new ones required.	9	5	5	225	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Burner to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
22	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	If current injectors not suitable for hydrogen mix, new ones required.	9	4	6	216	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Injector size to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
24	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	Inappropriate gas/air ratio.	9	4	6	216	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Testing performed to determine what would happen if not adjusted. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer trained in hydrogen admix. Government.
3	Appliance Layout & Location	Gas Safety	Gas accumulation within the appliance or in the vicinity of the appliance	Hydrogen rich gas atmosphere accumulated over time leading to uncontrolled ignition.	Appliance design or incorrect installation providing opportunity for H2 gas content released during normal operation (stop/start) to accumulate in high points.	10	3	7	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliances need to be assessed for areas that can accumulate Hydrogen and modified accordingly. Delayed ignition testing to take place. To be assessed during the local changeover process.	Manufacturer. Service Engineer - trained in hydrogen admix.
20	Burner	Combustion	Condensate dripping onto burner.	Burner corrosion. Long term durability issues. Blocked burner ports. Light back.	Increased condensate production.	7	5	6	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliance to be tested to determine whether it is an issue and preventative measures to be put in place if needed. Regular inspection to be added during annual service. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
OVERALL ASSESSMENT:				Low Overall Risk. Mitigations are available. Legacy appliances are a concern.								

7.2 FMEA –Boilers – Non Condensing (Atmospheric Combustion)

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET

ENERTEK PROJECT NUMBER E4357

APPLIANCE TYPE: CAST IRON FLOOR STANDING GAS BOILER - ATMOSPHERIC COMBUSTION

OBJECTIVE OF FMEA: To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.

DATE OF ISSUE:		COMPILIED BY:	Howard Ruston	PARTICIPANTS	HFR	PAN	LP	PW
ISSUE No:	1	APPROVED BY:	Paul Needley		DB	BM		

NOTES: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.

REF No.	PART OR PROCESS No.	PART/PROCESS FUNCTION	FAILURE MODE	EFFECT OF FAILURE	CAUSE(S) OF FAILURE	SEVERITY (1 - 10)	PROB-ABILITY (1 - 10)	DETECT-ABILITY (10 - 1)	RISK PRIORITY No. (RPN)	CONTROLS	SUGGESTED ACTION	RESPONSIBILITY FOR ACTION
5	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Joints on existing appliances may require service activity.	10	6	8	480	R&D Tests (Appliances currently in production). Soundness check.	Testing to be performed on types of joints and seals to determine suitability for hydrogen. Appliance and gas joints should all be tested for tightness once conversion is compelted by a qualified gas engineer. Cast iron fittings should be avoided in gas lines.	Manufacturer. Gas engineer performing soundness checks during conversion.
6	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Exisiting component sealing seats may not be suitable for long-term hydrogen use.	10	6	8	480	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures. Gas valves require life testing to prove that they are safe for purpose.	Gas engineer performing soundness checks.
22	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	If current injectors not suitable for hydrogen, new ones required.	9	6	6	324	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Injector size to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
16	Burner	Combustion	Higher Nox levels.	Higher Nox levels against standards.	Higher combustion temperatures.	8	5	8	320	R&D Tests (Appliances currently in production). -	To be assessed by R&D testing of appliance. Legacy appliances to be individually assessed.	Manufacturer. Government.

12	Ignitor	Burner Ignition and Flame Proving	Appliance gets a false flame signal.	Gas flow through the burner when there is no flame. Damage to appliance if ignited.	If flame rectification is used, too much moisture can generate false readings.	10	3	10	300	R&D Tests (Appliances currently in production). -	Appliance to be tested to provve safe operation. Legacy appliances to be individually assessed.	Manufacturer. Government.
1	General Components	Overall Assembly	Temperature of components exceeds design limits.	Component failure. Potential damage to safety devices. Potential leak of hydrogen gas.	Higher combustion temperatures.	9	4	8	288	R&D Tests (Appliances currently in production).	Check component temperatures against new ambient temperature of components. Legacy appliances to be individually assessed.	Manufacturer. Government.
23	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back. Excess primary air.	If current burner not suitable for hydrogen, new ones required.	9	5	5	225	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Burner to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
3	Appliance Layout & Location	Gas Safety	Gas accumulation within the appliance or in the vicinity of the appliance	Hydrogen gas atmosphere accumulated over time leading to uncontrolled ignition.	Appliance design or incorrect installation providing opportunity for H2 gas released during normal operation (stop/start) to accumulate in high points.	10	3	7	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliances need to be assessed for areas that can accumulate Hydrogen and modified accordingly. Delayed ignition testing to take place. To be assessed during the local changeover process.	Manufacturer. Service Engineer - trained in hydrogen admix.
20	Burner	Combustion	Condensate dripping onto burner during cold start.	Burner corrosion. Long term durability issues. Blocked burner ports. Light back.	Increased condensate production from a cold start.	7	5	6	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliance to be tested to determine whether it is an issue and preventative measures to be put in place if needed. Regular inspection to be added during annual service. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
OVERALL ASSESSMENT:				Low Overall Risk. Mitigations are available. Legacy appliances are a concern.								

8.4 FMEA –Boilers – Condensing (Pre-Mix Combustion)

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET												ENERTEK PROJECT NUMBER E4357
APPLIANCE TYPE: PREMIX & ATMOSPHERIC COMBUSTION CONDENSING BOILERS												
OBJECTIVE OF FMEA:	To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.											
DATE OF ISSUE:			COMPILIED BY:	Howard Ruston	PARTICIPANTS	HFR	PAN	LP	PW	**NOTES**: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.		
ISSUE No:		1	APPROVED BY:	Paul Needley		DB	BM					
REF No.	**PART OR PROCESS No.**	**PART/PROCESS FUNCTION**	**FAILURE MODE**	**EFFECT OF FAILURE**	**CAUSE(S) OF FAILURE**	**SEVERITY (1 - 10)**	**PROB-ABILITY (1 - 10)**	**DETECT-ABILITY (10 - 1)**	**RISK PRIORITY No. (RPN)**	**CONTROLS**	**SUGGESTED ACTION**	**RESPONSIBILITY FOR ACTION**
5	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Joints on existing appliances may require service activity.	10	6	8	480	R&D Tests (Appliances currently in production). Soundness check.	Testing to be performed on types of joints and seals to determine suitability for hydrogen. Appliance and gas joints should all be tested for tightness once conversion is compelted by a qualified gas engineer. Cast iron fittings should be avoided in gas lines.	Manufacturer. Gas engineer performing soundness checks during conversion.
6	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Exisiting component sealing seats may not be suitable for long-term hydrogen use.	10	6	8	480	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures. Gas valves require life testing to prove that they are safe for purpose.	Gas engineer performing soundness checks.
14	Burner	Combustion	Higher Nox levels.	Higher Nox levels against standards.	Higher combustion temperatures.	8	5	8	320	R&D Tests (Appliances currently in production). -	To be assessed by R&D testing of appliance. Legacy appliances to be individually assessed.	Manufacturer. Government.
11	Ignitor	Burner Ignition and Flame Proving	Appliance gets a false flame signal.	Gas flow through the burner when there is no flame. Damage to appliance if ignited.	If flame rectification is used, too much moisture can generate false readings.	10	3	10	300	R&D Tests (Appliances currently in production). -	Appliance to be tested to provve safe operation. Legacy appliances to be individually assessed.	Manufacturer. Government.

1	General Components	Overall Assembly	Temperature of components exceeds design limits.	Component failure. Potential damage to safety devices. Potential leak of hydrogen gas.	Higher combustion temperatures.	9	4	8	288	R&D Tests (Appliances currently in production).	Check component temperatures against new ambient temperature of components. Legacy appliances to be individually assessed.	Manufacturer. Government.
20	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back. Excess primary air.	If current burner not suitable for hydrogen admix, new ones required.	9	5	5	225	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Burner to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
21	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	Inappropriate gas/air ratio setting.	9	4	6	216	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Testing performed to determine what would happen if not adjusted. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer trained in hydrogen admix. Government.
3	Appliance Layout & Location	Gas Safety	Gas accumulation within the appliance or in the vicinity of the appliance	Hydrogen gas atmosphere accumulated over time leading to uncontrolled ignition.	Appliance design or incorrect installation providing opportunity for H2 gas released during normal operation (stop/start) to accumulate in high points.	10	3	7	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliances need to be assessed for areas that can accumulate Hydrogen and modified accordingly. Delayed ignition testing to take place. To be assessed during the local changeover process.	Manufacturer. Service Engineer - trained in hydrogen admix.
13	Burner	Combustion	Cracking burners.	Burner failure. Flame failure. Damage to appliance.	Burner skin not suitable for the higher temperatures of operating with hydrogen.	10	3	7	210	Check the materials used and their suitability to a hydrogen mixture.	Check grades of materials used and suitability for the temperature to be incurred. Legacy appliances to be individually assessed.	Manufacturer. Government.
18	Burner	Combustion	Condensate dripping onto burner.	Burner corrosion. Long term durability issues. Blocked burner ports. Light back.	Increased condensate production.	7	5	6	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliance to be tested to determine whether it is an issue and preventative measures to be put in place if needed. Regular inspection to be added during annual service. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
OVERALL ASSESSMENT:				Low Overall Risk. Mitigations are available. Legacy appliances are a concern.								

8.5 FMEA – Burners

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET

ENERTEK PROJECT NUMBER E4357

APPLIANCE TYPE: PREMIX & ATMOSPHERIC COMBUSTION BURNERS

OBJECTIVE OF FMEA: To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.

DATE OF ISSUE:		COMPILIED BY:	Bradley Meakin	PARTICIPANTS	HFR	PAN	LP	PW
ISSUE No:	1	APPROVED BY:	Paul Needley		DB	BM		

NOTES: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.

REF No.	PART OR PROCESS No.	PART/PROCESS FUNCTION	FAILURE MODE	EFFECT OF FAILURE	CAUSE(S) OF FAILURE	SEVERITY (1 - 10)	PROB-ABILITY (1 - 10)	DETECT-ABILITY (10 - 1)	RISK PRIORITY No. (RPN)	CONTROLS	SUGGESTED ACTION	RESPONSIBILITY FOR ACTION
2	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Exisiting component sealing may not be suitable for long-term hydrogen use.	10	6	8	480	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures.	Manufacturer.
13	Burner	Combustion	Higher Nox levels.	Higher Nox levels against standards.	Higher combustion temperatures.	8	5	8	320	R&D Tests (Appliances currently in production).	To be assessed by R&D testing of appliance.	Manufacturer.
9	Ignitor	Burner Ignition and Flame Proving	Appliance gets a false flame signal.	Gas flow through the burner when there is no flame. Damage to appliance if ignited.	If flame rectification is used, too much moisture can generate false readings.	10	3	10	300	R&D Tests (Appliances currently in production). -	Appliance to be tested to prove safe operation.	Manufacturer.
17	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back. Excess primary air.	If current burner not suitable for hydrogen mix, new ones required.	9	5	5	225	R&D Tests (Appliances currently in production).	Burner to be validated.	Manufacturer.
16	Burner	Combustion	Condensate dripping onto burner.	Burner corrosion. Long term durability issues. Blocked burner ports. Light back.	Increased condensate production.	7	5	6	210	R&D Tests (Appliances currently in production).	Appliance to be tested to determine whether it is an issue and preventative measures to be put in place if needed.	Manufacturer.

OVERALL ASSESSMENT:	Low Overall Risk. Mitigations are available.

8.6 FMEA – Control Valves

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET												
ENERTEK PROJECT NUMBER	E4357											
APPLIANCE TYPE: CONTROL VALVES												
OBJECTIVE OF FMEA:	To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.											
DATE OF ISSUE:			COMPILIED BY:	Bradley Meakin	PARTICIPANTS	HFR	PAN	LP	PW	**NOTES**: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.		
ISSUE No:		1	APPROVED BY:	Paul Needley		DB	BM					
REF No.	**PART OR PROCESS No.**	**PART/PROCESS FUNCTION**	**FAILURE MODE**	**EFFECT OF FAILURE**	**CAUSE(S) OF FAILURE**	**SEVERITY (1 - 10)**	**PROB-ABILITY (1 - 10)**	**DETECT-ABILITY (10 - 1)**	**RISK PRIORITY No. (RPN)**	**CONTROLS**	**SUGGESTED ACTION**	**RESPONSIBILITY FOR ACTION**
3	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas constituents through the valve when closed.	Exisiting component sealing seats may not be suitable for long-term hydrogen use.	10	6	9	540	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures. Gas valves require life testing to prove that they are safe for purpose.	Manufacturer.
2	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Joints on existing components may require service activity.	10	6	8	480	R&D Tests (Appliances currently in production).	Testing to be performed on types of joints and seals to determine suitability for hydrogen. Cast iron fittings should be avoided in gas lines.	Manufacturer.
1	Appliance Seals	Appliance Soundness	Melting/failure of seals.	Leakage of water. Leakage of gas. Leakage of combustion products	Higher combustion temperatures.	10	4	4	160	R&D Tests (Appliances currently in production).	Check temperatures at seal positions against material capabilities.	Manufacturer.
4	Gas Circuit	Gas Distribution	Material failure through hydrogen embrittlement.	Material failure resulting in gas leakage.	Inappropriate materials.	10	1	8	80	Checks on the materials used and suitability for use with hydrogen mix.	Check all materials used and check suitability on each component/ appliance.	Manufacturer.
5	Gas Circuit	Gas Distribution	Control valves unable to facilitate change in gas flow.	Control valves unable to supply gas effectively.	Change in gas flow properties.	4	3	5	60	None available	None - User has to accept some degree of downrating	User
OVERALL ASSESSMENT:	Low Overall Risk. Mitigations are available. Cast iron and threaded fittings are a concern.											

8.7 FMEA – Venting Products

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET

ENERTEK PROJECT NUMBER E4357

APPLIANCE TYPE: VENTING PRODUCTS

OBJECTIVE OF FMEA: To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.

DATE OF ISSUE: | COMPILIED BY: Howard Ruston | PARTICIPANTS HFR PAN LP PW DB BM | **NOTES**: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.

ISSUE No: 1 | APPROVED BY: Paul Needley

REF No.	PART OR PROCESS No.	PART/PROCESS FUNCTION	FAILURE MODE	EFFECT OF FAILURE	CAUSE(S) OF FAILURE	SEVERITY (1 - 10)	PROB-ABILITY (1 - 10)	DETECT-ABILITY (1 - 10)	RISK PRIORITY No. (RPN)	CONTROLS	SUGGESTED ACTION	RESPONSIBILITY FOR ACTION
3	Vent	Venting	Vents exceed standard limit temperature.	Damge to vent. Damage to installation area. Leakage of combustion products.	Increase in combustion product temperature.	9	3	5	135	Check materials used and their suitability against the higher vent temperatures.	R&D testing to determine increase in vent surface temperature to assess suitability of vents.	Manufacturer.
4	Vent	Venting	Increased corrosion in vent.	Damage to vent. Leakage of combustion products.	Increase in water vapour content of combustion products.	9	2	6	108	Check materials used and their suitability for use with hydrochloric condensate.	Determine whether increase in hydrochloric condensate will cause significant increase in corrosion.	Manufacturer.
2	Vent	Venting	Vents exceed rated temperature.	Damge to vent. Leakage of combustion products.	Increase in combustion product temperature.	9	2	5	90	Check materials used and their suitability against the higher vent temperatures.	R&D testing to determine increase in products temperature to assess suitability of vents.	Manufacturer.
6	Vent	Concatenated Vent Condensate Disposal	Condensate system can not withstand hydrochloric acid waste condensate.	Leakage of condensate. Leakage of combustion products.	Changes in composition of condensate (carbonic & hydrochloric acid).	8	3	3	72	Check the materials used and their suitability with a hydrochloric acid condensate.	Check grades of materials used and suitability for the acidity to be incurred.	Manufacturer.
7	Vent	Venting	Vent terminal dripping condensate.	Pooling of condensate around terminal. Potential damage to termination area. Potential that pooling water can be frozen causing health and safety risk.	Increase in water vapour content of combustion products.	4	5	3	60	-	Assess flue terminals for potential dripping points in design.	Manufacturer.
OVERALL ASSESSMENT:				Low Overall Risk. Mitigations are available.								

8.8 FMEA – Water Heaters

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET													
										ENERTEK PROJECT NUMBER		E4357	
APPLIANCE TYPE: PREMIX & ATMOSPHERIC COMBUSTION WATER HEATERS													
OBJECTIVE OF FMEA:	To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.												
DATE OF ISSUE:			COMPILIED BY:	Bradley Meakin	PARTICIPANTS	HFR	PAN	LP	PW	**NOTES**: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.			
ISSUE No:		1	APPROVED BY:	Paul Needley		DB	BM						
REF No.	**PART OR PROCESS No.**	**PART/PROCESS FUNCTION**	**FAILURE MODE**	**EFFECT OF FAILURE**	**CAUSE(S) OF FAILURE**	**SEVERITY (1 - 10)**	**PROB-ABILITY (1 - 10)**	**DETECT-ABILITY (10 - 1)**	**RISK PRIORITY No. (RPN)**	**CONTROLS**	**SUGGESTED ACTION**	**RESPONSIBILITY FOR ACTION**	
5	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Joints on existing appliances may require service activity.	10	6	8	480	R&D Tests (Appliances currently in production). Soundness check.	Testing to be performed on types of joints and seals to determine suitability for hydrogen. Appliance and gas joints should all be tested for tightness once conversion is compelted by a qualified gas engineer. Cast iron fittings should be avoided in gas lines.	Manufacturer. Gas engineer performing soundness checks during conversion.	
6	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Exisiting component sealing seats may not be suitable for long-term hydrogen use.	10	6	8	480	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures. Gas valves require life testing to prove that they are safe for purpose.	Gas engineer performing soundness checks.	
23	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	If current injectors not suitable for hydrogen, new ones required.	9	6	6	324	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Injector size to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.	

25	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	Inappropriate gas/air ratio.	9	6	6	324	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Testing performed to determine what would happen if not adjusted. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer trained in hydrogen admix. Government.
17	Burner	Combustion	Higher Nox levels.	Higher Nox levels against standards.	Higher combustion temperatures.	8	5	8	320	R&D Tests (Appliances currently in production). -	To be assessed by R&D testing of appliance. Legacy appliances to be individually assessed.	Manufacturer. Government.
13	Ignitor	Burner Ignition and Flame Proving	Appliance gets a false flame signal.	Gas flow through the burner when there is no flame. Damage to appliance if ignited.	If flame rectification is used, too much moisture can generate false readings.	10	3	10	300	R&D Tests (Appliances currently in production). -	Appliance to be tested to provve safe operation. Legacy appliances to be individually assessed.	Manufacturer. Government.
1	General Components	Overall Assembly	Temperature of components exceeds design limits.	Component failure. Potential damage to safety devices. Potential leak of hydrogen gas.	Higher combustion temperatures.	9	4	8	288	R&D Tests (Appliances currently in production).	Check component temperatures against limit temperatures of components. Legacy appliances to be individually assessed.	Manufacturer. Government.
24	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back. Excess primary air.	If current burner not suitable for hydrogen, new ones required.	9	5	5	225	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Burner to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
3	Appliance Layout & Location	Gas Safety	Gas accumulation within the appliance or in the vicinity of the appliance	Hydrogen gas atmosphere accumulated over time leading to uncontrolled ignition.	Appliance design or incorrect installation providing opportunity for H2 gas released during normal operation (stop/start) to accumulate in high points.	10	3	7	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliances need to be assessed for areas that can accumulate Hydrogen and modified accordingly. Delayed ignition testing to take place. To be assessed during the local changeover process.	Manufacturer. Service Engineer - trained in hydrogen admix.
21	Burner	Combustion	Condensate dripping onto burner.	Burner corrosion. Long term durability issues. Blocked burner ports. Light back.	Increased condensate production.	7	5	6	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliance to be tested to determine whether it is an issue and preventative measures to be put in place if needed. Regular inspection to be added during annual service. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
OVERALL ASSESSMENT:				Low Overall Risk. Mitigations are available. Legacy appliances are a concern.								

8.9 FMEA – Pool Heaters

AHRI PROJECT 8024 - FAILURE MODE & EFFECTS ANALYSIS (FMEA) - ASSESSMENT SHEET

ENERTEK PROJECT NUMBER E4357

APPLIANCE TYPE: PREMIX & ATMOSPHERIC COMBUSTION POOL HEATERS

OBJECTIVE OF FMEA: To assess the likelihood of field problems concerning safety, reliability or performance issues if the gas supply is changed from 100% methane to 80% methane and and 20% hydrogen by volume.

DATE OF ISSUE:		COMPILIED BY:	Bradley Meakin	PARTICIPANTS	HFR	PAN	LP	PW	**NOTES**: Due to Covid 19 social distancing requirements, participants were not convened together at the time of assessment.
ISSUE No:	1	APPROVED BY:	Paul Needley		DB	BM			

REF No.	PART OR PROCESS No.	PART/PROCESS FUNCTION	FAILURE MODE	EFFECT OF FAILURE	CAUSE(S) OF FAILURE	SEVERITY (1 - 10)	PROB-ABILITY (1 - 10)	DETECT-ABILITY (10 - 1)	RISK PRIORITY No. (RPN)	CONTROLS	SUGGESTED ACTION	RESPONSIBILITY FOR ACTION
5	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Joints on existing appliances may require service activity.	10	6	8	480	R&D Tests (Appliances currently in production). Soundness check.	Testing to be performed on types of joints and seals to determine suitability for hydrogen. Appliance and gas joints should all be tested for tightness once conversion is compelted by a qualified gas engineer. Cast iron fittings should be avoided in gas lines.	Manufacturer. Gas engineer performing soundness checks during conversion.
6	Gas Circuit	Gas Distribution	Gas line joints/components leaking gas.	Potential leak of hydrogen gas.	Exisiting component sealing seats may not be suitable for long-term hydrogen use.	10	6	8	480	R&D Tests (Appliances currently in production).	Replace fittings that are not sound and those likely not to be sound in the future based on failures. Gas valves require life testing to prove that they are safe for purpose.	Gas engineer performing soundness checks.
23	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	If current injectors not suitable for hydrogen, new ones required.	9	6	6	324	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Injector size to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
17	Burner	Combustion	Higher Nox levels.	Higher Nox levels against standards.	Higher combustion temperatures.	8	5	8	320	R&D Tests (Appliances currently in production). -	To be assessed by R&D testing of appliance. Legacy appliances to be individually assessed.	Manufacturer. Government.
13	Ignitor	Burner Ignition and Flame Proving	Appliance gets a false flame signal.	Gas flow through the burner when there is no flame. Damage to appliance if ignited.	If flame rectification is used, too much moisture can generate false readings.	10	3	10	300	R&D Tests (Appliances currently in production). -	Appliance to be tested to provve safe operation. Legacy appliances to be individually assessed.	Manufacturer. Government.

1	General Components	Overall Assembly	Temperature of components exceeds design limits.	Component failure. Potential damage to safety devices. Potential leak of hydrogen gas.	Higher combustion temperatures.	9	4	8	288	R&D Tests (Appliances currently in production).	Check component temperatures against limit temperatures of components. Legacy appliances to be individually assessed.	Manufacturer. Government.
24	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back. Excess primary air.	If current burner not suitable for hydrogen, new ones required.	9	5	5	225	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Burner to be validated. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
25	Combustion Chamber	Gas Distribution	Noise/ Poor Combustion.	Poor/ dangerous emissions from appliance. Possible light-back.	Inappropriate gas/air ratio.	9	4	6	216	R&D Tests (Appliances currently in production). Check on combustion when commissioning.	Testing performed to determine what would happen if not adjusted. To be tested during the local changeover process. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer trained in hydrogen admix. Government.
3	Appliance Layout & Location	Gas Safety	Gas accumulation within the appliance or in the vicinity of the appliance	Hydrogen gas atmosphere accumulated over time leading to uncontrolled ignition.	Appliance design or incorrect installation providing opportunity for H2 gas released during normal operation (stop/start) to accumulate in high points.	10	3	7	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliances need to be assessed for areas that can accumulate Hydrogen and modified accordingly. Delayed ignition testing to take place. To be assessed during the local changeover process.	Manufacturer. Service Engineer - trained in hydrogen admix.
21	Burner	Combustion	Condensate dripping onto burner.	Burner corrosion. Long term durability issues. Blocked burner ports. Light back.	Increased condensate production.	7	5	6	210	R&D Tests (Appliances currently in production). Service & Inspection.	Appliance to be tested to determine whether it is an issue and preventative measures to be put in place if needed. Regular inspection to be added during annual service. Legacy appliances to be individually assessed.	Manufacturer. Service Engineer - trained in hydrogen admix. Government.
OVERALL ASSESSMENT:				Low Overall Risk. Mitigations are available. Legacy appliances are a concern.								

9 CONCLUSIONS

9.1 The Hydrogen Roadmap.

9.1.1 Hydrogen is seen as a critical vector for decarbonisation worldwide. There is massive international interest in the production, distribution, and use of hydrogen.

9.1.2 However, there are multiple demands for hydrogen, and there are differing opinions as to whether hydrogen should be used as a storage medium, for industry, transport, or heating and cooking, and if the latter - whether it should be blended with methane or supplied as 100% hydrogen.

9.1.3 Fuel cells have an advantage over other gas products given their power generation and high efficiencies, and many countries see fuels cells as the future key to heating. This is likely to influence the most forward-looking policy makers.

9.1.4 Many countries including the UK, Germany and much of Northern Europe see blended hydrogen as an intermediate step to reduce carbon whilst simultaneously building hydrogen production capacity so that 100% hydrogen can be suppled in the future.

9.1.5 There are many major projects, mainly government backed to investigate the feasibility of hydrogen as a replacement for natural gas and arguably the UK is at the forefront of these developments, certainly with 100% hydrogen.

9.1.6 The US landscape appears to be changing and interest in hydrogen is accelerating to stem the threat of climate change.

9.2 Existing Hydrogen Enrichment Research Programmes.

9.2.1 The UK HyDeploy project is currently underway and will provide valuable feedback regarding the long-term effects of running appliances on 20% hydrogen blended with 80% methane (by volume). Results will be available during the next few months.

9.2.2 A major European research project ‘ThyGa’ commenced in January 2020 to look at the feasibility of blended hydrogen with various hydrogen concentrations. It is generally believed that the output from this project will inform most of Europe what the prospects are for blended gas. Interim results are being published throughout the project and final results will be available from late 2021 onwards.

9.3 Theoretical Analysis of Blended Hydrogen (Typically 20% Hydrogen, 80% Methane)

9.3.1 The properties of Hydrogen are very different to those of methane, with a lower density, viscosity, calorific value, molecular weight and radiant emissivity, but a higher flame speed, combustible range and flame temperature. However, their respective Wobbe numbers are remarkably similar and when hydrogen is blended with 20% methane the effects on overall performance counterbalance each other to a significant extent.

9.3.2 The effects of adding 20% hydrogen by volume to methane without any adjustments to an appliance can be summarised as:

- A reduction in heat input of approximately 5%.
- An increase in combustion products dewpoint of approximately 2°F.
- An increase in flame speed.
- A reduction in radiation heat transfer.
- A higher excess air level.
- A likely reduction in NOx (due to higher excess air level).
- An increase in burner temperature (due to higher flamespeed).
- An increase in water vapour.

9.3.3 The overall effect on performance is minimised because many of these attributes offset or counter-balance changes which would otherwise occur. For example:

- The lower heat input coupled with an increase in excess air level prevents a significant increase in flame temperature, and can cause a reduction in NOx.
- The effect on efficiency depends upon the appliance design and the relative counter-balancing of the above charateristics, but the lower heat input marginally increases efficiency wheras the higher excess air and lower radiation marginally decreases it.

9.3.4 Note that if the appliance is adjusted to recover the lost 5% heat input, the counter-balancing effect is lost and the above conclusions no longer apply. NOx, flame temperature and burner temperature all rise and efficiency is likely to fall.

9.3.5 Long term reliability issues are unknown but corrosion and leakage are areas where further research is needed.

9.3.6 Hydrogen embrittlement is a concern, but initial results from the THyGA project suggest that it does not pose a threat to gas appliances under normal conditions. However, its components and risks need to be understood with respect to the whole gas network, not just gas appliances.

9.3.7 Hydrogen is more volatile than methane and carries a higher risk of detonation if mishandled, hence as the percentage of blended hydrogen increases, safety becomes a bigger factor.

9.4 Risks to Appliances with Hydrogen Admixtures

9.4.1 The two greatest short-term risks to appliances are flame light-back and hydrogen gas leakage. Light-back is a dangerous condition (overheating and high CO levels), and leakage caused by hydrogen being able to seep through gaps which no other gas can do is also a safety risk, albeit at a very low level given the seepage rates if the pipework does not leak with methane. (Over time in a confined space this could build up).

9.4.2 From the analysis of appliances covered by this report, it appears that modern (current production) gas appliances will withstand the increased propensity to light-back without incident at a 20% hydrogen blend.

9.4.3 Pipe fittings and valves are potentially subject to hydrogen leakage and further work is needed to understand whether this is indeed a problem.

9.4.4 Hydrogen embrittlement of steel pipes and fittings is another area where further research is recommended, and this is particularly relevant to the US where steel is more commonly used for gas pipes than in the UK or Europe.

9.4.5 There is a concern with older appliances, (or legacy appliances) which have been out of production for many years. Enertek have direct experience 20 years ago with a US appliance which when tested with 22% hydrogen limit gas for certification in Europe lit back repeatedly and the burners had to be replaced before the manufacturer could meet the EC Certification requirements and sell the product in Europe (due to the limit gas requirements). Enertek know that many of these appliances were sold in the US and may still be in service today. If these are supplied with 20% hydrogen there will be problems.

9.4.6 With some legacy appliances the manufacturers may no longer be in business hence no support will be available, and these appliances will have to be identified and replaced.

9.4.7 Note that the old 'legacy' appliances will be operating much less efficiently than new appliances. It is likely that replacing a legacy appliance with a new one will save more $CO_{2\ than}$ the effect of adding 20% hydrogen to the gas supply! For this reason, it is not worth devoting R&D effort to overcome any issues, but it is worth seeking government policy support to assist with the cost of replacing them.

9.4.8 A calculator has been supplied with this report so that manufacturers can calculate the risk of light-back occurring on their own products and legacy appliances.

9.4.9 Enertek International have not found much difference in the risks associated with hydrogen enrichment for different types of US appliances. The risks are common to most models and are centred around ignition, combustion, light-back, materials and soundness.

9.4.10 Note that it is important not to adjust appliances at the time of changing the gas supply. The natural downrating of approximately 5% compensates for potential increases in temperature and flame speed which could take the appliances outside their normal operational envelope if they are adjusted to maintain heat input with blended gas.

9.4.11 Any appliances with combustion control (which maintain the excess air level) should be tested for compatibility with the higher temperatures before being supplied with blended gas.

9.4.12 Analysis of the products has however indicated that US appliances and installations are sufficiently different to their European equivalents to necessitate bespoke research programmes specific to the US market and environment. It is also worth noting that unlike their European counterparts, US appliances have not been tested for light-back with 23% hydrogen limit gas at the time of certification.

9.4.13 The validity of appliance certification needs to be considered. If the addition of hydrogen takes the gas outside the tolerance of the gas supply covered by certification, appliance warranties may become invalid and users could potentially have legal issues with insurers if their appliances effectively become de-certified.

9.4.14 If necessary, appliance certification requirements can be adjusted for new appliances, but this would exacerbate the problem for legacy appliances.

9.4.15 Note: Appliances whose combustion systems are set up and commissioned on site are deemed outside the scope of this project (these are usually commercial or industrial appliances), but it is worth noting that to set up and commission these appliances, the engineer must know what blend of gas is being supplied at the time. This could potentially impact the fitting of spare parts on appliances which are within the scope of the project.

9.5 Overall Conclusion

9.5.1 This report has followed the project brief to assess the uncertainties and safety implications of hydrogen-enriched natural gas by conducting a screening analysis and research to understand the potential impacts of hydrogen-enriched natural gas on factory (new) and currently installed (old) gas-fired products and components manufactured by AHRI Members to appropriately validate whether hydrogen-enriched fuel is safe or not.

9.5.2 Our overall conclusion is that subject to conducting further research in the key areas defined in the report, theoretical indications and initial evidence suggests that it should be safe to inject up to 20% hydrogen into the US gas main without significant risk.

10 RECOMMENDATIONS

10.1 The Hydrogen Scenario

10.1.1 Several hydrogen related research projects are already underway in the US, and AHRI are well positioned to find the government's perspective of the viability of a hydrogen blended gas network. Our recommended first step is to determine whether the US Government is likely to issue a hydrogen policy statement similar to what has happened in the UK and Germany and if so, try to influence and inform them what actions should be taken.

10.1.2 If a hydrogen admixture policy is to be implemented, government support should be sought to subsidise the replacement of legacy / obsolete products. (Recently the UK introduced a government backed 'boiler scrappage scheme' to encourage the adoption of new high efficiency boilers to reduce CO_2. The policy was very successful, enabled many consumers to purchase a new appliance and provided boiler manufacturers with additional sales).

10.1.3 The 'Hydrogen for heat' opportunity is being pursued around the world. AHRI may wish to consider commissioning a separate programme to more thoroughly document what is happening elsewhere and keep an up-to-date log of international government policies and incentives / programmes. This could be used to lobby the US government for support based on the need for the US to be at the forefront of technology development.

10.2 US Research Programme Strategy

10.2.1 In terms of a strategy for research into the performance of US appliances on blended hydrogen, we see two main options:

- Commission a US research programme specifically designed to address the risks identified in this report on US appliances. Or:
- Plug into what is happening in Europe and use the available knowledge from European trials and research to inform a similar programme in the US. This would be a partnership approach where in return for access to European results (ThyGa) you could share your results with the European team to enhance worldwide knowledge on a co-operative basis.

10.3 Quantification of risks – Theory v Practice

10.3.1 Enertek recommend that bespoke research and test work should be carried out on typical US appliances (new and old) to compare the theory and practice and to gather evidence to confirm that significant appliance modifications are not needed to operate on 20% hydrogen. US Standards and test procedures mean that the starting point is slightly different to the European equivalents, so additional test work is required to definitively validate that operating with a 20% admixture is safe.

10.3.2 Research should also be carried out to address the unquantified risk of hydrogen embrittlement (especially in supply pipes). An academic peer review of the report published by THyGA may be an appropriate starting point – physics and chemistry are international, even though appliance designs and usage patterns have significant differences.

10.3.3 A further research work package should be commissioned to evaluate the risk of leakage from typical joints and connections used in US installations.

10.3.4 Appliance Standards and Certification status should be investigated to ensure that legacy appliances are not effectively outlawed by any change to the gas supply.

10.4 **Legacy Appliances**

10.4.1 Manufacturers should use Enertek's 'Light-back Calculation Program' to determine the risk of light-back in legacy appliances.

10.4.2 Where appropriate, a field fix should be developed to reduce the risk (e.g. new burners with smaller ports).

10.4.3 Current production and new appliances should be tested with the appropriate hydrogen admixture to prove satisfactory performance.

10.4.4 For legacy appliances where the manufacturer is not known or is no longer in business, a risk assessment should be carried out by a competent gas engineer, and where possible the light-back calculation programme used, but if there is a risk of light-back the appliance should be replaced.

10.4.5 Alternatively, it would be possible to determine (through theoretical or experimental means) a relationship between port size and input in which case a formula could be used to assess unknown legacy appliances, or possibly a simple instruction that if an appliance has a burner port diameter or width area above 'x' it is deemed unsuitable for an admixture. ('x' is likely to be less than 1/8th inch).

11 BIBLIOGRAPHY / REFERENCES & LINKS

11.1.1 2020. *BEIS Hy4heat*. [online] Available at: <**https://www.hy4heat.info/>**

11.1.2 HyDeploy. 2020. *Hydrogen Is Vital To Tackling Climate Change - Hydeploy*. [online] Available at: **https://hydeploy.co.uk/**

11.1.3 Assets.publishing.service.gov.uk. 2020. *UK Ten Point Plan*. [online] Available at: **https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf**

11.1.4 Hydrogen Strategy for Canada – 'Seizing the Opportunities for Hydrogen A Call to Action' December, 2020. **https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf**

11.1.5 2017. Marcogaz Technical Association Bulletin.[23/24 December 2017]

11.1.6 2017. Marcogaz Briefing to the 33rd Madrid Forum, [23/24 October 2019]

11.1.7 Jones, D., Al-Masry, W. and Dunnill, C., 2018. Hydrogen-enriched natural gas as a domestic fuel: an analysis based on flash-back and blow-off limits for domestic natural gas appliances within the UK. *Sustainable Energy & Fuels*, 2(4), pp.710-723.

11.1.8 Thyga-project.eu. 2020. *Thyga | Testing Hydrogen Admixture For Gas Applications*. [online] Available at: **https://thyga-project.eu/**

11.1.9 Thyga-project.eu. 2020. *Deliverable D2.4: Non-Combustion Related Impact Of Hydrogen Admixture – Material Compatibility | Thyga*. [online] Available at: **https://thyga-project.eu/deliverable-d2-4-non-combustion-related-impact-of-hydrogen-admixture-material-compatibility/**

11.1.10 Thyga-project.eu. 2020. *Webinar "MATERIALS SCIENCE – IMPACTS OF HYDROGEN BLENDS" | Thyga*. [online] Available at: **https://thyga-project.eu/webinar-materials-science-impacts-of-hydrogen-blends/**

11.1.11 Thyga-project.eu. 2020. *WEBINAR "IMPACT OF HYDROGEN ADMIXTURE ON RESIDENTIAL AND COMMERCIAL COMBUSTION PROCESSES INSIGHTS FROM COMBUSTION SCIENCE" | Thyga*. [online] Available at: **https://thyga-project.eu/webinar-impact-of-hydrogen-admixture-on-residential-and-commercial-combustion-processes-insights-from-combustion-science/**

11.1.12 Thyga-project.eu. 2020. *Deliverable D2.2: Impact Of Hydrogen Admixture On Combustion Processes – Part I: Theory | Tyga*. [online] Available at: **https://www.google.com/search?q=%3Chttps%3A%2F%2Fthyga-project.eu%2Fdeliverable-d2-2-impact-of-hydrogen-admixture-on-combustion-processes-part-i-theory%2F%3E+%5BAccessed+9+December+2020%5D.&rlz=1C1CHBF_en-**

GBGB839GB839&oq=%3Chttps%3A%2F%2Fthyga-project.eu%2Fdeliverable-d2-2-impact-of-hydrogen-admixture-on-combustion-processes-part-i-theory%2F%3E+%5BAccessed+9+December+2020%5D.&aqs=chrome..69i57.1601j0j15&sourceid=chrome&ie=UTF-8

11.1.13 (Fig 3) (source E.ON Ruhrgas)

11.1.14 The Gas Appliance Regulation (GAR) Regulation (EU) 2016/426 on appliances burning gaseous fuels

11.1.15 European Standard BS EN437:2018 Test Gases–Test Pressures–Appliance Categories

1 Malmo Road
Sutton Fields
Kingston upon Hull, HU7 0YF

+44 (0) 1482 877500
enertekinternational.com
Registered in England No. 2262638